Investigation of High-Frequency Oscillation Discrepancies Presented by Distribution Transformers During Lightning-Impulse Voltage Tests

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Key words: distribution transformers, lightning-impulse voltage test, lightning overvoltages, high-frequency oscillations, partial discharge

Investigations, through a sample evaluation, aiming to evaluate the cause of the high-frequency oscillations presented by distribution transformers in impulse tests reveal that internal imperfections, such as cavities and floating particles, cause these oscillations.

Introduction

Distribution transformers are one of the main components of electricity distribution systems, being responsible for reducing the voltage levels from the utility's distribution network to the level for the final consumers. Distribution networks are often subject to transient overvoltages of atmospheric origin, one of the causes of network failures. These failures are inconvenient for consumers and bring financial losses to distribution utilities, due to damaged equipment and penalties resulting from the unavailability of electricity power supply.

Reports considering transients phenomena tests on transformers have been available since 1920, bringing relevant contributions to the electrical system [1], [2]. Besides, the implementation of lightning impulse test procedures was important to improve transformer constructive aspects [3].

A considerable number of failure indications were observed in distribution transformers manufactured in Brazil when subjected to lightning-impulse tests performed at LAT-EFEI (High Voltage Laboratory of Federal University of Itajubá) [4], [5]. Furthermore, a significant number of transformers showed minor discrepancies in small high-frequency oscillations.

In this context, this work proposed a scientific study with a sample evaluation to investigate the existence of correlations between high-frequency oscillation discrepancies in lightning-impulse measurements and internal imperfections in the transformer, which result in partial discharges (PD). In addition, it proposed a method to monitor transformer quality before and after the impulse test, applying electrical follow-up tests to check if after the impulse, changes in the transformer insulation quality were identified in correlation with these discrepancies.

Therefore, the main objective of this paper was to identify the cause of the high-frequency oscillation discrepancies registered in the impulse oscillograms, verifying if these discrepancies are associated with the presence of PD measured before the lightning-impulse test and evaluating the existence of a correlation between these discrepancies and possible changed results in the follow-up tests.

By identifying the cause of these small discrepancies in the impulse oscillograms of the distribution transformers, this work can contribute to suggest possible improvement points in the insulation quality and to recommend further application of PD electrical tests in distribution transformers.

Samples and Experimental Method

In this work, distribution transformers newly manufactured and not installed in the field, with voltage classes of 15, 24, or 36 kV, were used as samples.

The samples were single-phase and three-phase medium voltage transformers projected to operate in overhead distribution networks with a design similar to the transformer in Figure 1(A). The samples present different electrical characteristics such as voltage class, rated power, and basic insulation level, as shown in Table 1.

The equipment was cooled by oil natural and air natural, and the insulation was composed of mineral oil and paper. All three-phase transformers belonged to the Dyn1 vector group. In this configuration, the high-voltage winding is delta connected,

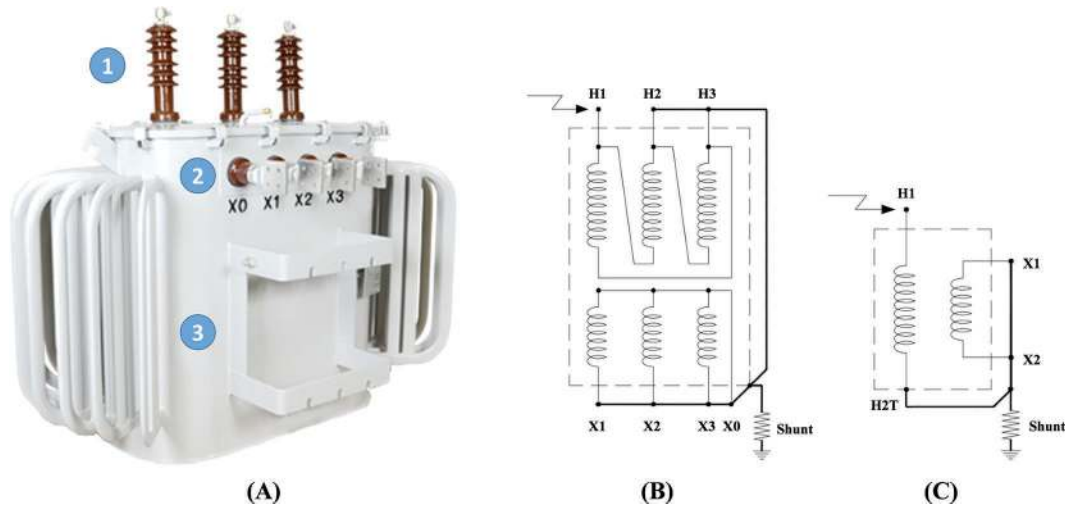

Figure 1. (A) Distribution transformer in 24-kV voltage class and with 300-kVA rated power. Design: 1 = high-voltage bushings; 2 = low-voltage bushings; 3 = tank. (B) Connection diagram for three-phase transformers, adapted from [4]. (C) Connection diagram for single-phase transformers, adapted from [4].

and the low-voltage winding is star connected. The low-voltage winding lags the high-voltage winding by 30°.

A total of 63 distribution transformers were tested, as summarized in Table 1, where *n* denotes the number of samples.

Table 1. Transformer sample characteristics

Item	Single phase (n = 35)	Three phase (n = 28)
Voltage class (kV)		
15	17 (49%)	14 (50%)
24	10 (29%)	8 (29%)
36	8 (23%)	6 (21%)
Basic insulation level (kV)		
95	17 (49%)	13 (46%)
110	0 (0%)	1 (4%)
125	10 (29%)	8 (29%)
150	8 (23%)	6 (21%)
Rated power (kVA)		
5	4 (11%)	
10	7 (20%)	
15	6 (17%)	
25	9 (26%)	
37.5	5 (14%)	
50	3 (9%)	
75	1 (3%)	
100	0 (0%)	
15		3 (11%)
30		4 (14%)
45		5 (18%)
75		5 (18%)
112.5		3 (11%)
150		2 (7%)
225		4 (14%)
300		2 (7%)

Impulse Tests in Distribution Transformers

Technical standards consider a smooth, full lightning-impulse voltage with a front time (T_1) of 1.2 microseconds and a time to half-value (T_2) of 50 microseconds, described as a 1.2/50 microsecond impulse, as standard [6], [7].

A multistage impulse generator circuit was used to perform the lightning-impulse voltage test [8]. For liquid-immersed transformers, the impulse shape is of negative polarity [9]. The two extreme tap positions and the middle tap position were used in three-phase transformers during the lightning-impulse test.

Voltage and current oscillograms were recorded for all applications, and the impulse application sequence was performed according to standardized procedures [9], [10]. The adopted impulse application sequence was as follows: one reduced full wave; one full wave; one reduced chopped wave; two chopped waves; two full waves. For tail-chopped lightning impulse, the impulse voltage was chopped between 2 and 6 microseconds after the virtual origin [11].

For impulse voltage measurements, a system approved according to standards was used [12]–[14]. Moreover, resistive shunts were inserted in the circuit for the line current fault detection method applied in this investigation. In this configuration, all non-impulsed terminals were short-circuited and connected to the tank, as depicted in diagrams (B) and (C) of Figure 1. The line current represents the sum of the winding current, current transferred, and the tank current and makes it possible to identify the distortions in the oscillograms coming from inside of the transformer. Besides the line current, there are other standardized methods (see [11]).

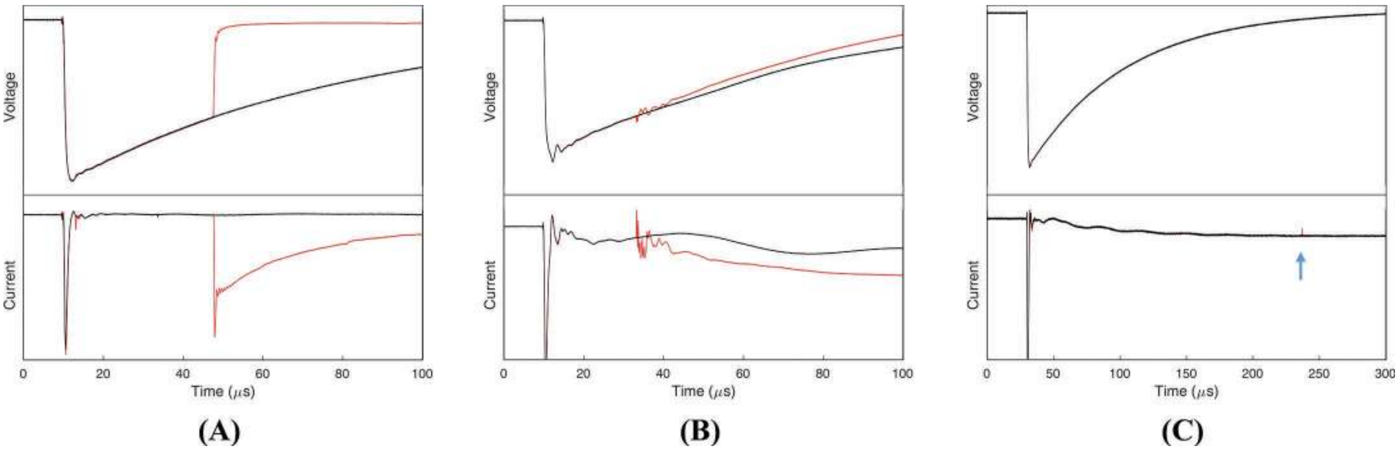

Figure 2. Types of discrepancies: (A) example of type D1, (B) example of type D2, and (C) example of type D3. In (A) and (B), black is the reduced full wave and red is the second full wave, after the chopped wave.

The conformity analysis process of the test consists of evaluating the recorded voltage and current oscillograms, by comparing full-wave oscillograms with the reduced full-wave oscillograms along with successive records. The reduced full-wave impulse was registered because, theoretically, it represents the transformer response without failure because the applied voltage is lower than the required full-wave impulse level.

These comparisons were made to search for evidence that the insulation withstood the dielectric stress imposed by the test due to the absence of discrepancies among the recorded oscillograms. Therefore, if there were no discrepancies between the oscillograms, the sample was considered approved.

Discrepancies between the recorded oscillograms may represent failure indications, and they can appear in different ways, such as disruptive discharges, changes in the frequency of oscillations, reduction in the duration of the wave tail of the test voltage, and high-frequency signals with subsequent alteration of the oscillation pattern. The type of discrepancy depends on the cause of failure.

During the conformity assessment process of the tests performed, the discrepancies among the records were classified into three types (D1, D2, D3):

D1—major discrepancies (collapse),

D2—minor discrepancies, distortion of portions of the records, and

D3—minor discrepancies, discrepancies in some small, high-frequency oscillations.

Figure 2 shows an example of each type of discrepancy.

The D1-type discrepancy is characterized by total voltage collapse, as shown in Figure 2(A). The voltage oscillograms are similar to a chopped-wave impulse, especially when the fault occurs from the winding extremity to earth. The D2-type discrepancy is distinguished by distortions in parts of the oscillogram, as presented on Figure 2(B), which shows a disruptive discharge across a section of the winding, with a reduction in time to half-value and increase of inductive current, due to impedance decrease.

The D3-type discrepancy was the main focus of this work due to the high rate of appearances of this type of fault in the tested samples. These discrepancies have high-frequency signals in the oscillograms, as indicated by the arrows in Figure 2(C), and may have an external or internal origin. The external and internal sources that can produce these discrepancies are listed as follows [3], [11], [15]:

- External disturbances: discrepancies caused by the test circuit (such as streamers), measurement circuit, and imperfections in impulse connection or in grounding system or
- Internal disturbances: internal problems such as PD or incipient breakdown (for example, discharges in core plates, air bubbles in the oil, corona, and PD in the insulation).

Experimental Method

To evaluate the insulation quality of the transformers before and after the stress imposed by the impulse test, the implemented method includes follow-up tests composed of routine and special tests:

- Frequency response analysis;
- Measurement of insulation power-factor and capacitance;
- Measurement of winding resistance;
- Measurement of transformation ratio;
- Measurement of load losses and short-circuit impedance;
- Measurement of no-load losses and excitation current; and
- Measurement of PD, with evaluation of maximum PD levels (PD_{MAX}) and the PD extinguishing voltage.

This scope was determined based on LAT-EFEI test capacity and tests applicable to maintenance and insulation quality control of transformers, covered by standards [10], [16]. This work adopts some of the most commonly applied tests for quality control purposes in power transformers.

D3-type discrepancies are the most difficult to associate with failures due to their diverse possible origins. Initially, trying to identify the source of the D3-type discrepancies detected in the oscillograms, the first hypothesis test evaluated was its association with PD presence in the follow-up test executed before the lightning-impulse test.

Table 2. Informative table for using Fisher's exact test, in which A, B, C, and D were the observed frequencies and N is the total number of samples

Impulse test	Changed results in follow-up tests?		
	No	**Yes**	**Total**
Without discrepancies	A	B	A + B
Type-D3 discrepancies	C	D	C + D
Total	A + C	B + D	N

Afterward, the results from the follow-up tests after the impulse test were evaluated in an attempt to establish a correlation between D3-type discrepancies and the possible changed results, caused by failures during the impulse test. The recorded frequency-response-analysis curves and the measured values (from the remaining tests) before and after the impulse test were compared to quantify the variation between the results. Equation (1) provides the variation (Δ_M) between the measured values before (R_{BEFORE}) and after (R_{AFTER}) the impulse test, with the test uncertainty (u).

The dissipation factor and the winding resistance were corrected to 20°C and the load losses and the short-circuit impedance to a reference temperature, according to [9], [17].

$$\Delta_M = |(R_{AFTER} - R_{BEFORE})/u| \quad (1)$$

The uncertainties related to the tests were obtained in a calibration process by comparison, evaluating the sample mean, with the adoption of the t distribution (Student distribution). The uncertainties were not expanded, obtaining a confidence interval of approximately 68% [18], [19].

Based on the z-score technique [20], the variations were classified as "unchanged results" if less than three times the test uncertainty and as "changed results" when greater than three times the test uncertainty. Thereby, the results were structured in tables, assembling a matrix as shown in Table 2. In these tables, the observed frequency values were inserted in items A, B, C, and D, according to the classifications.

For correlation analysis, as it is an assessment of the association between qualitative variables, the hypothesis test called Fisher's exact test was adopted [21], [22]. This test is recommended for small sampling and is nonparametric, as it does not depend on population variables, such as mean and dispersion [21].

The P-value parameter was calculated through Fisher's exact test, considering Equation (2), based on the observed frequency values, obtained directly from the samples. The P-value corresponds to the probability of occurrence of these observed frequencies.

$$P = \frac{(A+B)!(C+D)!(A+C)!(B+D)!}{N!A!B!C!D!} \quad (2)$$

In Fisher's exact test, it is necessary to determine the null and alternative hypotheses. Under the null hypothesis, it is expected there will be independence between the classifications; otherwise, the alternative hypothesis, which contains the investigation, is proposed [18], [21], [22].

The critical analysis of the results was performed based on the comparison with the significance level adopted: if the P-value is lower than the significance level, there is evidence to reject the null hypothesis [18], [21], [22]. Otherwise, there is evidence in favor of the stipulated alternative hypothesis. In this analysis, a typical significance level (α) of 5%, widely applied in analyses of experiments, was adopted [21]–[23].

Results and Analyses of the Laboratory Tests

From the impulse-test analysis, 11% of the samples did not present discrepancies among the oscillograms; therefore, they were classified as without discrepancies. The remaining 89% presented discrepancies, of which 5% were D1 type, 11% were D2 type, and 84% were D3 type. It leads to the conclusion that a high percentage of the discrepancies were related to the appearance of high-frequency signals in the oscillograms, as D3-type discrepancies.

In the next sections, the correlation analyses are presented.

Correlation Between D3-Type Discrepancies and PD Presence in the Follow-Up Test Executed Before the Impulse Test

The first hypothesis test evaluated the possible association between the PD presence in the follow-up tests before the impulse test and the D3-type discrepancies registered in the impulse oscillograms. For this scenario, the P-value was 0.0053%, a result smaller than the adopted level of significance, confirming there is evidence of association.

So, there is evidence that minor identified discrepancies, of small high-frequency oscillations, are correlated with PD presence in the samples. This correlation provides evidence that the source of this disturbance was present in the transformer samples, eliminating the possible external sources previously mentioned.

This correlation is coherent because similar high-frequency oscillations were obtained through a PD simulation circuit during impulse tests [24].

Due to the correlation between the identified D3-type discrepancies and the PD presence, further investigation was conducted to classify the probable source of the PD through the PD patterns recorded [25]–[27]. The results of the PD pattern analysis are summarized in Table 3.

As shown in Table 3, most of the samples with PD presence are related to internal cavities without contact to electrodes in the transformer. The second most common cause was floating particles.

Partial discharge related to internal cavities inside the transformer, without contact with electrodes, can occur due to bubbles present in the oil [28]. The floating conductive particles can be associated with the contamination by metal burrs in the insulating oil.

Table 3. Classification of probable origin of partial discharge

Type	Classification	%
1	Without partial discharge	11
2	Conducting material with direct contact with metallic electrodes	0
3	Conducting material without any contact with metallic electrodes	21
4	Conducting particles laying on the surface of the insulating material surface	0
5	Nonconducting material (cavity) with direct contact with metallic electrode	4
6	Nonconducting material (cavity) without any contact with metallic electrode	50
7	Type 3 and 6 simultaneously	14
Total		**100**

Partial discharge can cause progressive deterioration of oil/pressboard insulation and in some cases may lead to insulation failure [29]. The bubbles present in the oil can reduce the impulse strength of the transformer [30]. In addition, other possible sources of PD are divergent electric fields in the insulation of oil paper due to impurities, such as small drops of water and other tiny particles, which can cause erosion in the pressboard and generate bubbles [31].

Moreover, the results show that 61% of the samples present PD_{MAX} higher than 1 nC, whereas 33% had PD_{MAX} below 100 pC and 7% between 0.1 and 1 nC. For distribution transformers, the acceptable PD level is still not well defined, whereas for high-voltage transformers, it can be considered around 500 pC [9]. Considering this level as the acceptable PD level for distribution transformers and the fact that the applied voltage during the tests was below the standard voltage used in PD tests, many samples presented a high level of PD.

Correlation Between D3-Type Discrepancies and the Result Changes in Follow-Up Tests

With the purpose to assess correlations between D3-type discrepancies registered in the impulse oscillograms and the possible changes in the samples after the impulse application, the follow-up test result (before and after the impulse test) was compared, and the Fisher's test was used to obtain the *P*-value. An example of the *P*-value obtained from the short-circuit impedance-test data through Table 2 and Equation (2) are presented in Table 4. There are not 63 total samples because 9 samples showed type D1 or D2 discrepancies in the impulse test.

The calculated *P*-values for all the follow-up tests are shown in Figure 3. The lowest *P*-value found was around 7%, in the correlation analysis of the PD_{MAX} classification, which monitors variations in the maximum PD value recorded during the follow-up tests. For some samples, the PD level increased, but because the *P*-value was higher than the adopted significance level, it is not possible to affirm that there is a correlation.

Therefore, none of the follow-up tests provided evidence of changes correlated with D3-type discrepancies, without evidence in favor of the hypothesis that changes in the follow-up test results after the impulse test are associated with these minor discrepancies during the impulse test. In this way, there was not enough evidence of deterioration in the insulation condition of the transformers.

Conclusions

This work demonstrated that the minor discrepancies only in small high-frequency oscillations were caused by PD, due to internal imperfections of the transformer. This conclusion is based on the verified correlation between results of the PD follow-up test executed, before the impulse test, and the results of the impulse tests.

These imperfections demonstrate technical aspects related to manufacturing quality that can be improved or avoided, such as air bubbles in the oil; mitigated by improvements in the transformer oil filling system; and, in the case of burrs, avoided by better control in the core manufacturing process, for example.

The correlation analysis based on the results from the follow-up tests showed no evidence of changes in transformer

Table 4. Short-circuit impedance-test data and the correspondent *P*-value

	Changed short-circuit impedance?		
Impulse test	**No**	**Yes**	**Total**
Without discrepancies	6	1	7
Type-D3 discrepancies	43	4	47
Total	49	5	54
***P*-value**[1]	$P_{E_z} = \frac{(6+1)!(43+4)!(6+43)!(1+4)!}{54!6!1!43!4!} = 39\%$		

[1] E_z = short-circuit impedance.

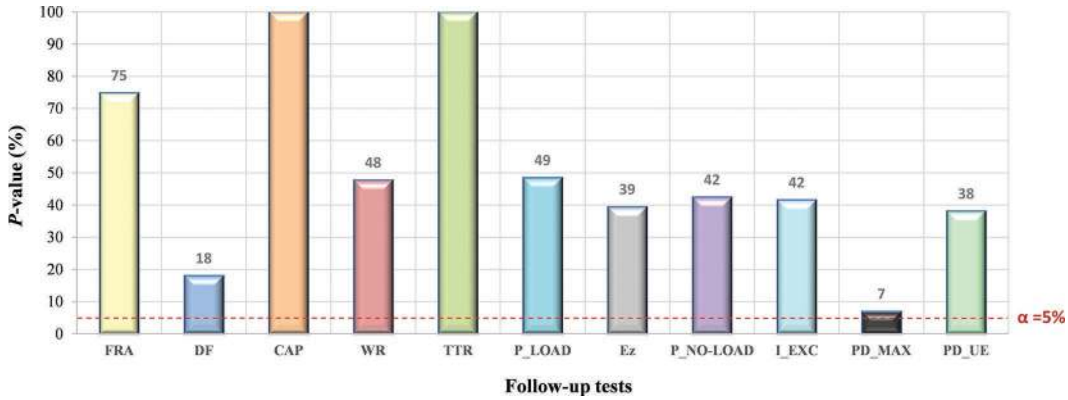

Figure 3. *P*-values for tests of correlation hypotheses between analysis of pulse oscillograms and changes in results recorded in all follow-up tests. FRA = frequency response analysis; DF = measurement of insulation power factor, CAP = measurement of capacitance; WR = measurement of winding resistance; TTR = measurement of transformation ratio; P_LOAD = measurement of load losses; Ez = measurement of short-circuit impedance; P_NO-LOAD = measurement of no-load losses; I_EXC = measurement of excitation current; PD_MAX = maximum partial discharge levels; and PD_UE = partial discharge extinguishing voltage.

quality due to the identified D3-type discrepancies. Therefore, these discrepancies caused by internal imperfections did not generate changes in the results of the follow-up tests.

On the other hand, such imperfections can evolve in the field and cause damage to the insulation of the transformer. Thus, the mitigation of these imperfections represents a reduction in the probability of occurrence of dielectric withstand decrease, capable of reducing the faults and power interruptions in distribution networks, caused by failures in transformer insulation.

Also, this paper recommends to manufacturers and purchasers more utilization of PD tests to identify these imperfections and improve the insulation quality of distribution transformers. Currently, the PD test for distribution transformers is classified as "other tests" and only performed when specified by the purchaser.

Acknowledgment

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior–Brasil (CAPES) and by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

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