

Review of Wind Turbine Technologies and Combined Scheme for DFIG FRT Capability

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Abstract

As the increasing installation of wind turbines, various wind turbine technologies have been developed. It is becoming more important that the wind turbine remain connected to the grid network during faults, so-called Fault ride through (FRT). An overview of different wind turbine technologies including their market shares and FRT grid codes from many countries are presented. Variable speed wind turbines offer many advantages when compared with fixed-speed turbines. In global market share, variable speed wind turbines based on DFIG are widely used. In this paper, two main controls for the DFIG wind turbine are summarized. Then, trends of DFIG wind turbine model and combined scheme of DFIG FRT capability are discussed. Finally, the proposed DFIG system model with a combined scheme of FRT capability is needed and deserve further examination.

Keywords: DFIG, Doubly-Fed Induction Generator, Wind turbine, FRT capability

1. Introduction

1.1 Wind Energy Penetration

To reduce the impact of conventional electricity generation on the environment, many countries have increasingly sought to use alternative environmentally friendly sources, i.e. renewable sources. This can reduce carbon emissions in the process of electricity generation by utilizing infinite natural sources. One renewable source that is of world-wide interest is wind power [1], as evident from Fig.1 showing installed world wind energy [2, 3].

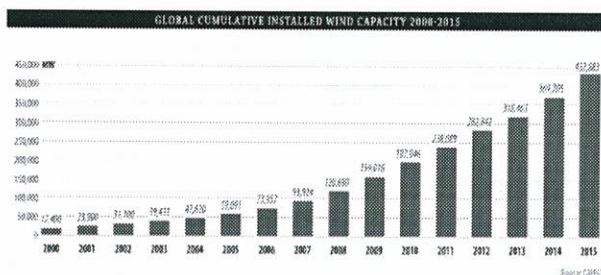


Fig. 1 Total world-wide installed wind generation capacity (2000-2015)[2]

According to the global wind report [2], the world has seen a new record in new wind installations. The

wind capacity increased by 63.18 GW from the end of 2014, and reached 433 GW within the 2015 for the total wind capacity of the world. Amongst the top 10 markets, China, USA and Germany were the most dynamic countries and saw the strongest growth rates. As shown in Fig. 2, these three countries shared the global wind market with 33.6%, 17.2% and 10.4%, respectively.

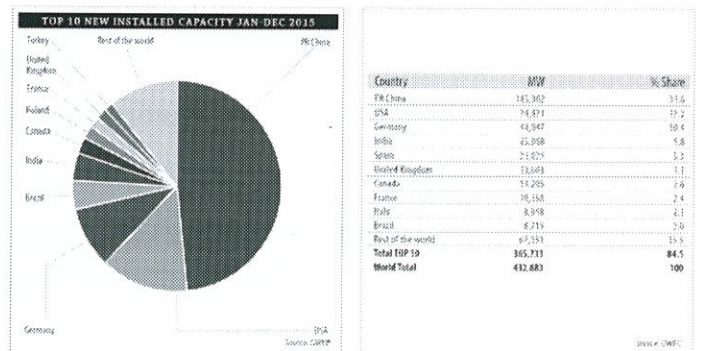


Fig. 2 Top 10 countries by total wind installations [2]

Increasing demand for wind power has resulted in many regions or countries developing the technical requirements for the connection of large wind farms with regard to the grid codes issued by Transmission System Operators (TSOs) [4]. These requirements are typically designed to ensure that large wind farms remain connected to the transmission system during disturbances (such as voltage dips), so-called fault ride through (FRT). Grid code requirements have been an important element in the development of wind turbine (WT) technology [5]. This paper is divided into 7 sections. Starting with an introduction in Section 1, Section 2 gives wind turbine technologies while section 3 presents the global market shares for wind turbine technologies. Section 4 covers fault-ride through requirement and some examples of grid code while Section 5 gives an overview of a DFIG wind turbine control. Finally, trend discussion and conclusion are carried out in Section 6 and 7, respectively.

2. Wind turbine technologies

Wind turbines are generally classified into two main technologies:

2.1 Type A: Fixed speed wind turbines

Squirrel cage induction generators directly connected to the grid are usually used for this type, as shown in Fig.3. The rotational speed of the generator is normally fixed with a slip of around 1%. These induction machines consume reactive power from the grid, hence capacitive compensation at the wind turbine grid connection is necessary. Their aerodynamic control is based on stall, active stall or pitch control. A variation of this scheme allows control of the speed of a wound rotor induction generator with external resistors up to 10% above synchronous speed [9].

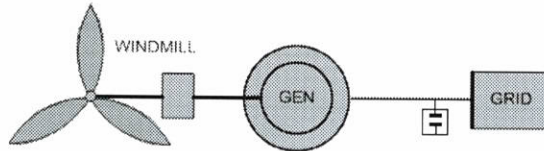


Fig. 3 Fixed-speed wind turbine (Type A)

2.2 Type B: Variable speed wind turbines

In this type of wind turbine, the rotor speed can be varied in line with prevailing wind conditions. There are two main types in this technology: The first (Type B1) is a synchronous/induction generator the stator of which is connected to the grid via a fully rated power converter, as shown in Fig. 4. The second (Type B2) is a Doubly-Fed Induction Generator (DFIG), as shown in Fig. 5. Here, the stator is directly connected to the grid while the rotor is connected to the grid via a four-quadrant converter [6-8] or back-to-back converter [9, 10]. The aerodynamic control of variable speed turbines is practically based on blade pitch control.

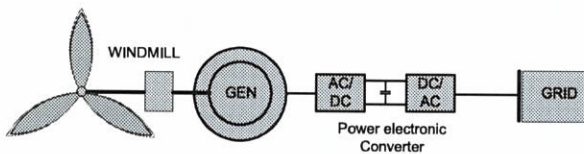


Fig. 4 Variable-speed wind turbine with fully-rated converters (Type B1)

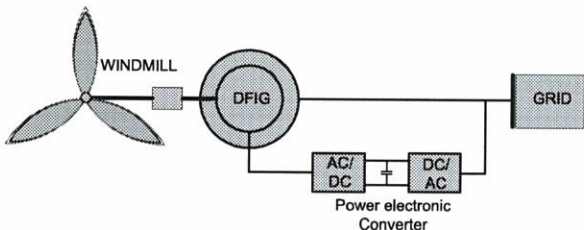


Fig. 5 Variable-speed wind turbine with partially-rated converters (Type B2)

Variable speed wind turbines offer a number of advantages [7, 11] when compared with fixed-speed turbines, such as operation over a wider range of wind velocities, independent control of active and reactive

power, reduced flicker and lower acoustic noise levels. In the case of variable speed wind turbines, the DFIG converter handles a fraction of the turbine power (about 30% in practice) compared with a fully-rated converter [11, 12]. As a result, the DFIG is more cost-effective and widely used for large grid-connected, variable-speed wind turbines.

3. Market Share for Wind Turbine technologies

As mentioned in the above description, Fig. 6 shows the share of each manufacturer in the onshore variable-speed wind turbine topologies used globally for the 2013 market [13].

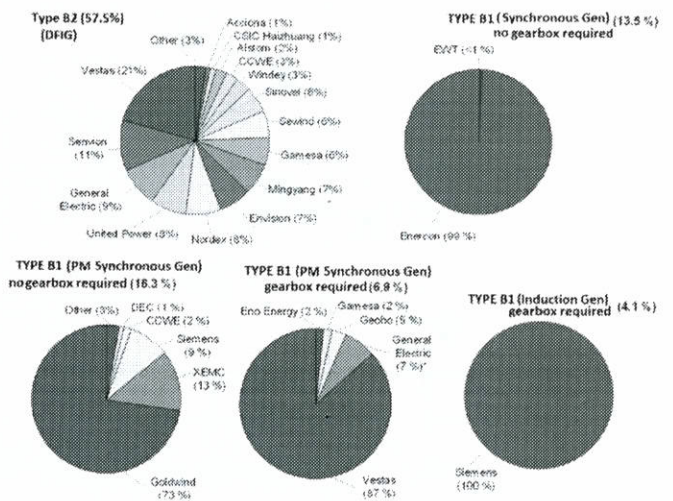


Fig. 6 Manufacturers' global market share for each variable-speed wind turbine during 2013 [13]

The global market share of each variable-speed wind turbine type is shown in brackets, while the indicated percentages of each manufacturer are mentioned in each type. The variable-speed wind turbines based on DFIG (TYPE B2) cover 57.5% of the total installed capacity while others (TYPE B1) are divided into four subsets: First based on electrically excited synchronous generator with no gearbox required, second based on permanent-magnet synchronous generator with no gearbox required, third based on permanent-magnet synchronous generator with gearbox required, and the last one based on induction generator with gearbox required. They are involved in 13.5%, 16.3%, 6.9% and 4.1% for their market share, respectively.

With the increasing penetration of wind power into the grid, transmission system operators (TSOs) have given rise to concern the impact of high power feeding into power system. To deal with this situation, TSOs have issued grid codes and grid requirements for wind turbines connection. The main issues of grid codes can be related to active power control, reactive power

control, voltage and frequency control, power quality, and fault ride-through capability.

4. Fault Ride Through (FRT) requirements

As stated in previous section, FRT requirements are developed to ensure that large wind farms remain connected to the transmission system during disturbances. Without these requirements, disconnecting large wind farms leads to power system network problems such as voltage collapse which may lead to whole system collapse. Various FRT grid codes [14, 15] from many countries are shown in Fig. 7. The German code from E.ON Netz GmbH, the GB code from National Grid Electricity Transmission, the Irish code published by ESB National Grid, the Nordic Grid code from Nordel TSO, the Denmark code of Danish TSO, the grid code for Belgium issued by the Belgian TSO, the grid codes of two Canadian TSOs issued by Hydro-Quebec and Alberta Electric System Operator (AESO), the USA rule for the interconnection of wind generators published by the Federal Energy Regulatory Commission (FERC), and codes from other countries such as Spain, Italy, Sweden and New Zealand.

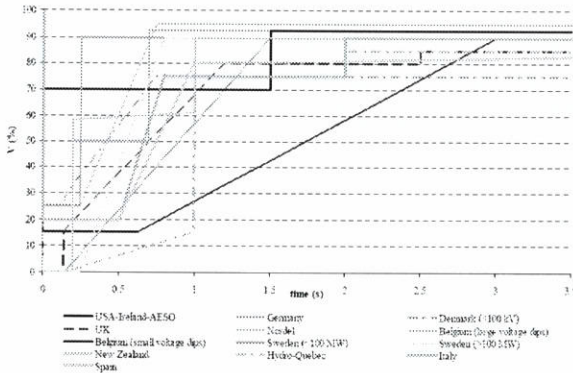


Fig. 7 Fault ride through requirements of various grid codes [15]

The Y-axis shows retained voltage (%) which then relates to the time duration (s) of FRT in the X-axis. The FRT requirements depend on the individual characteristics of each grid system. On or above the FRT line, a wind farm must ride through.

5. A DFIG wind turbine control

Normally, a wind turbine system consists of the aerodynamical, mechanical and electrical parts all operating with different time constants, with the electrical dynamics being typically much faster than the mechanical changes. Given the presence of the power electronics converter in the DFIG wind turbine, the difference in time constants becomes bigger in the case of a variable speed wind turbine [16].

Two main control systems are essential for controlling a DFIG wind turbine, as shown in Fig. 8.

These two control systems are significantly connected to each other, i.e. generator and wind turbine controls, of which the generator control operates much faster.

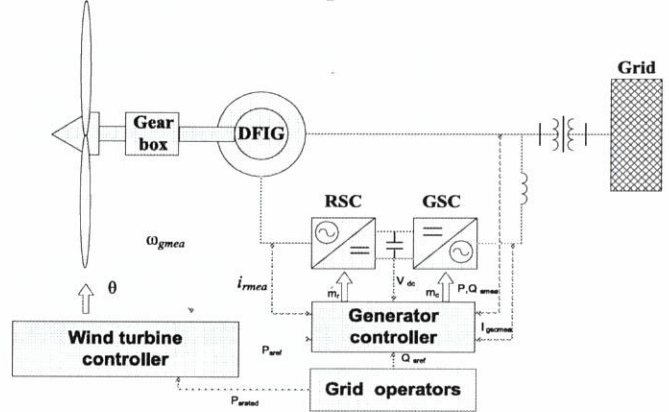


Fig. 8 Schematic diagram of the control system of a DFIG wind turbine

In summary, there are two main controls for the DFIG wind turbine: 1) DFIG control with three reference inputs: The reference active power (P_{sref}) provided by the wind turbine characteristic for RSC control as shown in Fig. 8. The reference reactive power (Q_{sref}) defined by the grid operators for RSC and GSC control. For instance, during fault conditions the DFIG is required to generate reactive power to support the grid system. The reference dc-link voltage (V_{dc}) defined by the size of the converter, the stator-rotor voltage ratio and the modulation factor of the power converter for GSC control. 2) Wind turbine control with two reference inputs: The reference active power (P_{sref}) for the generator control generated by the speed controller within the wind turbine controller as seen in Fig. 8, when the wind speed is less than the rated speed (V_{rated}) (see Fig. 9). The speed controller operates to keep the generator speed at the minimum limit, as well as maintaining the generator speed for tracking maximum wind power [16]. The pitch angle (θ) of the wind turbine blades is controlled by the pitch controller within the wind turbine controller, when the wind speed is higher than the rated speed. The pitch controller is in operation to limit the wind power capture at the rated turbine power (P_{rated}) [17] and [18].

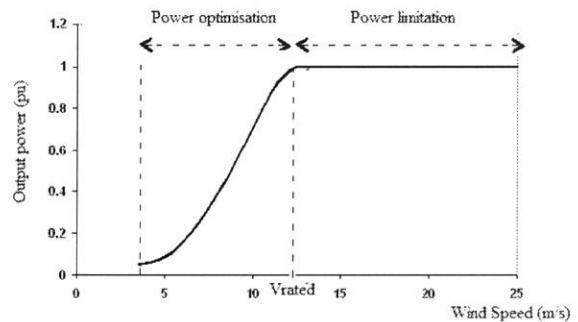


Fig. 9 A typical curve of output power and wind speed

6. Trend Discussion

6.1 Trend of wind turbine technologies

Variable speed wind turbines offer a number of advantages when compared with fixed-speed turbines, such as operation over a wider range of wind velocities, independent control of active and reactive power, reduced flicker and lower acoustic noise levels. In the case of variable speed wind turbines, the DFIG converter handles a fraction of the turbine power (about 30% in practice) compared with a fully-rated converter. **Therefore, the DFIG is more cost-effective and widely used for large grid-connected, variable-speed wind turbines.**

6.2 Grid connection requirement

As the penetration of wind power in power systems increases, wind farms are required to remain grid-connected during disturbances in order to keep systems stable. Many grid codes have been revised to ensure wind farms connected to the transmission system during faults – so-called **fault ride through (FRT) or Low voltage ride through (LVRT)**. Fault scenarios corresponding to three grid codes (Irish, GB and German) will be chosen to investigate FRT capability of the DFIG wind turbine. The Irish and GB codes are used to represent island systems, especially GB which has a high potential for off-shore wind farms, while the German code is used to represent a regional system which is connected to a European transmission system which is important for the wind farm market.

6.3 Trend of DFIG wind turbine model

A brief overview of the development of wind turbine models will be presented. Because this paper mainly focuses on large wind turbines connected to the grid, the modelling of large wind turbines (multi-megawatt size) is studied, especially the modelling of DFIG variable wind turbines published over the last decade. Third and fifth order models have been used by many authors to model the operation of a doubly-fed induction generator. A 3rd order model, presented by [19] and [20] represents the doubly-fed induction machine by a system of three differential equations, i.e. real, imaginary parts of the rotor flux and generator speed. Stator transients were neglected and the rotor voltage was assumed to have only the fundamental frequency while the third order model was used to study a DFIG under steady state operating conditions in order to increase the computational speed [21]. It has been showed that the third order model does not give sufficiently accurate results for disturbance conditions [22]. While a comparison between the 3rd and 5th order machine models has been examined by [23], the fifth

order model which includes the stator and rotor transients provided better results [24-27].

In [26, 27], the fifth-order model predicted better responses, especially the initial current occurring under transient and fault conditions. In a practical DFIG system, the converter voltage and current ratings as well as the size of the dc link capacitor are important to ensure good performance during grid disturbances. **Therefore, the 5th order machine model, including detailed modelling of the converter, is necessary to give more accurate results.**

6.4 Proposed DFIG system model with a combined scheme of FRT capability

Since 2003 a number of authors [28, 29, 30,] have published the essential elements of the combined scheme for FRT capability of a DFIG wind turbine. In [22], the DFIG model with representation of only the rotor converter (RSC) will lead to a higher rotor current than the model with RSC including the GSC and DC-link. Also, as a result of the higher rotor current protective devices and converters will need to be enabled or disabled at the value where that current ceases to be appropriate. **Therefore, detailed models of RSC, GSC and DC-link (back-to-back converters) are very important in the DFIG system.**

In addition, the combined scheme should be applied in the model for the FRT capability of a DFIG wind turbine. [31, 32] mentioned that both crowbar and DC-brake chopper are necessary for DFIG FRT capability to protect the rotor converter from over-current and overvoltage. [33, 34] also recommended that the combined scheme and control strategy helps to improve the FRT capability of a wind turbine driven DFIG but in connecting to DC-link, a battery energy storage system is used instead of a DC brake resistor. In 2013, [35] supported the usage of a crowbar and DC brake chopper for DFIG Fault ride through and also proposed the capacitance in a crowbar circuit. While in [36] the authors also used crowbar and DC-link chopper to improve the ride through ability of the DFIG system. As mentioned above, the conclusion is that the crowbar operating alone gives rise to a number of concerns because of an unacceptable increase in the DC-link voltage. Also the most important thing when using only the crowbar circuit is the difficulty in finding the proper removal operation [37]. **In order to overcome this, the combined scheme (using both crowbar and DC-brake chopper) continues to be a requirement.**

7. Conclusion

The paper provides an overview of different wind turbine technologies with their global market shares and FRT grid codes from many countries. Variable speed

wind turbines based on DFIG are widely used. Two main controls for the DFIG wind turbine are summarized. A review of wind turbine models was introduced identifying some omissions in the published research. Then, trends of DFIG wind turbine model and combined scheme of DFIG FRT capability have also been discussed. Finally, the proposed DFIG system model with a combined scheme of FRT capability is essential to investigate the DFIG FRT and deserve further examination.

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