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MULTIPLE LINEAR REGRESSION MODEL APPLIED TO A FRAMEWORK FOR INDICATORS ESTIMATE IN MAINTENANCE MANAGEMENT

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***Abstract**. The distribution systems of electric utilities in the Northeast are antique and have several types of problems. In an indirect way, these problems can be observed through the collective continuity indicators, provided by ANEEL (National Electric Energy Agency). These indicators are DEC (Equivalent Duration of Interruption per Consumer Unit) and FEC (Equivalent Frequency of Interruption per Consumer Unit). Observing these indicators, we found that most of the energy distribution feeders (Northeast Region), have values above the permitted levels, and as a result, these distributors are required to pay monthly fines. Interruptions of these feeders cause several problems of technical and financial order to their consumers. The objective of this work is to provide for businesses utilities, a support tool for decision making regarding the efficient use of predictive techniques such as thermography. A structure of model using Multiple Linear Regression was developed. The entry of the model is the data of all modes of failure that caused the interruption of the electric power distribution system. The outputs in each model are the estimates of the main quality indexes of a power distribution substation (DEC and FEC).*
The model obtained presented appropriate to perform the DEC and FEC's prediction of a given month, allowing the concessionaire to act directly on the feeders and the failure modes that contribute to the increase of these indices. Througt the simulation obtained by application of model, it is possible to identify what are the failure modes that can be detected by thermography, which are responsible for the variation of collective indicators of continuity.

***Keywords**: Modeling, Thermography, Electric Utilities and Maintenance.*

1. INTRODUCTION

The objective of this work was based on the growing demand for new tools that provide conditions to improve the reliability of distribution systems for managers of enterprises electric utilities. The reliability of these systems can be measured through the collective indicators of continuity. High values in DEC and FEC indicators show a low reliability and unfold in fines payments.

Distribution systems of electric utilities are constituted of substations. The substation is equipped with a set of cables and devices to modify the characteristics of electricity (voltage and current). The substation allows energy distribution to points of consumption and receiving the appropriate levels of use, Mamede (1997). The substations are divided into various feeders. Feeders are circuits that carry electricity from substations to distribution transformers, AES SUL (2015).

The lack of electricity can have three basic sources: the scheduled interruption; accidental interruption; and the defect in wiring, CHESP (2005). Analyzing the recorded incidents in this electric energy distribution company, found that 98.7% of the records, were caused not planned occurrences, Fig. 1.

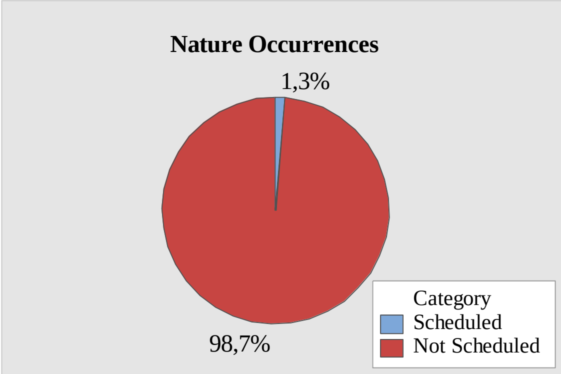


Figure 1 – Nature Occurrences

In recent works Jadin & Taib (2012) say that the costs of maintenance on electrical equipment contribute significantly to the composition of the operating cost of the Electric Power System.

In this paper, a model will be developed. In this model the faults that are likely to be monitored by thermography, will be evaluated. According to Korendo and Florkowski (2001), thermography allows taking measurements of the surface temperature of components, without physical contact with an installation (Security); check equipment in full operation (no interference in production); and inspect great surfaces in short time (High Yield). Thermography allows one to identify with huge success the possible failure modes in Systems Electricity Distribution. Jadin and Taib (2012), claim that the diagnostic systems based on thermography allow a preventive maintenance/predictive paragraph an early failure not forecast equipment, without interrupting the operation of the system.

The model developed in this study applied the Multiple Linear Regression Technique. According to Martins (2005), with the application of the Multiple Linear Regression you can design or estimate a new observation of the event.

To developing the mathematical models, we used the software MatLab®. According to Montgomery and Runger (2008), the use of models aims to evaluate the behavior of the output (Y) with the variation of one or more independent variables (inputs). Thus, it is possible to make inferences about the output variable, such as performing predictions of their behavior

The prospect of this model is to estimate the DEC and FEC from knowledge of the nature of faults occurring in the system. Through prior calculation of quality indicators proposed in this model, the electrical utility will be able to act in a more effective way in, fighting the most significant failure modes for the electric system. This model is a tool to support decision making.

2. QUALITY INDICES

The indices of quality defined by ANEEL for each electrical utilities in Brazil are called DEC and FEC and their main purpose is to measure and guarantee the quality of service provided by the electrical utilities, PRODIST (2015). If the values of the targets set for the DEC and FEC are exceeded, the electrical utilities must pay a fine, performing a financial compensation that is credited to the electricity bill of each consumer.

According to the Module 8 of the Distribution Procedures, PRODIST (2015), the DEC indicates the number of hours, on average, consumer units of a particular set were left without power for a certain period: monthly, quarterly or yearly. The FEC indicates how often, on average, the particular set of consumer units suffer interruption.

According to PRODIST (2015), these two indicators are calculated by Eq. (1) and (2) respectively, where DEC is an equivalent duration of interruption per consumer unit, expressed in hours and hour hundredths, DIC is duration of individual interruption per customer or per connection point, expressed in hours and hours of hundredths, FEC is the equivalent frequency of interruption per consumer unit, expressed in number of interruptions and hundredths of the number of interruptions, FIC is the individual interruption frequency per consumer unit or connection point, expressed in number of interruptions, i is index of consumer units served in Low Voltage (LV) and Medium Voltage (MV) billed in the whole set and Cc is a total number of consumer units billed around the set during the assessment period, in low and medium voltage.

$$DEC = \frac{\sum_{i=1}^{Cc} DIC(i)}{Cc} \tag{1}$$

$$FEC = \frac{\sum_{i=1}^{Cc} FIC(i)}{Cc} \tag{2}$$

The DIC and FIC are calculated by the Eq. (3) and Eq. (4), respectively, where DIC is duration of individual interruption per customer or per connection point, expressed in hours and hour hundredths, FIC is individual interruption frequency per consumer unit or connection point, expressed in number of interruptions, i is the consumer units interruptions rate during the assessment period, ranging from 1 to n, n is the number of consumer units considered interruptions, during the assessment period and t(i) is the interruption duration (i) consumer units considered in the assessment period;

$$DIC = \sum_{i=1}^{n} t(i) \tag{3}$$

$$FIC = n \tag{4}$$

The total time to account for the DEC, includes the time of preparation of teams, travel time and the runtime's own maintenance.

Table 1, according to ANEEEL (2015) shows some examples of DEC and FEC several electricity distribution companies in the Northeast.

Table 1 - Example of DEC and FEC several electrical utilities in 2014

Electrical Utilities	**Substation**	**Number of Consumers**	**DEC Determined**	**DEC Limit**	**FEC Determined**	**FEC Limit**
CELPE / PE	Afrânio	5.169	49,72	20,00	7,96	13,00
CEAL / AL	Arapiraca II	61.672	32,43	17,00	23,86	15,00
COELBA/BA	Angical	26528	57,23	30,00	14,32	11,00
CEPISA / PI	São Pedro	41620	100,44	28,00	49,04	29,00
COELCE / CE	Barra do Ceará	110967	7,07	10,00	3,12	9,00

3. PROPOSED METHOD FOR MODELING AND ANALYSIS

3.1 – Data Base

The energy distribution utility, object of this study, has a system composed of thirty-eight power substations. The substation studied in this article has eight feeders.

Based on the data of the discontinuity in the supply of energy obtained at the electric utility ranked all occurrences in 57 failure modes. Figure 2 (a) and (b) show the 10 failure modes that occurred more frequently in the years 2013 and 2014, both the DEC and for the FEC.

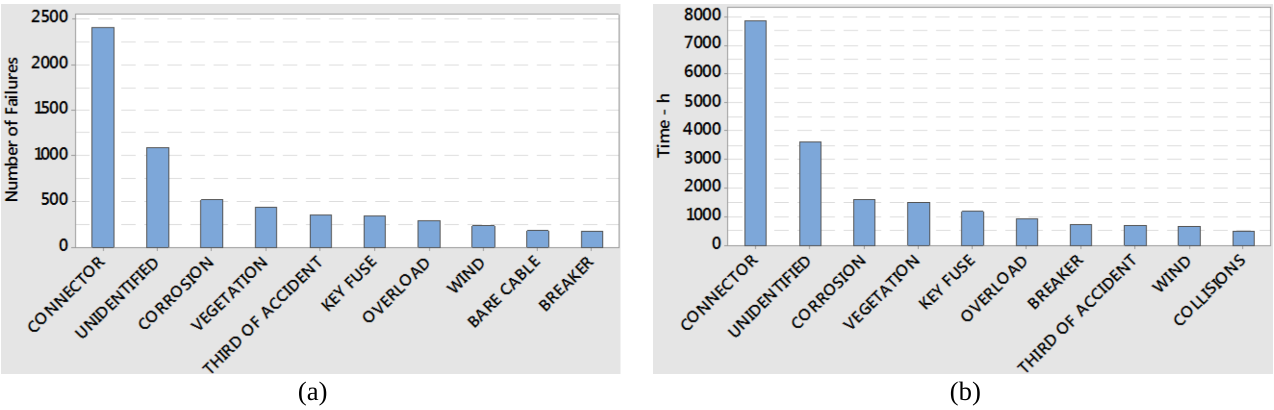


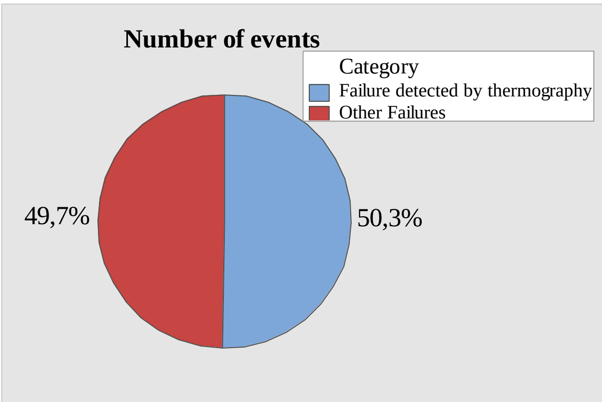
Figure 2. (a) Main events that influenced the DEC; (b) Main events that influenced the FEC

The monthly and yearly values for the DEC and FEC obtained in a substation of the Electrical Utility, between the years 2013 and 2014, can be seen in Tab. 2, ANEEL (2015). The number of consumers that the electrical utility had in this substation (2013-2014) were respectively 58957 and 61672 consumers. The values in columns DEC and FEC "LIMIT ANEEL" are the maximum values which should not be exceeded by the values of established indexes. When these values are exceeded, the concessionaire must pay. Table 2 is shown the values of DEC and monthly and annual FEC.

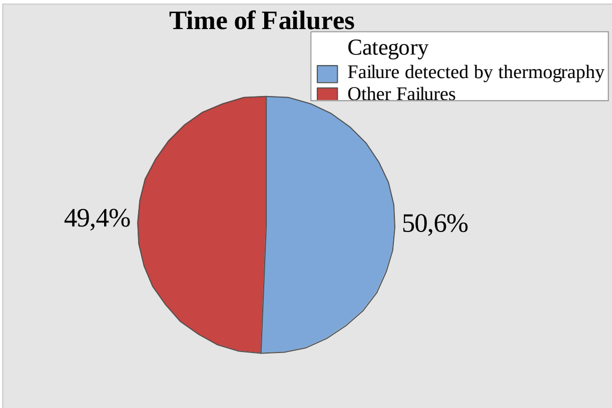
Table 2 – DEC and FEC stratified in 2013 and 2014

	DEC VERIFIED	DEC LIMITE ANEEL	FEC VERIFIED	FEC ANEEL LIMIT	DEC VERIFIED	DEC ANEEL LIMIT	FEC VERIFIED	FEC ANEEL LIMIT
Months	2013				2014			
January	3,27		1,49		2,31		2,92	
February	2,04		1,51		1,45		1,49	
March	2,67		3,48		2,19		1,1	
April	5,09		3,45		5,23		2,62	
May	2,24		1,82		6,34		3,43	
June	9,67		3,71		2,51		1,52	
July	0,72		0,41		1,47		1,14	
August	1,15		0,78		2,47		2,08	
September	2,08		2,07		1,12		0,97	
October	2,03		1,23		2,51		2,04	
November	4,31		2,41		2,94		2,20	
December	6,74		4,9		1,93		2,36	
Yearly	**42,04**	**17,00**	**27,28**	**16,00**	**32,43**	**17,00**	**23,86**	**15,00**

Figure 3 (a) and (b) show the relationship between failure modes that are capable of being detected by thermography in relation to other failure modes.



(a)



(b)

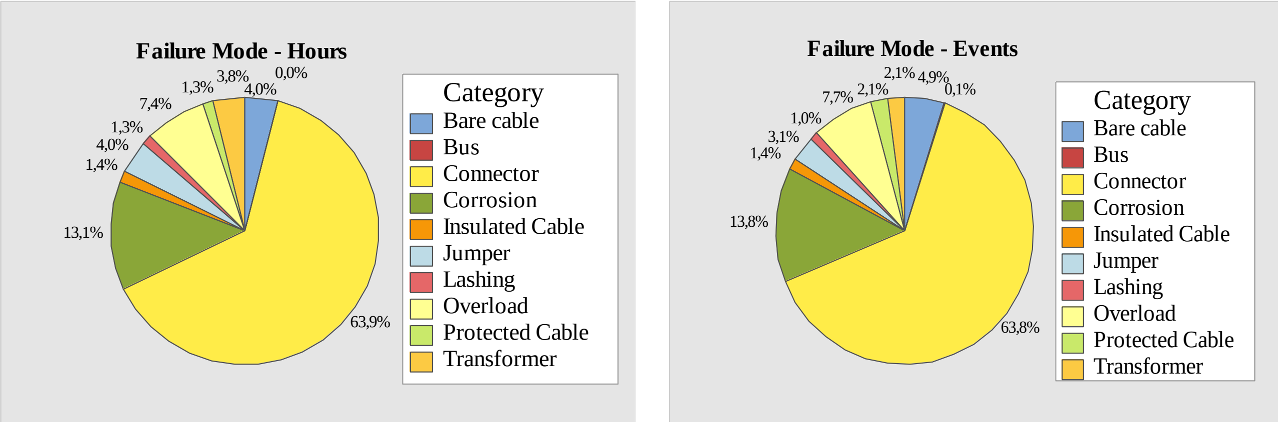
Figure 3. (a) Total of the Event Numbers; (b) Time in hours

All incidents recorded were classified among the 10 failure modes that can be detected by thermography. In Tab. 3, lists all failure modes, the object of analysis in this work. Table 3, corresponds to 3774 occurrences during the years 2013 and 2014. The situations of absences were analyzed: bare cable, bus, connector, corrosion, insulated cable, jumper, lashing, overload, protected cable and transformers.

Table 3 – Total Result of the fails in 2013 and 2014

Failure Modes	Interruption Time (Hour)	Total of occurrances
Bare cable	490,78	184,00
Bus	4,42	5,00
Connector	7874,74	2407,00
Corrosion	1610,41	521,00
Insulated Cable	169,13	52,00
Jumper	487,58	116,00
Lashing	155,8	39,00
Overload	909,55	290,00
Protected Cable	156,85	81,00
Transformer	470,4	79,00
Total	12329,66	3774,00

Figure 4 (a) and (b), graphically show the distribution of the failure modes.



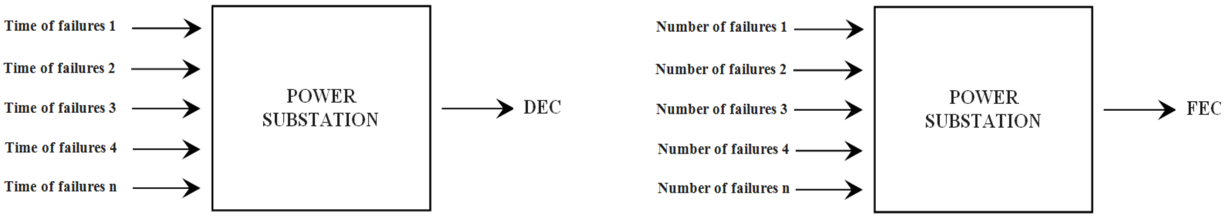
(a) (b)

Figure 4. (a) Modes of failure in hours; (b) Modes of failure in events

3.2 – Model Structures

Equation (1) and Eq. (2), applied to calculate the DEC and FEC, do not take into consideration specific characteristics of each substation, for calculating the DEC and FEC indices having as denominator the total number of consumers affected by failures in a period, PRODIST (2015). So the denominators of these equations do not take into consideration the characteristics of the distribution systems. For the Electrical Utility, responsible for the distribution, these equations do not contribute to an analysis of cause and effect and do not indicate what are the failure modes that are more fallible in its electrical system and that are contributing to the increase in the DEC and FEC. From the failure modes of classification, the Electrical Utility may have the perception of what are the gaps and how these failures contributed to the increase in DEC and FEC continuation rates.

The modeling of DEC was developed from the data set on which the entry was established as the amount of hours of each failure. For the FEC, from the data set on which the entry was established as the amount of faults. The database applied to the models considered the two years studied (2013 and 2014). Figure 5 (a) and (b) show the block diagram, whereas the input and the output to the FEC and DEC model, respectively.



(a) (b)

Figure 5. (a) Block Diagram, given the inputs and the output, for the DEC model; (b) Block diagram considering the input and the output for the FEC model.

According to Wichern and Johnson (2002), the linear regression analysis and a statistical method for predicting values of one or more response variables (dependent) from a collection of values of explanatory variables (independent).

Using for the development of the models MatLab® software, all quantities of failures and maintenance times were entered into spreadsheets and through the linear regression tools, we got the mathematical models described in Eq. (5) and Eq. (6). According to Johnson and Wichern (2002), this linear regression analysis can check the effects of the predictors (in case the types of failures), the output variables (DEC and FEC), developing the desired models.

3.3 Simulation with Model

Two empirical models have been developed MISO (Multiple Input, Single Output), for FEC and DEC. For adjusting the linear regression, the data were organized in 176 samples/measurements corresponding to 8 feeders, considering the monthly occurrences in the years 2013 and 2014. Each sample/measurement has 10 inputs (related to the type of fault) and 1 output (DEC or FEC).

In the model obtained an adjustment with parameter restriction was applied, optimizing the results. This optimization was carried out considering that the entries are directly proportional to the model outputs.

The linear regression model obtained in MatLab® for FEC and DEC are the Eq. (5) and Eq. (6) respectively, where X_1 is the downtime per hour in connectors, X_2 is the downtime per hour in bus, X_3 is the downtime per hour in jumper, X_4 is the downtime per hour in overload, X_5 is the downtime per hour in insulated cable, X_6 is the downtime per hour in corrosion, X_9 is the downtime per hour in transformers, X_{10} is the downtime per hour in bare cable, Z_1 is the amount of interruption in connector, Z_2 is the amount of interruption in bus, Z_3 is the amount of interruption in jumper, Z_4 is the amount of interruption in overload, Z_5 is the amount of interruption in insulated cable, Z_8 is the amount of interruption in protected cable, Z_9 is the amount of interruption in transformers and Z_{10} is the amount of interruption in bare cable

$$DEC = 0{,}00083908X_1 + 0{,}35437815X_2 + 0{,}000301232X_3 + 0{,}008556417X_4 + 0{,}004085252X_5 + 0{,}007882681X_6 + 0{,}000182584X_9 + 0{,}008657616X_{10} \quad (5)$$

$$FEC = 0{,}0025773Z_1 + 0{,}4922956Z_2 + 0{,}0118492Z_3 + 0{,}0183130Z_4 + 0{,}0163925Z_5 + 0{,}0161086Z_8 + 0{,}0511881Z_9 + 0{,}0108704Z_{10} \quad (6)$$

4. RESULTS AND DISCURSSION

As previously mentioned, the Eq. (1) and Eq. (2) that calculate the FEC and DEC do not take into consideration the type of fault, only the flaws and the amount of maintenance time of each, without characterizing it. With the equations originally applied for the official calculation of the quality indices of a distribution substation, you cannot identify the failure mode that is causing the increased system reliability indices. You can't determine the best way to do some planning of preventive maintenance either.

To better explain how the model can aid in maintenance planning a sensitivity analysis was done. In this sensitivity analysis, a chance to improve the maintenance was prepared only on devices that can be worked with thermography, which are: bare cable, bus, connector, corrosion, insulated cable, jumper, lashing, overload, protected cable and transformers

According to the data obtained by ANEEL, the total period of this DEC (2013 and 2014) to study the substation was 74, 45 hours, while the total FEC was added 47, 63 occurrences. Separating the modes of failure that are likely to be detected by thermography, we found that the contribution of these flaws in the DEC and FEC are respectively 35,35 hours and 23,17 events.

The estimate of these values when we use the model proposed in this work was 33,81 hours for DEC, and 23,55 records for the FEC.

Figures 6 and 7 show a sensitivity analysis for the main modes of failure. A sensitivity analysis was performed in order to evaluate the influence of the failure modes in DEC and FEC values , indicating the most significant failure modes. This analysis was a chance to set a reduction of 5 to 50% for each of the analyzed failures.

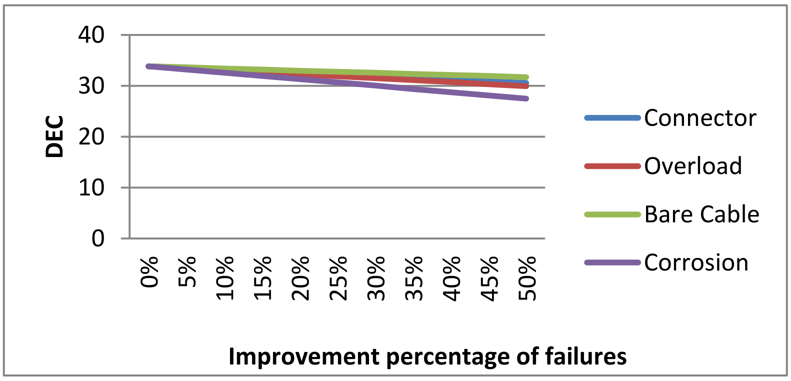


Figure 6 – DEC sensitivity analysis , with the decrease of occurrences of the event in various failures

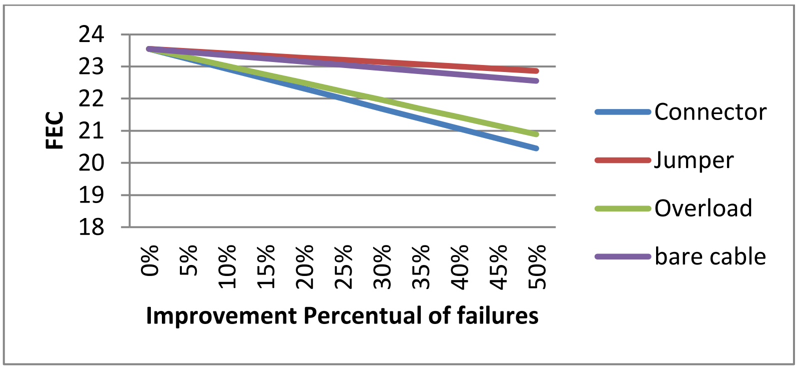


Figure 7 – Analysis of FEC sensitivity , with the decrease of occurrences of the event in various failures.

The graphs of Fig. 6 and Fig. 7, give an indication of what failure modes the company eletrical must act, as a priority, to reduce the DEC and FEC indexes respectively The graphs of Fig. 6 and Fig. 7, give an indication in the what failure modes the company must act, as a priority, to reduce the DEC and FEC. In Fig. 7, which has been evaluating the DEC, the fault that should primarily be considered is due to corrosion, then the fault overload, connectors and bare conductors.

According to Santos (2012), the results presented in Fig. 6 and Fig. 7, can be explained in part by the great number of connectors used in substations and because of the deterioration process of these components present in most cases heating due to the increase of the contact resistance.

According to Lizak and Kolcun (2008), for the future, virtually the whole process of generation and distribution, as well as all major manufacturing facilities and process will be using infrared thermography. In a recent article Bagavathiappan, et al. (2013), it states that infrared thermography allows the premature detection the fail in industrial processes.

5. CONCLUSION

We confirmed, through analysis of sensitivity obtained in Fig. 6 and Fig. 7, the models proposed in the article, can be used as decision making tools by the company managers. The model allows managers to define as thermography must act first.

The equations originally used for the DEC and FEC calculation does not allow for an analysis of the influence of the failure modes in the values assigned to these quality indices.

Through this model we identified failure modes that contribute to the occurrence of high values for the DEC and FEC indices.

6. REFERENCES

ANEEL, 2015. “Agência Nacional de Energia Elétrica. Indicadores de Continuidade”. 22 Abr. 2015. <http://www.aneel.gov.br/aplicacoes/indicadores_de_qualidade/pesquisa.cfm?regiao=NE>.

AES Sul, 2015. “AES Sul Distribuidora Gaúcha de Energia SA”. 15 Maio de 2015. <https://www.aessul.com.br/site/sobreenergia/EnergiaAZ.aspx>.

Bagavathiappan, B. B.; Jadin, M. S.; Taib, S.; Lahiri, T. Saravanan,, 2013. “Radiography & Thermography Section (RTS), Non-Destructive Evaluation Division, Metallurgy and Materials Group”. Infrared Physics & Technology, v. 60, p. 36-55.

CHESP, 2005. “Companhia Hidrelétrica de São Patrício”. “Manual do Consumidor” 15 Abr. 2015. <http://www.chesp.com.br/manual/manual.htm>.

Huda, A.S.N. Taib, S., 2013. “Suitable features selection for monitoring thermal condition of electrical equipment using infrared thermography”.InfraredPhys. Technol. 61, 184–191.

Jadin, M. S.; Taib, S. 2012. “Recent progress in diagnosing the reliability of electrical equipment by using infrared thermography”. Infrared Physics & Technology, v. 55, n. 4, p. 236–245.

Johnson, R. A.; Wichern, D. W., 2002. “*Applied multivariate statistical analysis”***.** 5th Ed. Upper Saddle River, New Jersey.

Korendo, Z.; Florkowski, M., 2001. “Thermography based diagnostics of power equipment”. *Power Engineering Journal*, v. 15, n. 1, p. 33–42.

Lizak, F.; Kolcun, M., 2008. “Improving reliability and decreasing losses of electrical system with infrared thermography. Infrared Physics & Technology, v. 8, n. 1, p. 60-63. ISSN 1335-8243.’

Mamede, 1997. “Sistemas Elétricos Industriais”. 5ª Edição, LTC – Livros Técnicos e Científicos LTDA, Rio de Janeiro.

Montgomery, D. C.; Runger, G. C., 2008. “Estatística Aplicada e Probabilidade para Engenheiros”. 2 Ed. LTC Editora. Rio de Janeiro:

PRODIST, 2015. "Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional. Módulo 8 – Qualidade da Energia Elétrica". Agência Nacional de Energia Elétrica – ANEEL. 27 Abr 2015. <http://www.aneel.gov.br/arquivos/PDF/MC3%B3dulo8_Revis%C3%A3o_6_Retifica%C3%A7%C3%A3o_1.pdf>.

Santos, L., 2012. "Classificação e Modelagem de Fatores de Influência sobre Inspeções Termográficas em Ambientes Desabrigados*" Tese (*Doutor em Ciências em Engenharia Elétrica.) Universidade Federal de Itajubá, Itajubá.

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