Condition Monitoring of the Wind Turbine Generator Slip Ring

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***Abstract*- The huge proliferation of wind farms across the world has arisen as an alternative to the traditional power generation and as a result of economic issues which necessitate monitoring systems in order to optimize availability and profits too. Equipments inside a wind turbine are subject to failures which, most of times lead to long downtime periods. When wind turbine is not running due to a failure, no profits are added and operation and maintenance costs increases. The development of advanced techniques to detect the onset of mechanical and electrical faults in wind turbines at a sufficiently early stage is very important for maintenance actions. Neural networks can be used to detect failures in some equipments of wind turbines, but to use them is necessary to create a model to the equipment under surveillance. The training of the neural network represents the big handicap of the developed method that will be presented here. However, after solving this problem, results are very interesting, and failures can be detected with several months in advance.**

***Index Terms*—Failures, failures detection, maintenance, neural networks, slip ring, wind generator.**

I. INTRODUCTION

Wind is nowadays one of the most important primary sources of energy in the world. It is a clean form of electrical energy production and has the big advantage of not emitting any greenhouse gases (GHG), unlike other forms of traditional energy production. In spite of 2010 has been a weak year in terms of installed capacity, 2011 reversed the situation and imposed a normal growth rate. The worldwide wind capacity reached 215 GW by the end of June 2011, out of which 18405 MW were added in the first six months [1].

In spite of wind energy has low marginal costs (because fuel is free) operation and maintenance costs of this kind of energy production cannot be negligible.

The objective of every wind energy producer is to reduce operational costs associated to the production, as a way to increase profits. One other issue that must be looked carefully is the equipment maintenance. Increase the availability of wind turbines by reducing the downtime associated to failures is a good strategy to achieve the main goal of increase profits.

Normally maintenance is defined by the wind turbines constructor, because most of wind farms are covered by the warranty. In those cases, maintenance is preventive and defined by time, normally every 6 months. When turbines stop due to a fault maintenance teams are urgently called out to try to solve the problem.

In older wind parks, in which warranty has finished, the wind park owner has his own maintenance teams to do the job or contracts out this specific job.

As a way to help in the definition of the best maintenance strategies, condition monitoring systems have an important role to play. Monitoring all mechanic and electrical equipments of a wind turbine is not economically feasible, but using the normal measures made in the wind turbines and some advanced techniques of treatment of them is possible to assess the condition of some equipments.

One of the advanced techniques that can produce good results, are the artificial neural networks (ANN). They are appropriated to work with big amounts of data and analyze if there is any correlation between them that could be impossible to detect by normal human analysis. In this paper will be present a fault detection technique based on the application of ANN.

The equipment that will be monitored is the slip ring of the electrical generator. This equipment is composed by collectors and brushes and is subject to enormous wear, due to the rotating motion. A fault in it can lead to the outage of the wind turbine.

II. WIND TURBINES MAINTENANCE

Faults are problems that must be avoided, in any equipment and more significantly in wind turbines, because most of the times it is necessary to move a maintenance team to the local to solve the problem and if the problem takes too much time to solve, monetary losses increase substantially.

The aging of equipments leads to an increase of operation and maintenance costs so, for that reason, good maintenance strategies are needed [1]. Fig. 1 shows the evolution of operations and maintenance costs with the number of years of operation of some wind parks.

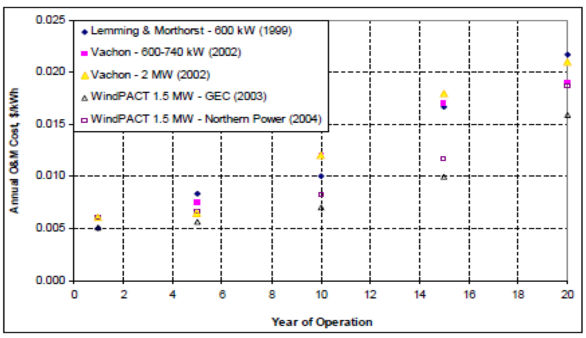

Fig. 1. Operation and maintenance costs of wind turbines [2].

As is possible to understand from the analysis of fig. 1, operation and maintenance costs are higher in older turbines. One other issue that is important to understand is the failure rate evolution. The “bath curve” is also applied to these equipments. Fig. 2 presents the failure rate evolution.

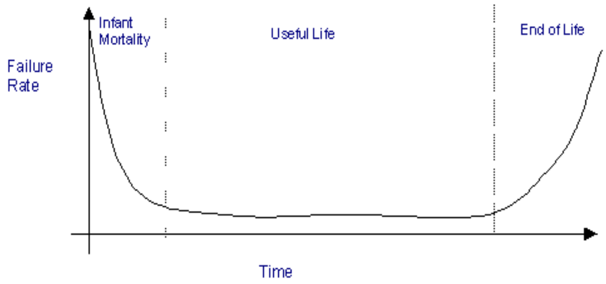

Fig. 2. Time fault evolution [3].

Failure rate is higher in the beginning, normally because of problems with the installation and adjustments. Then, during the useful life failure rate is low and in the end of life failure rate increase again. This is an important issue because older wind parks are no longer under warranty contracts and for that reason maintenance operations are contracted to the job, which implies a cost to the wind park owner.

Wind farms maintenance is classified into two types, the corrective maintenance and the preventive maintenance. The corrective maintenance is performed after the occurrence of a fault and the objective is to repair the systems and put it on running. Interventions to improve the overall equipment can be made even without failure.

Preventive maintenance is performed at predetermined periods of time or according certain criteria. The main objective is to reduce the probability of occurrence of an anomaly. The preventive maintenance can be divided into two sub types, the systematic or planned maintenance and condition based maintenance, differing only by the method of deciding when to perform maintenance.

The maintenance operations made to the oldest wind turbines was based on corrective actions. Operations were only made when a fault occurred. With the evolution in terms of capacity of production as well as in communication systems and monitoring systems, maintenance strategies changed and began to be adopted the preventive maintenance. In this kind of maintenance, periodical inspections are made with the objective of evaluate equipment condition.

Nowadays most of wind turbine producers impose a maintenance strategy based on time in which maintenance teams go regularly to the turbine to make inspections, repairs and substitution of equipments. Normally two maintenances are made per year. The major maintenance and a minor maintenance, made with six months interval. In the first maintenance is made an analysis of all equipments and will be substituted all damaged equipments. In the minor maintenance is normally made the visual inspection of equipments and the substitution of equipments subject to rapid wear. Normally major maintenance lasts not less than 7 hours and minor maintenance lasts at least 4 hours. All the times and dates are dependent on weather conditions. If there is bad weather conditions, with high wind speeds, maintenance cannot be performed, but on the other hand, if weather conditions are good to produce energy, maintenance cannot be performed too, because wind park owners do not let to stop machines, for economical issues. Maintenance can only be performed under specific weather conditions.

Enercon, one of the biggest wind turbines producers, has a different maintenance strategy. Every 3 months is made an inspection to the turbine, but inspections are specific to pre determined sectors of machine. Figure 3 shows the strategy and the sectors analyzed in each inspection.

While the first maintenance plan needs multidisciplinary maintenance teams, the maintenance plan imposed by *Enercon*, uses specialized maintenance personnel for each inspection.

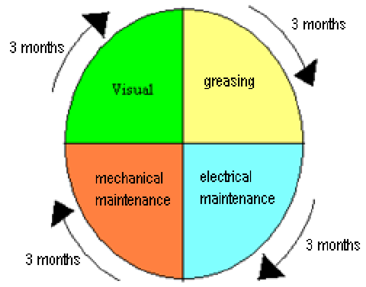

Fig. 3. *Enercon* maintenance planning [4].

Maintenance strategy based on time, has some handicaps. If time interval between maintenances is to short, operational costs increases and wind turbine outage time increases too, due to the necessity of stop the machine to do the work. On the other hand, more unexpected faults occur when time interval between inspections is long.

To solve this paradigm some producers and wind park owners started to develop maintenance strategies based on equipment condition monitoring. Using these techniques is possible to optimize the maintenance as a way of increase the availability and reduce operational costs.

Several studies were made about this issue, comparing the advantages and disadvantages of maintenance strategies. Fig. 4 shows the comparison between three of the most common strategies.

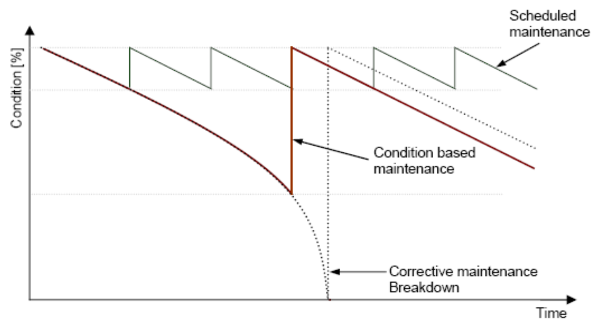

Fig. 4. Maintenance strategies comparison [5].

As is possible to conclude from the analysis of fig. 4, scheduled maintenance is executed more frequently than condition based maintenance. One disadvantage of the scheduled maintenance is that most of the time maintenance is executed while equipment is working correctly, with no problem. This can be considered as an excessive use of unnecessary resources and inherently an increment of maintenance costs. The corrective maintenance is not an option because is only made when the equipment is already on fault. Condition based maintenance is associated to good monitoring systems that can be the best choice in terms of reliability of the systems and in terms of optimization of maintenance costs.

III. Wind Turbine electrical Generator

At the present, three types of wind energy converters are normally used: the squirrel cage induction generator (SCIG), the permanent magnetic synchronous generator (PMSG) and the doubly fed induction generator (DFIG). The three configurations are shown in fig. 5.

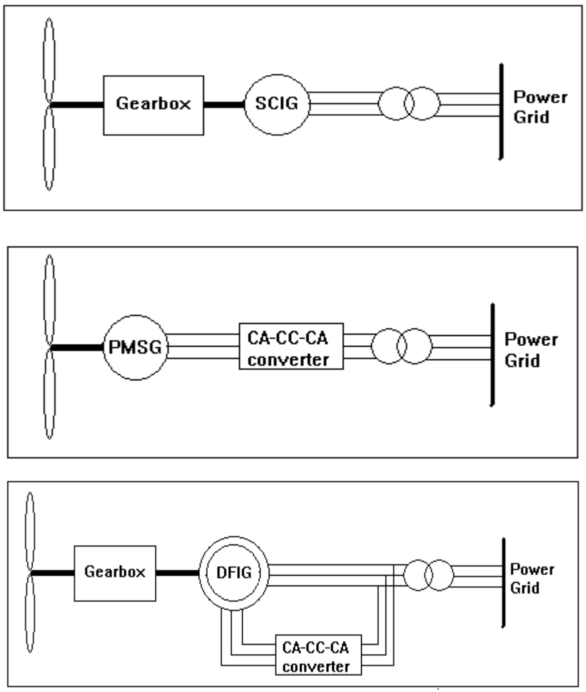

Fig. 5. Simplified diagrams of wind energy converter configurations.

The SCIG has a simple construction and its robustness, presents a lower investment cost but, on the other side, the controllability is very small. The machine is mechanically driven by a wind turbine through a gearbox which gives higher angular velocity to the electric machine.

In the PMSG the rotor is magnetized by permanent magnets. The generator works at variable velocity and the maximum power is transferred to the grid through a AC-DC-AC converter, that keeps the generator frequency constant and equal to the grid frequency. The generator is directly connected to the wind turbine with no need of gearbox which gives a reduction on the weight, noise and in maintenance costs, but needs a higher number of poles to compensate the lower velocity of operation.

In the DFIG the currents in the rotor winding can be controlled by the electrical converter, which gives the possibility of control the stator currents. In this way, the mechanical and electrical rotor frequencies are decoupled and the electrical stator and rotor frequency can be matched, independently of the mechanical rotor speed [6].

The wind farm used for this research study has 13 wind turbines of 2 MW, equipped with DFIG wind converters.

A. Slip ring

A typically slip ring of a wind turbine electrical generator is shown in fig. 6.

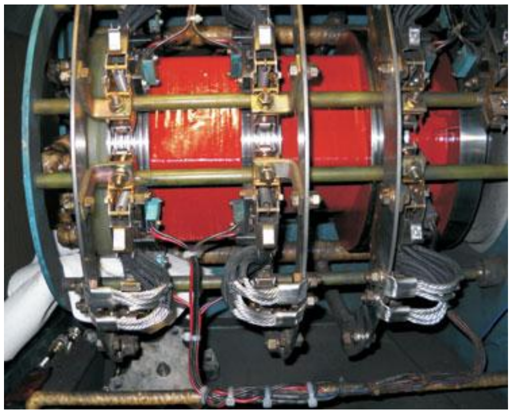

Fig. 6. Slip ring of a wind turbine electrical generator [7]

The slip ring is the equipment used to access to the rotor windings and connects them to the AC-DC-AC converter. The converter enables control of slip and power factor, thus giving a wider speed range for production and providing the ability to feed reactive power to support the grid.

The purpose of the AC-DC-AC converters is to ensure the maximization of the coefficient of the turbine power, especially in the characteristic region of the power depending on the wind and where the power is not controlled. Additionally, the control systems of converters maintain a given value of power factor at the interconnection point of the doubly fed induction machine with the electric power grid. In the characteristic region, where the turbine power is controlled, the converters AC-DC-AC control system keeps constant the total power extracted by the stator and rotor of the machine, complemented by the control system of step angle of the rotor blades. It is therefore concluded that the control system of wind generators equipped with double fed induction machine can maximize the electrical power delivered to the network in the range of variation of wind speed [6].

The slip rings and respective brushes are the equipments that connect the converter to the rotor windings. This equipment needs a lot of maintenance due to wear which is subject to.

In this particular wind park under study, some problems occurred with the slip ring system, which lead to the substitution of cables connected to the equipment.

IV. Developed Monitoring Strategy

Wind turbines have a huge number of sensors and measurement equipment installed with the objective of analyze the state of the system. All this information is saved in the wind park central computer and is sent to the control centre, if it exists. Then, control centre operators must analyze the data and try to detect any turbine problem symptom. Knowing that each machine can send to the control centre a list of about 800 signals, and that wind farms can have several machines, this work is not easy and for that reason the full potential of this information is not being used.

Depending on the wind turbine kind and producer, several measurements are made and saved in the central computer. In this particularly Portuguese wind park with 13 machines of 2 MW, the measurements are:

Time and date;
Wind speed;
Pitch angle;
Generator rpm;
Power;
Frequency;
Currents and voltages;
16 temperatures.

The 16 temperatures measurements are very important because they can hide a lot of information about the component's behaviour.

All the measurements are 10 minutes average values and are typical of data collection by commercial wind turbine supervisory control and data acquisition (SCADA) systems.

The existence of a very large number of measures led to the development of a monitoring method based in the application of neural networks (NN).

Neural networks application is dependent on the number of measurements and on their quality. The more quality of the data set will be translated in more quality of the results. If one year of measurements is used the data set is very large and can be used for learning, test and validation of the NN.

The neural network architecture used was feed-forward using the back propagation algorithm to the train of the network. In this type of neural networks neurons are organized in form of layers and each neuron of a layer is connected with all other neurons of next layer. The information is projected strictly from the input layer towards the output layer. Each connection has a specific weight, which represents the connection strength. It is the adjustment of these weights which is undertaken during network training. The training begins with random weights, and the goal is to adjust them so that the error will be minimal. During this process information can flow both sides. Fig. 7 presents the network architecture used in the monitoring process.

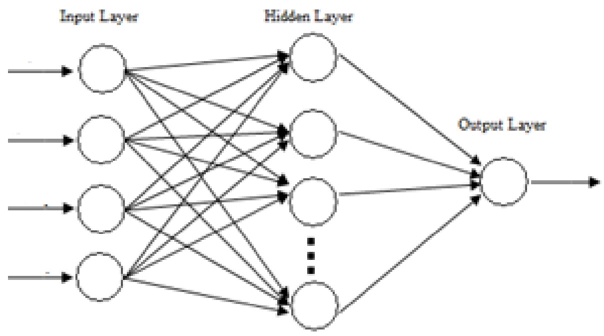

Fig. 7. Neural networks architecture

The main goal is to understand which measurements are important to use as input of the NN, because some measurements can have a weak influence on the process and it only contributes to wasting computational time. To solve this issue some methodologies were used and the final result fell on four input signals chosen from the measurement set. The variables are presented below.

- Current
- Environment temperature
- Bearing temperature
- Nacelle temperature

The chosen variable to be in the output layer was the generator temperature.

The network architecture has a hidden layer composed by 25 neurons.

For a good fault detection approach it is necessary to develop very accurate models, based on series of measures that effectively represents the normal operation of wind turbine. Only neural networks well trained can give very accurate results. In the model implemented the measurement set for training, test and validation of the neural network had 1 year interval.

V. Neural Network Results

The wind park used to make this study started its activity in 2004 and has 13 wind turbines of 2 MW, equipped with double fed induction generators. Some slip rings of electrical generator had problems that led to the equipment substitution or repair.

The developed model estimates the generators temperature and then the mean absolute error, between estimated and real temperature is calculated as a way to understand if there are problems with the electrical generator. Mean absolute errors greater than 4 ºC indicates that equipment may be with problems [8].

Results of simulations made for three wind turbines with problems in the slip ring are presented in Tables I, II, II and IV.

TABLE I
SIMULATION FOR WIND TURBINE AE6 [8]

	2006	2007	2008	2009
Jan	3.450	4.964		
Feb	3.785	5.961		
Mar	3.685	4.445		
Apr	3.889	no data available		
May	3.360	4.338		
Jun	3.744	4.613		
Jul	3.616	5.552		
Aug	3.205	4.995		
Sep	3.936	6.282		
Oct	**4.434**	6.671		
Nov	**4.975**	6.766		
Dec	**5.155**	7.408		

As is possible to see in Table I, until October 2006 MAE was always lower than 4 ºC. In December the service report made by the maintenance team indicates that slip ring was changed. Two months earlier, in October, the criterion used to alert the presence of problems was to exceed the limit of 4 ºC. It is possible to conclude that the developed method for monitoring that specific equipment detected the possible problem with two months in advance.

After the substitution occurred in December, MAE values are still high because the substitution of equipment implies the training of a new neural network. The results for the new network are presented in table II. The neural network was trained with the measurements of the first 9 months of 2007.

TABLE II
NEW SIMULATION FOR WIND TURBINE AE6 [8]

	2006	2007	2008	2009
Jan			2.811	3.604
Feb			**4.210**	3.461
Mar			**4.010**	2.889
Apr			3.745	3.054
May			2.426	no data available
Jun			2.560	no data available
Jul			2.758	no data available
Aug			3.701	no data available
Sep			2.836	no data available
Oct		2.592	3.274	no data available
Nov		2.635	3.135	no data available
Dec		2.953	4.281	no data available

In February of 2008 MAE is higher than the defined limit value and in March brushes of the slip ring were substituted. Once more the new monitoring method detected problems in the equipment 1 month in advance.

Table III presents the results for another wind turbine with problems in the slip ring.

TABLE III
SIMULATION FOR WIND TURBINE AE5 [8]

	2006	2007	2008	2009
Jan	**5.765**	4.901		
Feb	**5.741**	3.532		
Mar	**4.017**	3.628		
Apr	**4.442**	no data available		
May	3.076	3.392		
Jun	3.253	4.002		
Jul	2.878	4.058		
Aug	2.635	6.905		
Sep	3.169	5.850		
Oct	3.796	6.166		
Nov	3.670	6.211		
Dec	3.829	6.401		

In April 2006 maintenance service reports, indicate that slip ring cables were damaged and needed substitution. Since January that the monitoring method indicates, that something was wrong with that equipment. The problem was solved with the cables substitution and not of the entire equipment. For that reason there was no need of training another neural network. In 2007 values of MAE are high due to the occurrence of a big fault in the gearbox that led to the replacement of that equipment.

Once more the fault was detected in advance.

TABLE IV
SIMULATION FOR WIND TURBINE AE4 [8]

	2006	2007	2008	2009
Jan	**5.219**	4.803		
Feb	**5.027**	35.032		
Mar	**5.220**			
Apr	**4.572**	no data available		
May	2.924			
Jun	2.889			
Jul	2.828			
Aug	3.414			
Sep	3.858			
Oct	5.194			
Nov	4.457			
Dec	5.430			

Table IV presents the simulation results for wind turbine AE4. As it is possible to see in the firsts three months of 2006, MAE is high. At the end of March cables of the slip ring were substituted, because were damaged. Once more the new developed monitoring method, detected the fault with three months in advance.

After October 2006 the values are again high but that was caused by a big fault occurred in the electrical generator that led to the substitution of that equipment in February 2007.

The new developed method for wind turbines monitoring was applied to a wind turbine with no problems in the slip ring too. Results are presented in Tab V. Simulations were made till April 2009 because there was no more data available for study. Till the present there is no information about any problem occurred to that specific equipment.

TABLE V
SIMULATION FOR WIND TURBINE AE9 [8]

	2006	2007	2008	2009
Jan	3.35	3.369	2.768	2.898
Feb	3.898	3.875	3.504	2.922
Mar	3.158	3.901	2.796	2.448
Apr	3.147	no data available	2.482	2.626
May	2.995	3.866	2.522	no data available
Jun	2.963	3.799	3.421	no data available
Jul	3.155	3.758	2.596	no data available
Aug	3.352	3.887	2.935	no data available
Sep	3.569	3.759	2.949	no data available
Oct	3.245	3.86	2.916	no data available
Nov	3.115	3.304	3.367	no data available
Dec	3.259	2.988	3.224	no data available

It is possible to analyse from tab V, that during the period of time under monitoring, MAE is always lower than the established critical limit of 4 ºC. Service reports made by maintenance teams don't report any problem related with that equipment since January 2006 till now. Results obtained by the monitoring method indicates that there are no problems with the equipment. This can be used to validate the new tool developed to monitoring some equipments of a wind turbine, more specifically the slip ring.

VI. CONCLUSIONS

In this paper was presented a new monitoring methodology based in the application of neural networks used for the detection of faults in the electrical generator slip ring of a wind turbine.

Results obtained from simulations made in a real wind park in the north of Portugal, allow concluding that is possible to detect problems in the slip ring with some time in advance. This information can be useful for maintenance operators in maintenance scheduling, because it can help in the definition of new optimal maintenance strategies, based on the equipment condition and not only time based.

This new monitoring methodology was applied to the electrical generator slip ring, but similar results were obtained with the application of the method to the gearbox and to the electrical generator [9-10].

Although the results presented refer to problems arising in the past, it is possible to use the same method with online measurements as a way to warm some future faults in wind turbines components.

REFERENCES

[1] EWEA, "World Wind Energy Association – Statistics 2011." [Online]. Available at: http://www.wwindea.org,

[2] C. Walford, "Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs," Sandia National Laboratories, Albuquerque, NM SAND2006-1100, 2006

[3] J. A. Andrawus, et al., "Wind Turbine Maintenance Optimisation: principles of quantitative maintenance optimisation " Wind Engineering, vol. Volume 31, p. 10, March 2007.

[4] E. S. D. GmbH, "Maintenance Instructions," Enercom1 March 2007.

[5] J. Ribrant, "Reliability performance and maintenance - A survey of failures in wind power systems," Master, KTH School of Electrical Engineering, Stockholm, 2005-2006.

[6] J. B. Ekanayake, et al., "Dynamic modeling of doubly fed induction generator wind turbines," IEEE Transactions on Power Systems, vol. 18, pp. 803-809, May 2003.

[7] H. E. Inc. (2011, 12 July). H&N Wind. Available: http://www.hnelectric.com/wind_field_service.html#top

[8] R. F. Mesquita Brandão, "Assinatura Digital de Aerogeradores", PhD Thesis, Engineering Faculty of Porto University, Portugal, January 2012.

[9] R. F. Mesquita Brandão, J. A. Beleza Carvalho, F. P. Maciel Barbosa, "Wind turbines condition monitoring with neural networks applications", 12th Portuguese-Spanish Conference on Electrical Engineering (XIICLEEE),Azores, Portugal, 30 June -2 July, 2011

[10] R. F. Mesquita Brandão, J. A. Beleza Carvalho, F. P. Maciel Barbosa, "Neural Networks Applications for Fault Detection on Wind Turbines", International Conference on Renewable Energy and Power Quality (ICREPQ'11), Las Palmas de Gran Canaria, Spain, 13-15 April 2011.