Unsymmetrical Fault Analysis and Protection of 1.5 MW DFIG Wind Turbine Converters †

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1. Introduction

There has been a significant increase in the energy demand and environmental issues. The world is thus shifting towards renewable energy resources and its technologies, because these resources are clean and their operation is free of cost. Wind is one of the renewable energy resources. It should be of no surprise that electricity in the future will be produced largely through the installation of wind farms [1]. However, there are certain challenges associated with the use of wind energy, such as the impacts of wind turbine generators on the integration with the power systems, and also the variation in the wind speed. The concept of a variable-speed wind turbine (VSWT) with a doubly-fed induction generator (DFIG) is gaining popularity due to its distinct advantages over fixed-speed induction generators, such as increased power capture and a four-quadrant converter topology that allows decoupled and fast active and reactive power control, and lower mechanical stresses [2]. Due to the variable wind speed, wind turbines with DFIG doubly fed induction generators are extensively used, as they can be easily controlled under varying wind speeds and can maintain the connection with the public grid and the stability of the power output [3].

Although DFIG-based wind turbines have been successful, there are still several challenges that need to be solved. In a highly competitive power system, voltage imbalance with magnitudes that differ from one another is quite common, owing to faults [4]. In normal conditions, the rotor converter adjusts the rotor current during normal operation to obtain the active and reactive reference powers [5]. The single and three-phase line faults represent special cases of high currents and voltage dips. The voltage completely drops during faults [6–8]. High currents are induced in the machine during line faults, causing the system to become imbalanced [9]. Transmission line faults provide a large flow of current to the rotor side of the DFIG, which is connected by back-to-back converters; the
converters may be damaged due to these high currents. Thus, a proper protection scheme is needed to protect the DFIG and converter from the transients and faults [10].

This paper will examine the behavior and analysis of the asymmetrical single line to ground fault on a 22 kV HT line connected to a wind turbine. Whenever these faults occur, they can cause significant overcurrents and overvoltages, placing the entire facility at risk. This quickly causes the converter system to deteriorate if countermeasures are not taken. Thus, a proper protection scheme is needed to protect the generator and its converter from faults.

2. Analysis of DFIG in Normal Operation

The study has been conducted on a 1.5 MW industrial wind turbine model, as shown in Figure 1, in which the DFIG with a rating of 1.73 MVA is connected to back-to-back converters of rating 770 kVA. When the DFIG is operating in normal conditions, its nominal output voltage is 690 Volts. To raise its voltage, it is connected to a step-up transformer, which increases its voltage up to 22 kV. The other side is fed by a three-phase nominal voltage of 132 kV, which is reduced by a step-down transformer to 22 kV. The simulation results are shown in the following sections.

![Figure 1. Diagram of 1.5MW WT system under line to ground fault with crowbar protection.](image)

3. Normal Operation Results

The output results of active power, reactive power, voltage and currents were obtained during normal operating conditions. It is shown in Figure 2 that the output current is within $[−1, 1]$ per unit, having a base current of 1450 A at the rated wind speed of 13 m/s. Figure 3 shows the output voltage, which is within $[−0.75, 0.75]$ in p.u., with a base voltage of 690 V. The active power and reactive power outputs are also given in Figures 4 and 5, which are 1.5 MW and 0 MVar (as it was set as zero in the model for ease of understanding), respectively.

![Figure 2. Output current.](image)
which the maximum current should not be exceeded; here, the limit is set to 1.2 p.u. of its value, which is injurious to these DFIG converters (electronic devices and switches).

Because of the DFIG’s nature, the stator and rotor currents are coupled. This means that any changes in one will affect the other. For instance, when the stator current increases, the rotor current will also increase. Similarly, the back-to-back converters produce reactive power. Consequently, the generator becomes unstable due to the increase in the rotor current.

Moreover, the generator will become unstable due to the increase in the rotor current. Thus, the stator current and rotor current both will have effects on the stator current, and, due to magnetic coupling between the stator and rotor, the rotor current also changes. Thus, the stator current and rotor current both will increase. The result is shown in Figure 7.

During the increases in the fault stator and rotor current, mechanical disturbance will also be produced. Moreover, the generator will become unstable due to the increase in the current of the stator and rotor from the specific value. Similarly, the back-to-back converters of the DFIG are made up of power electronic devices and switches, which are expensive and vulnerable to damage due to different types of faults. A limit is pre-set for them in which the maximum current should not be exceeded; here, the limit is set to 1.2 p.u. of its current. The current on phase B passing through the power electronic devices is shown in Figure 8. It is illustrated in the figure that the amount of current exceeds its predefined value, which is injurious to these DFIG converters (electronic devices and switches).

4. Analysis of Unsymmetrical Fault

Regarding an unsymmetrical fault of type single phase (phase B) to ground, applied at a distance of 5 km on the line, the DFIG would react to this fault more strongly than if the same fault occurred at 10 km on the line. The duration of the fault is set to 1 s. The output current is shown in Figure 6. It is shown that the current on phase B increased to three to four times its normal current. The other phase’s current also increased. All of these changes have effects on the stator current, and, due to magnetic coupling between the stator and rotor, the rotor current also changes. Thus, the stator current and rotor current both will increase. The result is shown in Figure 7.

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5. Crowbar Protection

Crowbar protection is one of the most important types of protection to protect the converters from faults. In this type of protection, whenever a fault occurs, the crowbar protection circuit will be operated, which provides an alternative path for the rotor current. Thus, it will short-circuit the rotor-side converter and decrease the rotor current that passes through the converter. When the fault clears, the crowbar circuit will be deactivated and the rotor current will return to its normal value. The crowbar protection circuit consists of IGBT switches, a resistor and diodes. A high value of the resistor causes high voltage and a low value of the resistor causes a high rotor current and low voltage, so there is a tradeoff when choosing the value. In this circuit, a resistor with a value of 1 mΩ is used. The circuit is shown in Figure 1.

6. Simulation Results When Crowbar Activates

When the crowbar circuit activates during the fault, all of the rotor current will be bypassed and it travels towards the crowbar circuit instead of the rotor as shown in Figure 9.
Thus, during the whole fault duration, the current passing towards the rotor-side converter will be zero as shown in Figure 10, and it passed towards the crowbar circuit as shown in Figure 11. The rotor-side converter disconnects from the rotor and the DFIG is converted into an induction generator. Then, this generator absorbs the reactive power from the grid for the fault duration. When the fault ends, the crowbar will be deactivated as seen in Figure 12, so that the rotor-side converter connects to the rotor again, and the induction generator will again change into a doubly fed induction generator, which will then generate the active and reactive power for which it is designed, i.e., here, in this paper, it is designed to generate 0 MVAR. The output results of active power and reactive power are shown in Figures 13 and 14 respectively. In order to examine the behavior and operation of the crowbar circuit, the following figures are shown. The time for crowbar operation is equal to the duration of the fault.

**Figure 9.** Rotor current.

**Figure 10.** Phase B rotor converter current.

**Figure 11.** Crowbar current.
7. Conclusions

This paper presents a simulation model for the asymmetrical fault analysis and protection of a 1.5 MW DFIG wind turbine converter in EMTDC/PSCAD. A single line to ground fault is created and we then analyze its behavior in the DFIG and its converters. The crowbar protection scheme is presented and we then check the impact of overcurrents on the DFIG. The crowbar protection method has better performance with various grid faults, and this can be an effective method to eliminate faults and transients.

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