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Design of transformers for very fast transient overvoltages

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Summary **— Increasingly, for different technical-economic reasons, gas-insulated substations (GIS) are being used in electrical systems instead of conventional air-insulated substations (AIS). The switching transients originating in GIS are called Very Fast Transient Overvoltages (VFTO) and are completely different from those originating in AIS, with different frequencies, amplitudes and waveforms. Conventional power transformers are designed to withstand the standard lightning and switching impulses (LI, LIC and SI according to IEC 60076-3). Modelling and behaviour of transformers for the frequency range of these tests (< 500 kHz) is well known, proved in the factory acceptance tests, and validated by successful operation in service. For VFTO, however, no standard tests are available yet, therefore, the customer needs to define the VFTO test voltage that must be considered in the design of the transformer. The design of transformers that can withstand the effects of VFTO represents a great challenge and we will present in this work the state of the art of the dielectric design methodology including the selection of voltage wave shapes representative of VFTO, the transformer modelling requirements, the admissible electric field in insulating materials, the withstand of the different insulating structures and finally the proposed non-standard tests, when a transformer will be subjected to the effects of VFTO.**

Keywords **— Power transformers, shunt reactors, very fast transient overvoltages, transformer and reactor modelling, dielectric design, materials withstand.**

I. Introduction

Increasingly, for different technical-economic reasons, gas-insulated substations (GIS) are being used in electrical systems instead of conventional air-insulated substations (AIS).

The switching transients originating in GIS are completely different from those originating in AIS, with different frequencies, amplitudes and waveforms, and their effects on transformers have been a matter of discussion in CIGRE Working Groups from 1988 to 2005 [1], [2], [3].

These transients are called Very Fast Transient Overvoltages (VFTO) and are characterized by a very steep front wave and high oscillation frequency. The rise time of such a wave is in the range of some nanoseconds (5 to 20 ns) and the peak value is about 1.5 and 2.5 p.u. of the rated operating voltage. The oscillation frequencies are in the range up to 5 to 10 MHz. IEC 60071 uses the term Very Fast Front Overvoltage (VFFO) for such overvoltage.

Another important source of VFTO is the use of circuit breakers with vacuum arc interruption.

Conventional power transformers are designed to withstand the standard lightning and switching impulses (LI, LIC and SI according to IEC 60076-3). Modelling and behaviour of transformers for this frequency range (< 500 kHz) is well known, proved in the factory acceptance tests, and validated by successful operation in service.

For VFTO, no standard tests are available yet, therefore, the customer needs to define the VFTO voltage wave forms to be considered in the design of the transformer.

The conclusion of the CIGRE Working Groups [1] [2] [3] was that no new test is needed and the chopped wave lightning impulse test can be applied adjusting their parameters (rise time, time to chopping, fall time and under swing) according to the VFTO characteristics.

Although there is no statistical evidence that these VFTO cause a higher failure rate than conventional overvoltages, the fact of not being able to test the withstand of the equipment to VFTO during the factory acceptance tests leaves a big question open.

The dielectric design of transformers that can withstand the effects of VFTO represents a great challenge and we will present in this work the design process in the following chapters:

- dielectric design methodology
- voltages representatives of VFTO
- transformer modelling requirements
- admissible electric field in insulating materials
- withstand of insulating structures

We will also analyze representative VFTO tests that certain electric utilities and manufacturers have agreed to perform during factory acceptance tests of transformers in recent years.

Although there are more doubts than certainties in many of these topics, we will try to present the current situation or state of the art in the industry.

Investigating the above-mentioned problems has been a part of the objectives of launching this year the CIGRE WG A2/C4/D1.77 “Design of transformers for very fast transient overvoltages” whose Terms of Reference (ToR) is available in the CIGRE web page (www.cigre.org).

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Disclaimer: All presented values and formulas are based in my personal experience as transformer designer and transformer design reviewer and are only orientations that can vary widely between manufacturers.

II. Dielectric Design Methodology

Figure 1 shows a flowchart of the dielectric design process of a transformer for any type of transient (SI, LI, LIC, VFTO), standard or non-standard, represented by a voltage wave shape V(t), that it is applied to one of the terminals of the transformer. The connections of the other transformer terminals must be clearly defined, for example: connected directly to ground, connected to ground through an impedance, open without surge arresters, open with surge arresters, etc. Several papers on special termination lightning impulse test on power transformers have been published in IEEE and CIGRE since 1994 [4], [5], [6], [7].

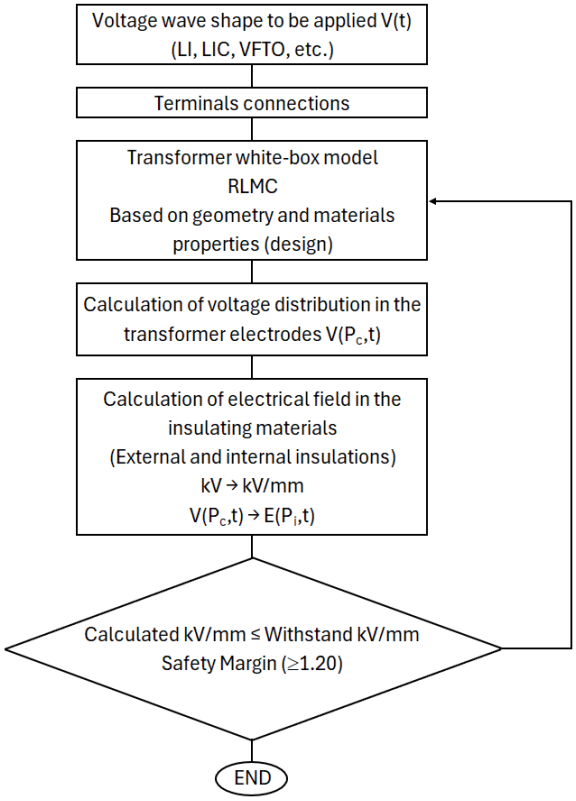

Fig. 1. Dielectric design flowchart

Once defined V(t) the first step of the design process is to construct an appropriate high-frequency model of the transformer, for the frequency range of the applied wave V(t), that allows us to determine accurately how the applied voltage is distributed inside the windings.

Once the transformer model has been built, we can determine by calculation the voltage that appears in each turn of the windings as a consequence of the VFTO applied at its terminals and from these voltages it is possible to calculate the electric field to which each of the insulating materials of the windings are subjected.

Finally, the calculated electric fields applied to the insulating materials must be compared with the field values that these insulating materials can withstand that depend on the amplitude, front time, oscillation frequency, and duration of the applied wave. At this stage one of the problems that arise is that there is little or no information regarding how liquids and solid insulating materials behave when they are subjected to VFTO.

Certain safety margins between the calculated and supported values must be verified, typically greater than 1.20, and if this condition is not met for any insulation, the design must be appropriately modified, the transformer model adapted to the changes made, and the design process repeated. The dielectric design process for a transformer is iterative.

Reference [8] is an excellent example of the complete dielectric design process of a transformer that must withstand the effects of VFTO, including factory acceptance tests that attempt to simulate the effects of VFTO on the transformer.

In the following chapters, we will examine each of the stages indicated in the flowchart of Figure 1 in more detail.

III. VFTO Applied Voltage

To verify the insulation withstand of a transformer to a specific transient phenomenon, we must know the voltage waveforms that appear at the transformer winding terminals as a result of the transient.

When designing a transformer to successfully pass factory dielectric acceptance tests, the magnitude and waveform of the voltages to be applied to the transformer are precisely defined by the standards [9], [10]: power frequency sinusoidal, switching impulse, and full and chopped lightning impulse.

For VFTO, however, we do not have standardized wave shapes that represent them. In chapter 3.2 of CIGRE Technical Brochure Nº360 [11] several non-standard lightning impulse waveform representatives of VFTO are defined that can be used in the dielectric design of the transformer (Figure 2).

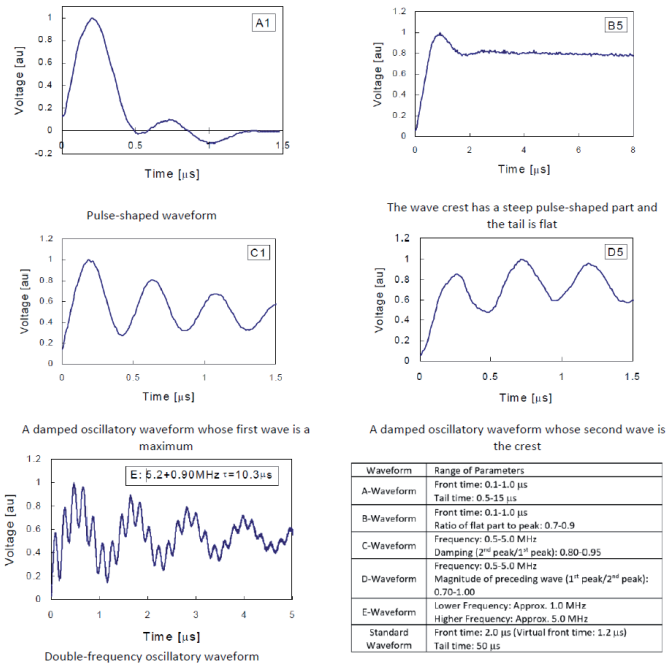

Fig. 2. Examples of non-standard impulse waveforms representative of VFTO [10]

The safer option is modelling in electromagnetic transients programs (EMTP-type) the interaction between transformer and GIS and obtain, case by case, the VFTO wave forms that are necessary consider in the dielectric design of the transformer.

Other option, used by certain electric utilities, is to include in the design review the study of transformer dielectric withstand for a series of standard lightning impulse waveshapes but with modifi-

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ed parameters (front time and time to half value). For these studies they use wave shapes with an amplitude of 2 per unit (example: 898 kV_{peak} for U_m = 550 kV_{rms}), a front time of 10±5 ns (between 5 to 15 ns) and a time to half value of 165±99 ns (between 66 to 264 ns).

Practice and studies carried out within the framework of Task Force C (Transformer transient simulations and dielectric withstand of transformer insulation system) of CIGRE WG A2.63 (Transformer impulse testing) have shown that these waves are generally more demanding on transformer insulation than those obtained from electrical system studies.

IV. Transformer Modelling Requirements

To determine accurately how the applied voltage is distributed inside the windings the manufacturers use in-house calculation programs called white-box models. The white-box models can be categorized as lumped parameters circuit models based on a spatial discretization of the windings, or distributed parameters models based on traveling wave-type approaches. The extraction of the model's parameters: resistance, self and mutual inductances, series and shunt capacitances (RLMC), is in all cases based on a detailed description of the transformer's geometry and materials properties. From this information, the model's parameters are calculated via formulae and/or finite element method (FEM) computations.

CIGRE Technical Brochure Nº900 [12] describes the most relevant white-box model types and the calculation procedures for determination of the fundamental input parameters, considering both analytical and FEM methods, with consideration to accuracy requirements. A strong emphasis is put on the handling of the core representation, and on the inclusion of frequency-dependent damping effects as is explained in detail in reference [13].

The white-box models used to analyse the withstand capability of transformers to standard impulse waves (LI, LIC) are typically lumped-parameter models that divide the windings into elements or branches containing one or two discs each and is assumed that the voltage is distributed uniformly inside the discs of the elements.

This approach cannot be used for the high frequencies involved in VFTO, where the voltage distribution in the windings is extremely non-uniform, and it is necessary to use turn-by-turn models for the windings [8] including detailed high frequency models of the capacitive bushings [14] [15] [16]. For VFTO studies the elements or branches in which are divided the windings are turn-by-turn, not disc-by-disc or for each pair of discs like is usual for standard impulses.

The quality of the model is fundamental to obtaining the necessary accuracy in calculating the voltage distribution inside the windings of a transformer when a VFTO is applied to one of its terminals.

V. Efects of Vfto on Transformers

When a VFTO reach the transformer windings terminals, two problems can arise inside the winding.

The first is the generation of high voltages concentrated in the first discs near the line terminal, produced by the strongly non-linear distribution of the VFTO within the winding. This is a consequence of the much higher frequency of VFTO compared to normalized impulse waves. Figure 3 shows the comparison between the voltage in the first element of a winding (two discs) when a normalized impulse wave is applied with a front time t_r = 1.2 μs (blue Line) and when a step wave is applied with a front time t_r = 0 μs (orange Step). An increase in the peak value of the order of 25% is observed when decreasing the rise or front time from 1.2 μs to 0 μs but inside the two discs of the element the situation is worse because the voltage distribution is also strongly non-linear.

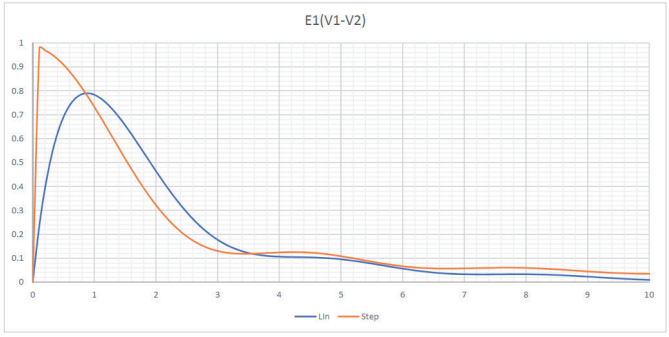

Fig. 3. Effect of front time in winding voltage distribution

Typically, for a standard 1.2/50 μs lightning impulse, the voltage between turns can reach approximately 6% of the applied voltage, and the voltage between discs can reach approximately 10% of the applied voltage. For VFTO, however, these values increase approximately to 10% and 16%, respectively.

Considering the effects of wave propagation also is observed that the maximum stress between discs does not occur any more at the inner or outer diameter of the winding but somewhere in the middle depending on the chosen method for increasing the series capacitances (interleaving or shielded wire technology).

The second is the resonance in certain parts of the winding caused by the oscillatory tail of the VFTO if his frequency coincides with one of the natural or resonance frequencies of the winding. This can cause oscillatory voltages of great amplitude within the centre and end sections of the winding.

Moreover, repetitive impulses are recognized as another event which can lead to inner insulation failure. This effect is described by the V-N characteristic [17] that can be represented by equation (1), where is the withstand voltage for one impulse (), is the withstand voltage for repetitive impulses and is dependent of the wave shape and of the insulation (turn to turn or disc to disc).

$$V_N = V_1 N^{-\frac{1}{n}} \quad (1)$$

VI. Admissible Electric Field in Insulating Materials

The maximum admissible electric field of an insulating material is defined as a value with a very low probability (less than 1.0%) of partial discharge inception, since in no case should partial discharges occur. Depending on material and geometry, the partial discharge inception value is between 70% to 80% of the dielectric breakdown value of the material.

The dependency of admissible electric field of insulating materials with material thickness and wave form (AC and LI) can be summarized with the following examples for cellulose paper and mineral oil:

- For a 1.6 mm paper thickness between flat electrodes, as occurs in the insulation between turns, the admissible electric field in AC, 1 minute, is 9 kV_{rms}/mm, while for the normalized impulse 1.2/50 μs it is 60 kV_{peak}/mm.

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For a 3.0 mm paper thickness these values become 8 kV_{rms}/mm and 53 kV_{peak}/mm, respectively.

- For an oil gap of 5.0 mm between isolated flat electrodes, as occurs in the insulation between discs, the admissible electric field in AC, 1 minute, is 8.8 kV_{rms}/mm, while for the normalized impulse 1.2 / 50 μs it is 23.4 kV_{peak}/mm.

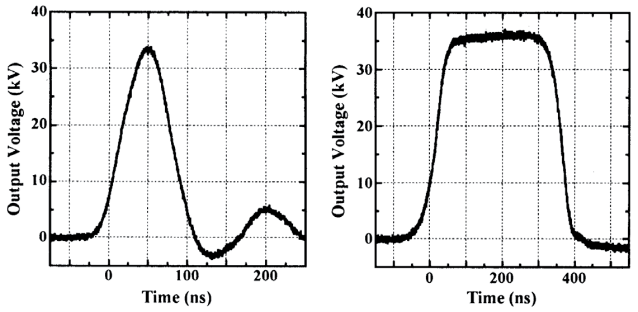
For an oil gap of 10.0 these values become 7.5 kV_{rms}/mm and 19.8 kV_{peak}/mm, respectively.

When we have insulating structures made up of a combination of various insulating materials, we must first determine the voltage distribution between the different materials, then calculate the electric field in each material and finally verify the supportability of each material.

On the other hand there is little or no information regarding how liquids and solid insulating materials behave when they are subjected to VFTO.

The most complete study published up today is the work of Ikeda [18] in which the V-t_{50} characteristics of oil and paper are determined experimentally for plane-plane electrodes (uniform electric field). These V-t_{50} characteristics give the peak voltage withstand of the insulating material V in function of the time t_{50} which it is the time that the voltage wave is above 50% of its maximum value V. Some designers use t_{50} defined by the first oscillation of the voltage wave and others consider the sum of all intervals during which the voltage exceeds 50% of the peak (positive and negative values shall be treated separately).

In Figure 4 are shown the waveforms used in the experiments with front times of 60 and 80 ns, t_{50} of 60 and 340 ns, and voltages amplitudes up to 100 kV.



(a) 60nsVFT (t_w = 60 ns) (b) 300nsVFT (t_w = 340 ns)

Fig. 4. VFTO waveforms used in reference [17]

The V- t_{50} characteristics of oil and paper can be expressed by equation (2) where n = 13.7 for oil and n = 150 for paper.

$$V_2 = V_1 \times \left(\frac{t_1}{t_2}\right)^{1/n} \quad (2)$$

If we use as reference the material withstand standard lightning impulse with t_{50} = 50 μs the equations for oil (3) and paper (4) can be written as:

$$V_{t_{50}} = V_{50\mu s} \times \left[\frac{50}{t_{50}(\mu s)}\right]^{1/13.7} \quad (3)$$

$$V_{t_{50}} = V_{50\mu s} \times \left[\frac{50}{t_{50}(\mu s)}\right]^{1/150} \quad (4)$$

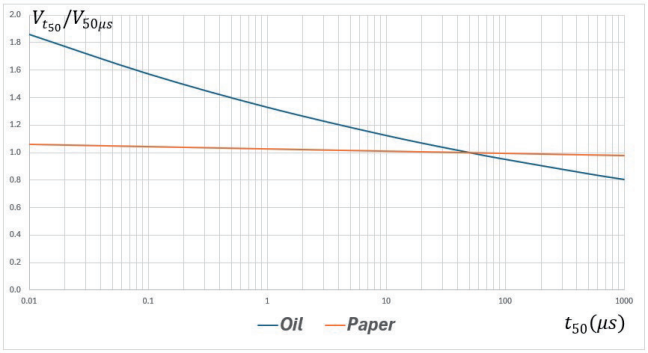


Fig. 5. Relative variation of oil and paper withstand with

In Figure 5 is represented the relation V_{t50} / $V_{50\mu s}$ in function of the time in μs. The conclusion is that for oil we have an important increase in the dielectric withstand when the time t_{50} is reduced from μs to ns, but for paper this increase is marginal. The behaviour of both materials for VFTO (t_{50} in the range of ns) is completely different.

As the tests was carried out with uniform electric field equations (3) and (4) can be converted into electric field changing the voltages by electric field.

VII. Withstand Of Insulating Structures

Most high-voltage windings in transformers and shunt reactors are disc-type with some mechanisms to increase their series capacity, such as different types of interleaving [19] – [21] or shielding [22], [23], [24], as is shown in Figure 6.

The main difference between shunt reactor windings and transformer windings is that reactor windings have a much higher number of turns per disk than transformer windings, which adds an additional challenge to their dielectric design not only for VFTO but also for standardized impulses (LI and LIC).

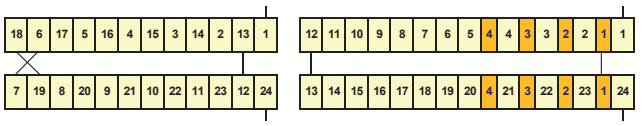


Fig. 6. Interleaved disc winding (left) and continuous disc winding with shields (right)

In this chapter we will review the basics of the dielectric design for VFTO of the two most important insulating structures in disc windings: the turn-to-turn insulation and the disc-to-disc insulation.

The formulas presented for the admissible electric field in paper and oil for VFTO are for guidance only and may vary widely between manufacturers.

A. *Turn-to-turn insulation*

First, we calculate the electric field in the paper of the turn-to-turn insulation in function of peak value of the calculated voltage between turns and the double thickness of the paper insulation between turns in equation (5) based on the formula of a flat-plate capacitor.

$$E_{PAP}\left(\frac{kV}{mm}\right) = \frac{V_{MAX}(kV)}{d_{PAP}(mm)} \quad (5)$$

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Normally, in the case of VFTO, V_{MAX} for interleaved windings (Figure 6, left) V_{MAX} appears in the entrance of the first pair of discs between turns 1 and 13, and in continuous disc winding with shields (Figure 6, right) appears also in the entrance of the first pair of discs but between the turn 1 of the principal conductor and the turn 1 of the shield conductor.

Then we calculate the admissible electric field in the paper $E_{ADM\ PAP}$ in function of the double thickness of the paper insulation between turns d_{PAP} and the t_{50} of the calculated waveshape between turns $V(t)$ whose peak value is V_{MAX} in equation (6).

$$E_{ADM\ PAP}\left(\frac{kV}{mm}\right) = [C_1 - C_2 \times d_{PAP}(mm)] \times \left[\frac{50}{t_{50}(\mu s)}\right]^{1/n_1} \quad (6)$$

The constants C_1 and C_2 and the exponent vary depending on the manufacturer's experience. For example, we can use $n1$=150 according with Ikeda experiments [17].

Finally, we check if the safety margin SF calculated in equation (7) is adequate, for example greater than 1.20.

$$SF = \frac{E_{ADM\ PAP}\left(\frac{kV}{mm}\right)}{E_{PAP}\left(\frac{kV}{mm}\right)} \quad (7)$$

B. Disc-to-disc insulation

The weakest point of the insulation is the oil gap between the discs.

First, we calculate the electric field E_{OIL} in the oil of the disc-to-disc insulation in function of peak value V_{MAX} of the calculated voltage $V(t)$ between discs, the thickness of the oil gap d_{OIL} and the double thickness of the paper insulation between turns d_{PAP} in equation (8) where ε_{OIL} and ε_{PAP} are the permittivity of oil and impregnated paper respectively. The insulation is modeled as two flat-plate capacitors in series, one representing the oil and the other representing the paper.

$$E_{OIL}\left(\frac{kV}{mm}\right) = \frac{V_{MAX}(kV)}{d_{OIL}(mm) + \frac{\varepsilon_{OIL}}{\varepsilon_{PAP}} d_{PAP}(mm)} \quad (8)$$

Normally, in the case of VFTO, V_{MAX} appears in the middle of the discs, between turns 15 and 10 for interleaved windings (Figure 6, left) and between turns 6 and 19 for continuous disc winding with shields (Figure 6, right).

Then we calculate the admissible electric field in the oil gap between discs $E_{ADM\ OIL}$ in function of the thickness of the oil gap d_{OIL} and the t_{50} of the calculated waveshape between turns $V(t)$ whose peak value is V_{MAX} in equation (9).

$$E_{ADM\ OIL}\left(\frac{kV}{mm}\right) = \frac{C_3}{d_{OIL}(mm)^{n_2}} \times \left[\frac{50}{t_{50}(\mu s)}\right]^{1/n_3} \quad (9)$$

The constant C_3 and the exponents and vary depending on the manufacturer's experience. For example, we can use n3 = 13,7 according with Ikeda experiments [17].

Finally, we check if the safety margin SF calculated in equation (10) is adequate, for example greater than 1.20.

$$SF = \frac{E_{ADM\ OIL}\left(\frac{kV}{mm}\right)}{E_{OIL}\left(\frac{kV}{mm}\right)} \quad (10)$$

VIII. Proposed Non-Standard Test

Regarding additional tests, representative of VFTO, the conclusions of CIGRE working groups were:

- CIGRE WG 12.11 [2]: "No new test is needed. The chopped wave test can be applied. However the parameters (rise time, time to chopping, fall time and underswing) have to be specified, reflecting the special characteristics (frequency spectrum and damping) of the GIS system that the transformer will be connected to."
- CIGRE JWG A2-A3-B3.21 [3]: "Many failures of transformers are reported in various statistics but there is not enough specific data pointing to the impact of fast transients and steep surges on the failures. Often the root cause analysis is missing and the failures are "unknown". Therefore, JWG concludes that no new type tests for transformers are warranted."

These conclusions from the CIGRE working groups have not satisfied users, as subsequent studies have shown that even modifying the parameters of the chopped impulse test within the limits allowed by the impulse test equipments does not cover all the possible transients that can be generated from the interaction between GIS and the transformers, and therefore are not being able to test the withstand of the transformers to VFTO during the factory acceptance tests leaves a big doubt without answer.

The first recorded VFTO tests on transformers were carried out in 2009 by WEG Equipamentos Elétricos at its plant in Blumenau, Brazil. These tests involved two GSU single-phase transformers, 256 MVA 60 Hz and 275 MVA 50 Hz, 525/√3/18 kV, which were manufactured for Itaipu Binacional [25] [26].

The VFTO in transformer terminal is obtained with a specific laboratory test device developed to execute the chop in SF6 under high pressure (600 kPa). The device allows external regulation of the gap in SF6 to obtain the desired chopped waveform. In Figure 7 is shown the test device and in Figure 8 the complete test circuit.

In Figure 9 is shown a chopped wave in SF6 (green curve) compared with the classical chopped wave in air (red curve) with a reduction in the fall time from 900 ns to 250 ns. The measured values are at the terminal of the bushing, however, as the chop happened in a gas enclosure system, the real time of the chop is much earlier than the time reported by the measurement. This means that it will be a significant increase in the frequency of this transient applied to the transformer.

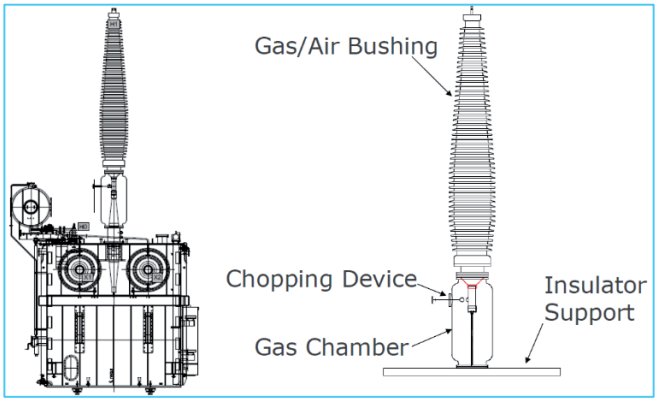

Fig. 7. VFTO test device [19]

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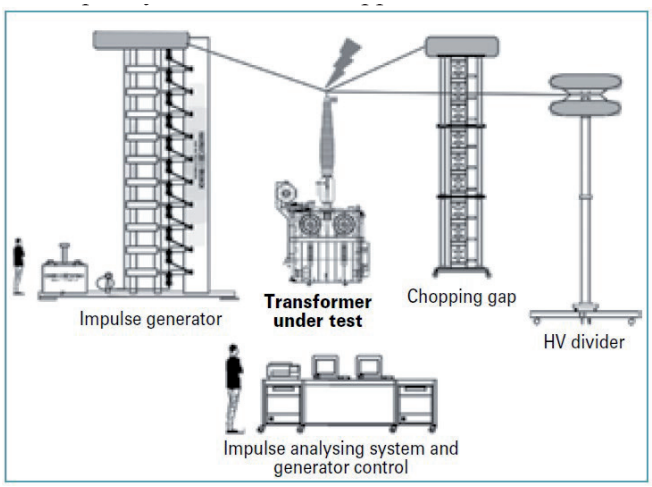

Fig. 8. Transformer prepared for VFTO test [20]

The VFTO test is performed in conjunction with the lightning impulse test, for each terminal of the transformer to be tested, according to the following sequence for a transformer winding with a highest voltage for equipment of 550 kV:

- Lightning impulse before VFTO
  - 1 reduced wave (930 kV)
  - 1 full wave (1550 kV)
  - 1 reduced air chopped wave (1023 kV)
  - 2 full air chopped waves (1705 kV)
  - 2 full waves – (1550 kV)
  - 1 reduced wave – (930 kV)
- VFTO
  - 3 gas chopped waves 900 kV
  - 3 gas chopped waves 1100 kV
  - 3 gas chopped waves 1350 kV
- Lightning impulse after VFTO
  - 1 reduced wave (930 kV)
  - 1 full wave (1550 kV)
  - 1 reduced air chopped wave (1023 kV)
  - 2 full air chopped waves (1705 kV)
  - 2 full waves – (1550 kV)
  - 1 reduced wave – (930 kV)

The test acceptance criteria is the same applied in chapter 13 of IEC 60076-3:2018 [27] for standard lightning tests.

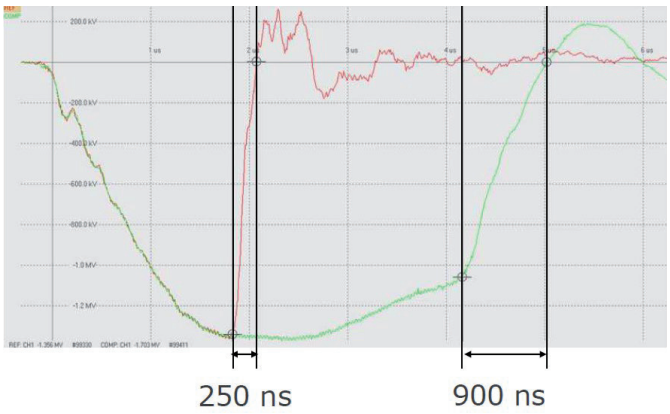

Fig. 9. Comparative of chopped waves in SF6 (green) and in air (red) [19]

The same type of tests were applied by ISA, which operates several electric utilities in South America, in the past ten years in the factory acceptance tests of transformers, autotransformers and shunt reactors intended to operate connected to GIS in 245 kV and 550 kV.

There is much controversy within the industry regarding whether these tests are truly representative of VFTO, and further research is needed to determine if it is possible to develop standardized tests in the future to verify the withstand capability of transformers under VFTO conditions.

IX. Conclusions

Transformers and shunt reactors intended to operate connected to GIS substations, at voltage levels equal to or greater than 245 kV, must be subject to special care at all stages of the procurement process: specification, design and testing.

In the specification stage the customer must clearly define the VFTO that the transformer or reactor will be subjected as consequence of their interaction with the GIS, so that the manufacturer can take them into account in the design of the equipment.

In the design stage, the manufacturer must develop high-frequency models of the transformer or reactor that allow for accurate calculation of how the VFTOs applied to the transformer terminals are distributed inside the windings.

Once the maximum voltages appearing in the most important insulating structures, insulation between turns and insulation between discs are determined, the electric field applied to the insulating materials (paper and oil) is calculated, and it is verified that they can withstand these electric fields with adequate safety margins.

Currently, there are still many questions about how paper and oil behave when subjected to the effects of VFTOs, and this is an area that requires further research.

Finally, research should also be conducted into the development of factory acceptance tests that are representative of VFTOs and that guarantee that if the transformer successfully passes these tests, it will then be able to operate without failure for many years in service subjected to those VFTOs.

These are all challenges facing the CIGRE WG A2/C4/D1.77 working group, which began its activities this year, and with which we hope to contribute to clarifying many of the aspects that are currently under discussion or are simply unknown.

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