Reliability of Special Synchronous Air Generators

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Wind power generators show a great number of constraints not only during production but also along their life cycle due to several reasons, among them the need of a long life cycle in order to provide an interesting ROI. This work uses a case study of special synchronous hexaphase multipolar generators to propose a methodology for reliability analysis in the area. The main results show the importance of using quantitative techniques (prognosis) to assure product reliability. A proposed model for dealing with reliability issues is the adaptation of the PDCA cycle leading to a SDCA cycle.

INTRODUCTION

The considerable growth in potential electricity consumption leads to the need to implement various energy sources (GWR, 2012; Bazmi *et al.*, 2011). Therefore, the issue of power generation is currently at stake, especially in developing countries such as Brazil. In this scenario, the wind power segment, which has experienced excellent growth rates, should continue to perform well in Brazil. The installed capacity of wind power in Brazil was about 3400 MW, representing approximately 3% of the total power in the country for 2014; the outlook is reaching a *plateau* of approximately 7300 MW (ABEEOLICA, 2014). To attain a long life cycle, which means at least 25 years to achieve adequate ROI, initial costs are very high and time is sometimes a limiting factor. Hence, the whole development has to respond to both technological and operational expectations.

It is worth noting that wind power generation is considered environmentally correct (Kaldellis *et al.*, 2011), its major impact occurring during air turbine production, although most of the consumed material can be recycled after its life cycle (Dones *et al.*, 2007). In fact, a decade ago, Nemet (2008) already pointed out the need for stimulating innovation in low-carbon energy technologies, such as wind power sector. In this case, the need of a framework based on pull demand and push technology policies in order to pursuit the required innovation is highlighted. Analyzing the wind power case in California, the author draws attention to three major characteristics regarding climate change prevention: non-greenhouse emission energy sources, which means considerable increase in wind power supply along the century, commercial availability of this long-lived technology and dramatic technological change that reduced wind turbines costs by a factor of five in two decades last century. However, the main driving forces of the well-established wind power model in that state, according to the author, is more owed to the gains from learning by-doing/and -using that are quick derived, often within a year or two, and the construction of the wind farm itself, that takes less than two years. However, the interval between making an investment and its payoff is longer; in other words “new devices must be adapted to real world conditions, integrated into large technological systems, and often require the development of supporting technologies for users to adopt them”. Thus, “push technology may dominate for radical innovations, and pull demand for incremental ones”. Nonetheless, such incremental approach allowed the costs of California wind power to decline by a factor of ten without any radical changes in design in three decades; which, at the end of century, also meant wind power without subsidies almost competitive with natural gas power. A similar analysis regarding the dichotomy between technology-push and demand-pull was presented by Taylor in her review of California's solar policy (Taylor, 2008), but the major argument was the importance of the environmental innovation policy since the dichotomy may be necessary, but not sufficient, for innovation to occur. Note that she considers the term solar energy technologies as “not only to technologies powered directly from the sun energy, but also to technologies powered indirectly from that energy, including wind power, tidal power, and biomass power”.

Innovation, pressure due to quick changes, cost reduction with increase in performance and environmental concerns is not a prerogative of the wind power sector; for instance, the electronic sector has dealt with such hindrances for at least five decades now. Thus, in order to respond to such issues, the ITRS (*International Technical Roadmap for Semiconductors)* group, historically responsible for the roadmap in semiconductor technologies, changed its approach in the last decade. Whereas until recently the application of Moore’s law – which states that the numbers of components on a chip double every year while costs decrease – was the driven force for a virtuous cycle that provide exponential growth of the semiconductor market and high investments in corresponding technologies, i.e., a roadmap based on the technology push approach, highly focused on the R&D efforts, the current trends have changed significantly. The drive force is now to incorporate functionalities that add value to devices, creating integrated systems with pre-determined functions. This new approach requires implementing a new methodology, which goes through the identification of new societal needs to the definition of technological gaps; then determining the physical and chemical parameters that are important limitations to technologies development (Arden *et al.*, 2010). An interesting feature is that the approach changed after decades of incremental performance using the same mechanism – scaling of integrated circuits – because this conception was reaching its physical and chemical fundamental limits (Roy *et al.*; Wristers, 2010). Moreover, the expensive and risky pursuit of new technologies also leads to innovative ecosystems, in which partnership not only reduces these costs and risks but also combines complementary knowledge in order to address complex problems; again, the semiconductor sector is a paramount example (Leten *et al.*, 2013).

With the previous considerations in mind, let us discuss the main technological constraints in wind farm and wind power life cycle. In fact, in a recent interview (Foyer; Wilcox, 2014), information of insurance concerns pointed out that to this industry “it's not the frequency of claims as much as it is the *severity* of the claims. For instance, a wind turbine blade damaged by lighting could result in a $500,000 claim. And that's just the damage to the blade itself — not any loss of income that may have resulted from the lack of activity”. Thus “maintenance becomes an issue the longer a wind farm is in operation” and “if a system is not properly maintained, then it will break down and subsequently shut off the income stream”, i.e., is not only preventive maintenance but also predictive maintenance, which comes from condition monitoring. According to Xin *et al.* (2014), wind turbine accidents are becoming a global concern. Auditing in China, top country in the world for installed capacity in 2012, the reasons for accidents in wind power sites, wind turbine burn and collapse showed to be the primary concern. Some explanation can be derived from the hurried application of new “technologies and concepts (such as large turbines, large blades, low wind speed, high-altitude wind turbine technology)”; furthermore, “with the low prices for wind power equipment, it is hard to invest sufficiently in areas such as technological improvement and product quality guarantee"; therefore, "quality problems of wind turbines are also coming along". Considering that wind turbines are produced in a few months but must remain operational for at least 20 years, the consequence is a highly critical scenario for this production area (Crawford, 2009) where quality issues, and specially reliability, should play an important role.

Thus, this work uses the case study of special synchronous hexaphase multipolar generators to propose a methodology for reliability analysis in that area. The importance of this study is to survey the data and possible causes for the problem, the theoretical correlation with the practice the way in which will both think the project design, process development and operation; such that the guarantee of product quality is improved from setting the correct product, specification and process.

THEORETICAL

Although Sustainability is not an easy concept, this paper presents straightforward assumption, i.e., it is considered as the application of the Sustainable Development concept, its praxis, to human processes. It is used herein as proposed by Poudel (2002), who described Sustainability as effectiveness in the form of management applied for obtaining certain objectives, which requires correctly defining the criteria to evaluate the objectives, goals and the actors involved in the issue, along with methods to determine criteria and indicators, which results in significant assessment tools. Furthermore, although slightly discordant concepts may have been used to define Sustainability in the last four decades, as Adeodato (2005) notes, all these approaches concern the search for long permanence of certain necessary features, desirable in a socio-political system and its natural environment, not infinitely durable but which is capable of transforming society. In addition to goals, targets and indicators, the time issue should be also evaluated. Finally, in the secondary sector, a very important concept is that of Industrial Ecology, which states that all waste/materials must be continuously recycled within the system and only the unlimited solar energy should be used in a dissipative way (Andersen, 2007). This should occur synergistically – thus, an analogy between industrial systems and natural ecosystems, which favors the evaluation of timing, in that there is concern about the flow of materials, which not only occurs between firms, but also in their interaction with the environment (Hauff; Wilderer, 2007), (White, 1994), (Seuring, 2004).

Sustainability, among other actions, requires the production of renewable energy as a primordial asset; therefore, wind power energy plays an important role. The manufacturing of wind power devices, on the other hand, can be an extremely impacting activity, and should hence be thoroughly studied. As aforementioned, among the parts and pieces that compose an air turbine, the greatest environmental concern device is the *generator*. There are several distinct features for wind power generators developed over time; however, the permanent magnet synchronous generator is a recent approach that presents several advantages and also differs from conventional generators, because instead of using excitation control to create the electromagnetic field, permanent magnets are employed. This type of generator will probably be extensively used in the near future for generating wind power due to the low amount of raw material applied and to the new technology being based on permanent magnetic devices, which leads to fewer moving parts. However, to enable this application, power electronics has its pivotal role. As the wind does not have a constant speed and cannot maintain constant voltage and frequency, converters have to be used to stabilize these parameters, causing a range of problems not yet known (Venugopal *et al.*, 2014), (Mohammad *et al.*, 2014).

Since the generator may be subjected to over voltages, generating unknown faults, the affinity diagram might be helpful. This matrix is a graphical representation of the particular relationship between variables, showing what is in common or distinguishes them. Furthermore, faced with a tangle of information, often loose and not clearly related, the Relations Diagram is used to logically assign the links of cause and effect. This tool has the following advantages: it simplifies the list of troubleshooting because divides it into its main points; it quantifies these main points; it shows the key points of the problems correlated to possible solution scenarios. Finally, to complement the review of the problems and their causes in order to build a realistic scenario of traceability and consequent reliability, the application of the Matrix Diagram is recommended. This tool relates multidimensional reasoning through a set of phenomena decomposed into factors, which may facilitate understanding the interaction between them (Toledo *et al.*, 2013).

METHODOLOGY

Despite the existence of a complex system for analyzing the failures (private information) in the wind power sector, there is also lack of information, and data must be gathered to permit observing patterns within a range of variables; ergo, a possible choice is using a series of tools, such as affinity and relations diagram, to unravel such data.

The case study herein has some issues that must be primarily considered. The main constraints in such case are the loose connection between the relevant data available and, at same time, the huge amount of such data. Thus, especially for this study, the affinity diagram is useful to gather data and to organize confused dispersed groups of data, such as e.g. the various components used by setting the generator in the timeline. In other words, in this case this tool was applied to:

- drive the problem solutions;
- organize information towards problem solutions;
- organize problem root causes;
- predict future situations – extrapolation;
- add a new methodology related to the evaluation process;
- data collection plan for future stratification.

However, only the affinity diagram would not be enough to solve the main problems, since this tool is useful to categorize the data in several distinct patterns, but is less powerful to correlate them. Therefore, the use of Relations Diagram was attempted although it presented some difficulties to be implemented in this study because:

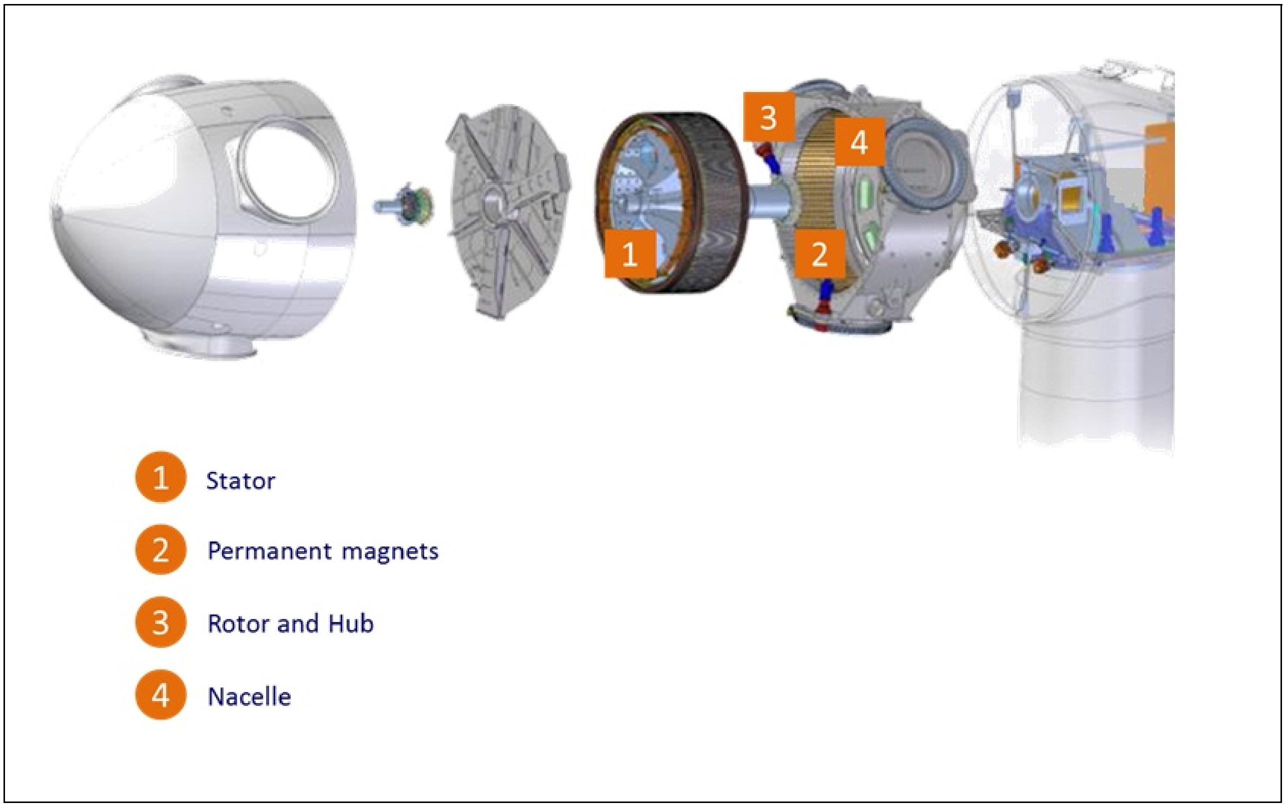
- the subject is complex and the relations of cause and effect are not easily visible;
- the correct sequence of actions is critical to the development of the theme;
- process revisions are constant and impact time;
- it clarifies the structure of the problem and assembling combinations;
- it provides means for achieving the goals.

As soon data is correlated in a cause and effect scheme, it is necessary to evaluate the importance of each parameter. Then, the Matrix in "L" was selected for the implementation due to the possibility of representing the data and their relationships in a Cartesian way. Its main task is to organize the quality systems and to show the relationship between the characteristics of the product and their quality control plans.

The case study was developed in a multinational industry belonging to the Energy Sector, located in 3 countries, Brazil, Argentina and Malaysia, which manufactures air and hydraulic turbines. This company has more than 1000 employees and it it is over 100 years old. This Company not only produces turbines, but also performs tests and has an important group of engineers to conduct R&D for new products.

The object of study chosen was an air turbine generator, composed of 4 main structures – the rotor and stator, which form the generator, and the hub and nacelle, responsible for the controls and actuations. Although this kind of turbine shows some of the most important technological advances in wind power sector, its life cycle is short, i.e., smaller than expected to provide a good ROI. Figure 1 shows the schematics of the air turbine.

FIGURE 1
SCHEMATICS OF THE AIR TURBINE



RESULTS & ANALYSIS

This section presents the qualitative and quantitative tools used to describe the investigation process and applicability of solving analysis method.

In order to achieve the correct data to build the affinity matrix, several classic quality tools were preliminarily applied to the air turbine case study. At this step, the main quality tools applied were: check list providing the main parameters to be checked during the air turbine operation. This check list was developed during several brainstorming encounters with expert people that defined, among other things, which parameters could be measured accurately, even if only qualitative information was provided. Then, Pareto was applied for ranking all the parameters available according to failure frequency and severity. Using this approach, the Ishikawa Diagram was modified to establish the possible causes for such failures.

Several checklists were developed and Figure 2 shows an example of a check sheet. Note that the proposed checklist aims to record and to collect data in a simple and feasible way for further use; furthermore, this sheet is a counting table, i.e. data is evaluated quantitatively. An example of the Modified Ishikawa Diagram can be seen in Figure 3. This diagram consists of a graphic representation that organizes logically and *in order of* importance, the potential causes contributing to an effect or given problem; in our case, generator failures.

FIGURE 2
DATA SHEET USED FOR FILLING TECHNICAL DATA GENERATORS

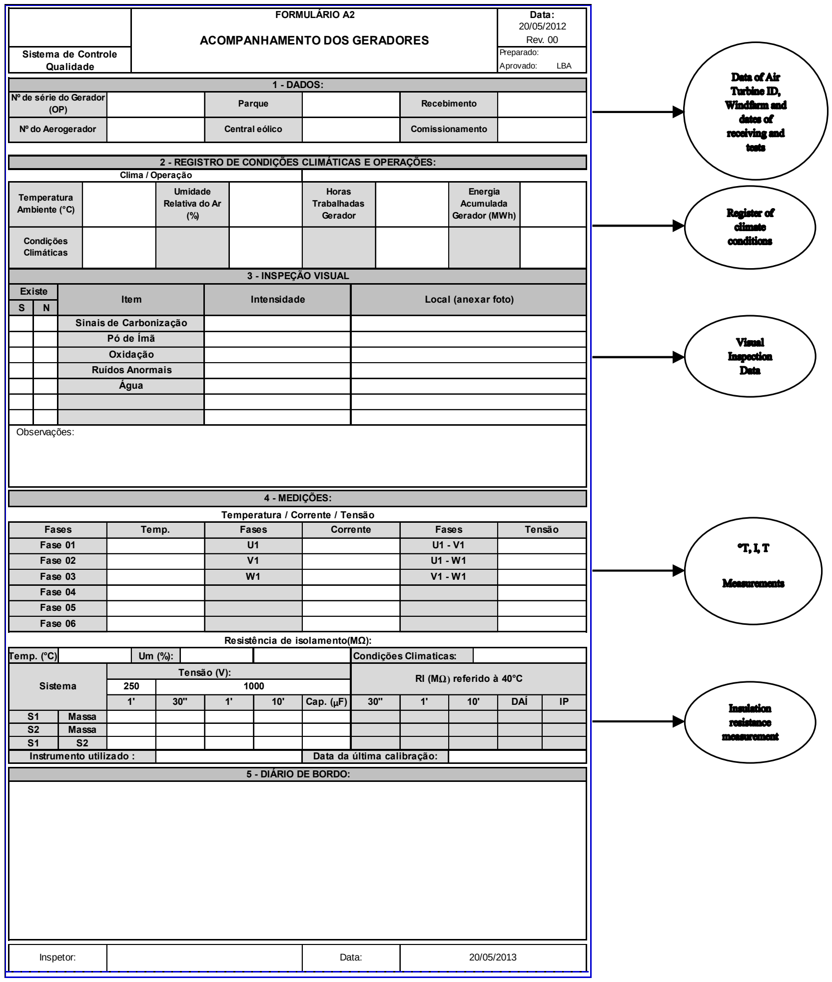
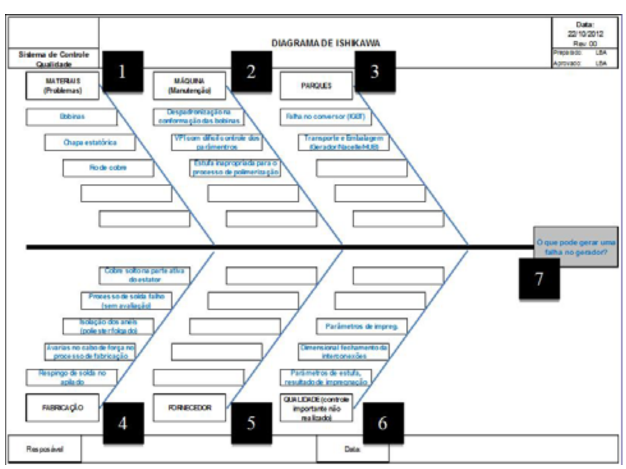


FIGURE 3
MODIFIED ISHIKAWA DIAGRAM: 6 M'S ADAPTED: 1. MATERIALS; 2. MACHINE; 3. WIND FARMS; 4. MANUFACTURING; 5. SUPPLIERS; 6. QUALITY CONTROL; 7 – CAUSES OF FAILURE



Affinities Diagram

Figure 4 shows an example of graphical representation of data groups that have some natural relationship among themselves that distinguishes them from others, applied to gathering scattered data or data groups randomly organized.

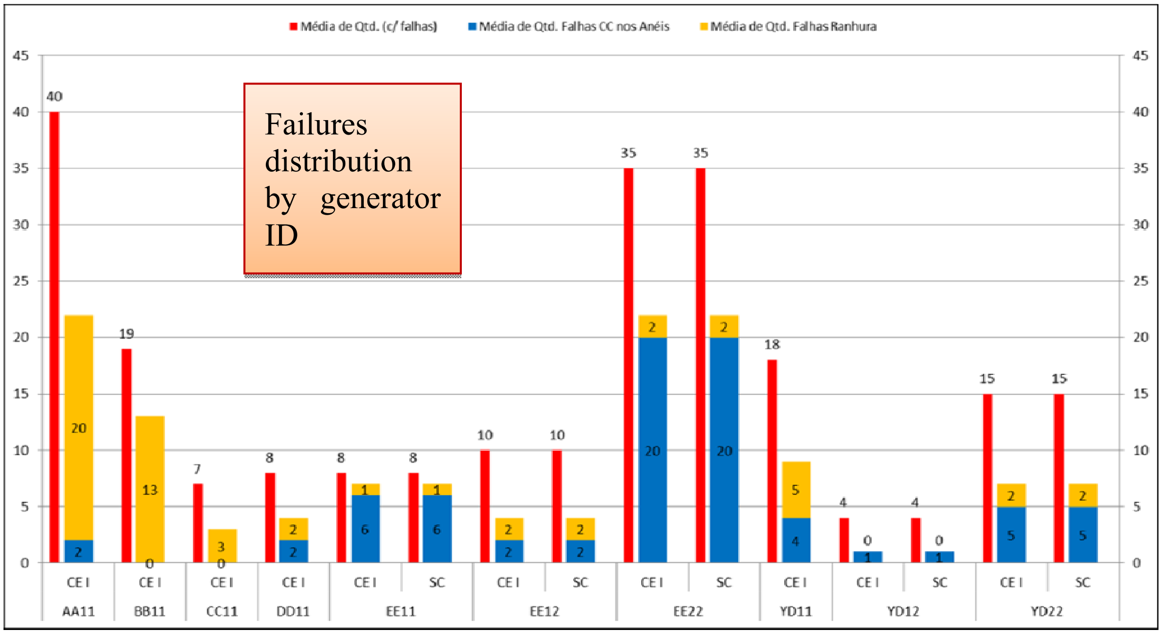
This graph presents technological evolution in time; a number of machines had to be repaired or installed simultaneously. The first main separation is the type of construction of each device; after that, identification. The advantage of this procedure is the diagnosis that allows instantly recognizing any operational point from each generator being analyzed. Note that this diagram has considered the 4 main parts of the generator, defined in the methodology section. In this case, only the important parts of the nacelle are presented. Furthermore, any generator that suffered remanufacturing is identified, which allows quickly verifying the dimension of the problems occurred, for example.

Therefore, in general, the generator could be classified by a set of letters characterizing the location provided in the wind farms, its configuration and possible improvements or repairs. Consequently, it is possible to generate graphs that represent failures percentage and cause, i.e. origins, providing the relations diagram that in Figure 5 corresponds to an example. The advantage of the approach is that, in a single graph, it is possible to visualize the air turbine localization for each configuration, i.e., respective wind farm, the total failure number and kind, and also the discrimination according to the affinities diagram, i.e., considering each device inside the air turbine. It was observed, for instance, that the EE11 configuration achieved a 50% higher survival rate than the DD11configuration. (Further details cannot be disclosed for reasons of confidentiality).

FIGURE 4
AFFINITIES DIAGRAM APPLIED TO COMBINE THE SEVERAL COMBINATIONS OF GENERATORS: EVOLUTION INFORMATION OF: 1. STATOR; 2. ROTOR; 3. NACELLE PARTS AND PIECES; 4. GENERATOR ID

Tipo	Estator	
A	Bobinas Sem Esmalte/Impr[illegible]oll Dip/Verniz Vermelho	1
B	Bobinas Sem Esmalte/Impregnação Roll Dip/ Verniz e Vermelho e Gotejamento	
C	Bobinas Sem Esmalte/Impregnação Roll Dip/ Verniz Vermelho/ Gotejamento e Silicone	
D	Bobina sem Esmalte/Impregnação Roll Dip/ Gotejamento/ Silicone e Pintura Off-Shore	
E	Impregnação Roll Dip/ Gotejamento/ Silicone e Pintura Off-Shore/ **Bobina com Esmalte**	
F	Silicone/ Pintura Off-Shore/ **Bobina com Esmalte/** Selo de Vedação/ Impregnação VPI	
G	Silicone/ Pintura Off-Shore/ **Bobina com Esmalte/** Selo de Vedação/ Impregnação VPI/ Cabo de força impregnado c/ VPI	
H	Silicone/ Pintura Off-Shore/ **Bobina com Esmalte/** Selo de Vedação/ Impregnação VPI/ Cabo de força impregnado c/ VPI/Encapsulamento do anel com silicone	
I	Silicone/ Pintura Off-Shore[illegible]**om Esmalte/** Selo de Vedação/ Impregnação VPI/ Cabo de força impregnado c/ VPI/03 voltas de mica com substrato de poliéster nos anéis - Melhoria nas interconexões	2
Y	Estator Recuperado	
Tipo	**Rotor**	
1	Imã Neodimio, Resina Curada em Temperatura Ambiente	
2	Imã Neodimio, Tubo entre os Pólos e Resina Curada em Temperatura Ambiente	
3	Imã Neodimio, Tubo entre os Pólos e Resina Curada com Resistência e Pós Molding (GRP)	
4	Tubo entre os Pólos, Resina Curada com Resistência, Pós-molding (GRP), Ímãs Neodimio "niquelados" (Ni-Co)	
5	Ímãs Neodimio, Resina Cur[illegible]esistência, Escudo GRP	3
6	Resina Curada com Resist[illegible]do de GRP, Ímãs Neodimio "niquelados" (Ni-Co)	
Tipo	**Cabeçote**	
1	Com 6 furos (Circular)	
2	Com 12 furos (Circular)	
3	Com 24 furos (Oblongo)	
4	Com 06 Escape de Água	4
Caracteres	**Descrição dasLegendas [illegible]ipo AA11)**	
1.° (A)	Novo ou Recuperado	AA11O = Novo (A), Tipo do estator (A), tipo do rotor (1), tipo do cabeçote (1), Observações (O)
2.° (A)	Tipo do estator	
3.° (1)	Tipo do rotor	
4.° (1)	Tipo do cabeçote	Y - Estator recuperado;
5.° (O)	Observações	

FIGURE 5
RELATION DIAGRAM THAT SHOWS THE QUANTITATIVE OF FAIL OCCURRENCES PER CONFIGURATION OF GENERATORS



Matrix Diagram

Once a failure is well defined, its description must be broken down by the expected correlations, in order to prevent those same conditions from being repeated in other equipment and also to improve new manufacturing processes. Therefore, a Matrix Diagram was carried out. Figure 6 shows an example of such a tool, in this case a matrix in 'L'. On the basic form of the matrix, two or more interrelated groups of items or variables are presented in rows and columns.

This matrix was performed in excel program in order to provide an easy manipulation of such data; in other words, since any operator can choose the data to be displayed in the matrix, the correlation and/or pattern will be visualized quickly, in a simple step. Thus, using the Relation Diagram, any operator chooses the pattern that seems important to provide a specific characteristic and then the matrix is tailored by combinatory analysis among parameters.

For Figure 6, e.g., considering all the quality tools previously applied, the data point out that although the technological improvements achieved from DD11 to EE1, for instance, were impressive, they were not enough to expand the life cycle, as required, for a convenient ROI, i.e. 25 years. This situation, on the other hand, requires the focus on the next developments to be placed on the new parts and pieces, now detected as new issues for development in a new technological cycle.

Modeling and Corresponding Proposed Methodology

The most important consequence of generating the Matrix Diagram is assembling the data, once this somehow allows the traceability of the entire process and product. Particularly, this traceability information consisted of design, materials and supplies; however, by monitoring the air turbine in operation, some characteristics are also measured, such as hours worked, power generated, electrical insulation and others. Furthermore, all environments could also be considered, which means adding environmental data, such as rainfall, presence of ionic compounds. In such a scenario, to a single location, it is possible to combine internal and external parameters for monitoring and, consequently, to optimize the performance.

FIGURE 6
EXAMPLE OF MATRIX IN ‘L’ TO CORRELATE CONFIGURATION OF GENERATORS WITH OCCURRENCES

Tipo de Gerado	Curto Circuito na ranhura problema elétrico	Curto Circuito na Ranhura falha mecânica	Curto Externo (anéis)
AA11	x		
DD11		x	
AA11		x	
EE12			x
DD11			x
AA11	x		
BB11	x		
YD11			
AA11		x	
EE11			
YD11		x	
YD11		x	
AA11	x		
YD11			
AA11		x	
AA11		x	
DD11			
AA11	x		
EE12			
YD11		x	
AA11		x	
YD11		x	
YD11			x
AA11		x	
YD11		x	
YD22		x	
AA11	x		
AA11		x	
EE11		x	
AA11		x	
EE22			x
EE22			x
AA11	x		
AA11			x
FF33			x
AA11		x	
YD11	x		
EE11			x
AA11	x		
EE11			x
YD22			x
CC11		x	
AA11	x		
AA11	x		
YD22			x
EE22			x
EE11			x
AA11	x		
YD11			x
EE11			x
DD11		x	
EE22			x
EE22			x
YD11		x	
EE22			x
CC11		x	
FF43			x
EE22			x
CC11	x		
EE22			x
BB11	x		
EE22			x
BB11	x		
EE22			x
BB11	x		
EE22			x
BB11	x		
EE22		x	
BB11	x		
AA11	x		
AA11	x		
EE22			x
EE22			x
EE22			x
EE22			x
BB11		x	
EE22			x
BB11	x		
EE22			x
BB11		x	
EE22			x
EE12		x	
AA11			x
BB11	x		
EE22			x
BB11		x	
BB11	x		
YD22			x
BB11	x		
EE12	x		
EE22	x		

Exploded matrix with split of failures by generator

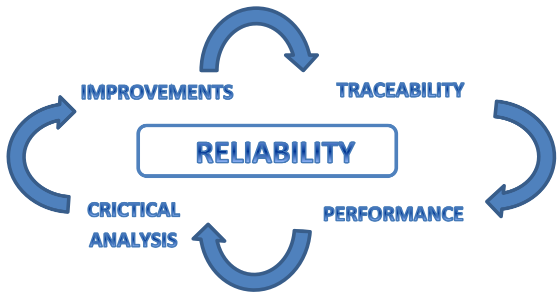
According to Caldeira Filho (2004) *apud* Deming (1981), improvements, i.e. the pursued optimization, requires planning, action and checking. However, it is impossible to act without previous tests, at lab or pilot scale, which is time-consuming and sometimes not cost effective, especially for a high technological and demanding area, such as wind power. Therefore, we employed the consecrated idea of a PDCA cycle leading to a SDCA cycle but adapted it to include reliability. Figure 7 shows the proposed model. Thus, the cycle is as follows: traceability is aimed by the use of conventional quality tools that indicate the main issues to be considered in development and in process production.

The main approach to reduce risks in this proposal is to define traceability as the major pillar in the development and production areas. This assumption makes obtaining information for several different parameters mandatory and, as a consequence, any failure can be quickly combined with a pattern (group of parameters) or correlated situations (strong correspondence between parameters). This roadmap assures quick response to malfunctions while still permitting marked changes in development and project. More important, if this approach is quickly linked with other procedures, such as lab analysis, carried out simultaneously with project modifications, the system will be much more robust.

Although this study proposes a conceptual map, shown in Figure 7, for reliability analysis in the wind power sector, this structure could be easily adapted to any other area where changes in production are quick and demand process changes without extensive laboratorial tests, such as the ones developed in prototypes.

Finally, the path proposed in this study allows inferring information on material flows and cycles, mandatory in the Industrial Ecology approach in order to increase sustainability.

FIGURE 7
MODEL PROPOSED FOR WIND POWER RELIABILITY ANALYSIS



CONCLUSIONS

We proposed a methodology for reliability analysis for a production area in which development is quick and leads to so high change rates that hinder many conventional attitudes to assure reliability in process production and product use.

After using conventional quality tools, such as brainstorm, to define the main parameters to be analyzed and data to be collected, several data sheets were provided and data compiled in a way that allowed to be gathered in an affinity diagram with Matrix in 'L' for composing the statistical analysis. The result of this study generates points of improvement since these time problems are identified at their root cause, which validates the whole production process, which means concluding an entire operating cycle of the proposed methodology, by the use of reliability analysis.

Thus, logic of quality tools was presented herein, providing a method for reliability analysis of sequence generators. From the proposed methodology, some conditions for problems were predetermined, and the points to be collected and analyzed in the special synchronous generators applied to wind generation. An example of the strength of this methodology is the improvement in generators (listed previously as DD11 configuration replaced by EE11 configuration) that continuously shows decrease on causes of failures, i.e. from each previous version. Applying a technical study from a statistical methodology based on reliability was found to generate meaningful results.

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