Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.7 n.29, p. 62-68. May/Jun, 2021

DOI: https://doi.org/10.5935/jetia.v7i29.753

RESEARCH ARTICLE OPEN ACCESS

EVALUATION OF DISTRIBUTION TRANSFORMERS BASED ON POWER QUALITY PARAMETERS IN FRONT OF DIFFERENT LOAD PROFILES

Salvador Paes Ribeiro Junior[1], Ricardo Chagas Tolentino[2], Marcio Zamboti Fortes*[3] and Guilherme Gonçalves Sotelo[4]

[1, 2, 3, 4] Federal University of Fluminense - UFF. Niterói, Rio de Janeiro, Brazil.

[1] http://orcid.org/0000-0002-8484-271X, [2] http://orcid.org/0000-0001-8284-8600, [3] http://orcid.org/0000-0003-4040-8126, [4] http://orcid.org/0000-0002-5393-7206

Email: salvadorjunior.rj@gmail.com, ricardo-tolentino@hotmail.com, *mzamboti@id.uff.br, gsotelo@id.uff.br

ARTICLE INFO

Article History
Received: May 14th, 2021
Accepted: June 23th, 2021
Published: June 30th, 2021

Keywords:
Power quality,
Power Transformers,
Electrical Equipment.

ABSTRACT

This article presents a study to monitor the power quality supplied by a power distribution concessionaire operating in the State of Rio de Janeiro, Brazil. Three electric power transformers of the same nominal power installed from a Brazilian company were selected as case studies. The data were collected and analyzed to evaluate the power quality according to the formulation regulated by the Electricity Distribution Procedures in the National Electric System - PRODIST, which is the Brazilian legislation in force for the energy distributors. The experiment consists of checking the supply voltage, the power factor, harmonic distortion, voltage unbalance, and frequency variation. Two of the three transformers analyzed showed a failure in the power quality supplied in the frequency variation indicator and all transformers failed in the Power Factor indicator. Thus, this research verifies the importance of monitoring power quality parameters to ensure that the energy obtained by consumers has sufficient characteristics for the proper functioning of electrical equipment.

I. INTRODUCTION

It is well known that the focus on power quality (PQ) is partly attributable to the fact that the electricity sector is being reformulated for the consumer market. Consumers are more demanding and the main product purchased is electricity. Consumers prefer to achieve energy with sufficient quality parameters at the lowest possible cost. In this case, both regulatory agencies, such as ANEEL in Brazil, as well as the market itself, encourage electric system operators to provide information on operating conditions or to provide details about events that have occurred and that have affected consumers [1].

"Power quality" is a term that has different meanings. From the customer's point of view, a PQ problem can be defined as any power condition that causes the equipment to malfunction or becomes unusable. From the concessionaire's point of view, PQ problems can be seen as non-compliance with several pre-established standards [2].

Still, in the understanding of PQ, the Institute of Electronics and Electronics Engineers (IEEE) defines power quality as "the concept of providing energy and adequate grounding for sensitive electronic equipment". Electrical equipment is significantly affected by PQ and can be severely affected if electrical energy is outside the standards [3].

Research shows that there are expenses associated with the loss of PQ. For more than a decade, the costs associated with disrupting manufacturing processes in the United States have been estimated at approximately $ 10 billion. At the same time, in Europe, the estimated cost associated with various interferences reaches around 1.5% of Gross Domestic Product (GDP) [1].

Still in this context, Petr et al. [4], presented an article to help engineers choose the best solution to improve the quality of energy in a specific energy network at the distribution level. The article also presents the characteristics of an active shunt harmonic compensator, which is a very modern PQ controller that can be used in several cases, or in combination with other controllers.

When searching the literature for works related to distribution transformers aimed at PQ, research such as Brida Neto [5] is found that sought to evaluate the loss of electrical energy through the conversion of medium and low voltage due to the insufficient size of the distribution transformer.

In the planning aspect of the power distributor, there is research that finds that the economic management of distribution transformers contributes to the economic planning of power utilities as they are abundant in electrical systems [6].

There are more specific researches, which are important for the knowledge of the study of transformers as is the case presented by Gonen [7]. In this work, it is possible to understand several issues, such as the applicability and characteristics of transformers, PQ, and smart grid concepts with the use of transformers.

Following this research plan, the present work aims to analyze the data collected for three transforming units of the same nominal power that differ by the characteristics of loading in the aspect of non-technical losses (NTL) and named as TR1, TR2, and TR3. This research analyzes performed and check the supply voltage, the power factor, harmonic distortion, voltage unbalance, voltage fluctuation, frequency variation, and short-term voltage variation.

The characteristics of these transformers are:

TR1 – Transformer with a less incidence of NTL (<10%).

TR2 - Transformer with a high incidence of NTL (> 30%).

TR3 - Transformer with an average incidence of NTL (Between 10% and 30%).

To evaluate de PQ index PRODIST parameters - Module 8 will be established in its 10 reviews, approved by the National Electric Energy Agency (ANEEL) [8].

In research carried out in academic databases, it is noticed that Brazil has a good contribution to this theme. The researched documents include Papers, Articles, Letters, Reviews, and Proceedings Paper published between the years 2015 and 2020.

The research was carried out based on the keyword "Energy". The result of this initial research placed Brazil in the 15th position in the ranking of the countries that most publications on the subject. Brazilians are responsible for 2.524% of publications, thus confirming the concern and interest that this topic arouses among Brazilian researchers.

Then, the word "quality" was added to the search field and the previous settings were repeated. Thus, Brazil rose to the eleventh position, and the percentage of documents published to the world increased slightly. This became 3.582%.

Thus, it is hoped that the research presented in this text can contribute to Brazilian research and add to other international works related to the PQ issue in distribution systems since this problem is common to all.

II. THEORETICAL BASIS

II.1 SUPPLY VOLTAGE

According to Rocha [9], the steady-state voltage is assessed by obtaining two performance indicators: the relative transit time index (DRP) of the unstable voltage and the relative transit time index (DRC) of the critical voltage, where *nlp* and *nlc* indicate the maximum value between the phases of the number of measurements within the stable and critical range.

$$DPR = \frac{npl}{1008} x\ 100\% \quad (1)$$

$$DPC = \frac{npc}{1008} x\ 100\% \quad (2)$$

Santiago [10] highlighted the importance of analyzing voltage permanently. His research details a strategy for voltage control that involves nonlinear programming. Such research contributed to the stress profiles in the steady state, of his experiment, to be within the parameters allowed by PRODIST.

II.2 POWER FACTOR

According to PRODIST - Module 8 in its revision 10, the value of the power factor (PF) must be calculated according to the registered active and reactive power (P, Q) or the corresponding energy (EA, ER) using (3) and (4) [8].

$$\text{FP} = \frac{P}{\sqrt{P^2+Q^2)}} \quad (3)$$

Or

$$\text{FP} = \frac{EA}{\sqrt{EA^2+ER^2)}} \quad (4)$$

The reference values are: for the consumer unit or connection between distributors with a voltage lower than 230 kV, the PF at the connection point must be between 0.92 and 1.00 inductive or 1.00 and 0.92 capacitive, according to current regulations.

Knowledge of the PF is so important that distributors punish customers who demand high reactive power. This happens because the companies that make up the electric sector need to make greater investments in power generation equipment, expanding the capacity of the transmission and distribution lines, and transformers for transmission and conversion of reactive power. The voltage will affect the stability of the network [11].

II.3 HARMONIC DISTORTION FACTOR

According to PRODIST, harmonic distortion is a phenomenon related to the deformation of voltage and current waveforms concerning the sine wave of the fundamental frequency. The limits must be included between the intervals in Table 1.

Table 1: Limits of harmonic distortions (in % of the fundamental voltage).

Indicator	Nominal Voltage (kV)		
	Vn≤1.0	1.0<Vn<69	69≤Vn<230
DTT95%	10.00%	8.20%	5.00%
DTTp95%	2.50%	2.00%	1.00%
DTTi95%	7.50%	6.00%	4.00%
DTT395%	6.50%	5.00%	3.00%

Source: [8]

Harmonic distortion is a phenomenon related to the deformation of voltage and current waveforms concerning the fundamental sinusoidal frequency wave [8].

In this case, in the context of the PQ, phenomena related to harmonic distortion have been emphasized in recent years. Some of the main effects of voltage and current waveform distortion are heating equipment, reduced component life, overvoltage, reduced energy supplied by the equipment, malfunction of various equipment, impact on the PF, and interference telecommunications lines [12].

II.4 UNBALANCE MAGNITUDE OF SUPPLY VOLTAGE

Voltage unbalance is an indicator of PQ that has been extensively explored in research. [12] used this parameter to practically analyze some PQ disorders in a given power supply in the power distribution network.

According to [9] voltage unbalance is a disturbance related to the lack of quality in the supply of electricity and this unbalance can be caused mainly by the uneven distribution of single-phase loads in the system (such as electric arc furnaces and welding machines) and defects in equipment applied in the distribution, for example, fuse blown in the phase of the three-phase capacitor bank.

According to the Energy Distribution Program in the National Electric System (PRODIST), the following definition exists: "Voltage unbalance is a phenomenon that is characterized by any difference in amplitude between the three-phase voltages of a given three-phase system and/or 120º. The electrical difference between the phase voltages of the same system.

PRODIST - Module 8 in its revision 10 defines the unbalance factor as the relationship between the negative sequence voltage module and the positive sequence voltage module [8].

$$FD\% = \frac{V-}{V+}100\% \quad (5)$$

where:

V- = Negative sequence voltage module.

V+ = Positive sequence voltage module.

FD% = unbalance factor.

However, since most measuring devices are limited in obtaining the voltage angle, (6) and (7) can also be used:

$$FD\% = 100\ \sqrt[2]{\frac{1-\sqrt[2]{3-6\beta}}{1+\sqrt[2]{3-6\beta}}} \quad (6)$$

Being:

$$\beta = \frac{V_{ab}{}^4 + V_{bc}{}^4 + V_{ca}{}^4}{(V_{ab}{}^2 + V_{bc}{}^2 + V_{ca}{}^2)^2} \quad (7)$$

Where V_{ab} , V_{bc} e V_{ca} are line voltages modules.

And the unbalance voltage limits corresponding to FD95% are 3.0% for V_n less or equal 1.0 kV and 2.0% for V_n between the interval of 1 kV and 230 kV.

II.5 FREQUENCY

Frequency is an important parameter to assess the operational characteristics of electrical systems. According to PRODIST, the distribution system and the generation facilities connected to it must, under normal operating conditions and permanently operate within the frequency limits between 59.9 Hz and 60.1 Hz.

When disturbances occur in the distribution system, the generation facilities must ensure that the frequency returns, in the time interval of 30 (thirty) seconds after the transgression, to the range of 59.5 Hz to 60.5 Hz, for allowing the recovery of the load-generation balance.

If there is a need to cut generation or load to allow the recovery of the load-generation balance, during disturbances in the distribution system, the frequency:

a) may not exceed 66 Hz or be less than 56.5 Hz in extreme conditions;

b) can remain above 62 Hz for a maximum of 30 (thirty) seconds and above 63.5 Hz for a maximum of 10 (ten) seconds;

c) may remain below 58.5 Hz for a maximum of 10 (ten) seconds and below 57.5 Hz for a maximum of 05 (five) seconds.

Camporez et al. [13] considers that the frequency variation represents the frequency varies from a predefined value. The value is defined at 60 Hz and according to PRODIST - Module 8 in its revision 10, the system under normal conditions must operate between 59.9 and 60.1 Hz.

Bandeira et al. [14] used this parameter to analyze the electrical PQ of a photovoltaic system connected to the grid. The experiment allowed us to observe that the collected data were within the standards allowed by PRODIST.

The frequency shift is the deviation from the fundamental frequency value, usually caused by large loads in connection and disconnection step and this event affect the power system.

III. METHODOLOGY

PRODIST - Module 8 in its revision 10 adopted as consultation and parameter setting. This establishes the procedures related to the PQ, and its scope reaches all consumers connected to the distribution network.

This work aims to evaluate the PQ parameters of distribution transformers against different load profiles, classifying them by NTL in these transformers, three (3) NTL indexes were selected:

Loss index 1: Transformer with NTL up to 10% (low index); Loss index 2: Transformer with a NTL greater than 30% (high rate); Loss index 3: Transformer with a NTL between 10% and 30% (average rate), the transformers have the same nominal power.

The methodology consists of selecting the transformers, collecting data, organizing the information, selecting the PRODIST parameters, and analyzing, verifying how much each loss index influences the behavior of the equipment regarding the PQ (Figure 1).

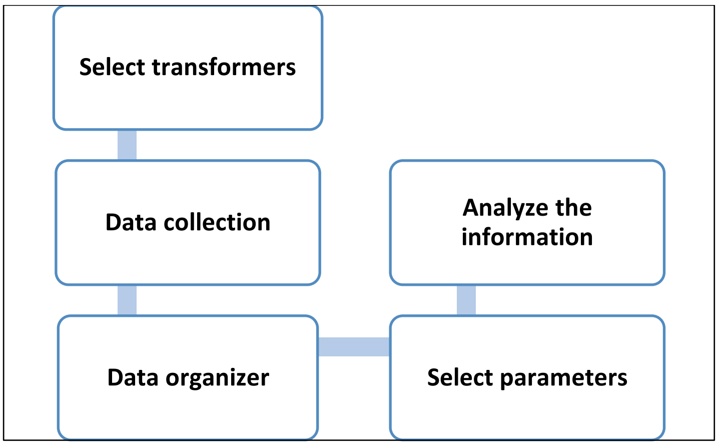

Figure 1: Methodology sequence.
Source: Authors, (2021).

The PQ parameters adopted in the experiment are:

- Supply voltage;
- PF;
- Harmonic distortion;
- Unbalance voltage; and
- Frequency variation

IV. MEASUREMENTS

To make the necessary analysis proposed in this document possible, the data memory for each type of load of the transformers was obtained in addition to what is indicated in PRODIST (1008 valid records in most indicators). In this research, equipment data were acquired in 168 hours of equipment monitoring with data recorded every 120s, exceeding 5000 valid data records.

The equipment used for data acquisition was of the model: PowerNET P-600 from IMS manufacter with measurement class A according to IEC61000-4. The ambient temperature in the location where the transformers are installed showed a maximum of 30ºC and a minimum of 18ºC during the measurement period, so we consider that there was a minimal intervention of the external ambient temperature in the measurements performed.

At the end of the data acquisition, the analyzes reported in item 5 started.

V. RESULTS ANALYSIS

Based on the PQ indicators mentioned in item 2 and on data acquired in the measurements considered for this research the analysis was started. In this item, the results obtained regarding the impacts of the load imposed on the transformers by the amount of NTL in the equipment stand out and show the behaviour of each of the quality indicators that could be measured in the measurements performed.

The first indicator analyzed is the Permanent voltage regime, within the PRODIST limits, there was no violation of the indicator in any of the analyzed equipment, according to the data in Figure 2.

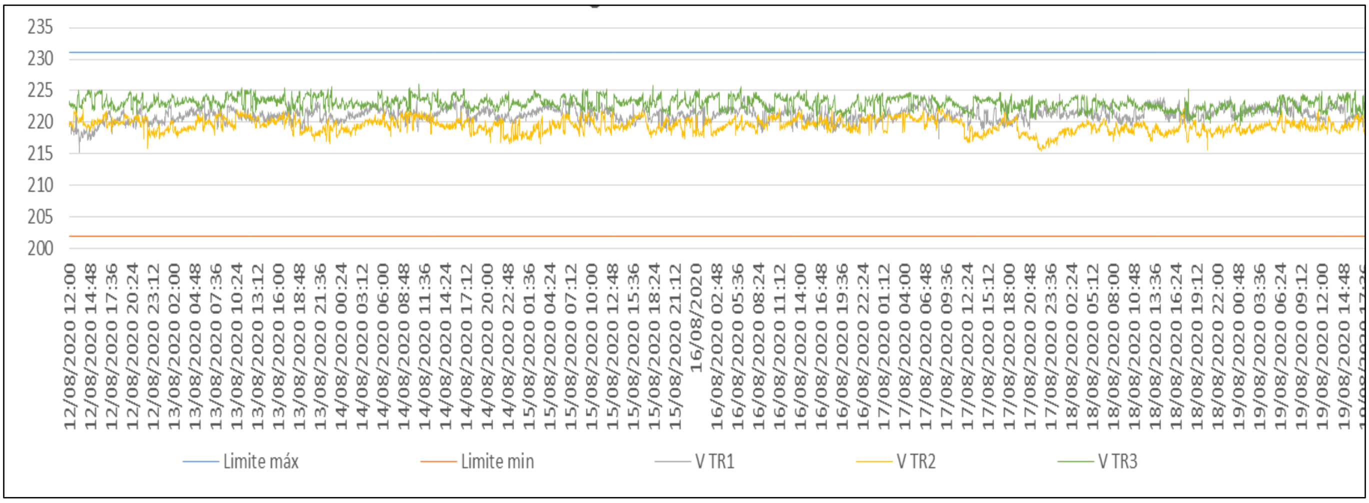

Figure 2: Supply voltage indicator graphic.
Source: Authors, (2021).

However, some peculiarities can be observed between the three transformers and their different loads. We can highlight that transformer 1 with the lowest NTL index presents a smaller variation in this indicator, despite not being the highest average voltage during the measurement period. This higher average is shown in the measurement of transformer 3 and we can also perceive a period of "sinking" of voltage presenting a lower voltage than the average of the period in transformer 3. This period is highlighted in the graph. However, nothing that would interfere with the good performance of transformers in this indicator.

The next indicator is the voltage unbalance which is also in compliance with the limits determined in PRODIST when monitoring transformers.

Analyzing the result of each transformer in this indicator, it can be seen that transformer 1, with a lower rate of NTL, showed greater variation in voltage unbalance to the other transformers, being, as we can analyze by Figure 2, higher values of concentrated unbalance at times considered off-peak, that is, with smaller loads.

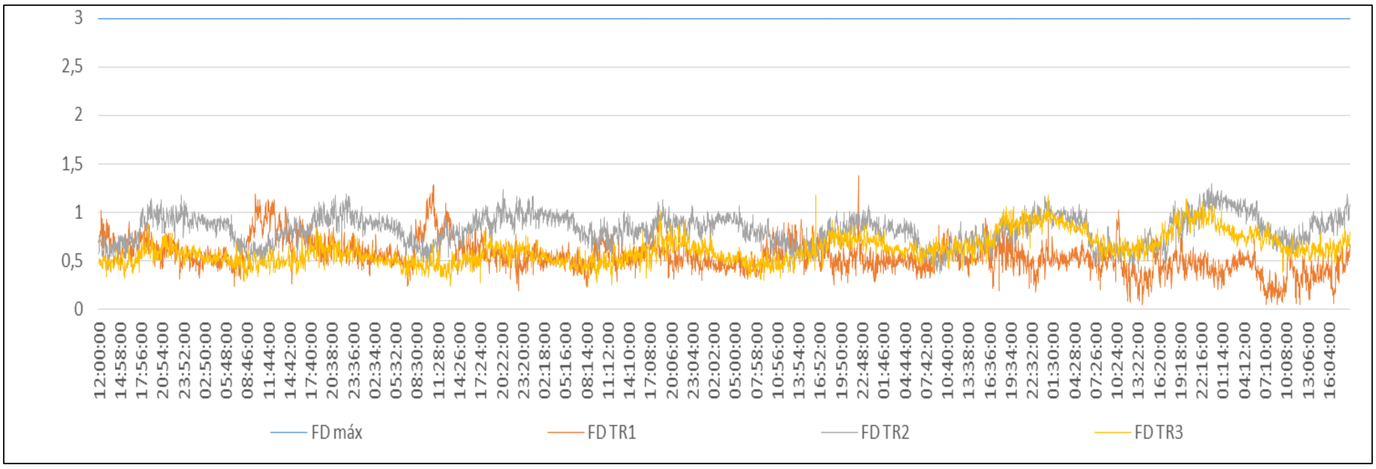

Figure 3: Unbalance factor indicator graphic.
Source: Authors, (2021).

In opposite to what was observed in transformer 1, transformer 2, which has the highest rate of NTL, showed a large variation in the voltage unbalance indicator, but a variation with regularity, with the greatest unbalance during peak hours and at dawn, and it also maintains the highest average unbalance factor value among the monitored transformers. Another observation regarding transformers 1 and 2 with the lowest and highest non-technical loss index, respectively, perceived that to the unbalance factor in the times when the FD is higher in one transformer, it is lower in the other and they continue alternating during the monitoring period.

Transformer 3 presents, as shown in Figure 3, a greater balance in the value of the unbalance factor.

It appears that there were distinct impacts on the voltage unbalance indicator in each of the measured transformers, but we cannot affirm that this presented unbalance factor was caused directly by the NTL index that is acting in each one, the loads profiles other than the monitored equipment cause this variation in voltage unbalances, another point to note is that the measuring equipment did not exceed the limits defined in PRODIST for the indicator in this item presented, thus not characterizing any impacts on the PQ according to this indicator.

The indicator evaluated later is the PF, an indicator linked to active and reactive power (inductive and/or capacitive) consumed by the loads demanded in each equipment.

This is the indicator that suffered the most impact on the monitored equipment during long periods and at different times it was below the minimum index indicated by PRODIST.

As shown in Figure 4, we verified that in transformer 1, the impact of loading the equipment is the lowest in this indicator, with the equipment with the lowest rate of NTL being evaluated, and even so it presented itself outside the ideal indicator impacting the PQ in this equipment.

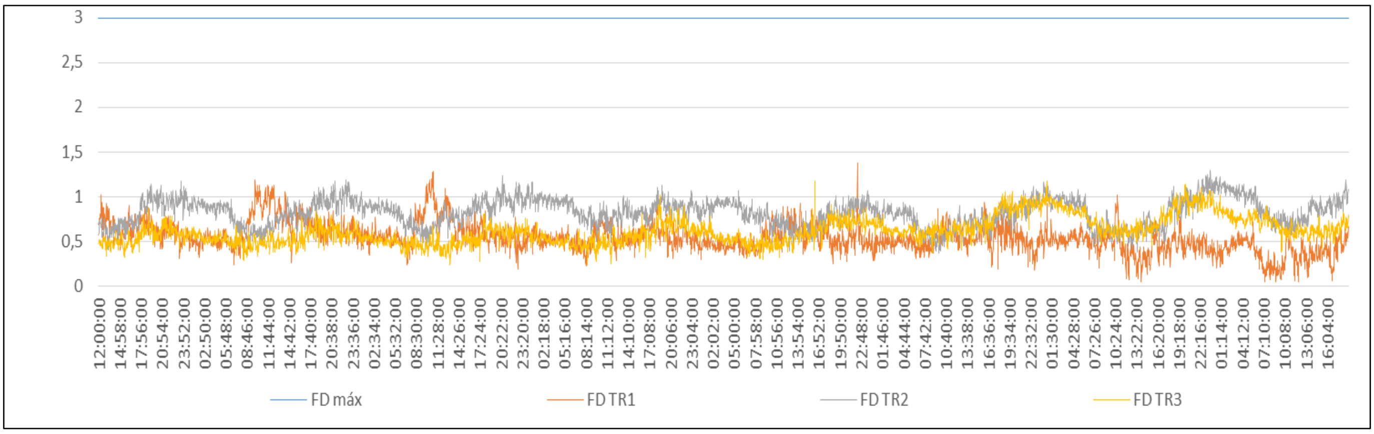

Figure 4: PF indicator graphic.
Source: Authors, (2021).

In transformer 2 the impact of the load on the equipment is perennial in the PF indicator, because during practically the entire monitoring period the indicator remains below the ideal, showing that the NTL interfere a lot in this indicator as we can see in Figure 4.

Following the analysis of the PF, the measurements performed show, according to Figure 4, that transformer 3 was the one that had the most significantly impacted performance and with a great variation of the PF value, varying between very high values, close to 1.00 and very low values, below 0.70.

In this indicator, it was verified that the PRODIST PF limits were extrapolated in all three measured equipment and the PQ supplied by them will be affected by the characteristics of their loads.

In the Total Harmonic Distortion (THD) indicator, there was no extrapolation of the indicator limits, as shown graphically by Figures 5, 6, and 7. Recalling that the distributor is directly responsible for monitoring and managing this indicator vis-à-vis regulatory agents.

This is the indicator resulting from the calculation performed based on PRODIST taking into account the fundamental voltage of the monitored transformers, in which there was no violation of the PQ.

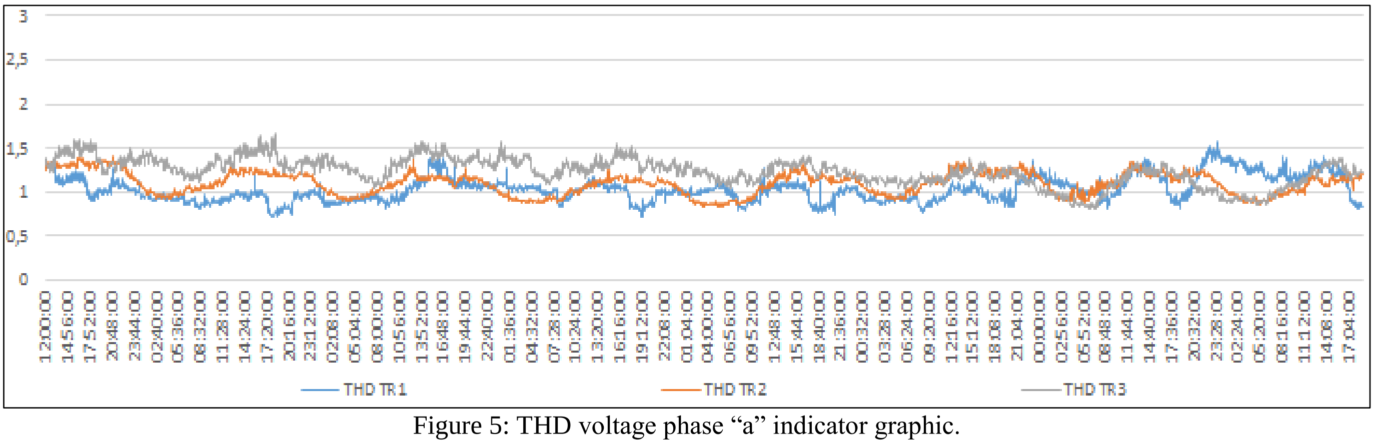

Figure 5: THD voltage phase “a” indicator graphic.
Source: Authors, (2021).

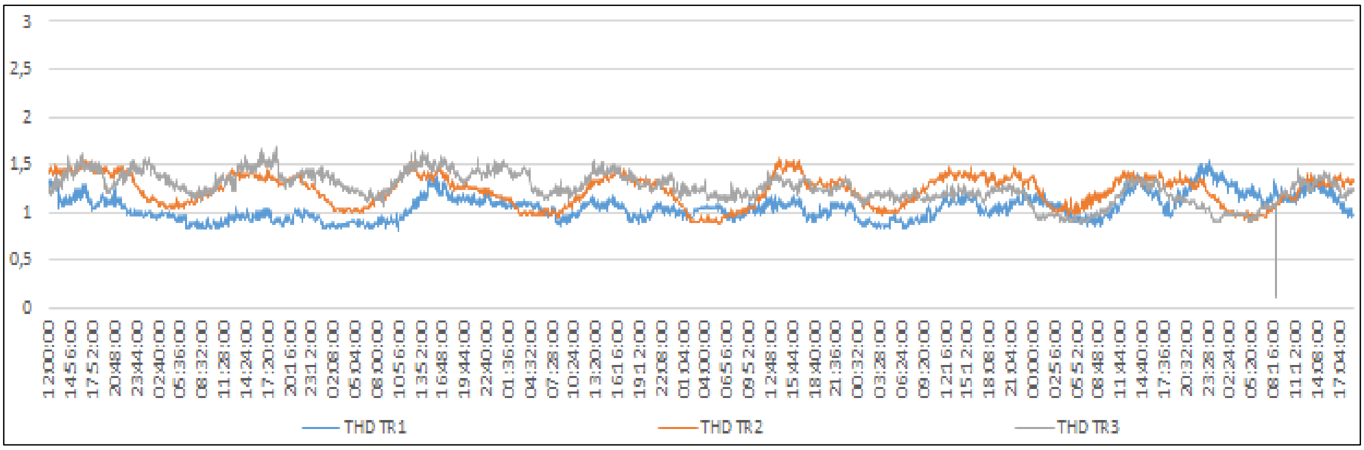

Figure 6: THD voltage phase "b" indicator graphic.
Source: Authors, (2021).

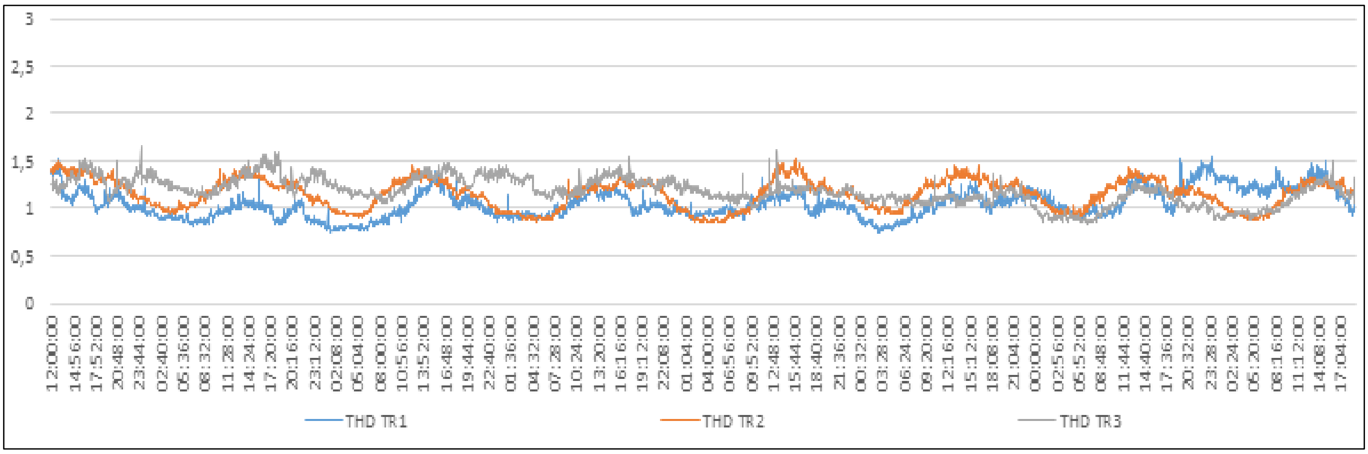

Figure 7: THD voltage phase "c" indicator graphic.
Source: Authors, (2021).

In the Variation of Frequency indicator, Figure 8 illustrates the transformers results, in this regard, there were some moments when the value of the frequency exceeded the minimum and maximum values of PRODIST limits.

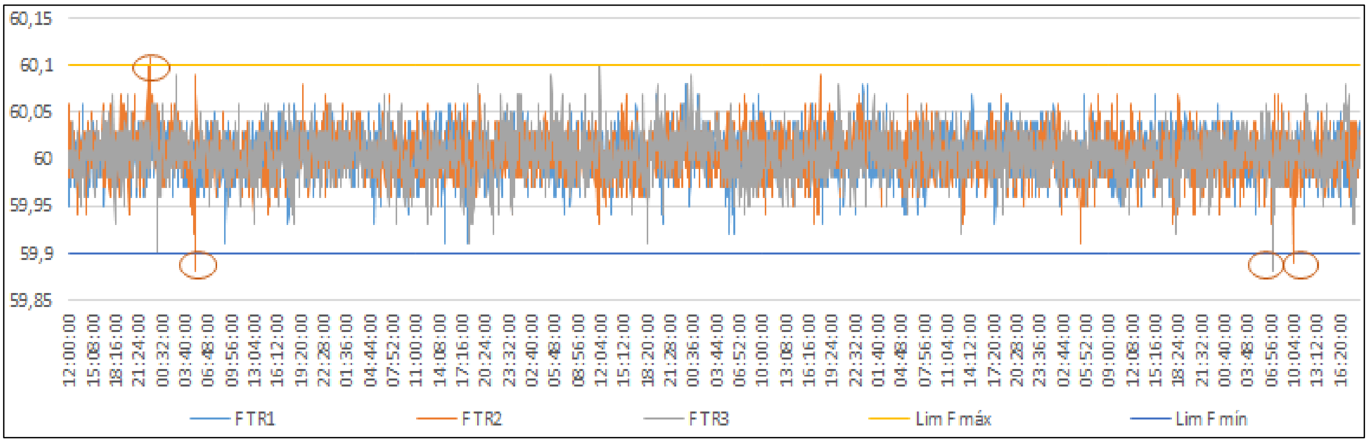

Figure 8: Frequency variation indicator graphic.
Source: Authors, (2021).

We can see in the graph that transformer 2, in this regard, presented in a moment extrapolation of the upper limit and for two moments of the lower limit of the frequency.

In transformer 3, the lower limit of the indicator was extrapolated.

Therefore, this work presents graphically 05 of the 07 indicators of PQ contained in PRODIST – Module 8, illustrating the importance of monitoring these parameters in the guarantee of the supplied PQ. It should be noted that in the next item.

VI. CONCLUSIONS

Five items of PQ assessment were measured and among these results were obtained outside the limit parameters determined in PRODIST in 02 of these indicators, which were the PF indicator, significant impacts, and the Frequency Variation indicator.

The transformers that suffered the impacts were mainly transformers 2 and 3 with high (above 30%) and average (between 10 and 30%) NTL respectively, results that reinforce the main idea of this document to analyze the impacts of these load profiles at the PQ, these two transformers presented a failure in the PQ supplied in the Frequency Variation indicator.

Specifically, in the PF indicator, all transformers failed in the supplied PQ, remaining with performance below the ideal.

In general, the impact of each load profile and not only evaluating the limits of each indicator but it is also concluded that the loads on each of the transformer's impact on other PRODIST indicators even if they remain within the limits of the indicators, they are the cases of the Permanent voltage regime and voltage unbalance factor indicators that showed the greatest impact on the transformer that presented the highest rate of NTL. Table 2 presents a summary of the results of each of the indicators of PQ monitored in the equipment of this study.

Table 2: Summary results of PQ indicators.

Indicator	**TR1**	**TR2**	**TR3**
Steady State Voltage	Indicator – OK	Indicator – OK	Indicator – OK, however it had impacts during peak hours
Imbalance Factor	Indicator – OK	Indicator – OK	Indicator – OK
Power Factor	Violated Indicator	Violated indicator, during almost any monitoring period	Violated indicator, with significant impacts in this indicator
Total Harmonic Distortion	Indicator – OK	Indicator – OK	Indicator – OK
Frequency variation	Indicator – OK	Violated indicator	Violated indicator

Source: Authors, (2021).

It is worth mentioning that PRODIST has seven (7) PQ indicators and a deeper analysis can be supported by the results obtained in this document and the impacts that PQ may suffer from the influence of NTL in distribution transformers.

This work presented for a case study of a distributor a critical analysis of the indicators of PQ considering a concern aspect to the distributors that are the high value of NTL. It is perceived that actions to reduce these losses will directly impact the energy quality parameters, that is, less non-technical loss, better service of supplying quality energy to the final consumer.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Salvador Paes Ribeiro Junior, Marcio Zamboti Fortes.
Methodology: Salvador Paes Ribeiro Junior, Ricardo Chagas Tolentino, Marcio Zamboti Fortes.
Investigation: Salvador Paes Ribeiro Junior, Ricardo Chagas Tolentino.
Discussion of results: Ricardo Chagas Tolentino, Marcio Zamboti Fortes, Guilherme Gonçalves Sotelo.
Writing – Original Draft: Salvador Paes Ribeiro Junior, Ricardo Chagas Tolentino.
Writing – Review and Editing: Marcio Zamboti Fortes, Guilherme Gonçalves Sotelo.
Resources: Salvador Paes Ribeiro Junior.
Supervision: Marcio Zamboti Fortes.
Approval of the final text: Salvador Paes Ribeiro Junior, Ricardo Chagas Tolentino, Marcio Zamboti Fortes, Guilherme Gonçalves Sotelo.

VIII. REFERENCES

[1] S.M. Deckmann and J.A. Pomilio. "Avaliação da qualidade da energia elétrica," [Online]. Available: http://www. dsce. fee. unicamp. br/antenor/pdffiles/qualidade/b5. pdf. [Accessed 13 05 2021].

[2] R.E. Brown. Electric power distribution reliability. CRC press, 2017. ISBN 978-0849-3756-82

[3] C. Sankaran. "Power Quality",CRC press, 2017. ISBN: 978-813-5183-6050.

[4] P. Cernek, M. Brejcha, J. Hájek and J. Pígl. "A Comparison of Power Quality Controllers," Acta Polytechnica, vol. 52, n. 5, pp.22-25, 2012.

[5] R. Brida Neto. "Perdas de Energia em Transformadores de Distribuição: Análise Técnica e Econômica em Função do Carregamento", Final Project Engineering Electric Course, UNISUL, Tubarão, SC Brazil, 2018.

[6] N. Kalache. "Gerenciamento de transformadores de distribuição operando em redes inteligentes", Doctorate Thesis, Universidade Estadual Paulista, Ilha Solteira, SP, Brazil, 2016.

[7] T.Gonen. "Electric power distribution engineering". CRC press, 2015.ISBN 978-1-4822-0705-7.

[8] ANEEL. "Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional – PRODIST- Módulo 8", 2020. [Online]. Available: <https://www.aneel.gov.br/modulo-8>. [Accessed 29 08 2020].

[9] G.V.S. Rocha. "Sistema inteligente de suporte a análise da qualidade da energia elétrica em regime permanente," Master Dissertation, Universidade Federal do Pará, Belém, PA, Brazil. 2017.

[10] P.M. Santiago. " Cálculo e análise computacional de campos elétricos gerados por linhas de transmissão de alta tensão em regime permanente," In: XVI CEEL, UFU, 2018. ISSN: 2178-8308.

[11] I.S. Machado. "Software para auxiliar na correção do fator de potência," Sinergia, vol.17, n.1, pp.15-21, 2016.

[12] G.G. Santos et al. "Uma proposta para definição de áreas de sensibilidade às distorções harmônicas," In: XIV CEEL, UFU, 2016. ISSN 2178-8308.

[13] H.A.F. Camporez et al. "Protótipo para análise da qualidade e controle da demanda pelo lado do consumidor em smart grid", 2016.

[14] S.L. Bandeira, R.G. Vieira and M.I.S. Guerra. "Análise da qualidade de energia elétrica de um sistema fotovoltaico conectado à rede", 2018.