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Analysis of the wind average speed in different Brazilian states using the nested GR & R measurement system

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ABSTRACT

Brazil presents remarkable potential for wind power generation. This study aims to evaluate the behavior of wind average speed at the four major wind energy-producing states. The main contribution of this research is to use the NGR & R study (Nested Gage Repeatability & Reproducibility), generally applied on manufacturing quality management. Wind average speeds were collected for each month in four states, between the years of 2012 and 2015. Seasonality impact, measurements recurrence over the years and difference between states on wind average speed were assessed in this research. Time series, boxplot and control charts have been used to investigate not only wind average speed between months and states, but also range variation for each state by month. Study results show that the impact of these three factors is statistically significant and that the different location of these states presents the most relevant impact to wind mean speed variation in the country.

1. Introduction

Renewable Energy Sources (RES) are able to reduce both greenhouse effect gases emissions and dependence of society on fossil fuels for power generation [1,2]. In this aspect, wind energy is one of the low carbon dioxide (CO_2) emitting RES, although the technology related costs to exploit this source are superior in comparison to conventional sources [3,4].

Therefore, government entities from several countries have issued policies in order to attract investors financially to power generation, especially electric power, through RES, such as wind power [5–7]. Past the energy crisis on 2001 and 2002, Brazil was one of the countries to adopt incentive policies for the renewable energy market. The country launched the Program of Incentives for Alternative Electricity Sources (PROINFA), intended to assign 3300 MW of electric power, produced by wind power, small hydroelectric power plants and biomass [8].

Approximately 1422.92 MW of wind power were assigned with PROINFA [8–10] and, since then, this power source has exponentially grown in the Brazilian electric power matrix. From 2009 onwards, wind power generation projects have gradually started to be assigned through auctions and, afterwards, free market as well, so that prices have become lower than on PROINFA and productive capacity have increased yearly [11].

According to the Brazilian Wind Power Potential Map, issued by CEPEL [12], and to Pereira Junior et al. [9], the country presents higher wind power generation potential in the Northeast and South regions, and the average capacity factor of wind farms in Brazil is 38.1%, performance superior to several countries [13]. In addition, presently there are wind farms in eleven Brazilian states, and these are the states where productive capacities are higher: Rio Grande do Norte (RN) (3408.1 MW), Bahia (BA) (1897.8 MW), Ceara (CE) (1759.1 MW) and Rio Grande do Sul (RS) (1644.4 MW) [14].

A determining factor for wind power generation is the wind speed intensity on areas where wind turbines are installed. Because in Brazil the territory is extensive and wind power generation potential is present on regions with diverse weather conditions, the hypothesis of occurrence of different intensities on wind formation in these locations can be argued. Moreover, there is the possibility of seasonality differences at each month and from one year to another.

Hence, the present study aims to identify whether statistically significant differences exist among the wind average speed of the four major states on wind energy productive capacity. Furthermore, it aims

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to verify whether there is also a difference among the wind average speed in each state from 2012 to 2015. The performance of the Nested Gage Repeatability e Reproducibility (NGR & R) measurement system analysis is an innovation proposed by this study, to use a measurement system commonly adopted by the manufacturing industry in the behavioral analysis of wind average speed in several Brazilian locations.

According to Burdick et al. [15] and Pereira et al. [16], Gage Repeatability and Reproducibility (GR & R) is a particular study of measurement system analysis employed to determine whether the variability of the measurement system is relatively less than the variability of the monitored process. In this aspect, repeatability is the variation of common or internal cause represented by multiple measurements of an operator, using a certain instrument, which evaluates a quality characteristic of an object. Reproducibility, in turn, is the variation between or special cause related to the average of distinct operators on the measurement of a quality characteristic of an object [17,18]. Several graphs can be used to identify significant sources of measurement error. In NGR & R studies, the main effects plot of the operator factor is used to evaluate the reproducibility error and the R control chart to evaluate the repeatability error. Examples applying these graphs to evaluate repeatability and reproducibility errors can be seen at [19–21].

2. Materials and methods

Measurement system capability, through GR & R, is an important study of quality improvement efforts [15]. By the use of GR & R, it is possible to estimate the amount of variation resulting from the measuring gauge and evaluate its adequacy for a specific application. According to Wang and Chien [22], there are two methods commonly used for GR & R analysis: the variance analysis (ANOVA) and the Xbar and R graphics. Yet, the authors emphasize that ANOVA is the favorite method among analysts, because it is able to quantify the measurement error considering interaction between the part and the operator, more details on the ANOVA method can be found on Wang and Chien [22].

Based on GR & R studies, it is possible to estimate how much of the variation is due to the measuring gauge and evaluate whether the measurement system is adequate for a given application [16,23]. In GR & R studies, when the levels of one factor are similar but not exactly the same levels of the other factor, the arrangement is called nested design [24,25]. In such arrangement, there is no interaction term between the two factors and the ANOVA model can be written as follows [15,26]:

$$Y_{ijk} = \mu_Y + \beta_j + \alpha(\beta)_{i(j)} + \varepsilon_{ijk} \begin{cases} i = 1,...,p \\ j = 1,...,o \\ k = 1,...,r \end{cases} \tag{1}$$

where Y_{ijk} is the variable of measured response; μ_Y is the average of measured values; $\beta_j \sim N(0, \sigma_\beta)$; $\alpha(\beta)_{i(j)} \sim N(0,\sigma_{\alpha(\beta)})$ and $\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon)$ are random and independent variables in relation to operators, parts nested within operators and the error term, respectively; p, o and r are the numbers of parts, operators and replicates, respectively.

The variance components in Eq. (1) can be translated into NGR & R notation, as observed in the following [15]:

$$\sigma^2_{process} = \sigma^2_{\alpha(\beta)} \tag{2}$$

$$\sigma^2_{repeatability} = \sigma^2_{\varepsilon} \tag{3}$$

$$\sigma^2_{reproducibility} = \sigma^2_{\beta} \tag{4}$$

$$\sigma^2_{NGR\&R} = \sigma^2_{repeatability} + \sigma^2_{reproducibility} \tag{5}$$

$$\sigma^2_{total} = \sigma^2_{process} + \sigma^2_{NGR\&R} \tag{6}$$

Aforementioned variance components can be estimated by using the equations below:

$$\sigma^2_{\varepsilon} = MS_{\varepsilon} \tag{7}$$

$$\sigma^2_{\beta} = \frac{MS_{\beta} - MS_{\alpha(\beta)}}{pr} \tag{8}$$

$$\sigma^2_{\alpha(\beta)} = \frac{MS_{\alpha(\beta)} - MS_{\varepsilon}}{r} \tag{9}$$

The mean squares for operators, parts within operators and the error term can be estimated by the nested ANOVA in Table 1. Variables in this Table are described as such: x_{ijk} is each observation; $\bar{x}_{ij.}$ is the mean for part i, within operator j; $\bar{x}_{.j.}$ is the mean of each operator j and; $\bar{x}_{...}$ is the grand mean.

Basically, the nested ANOVA distinguishes from a crossed ANOVA when estimating GR & R components of variation in Eqs. (1)–(4), the mean squares in Eqs. (7)–(9), and the sum of squares related to process variation. More details on nested and crossed designs in GR & R studies, see Burdick et al. [27].

After variance calculation by means of nested ANOVA, in order to evaluate if the measurement system is acceptable or not, the ratio calculation between the NGR & R standard deviation and total standard deviation must be performed [18]. Eq. (10) represents the calculation utilized to evaluate the measurement system:

$$\%NGR\ \&\ R = \left(\frac{\sigma_{NGR\&R}}{\sigma_{total}}\right) \times 100\% \tag{10}$$

It is worth mentioning that in order to obtain the contribution percentage in relation to the other variation components, the numerator of Eq. (10) must be changed.

If the index demonstrates a result below 10%, the measurement system is considered acceptable, if the result lies within 10% and 30%, the measurement system is considered marginal (depending on the application it is acceptable), and for results above 30%, the measurement system is considered unacceptable [16,28,29].

Another metric utilized to evaluate the measurement system is the signal to noise ratio or number of distinct categories (ndc) which is presented by Eq. (11). A value greater than five is expected; a value less than two indicates that the measuring system is not effective to monitor the process [15,28,29].

$$ndc = \sqrt{\frac{2\sigma^2_{process}}{\sigma^2_{NGR\&R}}} = \sqrt{2}\frac{\sigma_{process}}{\sigma_{NGR\&R}} \tag{11}$$

Table 1
Analysis of variance table for the nested design.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-values	P-values
Operator	$SS_\beta = pr\sum(\bar{x}_{.j.} - \bar{x}_{...})^2$	$o-1$	$MS_\beta = \frac{SS_\beta}{DF_\beta}$	$\frac{MS_\beta}{MS_{\alpha(\beta)}}$	$F_0 > F_{0.05,o-1,o(p-1)}$
Part (Operator)	$SS_{\alpha(\beta)} = r\sum\sum(\bar{x}_{ij.} - \bar{x}_{.j.})^2$	$o(p-1)$	$MS_{\alpha(\beta)} = \frac{SS_{\alpha(\beta)}}{DF_{\alpha(\beta)}}$	$\frac{MS_{\alpha(\beta)}}{MS_\varepsilon}$	$F_0 > F_{0.05,o(p-1),op(r-1)}$
Repeatability	$SS_\varepsilon = \sum\sum\sum(x_{ijk} - \bar{x}_{ij.})^2$	$op(r-1)$	$MS_\varepsilon = \frac{SS_\varepsilon}{DF_\varepsilon}$		
Total	$SS_{Total} = \sum\sum\sum(x_{ijk} - \bar{x}_{...})^2$	$opr-1$			