Electrical Transient Interaction between Transformers and the Power System

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Introduction

Transformers are constantly exposed to different types of transient events during their daily operation, which often imposes high stresses on their insulation structure. Field experience has shown that even when good insulation coordination studies and well-known insulation design practices are applied, a significant number of transformers suffer dielectric failures. Such failures may be caused by previous transient events, which are not necessarily related to any system condition at the time of the failure. The analysis of the failures and their prevention requires a thorough knowledge of the transient interaction between the 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 entities, such as the transmission system operators, generators and distributors, requires the development of new operation procedures. These new system operation conditions, when combined 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, which increases the dielectric stress on their insulation.

Although previous IEEE and CIGRE working groups have reported important findings on this subject, additional examination with a wider scope was found necessary in an effort to improve transformer reliability regarding transients. With this focus, Cigre JWG A2/C4-39 "Electrical Transient Interaction between Transformers and the Power System" was created with the goal of furthering the industries understanding of this problem. It should be borne in mind that new approaches and challenges in this field are expected to arise as new technologies are introduced together with different power system scenarios.

Also, a thorough knowledge of the transient interactions between the transformer and the power system cannot be reached without a close working relationship between manufacturer and clients with their respective expertise.

The investigation carried out by the group is presented in a technical brochure which has been divided into two parts, "Part 1: Expertise" and "Part 2: Case Studies". The following Sections II to IX summarize the chapters of the Technical Brochure, Part 1. Section X gives an overview of the Technical Brochure, Part 2.

Standards and Service Experience

From its earliest development, the improvement of power grid reliability has been a constant goal of engineers. This focus has not only been on improving the reliability of operation but more specifically the improvement of the reliability of components. A power transformer is one of the most strategic and costly piece of equipment in the power system, requiring a high level of reliability and availability. As such, transient overvoltages have long been recognized as one of the important causes of equipment failure and thus, unavailability.

This chapter addresses how users, manufacturers and the standards have dealt with high frequency transient overvoltages in transformers. Additionally, several examples •••

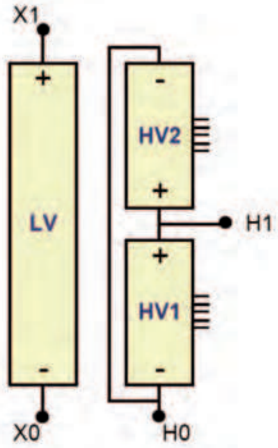

Figure 4 – Fictitious transformer geometry

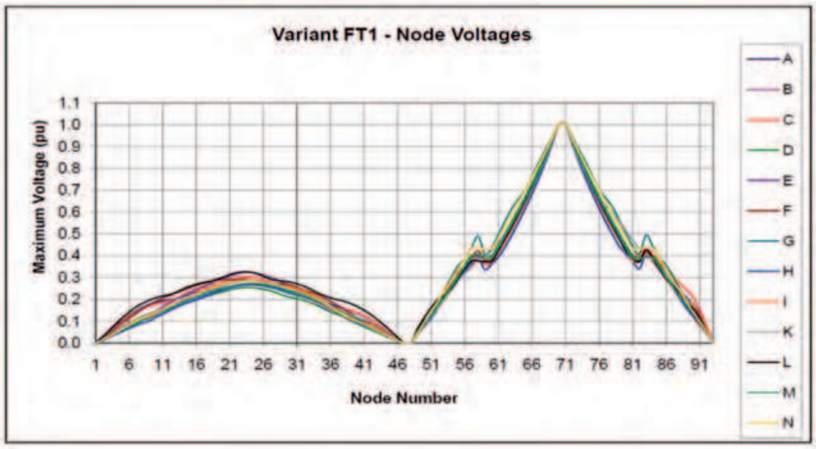

Figure 5 – Distribution of internal transient voltages

of failures in service are provided. Figures 1, 2 and 3 illustrate some of these type of failures.

A short summary of the contributions of previous CIGRE and IEEE Working Groups, relating to transient interactions between power transformers and the power Grid, is also presented.

Electrical Network Transient Modelling

Proper modelling of the network is an important issue, since it will have a major effect on surges entering the transformers. The modelling of the different equipment at high frequencies is described for lines, cables, substations, circuit breakers, disconnectors, and surge arresters. The case of switching surges due to faults, lightning surges and very high frequency phenomena due disconnectors switching is addressed, with a special focus on reignition phenomena in circuit breakers.

Transformer Modelling

This chapter gives an overview of the main procedures for building wide-band models of transformers for high frequency transient studies. It is also discusses the importance of the application of a model in accordance to the type of transient interaction being considered. Thus, if the principal interest is just the interaction of the transformer with other system component, e.g., in some study of circuit breaker transient recovery voltage, a terminal model could be enough. However, if the goal is the determination of transient voltages within the transformer, a more detailed model has to be implemented. Therefore, this chapter is divided into five main sections, covering what is available in the literature on this important subject.

Network Interaction With Transformer

All transformers have internal resonances in the range of a few kHz to hundreds of kHz. Any system transient that includes frequency components in this range can potentially provoke resonant overvoltages in a transformer, even when the overvoltage impinging the transformer terminals is lower than the protective level of surge arresters. Typical situations include circuit breaker closing and opening operations, disconnector operations, and fault initiation. The actual network layout, lengths of transmission lines and cable sections are major factors which affect the impinging •••

voltage wave shape and its dominant frequency components. Transformers experiencing frequent switching operations are more likely to fail from resonant overvoltages, due to the stochastic nature of switching operations, breakers' location and characteristics.

Assessment of Transformer Voltage Stress

Different methodologies to evaluate the voltage stress on transformers due to transient overvoltages are discussed in this chapter. The first one is the conventional approach used by the manufacturer. This involves the conversion of the transient overvoltage to a corresponding lightning impulse stress followed by a comparison with the acceptance test level.

The second method considers a time-based model where the transient voltage at each position of the winding is compared to the transient of the acceptance test, thus comparing the in-coming voltage stress to the one the transformer is tested for. The ratio, named Time Domain Severity Factor (TDSF), used in the evaluation is presented below:

$$TDSF(t) = \Delta V_{max\ sw}(t) \qquad \Delta V_{enveloppe}(t)$$

In the third methodology, similar to the second, the transient is also compared to the acceptance test, but now in the frequency domain. All spectra of the incoming transients Fast Fourier Transform (FFT) are evaluated against the spectrum amplitude of the acceptance tests. The ratio, named Frequency Domain Severity Factor (FDSF), used in the evaluation is:

$$FDSF(jw) = \frac{[X(jw)transient]^2}{[Xe(jw)]^2}$$

Impact on Transformer Insulation

This chapter presents an overview of many aspects involving the design of transformer insulation structure. It also describes some important effects imposed on the transformer insulation during its operational life in the electric system that may affect its properties and result in a decrease in its dielectric strength.

The effects of insulation aging are presented based on the degradation of insulating oil and paper based on field-aged transformers. Even though the degradation degree is small, the breakdown voltages of insulating oil and paper do decrease due to aging. Therefore, for highly aged transformers or transformers, which are exposed to overvoltages frequently, consideration must be given to age-related degradation of the insulation performance.

Another important topic addressed in this chapter is the effect of repetitive impulses on the decrease of insulation strength. For transformers installed in a system that has switches, which operate frequently, a decrease in the dielectric strength due to repetitive voltage stresses is to be expected.

Finally, it is emphasized that a full understanding of how rapidly rising voltages affects insulation system is still a challenge and deserves future investigation. Some work in the literature have shown an important influence of the wave shape on the voltage breakdown, and a possible decrease of the withstand due to shorter rise times. A better understanding of this effect will, most assuredly, provide an improvement to the design of the insulation system when exposed to fast transients.

Transient Simulation Software Benchmarking - Fictitious Transformer

In this chapter, the geometry of a transformer, 100 MVA, 230/69 kV, showed in Figure 4, is defined and used to test different transformer "white-box" mathematical models designed to compute the distribution of internal transient voltages. The results of the modeling using various programs are reported (for example, see Figure 5). This provides valuable information to the transformer industry about the state-of-the-art of the computing of voltage transients inside transformers.

Recommendations

General recommendations are presented in the last chapter. Some of the recommendations are:

. Transformer specifications should reflect the unique requirements caused by the power system, especially in critical configurations. ...

Topic	Sub Topic	1	2	3	4	5	6	7	8	9	10	11	12	13
Case study number		Cable-transformer high-frequency interaction and transformer overvoltages on a generator step-up transformer	High-frequency interaction between a wind turbine transformer and the power system	Laboratory tests on the interaction between a wind power transformer, cables, and a vacuum circuit breaker	Failure Analysis of two step-up transformers at Tres Marias Hydroelectric Power Plant	Analysis of dry-type transformer failure caused by SF6 switching operation	Analysis of dry-type transformer failure caused by VCB switching operation	The effect of the connecting cable on the transformer transients	Input hydro-electric plant, comparison between black-box and grey-box modeling approaches	400kV transformer failure case caused by resonance overvoltage due to lightning surge intrusion from a transmission line	Distribution transformer failure caused by lightning backflashover and resonant voltage buildup	500/77.5kV transformer failure caused by resonance overvoltage due to the closing surge of the breaker in a cable-system substation—Combined phenomena of switching and transferred overvoltages	High-frequency modeling of a 500 kV transformer—Detailed models vs. simplified model	Frequency Dependent Transformer model for switching simulations by using FRA and transient measurements
Origin of overvoltage	Circuit breaker	x	x	x		x	x	x						x
	Disconnector				x				x					x
	Lightning									x	x	x	x	
	Fault initiation	x	x			x	x							
Model Type	Black box	x	x		x				x					x
	White box				x	x	x	x		x	x	x	x	
	Grey box								x					
	Simplified model		x	x	x				x			x	x	x
Field measurement(s)			x	x			x	x						x
Simulation(s)		x	x	x	x	x	x	x	x	x	x	x	x	x
Insulation stress assessment	FDSF	x	x	x	x	x	x	x						x
	Internal stresses				x	x	x	x	x	x	x	x		
	BIL or SIL v.s peak voltage	x	x	x				x				x		x

Table 1 - Case studies summary.

. It is highly desirable that the manufacturer provides the utility with an appropriate high frequency model of the transformer to allow for system transient studies.

. The importance of close cooperation between the manufacturer and purchaser cannot be underestimated. The technical specification is the most important means of this communication and joint analysis can be carried out in the design stage and verified in the design review.

. Some specific evaluation (transient measurement, system studies, etc.) should be carried out as part of transformer failure analysis when transients may be involved. Many failures are considered unknown due to the lack of this type of evaluations which may be complex and time consuming.

Case Studies

The second part of this brochure presents 13 case studies covering transformer failure analysis, examples of interaction with circuit breakers and different modelling application. Table 1 presents an overview of the case studies and their main focus.

It is hoped that the technical brochure fulfills its intention to provide clients and manufacturers with an update in the study of this wide and complex topic in order to improve transformer reliability due to transients. ■