

Impact of Power Converter Size on Variable Speed Wind Turbine.

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ABSTRACT

The effect of a variable speed wind turbine power capacity size during grid fault is investigated in this paper. Power converter capacity sizes of 20%, 25%, and 30% of the rated wind generator power were used in the analysis, respectively. A simple model aggregated doubly fed induction wind generator connected to an infinite bus bar was considered in the study. A severe (worst case) three-line to grid fault (3LG) was applied to the model system, to demonstrate the effect of the power converter sizes. Simulations were carried out in standard laboratory power system computer aided design/electromagnetic transient including DC (PSCAD/EMTDC). The simulation results show that the higher the power converter capacity of the variable speed wind turbine, the better the performance during grid fault in the power system. This is because more reactive power could be injected into the power system during the short transient or disturbance in the power network.

(Keywords: variable speed wind turbine, wind energy, power converter, grid fault, reactive power)

INTRODUCTION

With the increasing shortage in fossil fuels, and pollution problems, renewable energy has become an important energy source. Wind power is the world's fastest growing energy source with a growth at an annual rate in excess of 30% and a foreseeable penetration of 12% of global electricity demand by 2020 [1]. The rapid growth in wind power is a result of improvements accomplished in technology [2].

The doubly fed induction generator (DFIG) is recently considered to be an attractive solution for wind energy conversion systems [3], since they can be controlled efficiently in a wide speed variable range. The major advantage of the DFIG, which has made it popular, is that the power electronic equipment only has to handle a fraction (20-30%) of the total system power [4]. This means that the losses in the power electronic

equipment can be reduced, in comparison to power electronic equipment that has to handle the total system power as for the direct-driven synchronous generator, apart from the cost saving of using a smaller converter. This paper investigates the effect of the power converter sizes for a DFIG system. Power converter sizes of 20%, 25%, and 30% were analyzed and simulated in PSCAD/EMTDC.

WIND TURBINE AERODYNAMICS

Aerodynamics is a science and study of physical laws of the behavior of objects in airflow and the forces that are produced by airflows [2, 5]. Different models of aerodynamic analysis of wind turbine system have been reviewed in the literature. The wind turbine characteristic shown in [6, 7] is considered in this study. The wind turbine modeling and the pitch controller model is also taken from [6, 7].

AGGREGATED MODEL SYSTEM

The simple model system considered for this study is shown in Figure 1, where a 20MW aggregated doubly fed induction generator variable speed wind turbine (VSWT) system is connected to an infinite bus. The line parameters for self capacity base and system base are also shown in the model system. A fault point is shown for a three-line to ground fault, which is the most severe case. The fault is applied when the wind turbine is on its steady state, running at its rated velocity in m/s and its rated power. The circuit breakers help for protection during the fault.

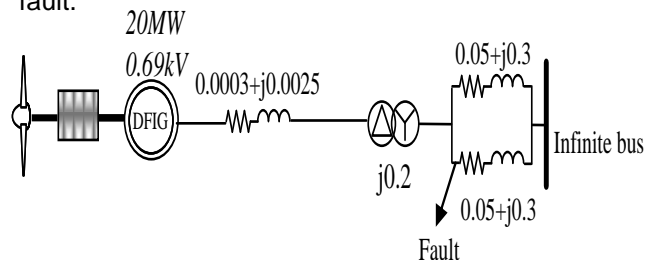


Figure 1: Model System of Aggregated DFIG Connected to an Infinite Bus.

A DFIG VSWT is basically a standard wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter. The AC/DC/AC converter is divided into two components: the rotor side converter (RSC), and the grid side converter (GSC) as shown in Figure 2. These converters are voltage sourced converters that use force commutated power electronic devices to synthesize an AC voltage from a DC source [8].

A capacitor connected on the DC-link acts as the DC-link voltage source. A coupling inductor is used to connect the GSC to the grid. The three phase stator winding are directly connected to the grid. The control system generates the pitch angle command and the voltage command signals for the RSC and GSC, respectively. Thus, the power of the wind turbine, the DC-link voltage, and the reactive power or the voltage at the grid terminal are effectively controlled both in steady and transient states of the DFIG. The detail control structure of the DFIG VSWT system is shown in Figure 2.

A phase lock loop (PLL) is used to determine the angle of transformation (abc-dq0 or dq0-abc) for the stator and the rotor side converters respectively, based on the line voltage detections. The voltage controlled voltage source converters are incorporated with a proportional integral (PI) controller, which has both time and gain constants. The values of the PI in this study were determined by trial and error method, which makes it quite tedious.

The RSC controls the terminal (grid) voltage to 1.0pu. The d-axis and q-axis currents of the d-q transformation control the active power and reactive power of the wind turbine respectively. The voltage and frequency are variable for the RSC, while for the GSC, the voltage and frequency are fixed as shown in Figure 2.

Also, the GSC system of the DFIG is used to regulate the DC-link voltage (V_{dc}) to 1.0pu. The d-axis current controls the DC-link voltage, while the q-axis current controls the reactive power of the grid side converter to be maintained at 0 p.u.

It should be noted that in the RSC and the GSC systems, a carrier wave is compared with the obtained reference voltages via a signal comparator system. The resultant signal is thus used for the IGBTs (insulated bipolar transistors)

switching as displayed in Figure 2, which is obtained from the pulse width modulation (PWM).

INFLUENCE OF POWER CONVERTER SIZE OF WIND TURBINE ON ENERGY PRODUCTION

The most important quantity in variable speed wind turbine application is the energy delivered to the grid (electric energy capture). In order to do this, the distribution of wind speeds must be known [9]. The most commonly used probability density function to describe the wind speed is the Rayleigh function [10]. Given a probability density function, $f(w)$, the average (or expected) value of the power, $P(w)$, can be found as

$$P_{avg} = \int_0^{\infty} P(w)f(w)dw \quad (1)$$

where, w is the wind speed.

It is not possible to obtain a full speed range with the DFIG VSWT system, if the converter is smaller than the rated power of the wind turbine. This means that the smaller the converter is, the more the VSWT will operate at a non-ideal tip-speed ratio, for low wind speeds. The impact of having a smaller power converter is that a smaller rotor speed range would be achieved, thus the aerodynamic losses become higher. In [9], it was shown that a smaller rotor-speed range implies smaller ratings of the converter. Also, the converter losses are lower for smaller rotor speed ranges or smaller power converter ratings. Since, gain in energy increases with the rotor speed range or power converter size, thus the increased aerodynamic capture has a larger impact than the increased converter losses. Hence, the rotor speed range is of greater importance for a low average wind speed compared to a high average wind speed.

ANALYSIS OF WIND TURBINE POWER CONVERTER LOSSES

A brief analysis of the power converter losses for a wind turbine based on [9, 11, and 12] is as follows:

The losses of the converter can be divided into switching losses and the conducting losses. The switching losses are the turn on and turn off losses of the transistors, which is the reverse and recovery energy. The conducting losses arise

from the current through the transistors and diodes. The transistors and the diodes can be modeled as constant voltage drops, V_{CE0} and V_{TO} with a resistance in series, r_{CE} and r_T , respectively. The expressions of the transistor's and diode's conducting losses, for a transistor leg with a third harmonic voltage injection are thus:

$$P_{C,T} = \left(\begin{aligned} & \frac{V_{CE0} I_{rms} \sqrt{2}}{\pi} + \frac{I_{rms} V_{CE0} m_i \cos(\phi)}{\sqrt{6}} + \frac{r_{CE} I_{rms}^2}{2} \\ & + \frac{r_{CE} I_{rms}^2 m_i}{\sqrt{3} \cos(\phi) 6\pi} - \frac{4r_{CE} I_{rms}^2 m_i \cos(\phi)}{45\pi\sqrt{3}} \end{aligned} \right) \quad (2)$$

$$P_{C,D} = \left(\begin{aligned} & \frac{V_{TO} I_{rms} \sqrt{2}}{\pi} - \frac{I_{rms} V_{TO} m_i \cos(\phi)}{\sqrt{6}} + \frac{r_T I_{rms}^2}{2} \\ & - \frac{r_T I_{rms}^2 m_i}{\sqrt{3} \cos(\phi) 6\pi} + \frac{4r_T I_{rms}^2 m_i \cos(\phi)}{45\pi\sqrt{3}} \end{aligned} \right) \quad (3)$$

where I_{rms} is the root mean square value of the sinusoidal current to the grid or the generator, m_i is the modulation index, and ϕ is the phase shift between the voltage and the current. Making approximations of,

$$r_{IGBT} = r_{CE} \approx r_T, V_{IGBT} = V_{CE0} \approx V_{TO} \quad (4)$$

The conduction losses can with the above approximations in equation (4) be written as:

$$P_C = P_{C,T} + P_{C,D} = V_{IGBT} \frac{2\sqrt{2}}{\pi} I_{rms} + r_{IGBT} I_{rms}^2 \quad (5)$$

If the switching losses of the transistor is assumed to be proportional to the current, for a DC-link voltage, then:

$$P_{S,T} = (E_{on} + E_{off}) \frac{2\sqrt{2}}{\pi} \frac{I_{rms}}{I_{C,nom}} f_{sw} \approx V_{sw,T} \frac{2\sqrt{2}}{\pi} I_{rms} \quad (6)$$

$$P_{S,D} = E_{rr} \frac{2\sqrt{2}}{\pi} \frac{I_{rms}}{I_{C,nom}} f_{sw} \approx V_{sw,D} \frac{2\sqrt{2}}{\pi} I_{rms} \quad (7)$$

where, $P_{S,T}, P_{S,D}$ are the switching losses from the transistor and the inverse diode respectively, and E_{on}, E_{off} are the turn on and turn off energy losses for the transistor. $E_{rr}, I_{C,nom}$ are the reverse recovery energy for the diode and the nominal current through the transistor respectively. Thus, the total losses from the three transistor legs of the converter can be written as:

$$P_{loss} = 3(P_C + P_{S,T} + P_{S,D}) \quad (8)$$

$$P_{loss} = 3[(V_{IGBT} + V_{sw,T} + V_{sw,D}) \frac{2\sqrt{2}}{\pi} I_{rms} + r_{IGBT} I_{rms}^2] \quad (9)$$

From Figure 2, the back to back converter can be seen as two power converters which are connected together, i.e., the rotor side converter (RSC) and the grid side converter (GSC).

Finally, the losses of the back to back converter can be written as:

$$P_{loss,converter} = P_{loss,GSC} + P_{loss,RSC} \quad (10)$$

If a sketch of the total converter losses is made as a function of wind speed, it could be depicted that the converter losses in DFIG VWST system are much lower compared to the full power converter system used in other wind turbine systems.

ANALYSIS OF SIMULATION RESULTS

The time step and simulation time, for this study have been chosen as 0.00001 sec and 10 sec respectively. The most severe three line-to-ground (3LG) fault as shown in the model system (Figure 1) was considered as the network disturbance. The fault occurs at 100ms (0.1 sec). The circuit breakers (CB) on faulted line are opened at 200ms (0.2 sec), and at 1000ms (1.0 sec) the circuit breakers are re-closed. For transient stability analysis, the wind velocity is kept constant at 15 m/sec, where the DFIG VSWT is operating at its rated power. A simple one-mass drive train model was used for the DFIG VSWT system for the simulation analysis. Three cases were considered in this analysis. In the first case, a 20% DFIG VSWT power converter capacity was used. The second case has a 25% DFIG VSWT power converter

capacity. A 30% DFIG VSWT power converter was considered in the third case.

All cases were analyzed under the same fault condition, model system and line parameters. Simulations have been done by using PSCAD/EMTDC [13]. Some of the most important variables of the system are presented from Figure 3 to Figure 6, to demonstrate the effect of the power converter sizes on the DFIG VSWT during transient condition.

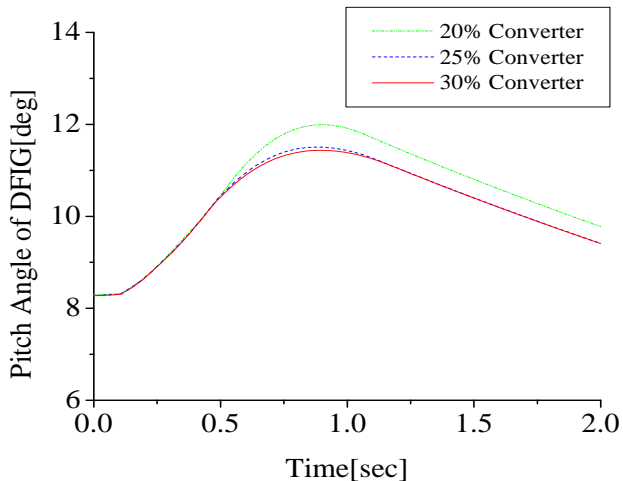


Figure 3: Pitch Angle of DFIG VSWT (all cases).

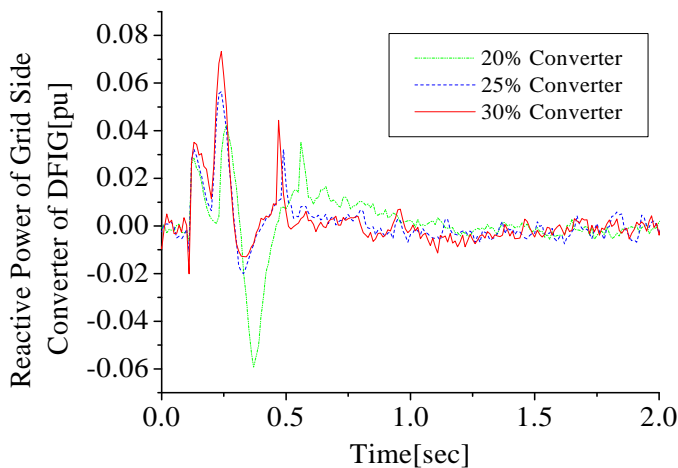


Figure 4: Reactive Power of Grid Side Converter of DFIG VSWT (all cases).

Figure 3 shows the response for the DFIG pitch angle, where the pitch angle control actuates slightly less for the DFIG VSWT with 30% of the rated power. The pitch angle control reaches higher values for 20% power converter in Figure 3, with slow recovery of the reactive power from

the GSC of the DFIG VSWT (Figure 4), thus consuming more reactive power from the grid.

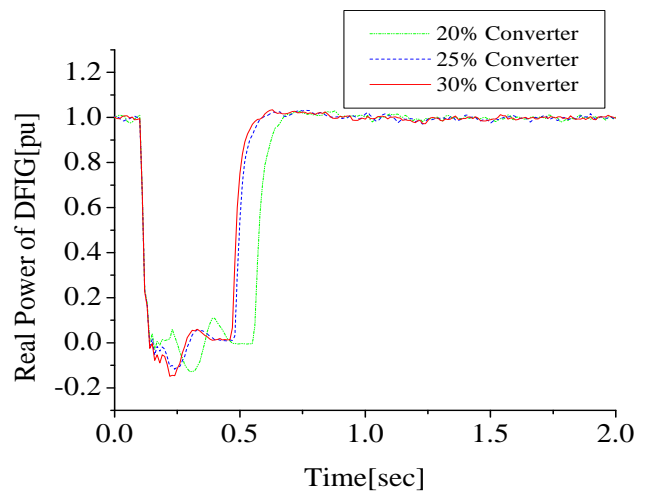


Figure 5: Real Power of DFIG VSWT (all cases).

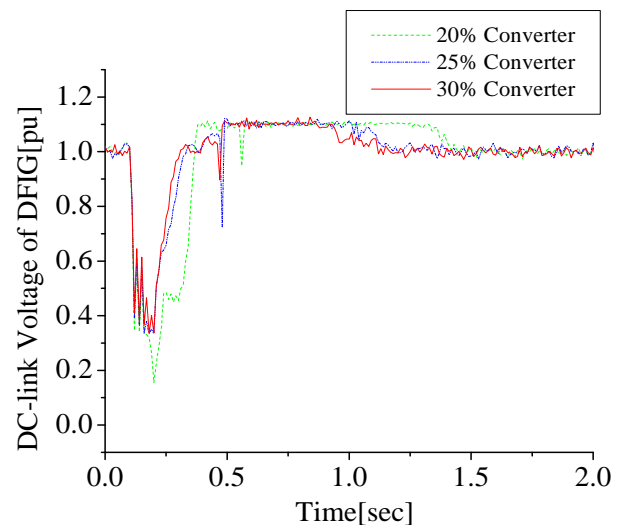


Figure 6: DC-link Voltage of DFIG VSWT (all cases)

Also, the reason why the DFIG VSWT 30% power converter capacity assumes lower value could be explained by the injection of reactive power into the grid by the GSC (Figure 4). In the 20% or 25% power converter capacity, the generator consumes more reactive power than the converter could supply during transient (grid fault) or network disturbance, and takes this difference from the grid system. Since the terminal voltage level also influences directly the real power of the DFIG VSWT, the response of the DFIG real power for 30% power converter capacity (Figure 5) is better than that of 20% or

25% power converter capacity responses, respectively. This is due to the fact that the real power recovery time is faster for the 30% rated power converter capacity than the 25% or 20% converter rating.

The response for the DC-link voltage of the DFIG VSWT is shown in Figure 6. It could be seen that when the 30% power converter rating was considered, less oscillations and more stable response was achieved. Also, the DC-link voltage dip for the 20% power converter is much higher during the grid fault, thus making the power converters more vulnerable in this case.

CONCLUSION

This paper performed an analysis of a doubly fed induction generator (DFIG) variable speed wind turbine (VSWT) system during transient, taking into account different power converter capacities (20%, 25% and 30% of the wind generator rated power). The overall control strategy for the DFIG VSWT system is discussed. The transient performance is evaluated with a 3LG fault (severe case or worst condition). The DFIG VSWT system is found more stable for the 30% power converter capacity under network disturbance.

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