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Electrical Transient Interaction Between Transformers and the Power System

Part 1- Expertise

Joint Working Group A2/C4.39

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ELECTRICAL TRANSIENT INTERACTION BETWEEN TRANSFORMERS AND THE POWER SYSTEM – PART 1: EXPERTISE

JWG A2/C4.39

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EXECUTIVE SUMMARY

A number of transformer dielectric failures have been attributed to transient overvoltages, even when good practices for insulation design and insulation coordination have been followed. CIGRE WG A2/C4.39 was formed with the objective to clarify possible reasons for such failures and to recommend remedial actions, in the context of high-frequency transients and insulation design practices.

The principal conclusions of this work are:

- The current factory proof tests contained in the standards do not completely address all types of transient events that occur in the field. The use of the standard lightning impulse wave shape is not appropriate in the case of the fast-front or oscillatory waveforms occurring in actual service conditions with reactor switching, HVDC converters, capacitor banks switching, GIS switching and transformer energization via feeder cable. In addition, these tests are performed with the non-excited terminals grounded which do not adequately take into consideration the voltage transfer between terminals.
- The manufacturing industry and transformer purchasers have assumed that the problems of transient voltage have been adequately addressed by current impulse standards. This is not the case. There are still failures recently reported due transients, and many unknown failures are of dielectric origin and may be related to transient phenomena.
- Other working groups have addressed this problem but it still requires attention.
- For certain network configuration, there is a high probability that system-initiated transients may contain oscillatory voltage wave at the transformer's terminals which coincide with the transformer's natural frequencies. These internal voltages can exceed the insulation withstand capability of the transformer by resonant voltage buildup. Failures may occur even if their amplitude of the impinging overvoltage is much lower than the arrester protection level. As far as the transformer design is concerned, this type of vulnerability cannot be avoided.
- The transformer affects the wave shape of the transient overvoltage at its terminals due to its frequency-dependent impedance. An appropriate model of the transformer should therefore be applied in transient simulations. There are several different approaches and levels of sophistication for obtaining such models. Manufacturers typically create detailed models for studying internal winding stresses based on information about geometry and material properties. Others, due to a lack of this detailed winding information, create terminal equivalents based on measurements at the terminals. Most models are compatible with common circuit simulators.
- For the representation of the adjacent power system in transformer overvoltage studies, the standard simulation tools provide sufficiently accurate models for most situations.
- The standard approach to assess the internal transformer voltages stress is to use analysis tools and design information normally only available to manufacturers. The utility on its side can make an initial evaluation using the so called frequency domain severity factor (FDSF) which is obtained via a time domain simulation with a terminal equivalent transformer model. The FDSF approach can thus be used both for design review upon incoming transients and in analysis of failures. When combined with online monitoring, it can also be used as indicator of increased transient risks for a unit.
- Repetitive transient overvoltages and ageing reduces the insulation withstand capability and must be recognized in the design of the transformer insulation system. The breakdown characteristics of solid materials due to high frequency transients are still not well known and deserve future work.
- Thirteen case studies are presented in “Part 2: Case Studies”, which demonstrate situations where system transients lead to excessive overvoltages in transformers. These studies clearly show the importance of considering not only the peak of these overvoltages but also the frequencies involved. Some of these case studies are related to failures with overvoltage as probable cause.

- A “Fictitious Transformer” was defined to evaluate the performance of the white box models when calculating the internal voltage distribution due to different types of transients applied to its terminals. The simulation results obtained by 11 independent parties (manufacturers, universities, consultants) were in good agreement in the case of the internal voltages maximum values, but some differences were found in the wave form shapes.

- The resonance frequencies are strongly dependent on the values of the inductances (self and mutual) and capacitances that were used to represent the transformer. Some members performed examples using the same values of inductances and capacitances and in that case the internal voltages obtained with the different softwares were identical.

- Manufacturers must improve their models in order to achieve more accurate values for the maximum internal voltages throughout the winding and consequently better responses in the time domain. An improvement in these models requires better methods for calculating the inductances and capacitances that represent the transformer windings.

- Good system operation and design practices may help to prevent transformer failures due to transients, but it is very important that the transformer insulation structure addresses the presence of these transients. This can be achieved by writing a specification that appropriately reflects the unique requirements of a utility system (for example, special test voltage). This requires a close cooperation between the manufacturer and the purchaser. In such cooperation, it is desirable that the manufacturer provides the utility with an appropriate terminal equivalent of the transformer so that transient studies can be performed. An outcome of such studies can also be that the excitation of transformer internal resonances can be detuned by small modifications to the power system.

1 INTRODUCTION

Transformers are constantly exposed to different types of transient events during their daily operation which imposes high stresses on their insulation structure. Field experience has shown that even when good insulation coordination studies and well-accepted insulation design practices are applied, a significant number of transformers suffer dielectric failure as reported in the literature. Such failures may occur due to transient events which are not necessarily related to any system event at the time of its occurrence. The analysis of the failures and their future prevention requires an in depth knowledge of the transient interaction between transformer and the power system.

In this context, another important aspect to consider is the fact that, under the new power system deregulation scenario, the necessity to integrate different agents, such as the transmission system operators, generators and distributors, requires the development of new operation procedures, when compared to the operation procedures previously used. These new system operation conditions in combination with a more extensive usage of transient generating technologies and the trend of keeping the equipment longer in operation create a new electrical environment for transformers with an expected increase of the dielectric stress on their insulation.

Although previous IEEE and CIGRE working groups [1.1, 1.2] have reported important findings on this subject, additional evaluations with a wider scope was found necessary to improve transformer reliability regarding transients [1.3]. The extended scope should include transformer design and testing with consideration to its insulation system high frequency behavior and its modelling for system studies. With this focus, CIGRE JWG A2/C4-39 "Electrical Transient Interaction between Transformers and the Power System" was formed as an additional contribution to this task. This Joint Working Group began its operation in 2008, comprising members representing generation, transmission and distribution utilities, transformer manufacturers, universities and research centers. A significant number of technical contributions were received throughout the work from experts of 20 countries.

This technical brochure presents a summary of the investigation carried out by the group and has been divided into two parts, "Part 1: Expertise" and "Part 2: Case Studies". The "Part 1: Expertise" has nine chapters, dealing with:

- Chapter 2 presents an overview of the work of previous group on this subject, some examples of transformer failures due to transients and the status of the current standards regarding these phenomena.
- Chapter 3 discusses some aspects regarding the network modelling for transient studies.
- Chapter 4 deals with the state of art of transformer modelling covering different approaches such as black box, grey box and white box modelling.
- Chapter 5 covers some theoretical aspects concerning high frequency transformer resonant overvoltages.
- Chapter 6 describes new concepts of analysing the proper electrical stress imposed on the power transformer due to non-standardized impulse.
- Chapter 7 discusses different aspects regarding the impact of transients on transformer insulation.
- Chapter 8 compares different computational tools for transient voltage calculation along the winding of a "Fictitious Transformer".
- Chapter 9 presents general recommendations regarding transformer specification, transient measurement and dielectric tests.

The second part of this brochure, presents case studies carried out covering transformer failure analysis, examples of interaction with circuit-breakers and different modelling application.

The main goal of this document is to provide an update in the study of this broad and complex topic with focus on some relevant aspects, including resonant overvoltages. It should be borne in mind that new approaches and challenges are expected to arise as new technologies are introduced together with different power system scenarios.

It is clear that a good knowledge of the possible transient interactions between the transformer and the power system cannot be reached without a close contact between manufacturer and clients with their respective expertise. Good communication, not only during the transformer procurement process but through its life in operation, is essential in this pursuit.

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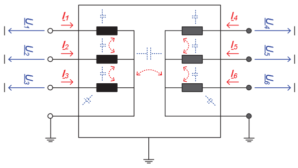
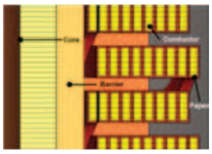
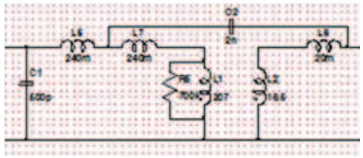
4.5 Comparison Table

	Black Box 	White Box 	Grey Box 
Typical applications	System interactions	System interaction and internal overvoltages	System interactions
Typical Model Bandwidth	up to 2MHz (depends on the measurements quality)	Approximately 20th natural frequencies, that is, up to 500k to 800kHz for large transformers	up to 500kHz
Very Fast Transients, above 2MHz	Difficult to obtain reliable measurements	Possible to be obtained, it depends on how each model element will be represented. The initial part of the winding should be well represented.	
Data Basis	Measurements	Design Geometry	Measurements and Design Data
Model Extraction	Optimization	numerical field analysis methods, analytical methods	Optimization
Model Complexity	Medium / High	High	Small / Medium
Simulation Time	Small	Small / High	Small/High
Integration with EMTP type software	Yes (RLC model or Convolution)	Yes	Yes, for linear representations

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6.3 Time Domain Severity Factor

6.3.1 Introduction

Reliability of power transmission depends on reliable operation of transformers insulation systems. Therefore, the impulse test is required to verify the correctness of the winding insulation design and manufacturing process.

It is possible to determine the transfer function either by using time or frequency domain measurements. Classically, from time domain analysis the voltage values along each winding are possibly evaluated for a particular input transient voltage. Thus, the voltage drop between facing turns and turns and ground are calculated at each step time in order to verify that the maximum dielectric strength value is lower than the permissible dielectric strength value of each material for its dielectric breakdown.

Therefore, the visualization in time domain of the electric field intensity distribution within the transformer insulation structure makes design decisions easier.

Previous work already consider the evaluation of the overvoltages in transformer associated to switching transients by coefficients, such as the frequency domain severity factor (FDSF). But this factor, as a global coefficient, could not assess the severity along windings to localize dielectrically weak points. To overcome this limitation an alternative coefficient was proposed and was identified as time domain severity factor (TDSF) in the Alvarez-Mariño´s paper [6.19]. The aim TDSF is to assess the severity supported along transformer windings when the transformer is subjected to a transient voltage waveform from the power system.

Since each transient waveform depends on the electrical interaction between transformer and the power system, it implies that each of those combinations is characterized by a TDSF. To obtain the TDSF implies the use of two different models of the transformer under consideration. First, a terminal model (black box model) of the transformer is built to compute the transient voltage waveform at the transformer terminals during the transient event that occurred in the power system where the transformer is connected [6.20]. Then, a detailed model (white box model) of the transformer is used to compute the internal transient voltage distribution along transformer windings.

6.3.2 Time Domain Severity Factor Computation

The TDSF coefficient assesses the severity in terms of overvoltage due to the internal transient response along transformer windings induced by the transients coming from the power system, compared to the internal transient response due to standard dielectric tests in the time domain. The expression of this coefficient is [6.19]:

$$TDSF(t) = \frac{\Delta V_{\max sw}(t)}{\Delta V_{\text{envelope}}(t)} \quad (6.2)$$

where ΔV_{max_sw} is the maximum voltage drop between disks along of the windings, or turn to turn, due to the transient event occurred in the power system (switching operation of VCB, for example) and $\Delta V_{envelope}$ is the maximum voltage drop between disks along windings for all standard dielectric tests (envelope waveform of standard tests).

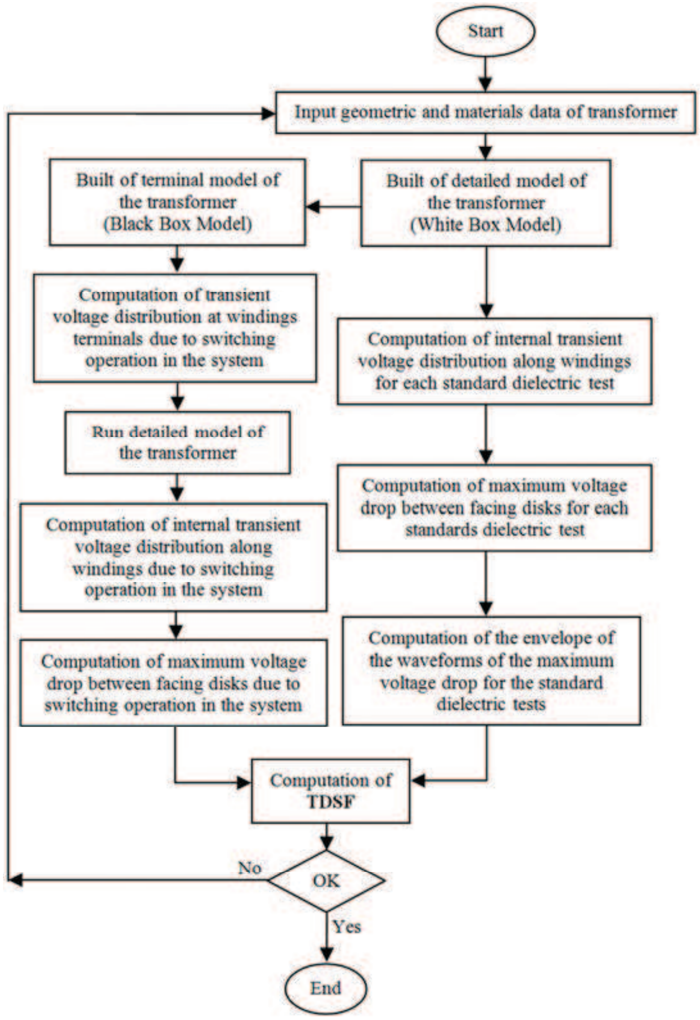

Figure 6.3: Flowchart to compute the TDSFs according to Alvarez-Mariño´s paper [6.19].

In Figure 6.3, the flowchart for TDSF computation is shown. First, the building of a transformer detailed model from the transformer geometry and material data is carried out [6.20].

The detailed model allows the internal transient voltage distribution along transformer windings for each standard dielectric test to be obtained. Once the transient voltage distribution is available, the maximum voltage differential distribution between facing disks of each winding and the envelope of the waveforms of the maximum voltage drop of all standard dielectric tests are available [6.3,6.15,6.20].

With the detailed model available: the terminal model can be constructed, which can be used with a power system model in EMTP to obtain the transient waveforms at transformer terminals. With the waveform at the transformer terminal available the internal transient voltage distribution within the transformer winding can be computed. Once the transient voltage distribution is available, the maximum voltage drop distribution between facing disks of each winding is evaluated [6.20].

Finally, the maximum voltage drop during the transient operation is compared to the maximum voltage drop during all standard dielectric tests along each winding, checking the TDSF [6.19]. If the computed values of TDSF along windings are lower than the unit, the transformer insulation system is well designed for that particular transient event occurred in the power system and supported by the transformer. Otherwise, the transformer insulation system might not be suitable to be used into the power system and must be modified.

An application example illustrating how TDSF can be applied is shown in Chapter 8.

6.6 References

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From comparative results in Appendix A.7 to A.10, it can be concluded:

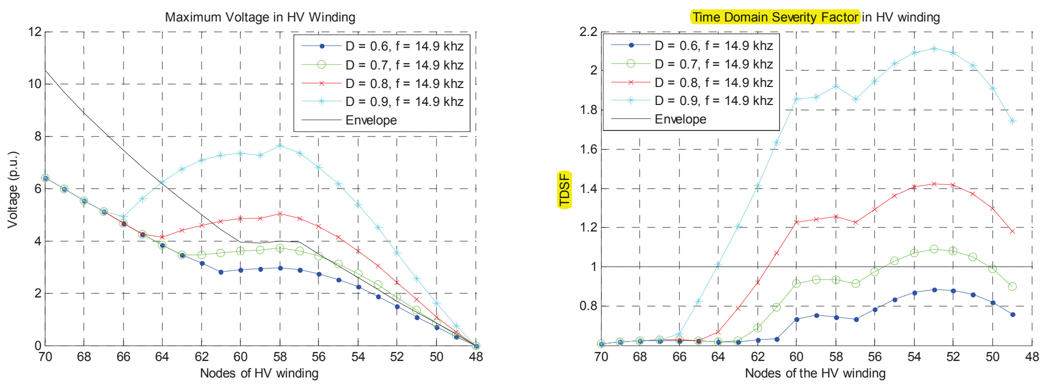
- There are differences in the calculated first resonance frequency of the transformer with the different softwares (Between 8 kHz to 15 kHz). As consequence it can be seen differences in the temporal wave shapes (similar wave forms with phase differences as consequence of different frequencies).
- Similar tendencies in all softwares temporal responses relating to maximum voltage values (with and without taking into account the damping effects inside the transformer).
- The transformer damping effects, when taking into account, give similar amplitude results for all tested softwares.
- The transformer damping effects are very important in the amplitude values of the resultant waves. Its influence increase when the damping factor D of the oscillatory wave shape increase. For $D = 0.6$ the amplitude reduction due to transformer damping effects is around 38% and for $D = 0.9$ the amplitude reduction due to transformer damping effects is around 66%.

8.6 Time Domain and Frequency Domain Severity Factors

For Variants FT5, FT6, FT7 and FT8 the Time Domain Severity Factor (TDSF) and the Frequency Domain Severity Factor (FDSF) for the "Fictitious Transformer" are calculated when an oscillatory wave shape with a frequency of 14.91 kHz is applied in the high voltage terminal H1 (Node 70).

The wave shapes in the center of the lower part of the high voltage winding (Node 60) when the oscillatory wave shape is applied to H1 terminal (Node 70) are showed in Appendix A.7, A.8, A.9 and A.10, in the curves labeled with F (transformer model taking into account internal damping effects).

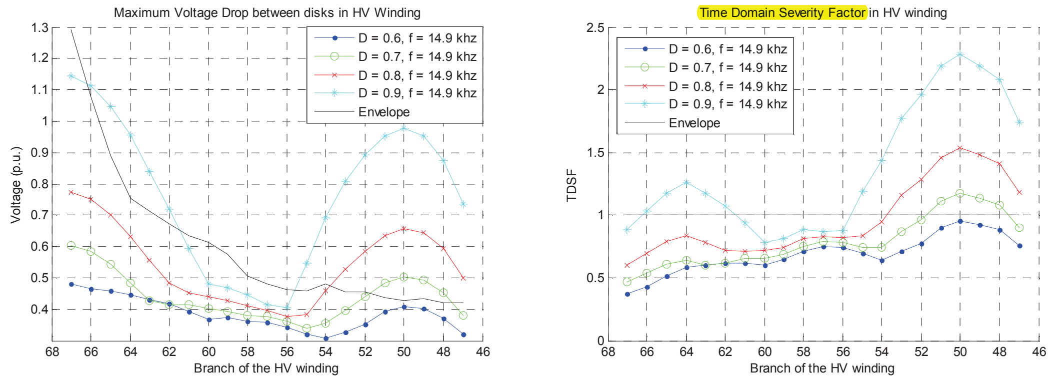
The maximum voltages to ground and the TDSF of the HV winding nodes for the different damped oscillatory waves are shown in the Figure 8.20.



(a) (b)

Figure 8.20 a) Maximum voltage to ground of the HV winding nodes for different damped oscillatory waves. b) TDSF of the HV winding nodes for different damped oscillatory waves.

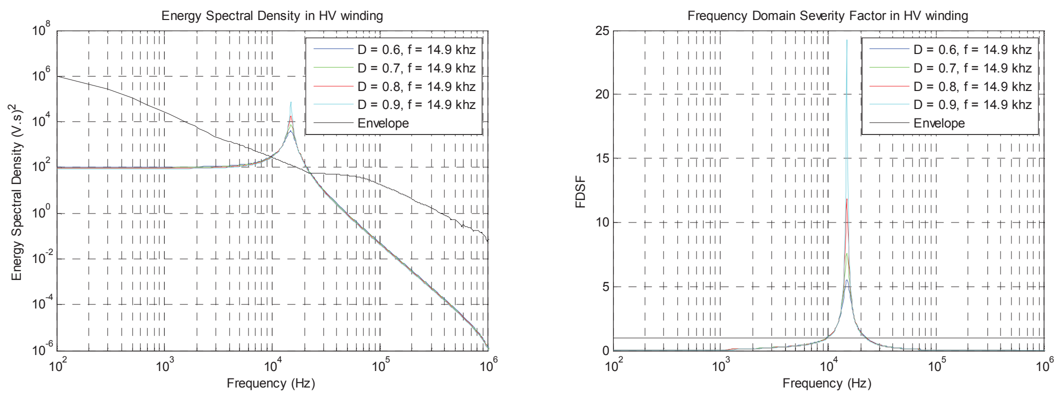
The maximum branches voltages of the HV winding and the corresponding TDSF for the different damped oscillatory waves are shown in Figure 8.21.



(a) **(b)**

Figure 8.21 a) Maximum voltage drop between HV winding discs for different damped oscillatory waves. b) TDSF between HV winding discs for different damped oscillatory waves.

Figure 8.22 presents the energy spectral density and the FDSF for different the damped oscillatory waves.



(a) **(b)**

Figure 8.22 a) Energy spectral density of the different damped oscillatory waves. b) FDSF of the different damped oscillatory waves.

Only for the Variant FT5 with $D = 0.6$ the TDSF is less than one for all the nodes and branches. For the other cases, with lower damping factors, it can be found nodes and branches with TDSF higher than one. In particular for the Variant FT8 with $D = 0.9$ most of the nodes and branches present TDSF higher than one.

This confirm that there is a high fault probability when oscillatory wave shapes with frequency equal to one of the resonance frequencies of the transformer are applied.

In the frequency domain all the waves present values higher than the reference envelope (impulse test). This shows that the FDSF is more conservative than TDSF.

8.7 Conclusions

From the analysis of calculations results from section 8.5, for lightning impulse wave and damped oscillatory waves, the principal conclusions are:

- Good agreement in maximum voltage values for nodes and branches

  This result validated these calculation tools for safety dielectric transformer design regarding to internal insulation distances inside and outside the windings.

- Differences in natural frequencies with the consequence of poor agreement in temporal responses. Different transient simulation programs will lead to a different internal oscillating behavior of the winding. For that reason the simulated admittance matrix might not match exactly the measured admittance matrix.

- The resonance frequencies are strongly dependent on the values of the inductances (self and mutual) and capacitances that were used to represent the transformer.

  Some members performed examples using the same values of inductances and capacitances and in that case the internal voltages obtained with the different softwares were identical.

- All compared softwares use lumped parameters to model the transformer. For the usual modelling practice for windings using one branch for each two disc the validity frequency range go up to approximately 500 kHz.

  Degeneff [8.1] states the rule to know the validity frequency range of a lumped parameters model: "*In a valid model, the highest frequency of interest would have a period at least ten times larger than the travel time of the largest winding segment in the model*".

- To modelling for higher frequencies using lumped parameters models is necessary divide the windings turn by turn and the behavior of leads, bushings, tank wall, shield, should be considered detailed too.

- For Very Fast Transient Overvoltages the transformer is modelled using transmission lines (distributed parameters models). Marjan Popov [8.2] uses a hybrid model which is a combination of the multiconductor transmission line model (MTLM) and the single-transmission line model (STLM).

- These different oscillating behavior of the models leads to the fact that the simulation of the transient interaction between transformer and power grid might have a reduced accuracy especially for high frequencies (higher than 1 MHz) if usual calculation models are not improved.

- This study proof that the tools used by manufacturers are good for transformer dielectric design but are not capable for accurate determination of the natural or resonance frequencies of the transformers. In every case that an internal resonance problems in the network-transformer interaction should occurs is necessary the determination of resonance frequencies by measurement.

- Manufacturers must try to improve their models with the objective not only to obtain good approximations for the maximum values of internal voltages but also obtain better temporal responses. For this, is essential an improvement in the used methods for calculating inductances and capacitances that represent the transformer.

8.8 References

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