Reliability comparison of DFIG drive train configuration with PMG drive train configuration in the first 5 years of operation

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Abstract

Modern wind turbines vary greatly in their drive train configurations. With the variety of options available it can be difficult to determine which type is most suitable for on and offshore applications. A large percentage of modern drive trains consist of either doubly fed induction generators with partially rated converters or permanent magnet generators with fully rated converters. These configurations were the focus of this empirical reliability comparison. The turbine population for the analysis contained over 1800 doubly fed induction generator (DFIG) turbines and 400 permanent magnet generator (PMG) fully rated converter (FRC) turbines. The findings of this analysis show that, due to the poorer reliability of the FRC, the DFIG configuration proved the most reliable.

1. Introduction

A wind turbine's failure rate contributes to its overall cost of energy; typically a higher failure rate will lead to a higher cost of energy. As a result of this wind farm developers will try to select a turbine with low failure rates. Due to accessibility issues, the failure rates of turbines become even more important as offshore wind generation increases [1]. This paper will show the results of an analysis to determine which of the two turbine configurations have a lower failure rate.

Based on over 2,200 onshore wind turbines from a leading manufacturer the failure rate of the two different generator and converter types were analysed. All turbine generators and converters were in their first 5 years of operation and from wind farms throughout Europe. The full data set consists of over 34,000,000 turbine hours of data.

Both generator and converter types in the two different drive train configurations have the same rated power and have been installed in turbines that are identical except for their drive train configurations.

In order to ensure confidentiality the exact nominal power or blade size of the turbine type used in this analysis will not be provided, however; it can be stated that it is a modern MW scale turbine type with an identical blade size and nominal power in all 2,222 turbines. As a guide to the size of the

turbine type, the blade size is between 80 and 100m and the nominal power is between 1.5 and 2.5MW.

The novelty of this work is in the large modern sample size for both drive train configurations and the identicalness of the turbine population when the drive train differences are disregarded.

Other reliability studies in the public domain that have similarly large population sizes are for older smaller turbine types as low as 200kW and up to 20 years old [1,2,3]

Recent reliability studies on larger turbines still contain turbines in their population that are as low as 850kW and have far smaller population sizes of 350 turbines [4] in comparison to the 2,222 turbines in this paper.

This paper is also unique because of the separation of the analysed population into different drive train configurations. Current generator and converter failure rates in the public domain are for one generic generator or converter type that has been obtained from a population consisting of many different generator and converter types [2,3]. The opportunity to compare failure rates from identical turbines apart from the drive train allows for a unique reliability comparison of the two different drive train configurations. This analysis will provide failure rate differences for each configuration. Unlike many of the existing reliability papers this paper will also provide cost of failure details. As the drivetrain is the part of the turbine that varies most in modern wind turbines this drivetrain failure rate and failure cost analysis will eventually contribute to efforts in calculating the overall Cost of Energy for different wind turbine types.

2. Generator and converter types in this analysis

The first drive train configuration in this analysis consists of an induction generator; a doubly fed induction generator which is partially decoupled from the grid with partially rated converters.

The other drive train configuration in this analysis consists of a synchronous machine; a permanent magnet generator that is completely decoupled from the grid with fully rated converters.

Both the DFIG and or PMG FRC configuration can be seen in figure 1. The rated power of both configurations is the same but as previously mentioned the exact rated power cannot be disclosed for confidentiality reasons.

Figure 1: DFIG and FRC configurations [5]

3. Population Analysis.

3a. DFIG Population

The DFIG configuration has a sample size building up to 1822 turbines over a five year period. This sample size provides 3391 years or ~29.7 million hours of turbine data. The installation years for this sample can be seen in figure 2.

Figure 2: DFIG Population Installation Year

The generator run hours are binned in groups of 5000 hours and their occurrences are graphed in figure 3. The generator run hours are the number of hours that the wind speed is above cut in speed, below cut out speed and the generator is in use. It can be seen that there are occurrences in the bins greater than 20,000 hours which is not the case for the PMG population in figure 6; this is a reflection of the older DFIG population.

Figure 3: DFIG Population Run Hours

The capacity factor of the DFIG population is shown in figure 4. The average capacity factor of 30.7% is greater than the European average of 24% [6]

Figure 4: DFIG Population Capacity Factor

3b. PMG FRC Population

The PMG FRC configuration has a sample size building up to 400 turbines over a three year period. This sample size provides 511 years or ~4.5 million hours of turbine data. The installation years for this sample can be seen in figure 5.

Figure 5: PMG FRC Population Installation Year

Similarly to the DFIG population the PMG run hours are binned in groups of 5000 hours and their occurrences are graphed in figure 6. It can be seen that there are no occurrences greater than 20,000 hours; this is a reflection of the newer PMG population.

Figure 6: PMG FRC Population Run Hours

The capacity factor of the PMG FRC population is shown in figure 7. The average capacity factor of 28.8% is again greater than the European average of 24% but ~2% below the DFIG population capacity factor. [6] The capacity factors calculated in this paper include downtime and are in the paper to show that there is not a major difference between the types of sites that both populations are placed.

Figure 7: PMG FRC Population Capacity Factor

4. Failure Data and Definitions

4a. Failure Definition

For the purpose of this analysis a failure is defined as a visit to a turbine, outside of a scheduled operation, in which material is consumed. A material is defined as anything that is used or replaced in the turbine, this includes everything from consumable material such as brushes, oil etc. to replacement parts such as full IGBT units and full generators.

This failure definition does not cover faults that are resolved through remote, automatic or manual restarts. However, if these faults repeatedly occur they will require a visit to the turbine in which material will be used and the failure will then be captured in this analysis, providing the visit is outside of a scheduled service.

4b. Failure rates

In this analysis the failure rates are in per turbine per year format as seen in references [1], [2], [7]. The formula used to determine failure rate per turbine per year in this analysis can be seen below, it is the same formula used by Tavner to calculate failure rates in reference 7:

$$\lambda = \frac{\sum_{i=1}^I \sum_{k=1}^K n_{i,k} / N_i}{\sum_{i=1}^I T_i / 8760}$$

where

λ = failure rate per turbine per year

I = number of Intervals for which data were collected

K = the number of subassemblies

$n_{i,k}$ = the number of failures

N_i = the number of turbines

T_i = the total time period in hours

The numerator $\sum_{i=1}^I \sum_{k=1}^K n_{i,k} / N_i$ = the sum of the number of failures in all periods per turbine and the denominator $\sum_{i=1}^I T_i / 8760$ = the sum of all time periods in hours divided by the number of hours in a year.

4c. Failure rate categories

The failure types were categorised into three groups. These groups were based on the Reliawind categories from reference [8] in which failures are classified as a minor repair, major repair or major replacement. For the purpose of this analysis any failure with a total repair material cost of less than €1000 was considered a minor repair, between €1000 and €10,000 a major repair and above €10,000 a major replacement as seen in table 1:

Category	Material Cost
Minor Repair	< €1,000
Major Repair	€1,000 - €10,000
Major Replacement	> €10,000

Table 1: Failure Categorisation

5. Method

The process in the following paragraphs was carried out for the DFIG and then repeated for the DFIG converters, PMG and FRC.

The wind turbine manufacture that provided access to their data has a database containing all work orders carried out on each of their wind turbines and a database detailing the material used in each of the work orders.

Using SQL, both databases were connected using an inner join on the work order number to determine the materials used in each work order. The data was then cleaned to remove any work orders that were not related to the DFIG. The data was also cleaned to remove any scheduled operations, e.g. scheduled services, scheduled inspections etc.

Once each failure related to a DFIG was identified its total material cost was calculated and the failure was then categorised as a minor repair, major repair or major replacement as described in section 4c.

Using the formulae from section 4b the failure rates were calculated in a per turbine per year format.

6. Results and Discussion

6a. Generator and Converter Failure Rates

The difference in failure rates for the permanent magnet generator (PMG) and the doubly fed induction generator (DFIG) can be seen in figure 8. Both failure rates include the failures for the generator auxiliary systems, such as cooling, lubrication etc. The failure rate difference of 38% was as expected due to the fewer possible failure modes in the PMG.

Figure 8: Generator Failure Rate

The difference in failure rates for the DFIG converters and the PMG fully rated converters (FRC) can be seen in figure 9. Both failure rates include the failures for the converters auxiliary cooling system. The higher failure rate was expected from the FRCs due to the greater stress on the converters which cannot be shared with the generator as in the DFIG system.

Figure 9: Converter Failure Rate

The combined failure rates for the PMG with a FRC and the DFIG configuration can be seen in figure 10. The PMG configuration's failure rate is nearly three times greater than the DFIG configuration failure rate. The driver for this large difference in the overall configuration failure rate is the FRC in the PMG configuration. As seen in fig 8, the PMG has a lower failure rate than the DFIG but the much larger FRC failure rate means the combined PMG and FRC configuration failure rate is far higher overall.

Figure 10: Drive train Config. Failure Rate

6b. DFIG generator detailed analysis

The DFIG failure rate is broken down into the three failure categories as described in section 4C, this break down is shown in figure 11. The majority of the failures that occur in the DFIG are minor repairs, costing less than €1000. Approximately 25% of failures are major repairs costing up to €10,000 and ~1.6% of the 0.123 failures / turbine / year are major replacements that cost over €10,000.

Figure 11: DFIG Failure Rate / Category

The year of operation in which failures occur are shown in figure 12. It can be seen that the higher failure rates and major replacements (costing over €10,000) occur in the earlier years of operation.

Figure 12: DFIG Failure Rate / Year of Operation

6c. PMG generator detailed analysis

As with the DFIG in the previous section the PMG failure rate is broken down into the three failure categories as described in section 4C, this break down is shown in figure 13. Even more so than the DFIG the vast majority of the failures that occur in the PMG are minor repairs, ~ 97.4% of all the failures are minor repairs below €1,000. Approximately 2.6% of failures are major repairs costing up to €10,000 and there are no major replacements or repairs over €10,000.

Figure 13: PMG Failure Rate / Category

The year of operation in which failures occur can be seen in figure 14. There are PMG turbines in their third year of operation but due to the PMG having a lower failure rate and a smaller sample size for a lower number of years we only have failures occurring in two years of operation with no major repairs occurring after year one.

Figure 14: PMG Failure Rate / Year of Operation

6d. DFIG converter detailed analysis

Figure 15 shows the failure categorization for the partial converters used in a DFIG system. Over 99% of the failures are below €10,000 with 64% of these failures costing under €1,000.

Figure 15: DFIG Converter Failure Rate / Category

The year of operation in which failures occur is shown in figure 16. Similarly to the DFIG generator it can be seen that the higher failure rates and major repairs occur in the earlier years of operation. Similarly to the generator used in the DFIG configuration the failure rate drops in year 4. An explanation for this drop could be a combination of both infant mortality and the decline in the number of turbines operating in their 4th year making the sample size smaller.

Figure 16: DFIG Converter Failure Rate / Year of Operation

6e. PMG fully rated converter detailed analysis

The fully rated converter used in the PMG configuration has the highest failure rate of all the parts analysed in this paper. In figure 17 the failure categorisation is shown. It is worth noting that for the FRC the major repair failures alone are higher than all category failures combined for the converters used in the DFIG configuration. A possible explanations for such a high failure rate with the FRC could be the fact that it is a newer technology than the DFIG technology so higher failure rates are being experienced until the technology matures.

Figure17: FRC Failure Rate / Category

The year of operation in which failures occur are shown in figure 18. Similarly to the DFIG converter it can be seen that the FRC converter also has higher failure rates and major replacements (costing over €10,000) occurring in the earlier

years of operation. It can be seen that there are failures in the third year of operation for the FRC, this was not the case for the generator used in this configuration. This highlights the superior reliability of the generator over the FRC in this configuration type.

Figure18: FRC Failure Rate / Year of Operation

7. Discussion and Conclusion

This paper has shown that the PMG has a lower failure rate than the DFIG. The DFIG has ~ 40% more failures than the PMG, this difference would grow further if the generator auxiliary systems were removed from the analysis because the majority of the failures for the PMG are minor failures related to its cooling and lubrication system.

It can also be seen that the partially rated converters used in a DFIG configurations are far more reliable than the fully rated converters used in a PMG configuration. This analysis shows that for this particular turbine type the failure rate of the FRCs is over five times greater than that of the partially rated converters in the DFIG configuration.

When the generator and converter failure rates are combined for the different configurations, the gain in reliability from the PMG is completely reversed through the poorer reliability of the FRC. The overall combined failure rate for each configuration is shown in section 5A. The PMG FRC configuration shows an overall failure rate nearly 3 times greater than the DFIG configuration.

Based on the previous paragraphs and considering failure rate alone, the DFIG configuration is an obvious choice for drive train selection. However, drive train selection cannot be based on failure rate alone so further work could also look at MTTR, energy production and hardware costs to determine an overall cost of energy comparison for the different configurations. This overall CoE comparison would allow for more definitive conclusions on which of the two drivetrain configuration types suits best for a particular site. Based on the results from this analysis the PMG FRC configuration would need to have greater power production and/or a lower hardware cost than the DFIG configuration in order for the CoE to be lower.

Additional further work could investigate failure modes for each of the generators and converters. This failure mode analysis would help in determining what are the driving factors for such a high failure rate in the fully rated converter. It would also assist in identifying key areas for reliability improvement.

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