Frequency Domain Severity Factor (FDSF) - Transient Voltage Performance - Transformer Outside/Inside

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Abstract — **This paper presents a study of the response of the transformer in the frequency domain under switching operation. The applied methodology allows to simulate the behavior of the internal stress along windings and also to check whether the insulation system of transformer designed from standard dielectric tests withstands the level of voltage under transient phenomenons. The study is based on the calculation of Frequency Domain Severity Factor in transformer windings. To perform this calculation, a detailed model based on RLCG lumped parameters frequency-dependent and modal analysis are applied to obtain the solution in frequency domain.**

Keywords **— Dielectric tests, Strengh field, Insulation system, Frequency domain severity factor, Energy spectral density, Switching operation.**

I. INTRODUCTION

The electrical power transformer must be configured to withstand very fast electromagnetic transient covered in the design specification of standard dielectric test and realistically expected in service. Such constraint has great impact on other design issues, and effect on the overall transformer cost, performance and configuration.

Transformers can be subjected to overvoltages in a wide range of frequencies according to standards tests. However, a series of complex voltage transients due to circuit breaker contact re-ignitions can reach the transformer, inducing resonance in its windings with the risk of destructive voltage excursions [1]. This is due to some oscillatory excitations, which even being of low amplitude, may occur in frequencies that may excite a part winding resonance resulting in a local amplification [2]. A high number of failures in the insulation system of power transformers are caused by the overvoltages of switching operations, while all those transformers passed all the standard tests [3].

Therefore, it is necessary that both utilities and manufacturers earn a better knowledge about the dielectric stresses on the transformer as a result of the interaction with the electric power system with which is connected. It motivated the formation of a Cigre Joint Working Group JWG A2/C4.39 called “Electrical Transient Interaction between Transformers and the Power System”. The group’s main goal is to acquire a better knowledge of this phenomenon, discuss new actions to prevent failures and thus contribute to the improvement of system reliability.

In the heart of JWG A2/C4.39 a new parameter was devised to measure the ratio of spectral density of the voltage *Vs* calculated from the transient analysis to the *Vs* associated with the standard impulse test waves. Such transient system events on transformers will be assessed introducing the Frequency Domain Severity Factor (FDSF) [4]. That factor is proportional to the energy of the voltage frequency components which helps to detect those transient voltage frequencies higher than the standard dielectric strength.

In this paper a study in frequency domain to analyze the internal response severity of the transformer subjected to a switching voltage transient is presented. The concept of FDSF was applied to evaluate the associated energy to each voltage component frequency which appears outside/inside the transformer during transient phenomena. In order to study the internal response of the transformer subjected to overvoltages associated to switching transients a proper detailed RLGC lumped parameter frequency-dependent has to be used [5].

II. TRANSFORMER MODEL

For the simulation of transient overvoltages in transformers with *W* windings the Maxwell's equations for transverse electromagnetic waves on lossy transmission lines can be applied [6]. Such *W* windings can be discretized into blocks, which are represented by means of equivalent π-circuits with frequency-dependent lumped parameters [5].

The proposed model consists in dividing the *W* windings of the transformer into elementary lumped blocks. They become lumped parameter circuits incorporating mutual coupling between RLGC parameters. Each block is formed by one coil-turn or combining several turns.

Lossy parameters RLCG are calculated from the geometric dimensions and physical properties of the materials [6]. Inter-turn series capacitances C_S and earth capacitances C_g of the turn facing the core, tank and yoke are included to model the electric coupling between turns of each winding [7]. Also, shunt capacitances C_p between facing windings are introduced to simulate the electric coupling between the windings.

Concerning the magnetic coupling, the self inductance of each turn is calculated using it as a circular wire with a rectangular cross-section, and for mutual inductance between turns the Lyle's method is applied [6]. The mutual inductance between turns of different windings has also been considered for taking into account inductive coupling between windings.

As it is well known, losses play an important role in an accurate simulation of the voltage distribution. Therefore, frequency dependent copper losses (skin and proximity effect) and dielectric losses are included [8].

Once all RCLG parameters are calculated, each block is represented by an equivalent π-transmission line. Finally, the LPM can be built and the waveform of transient voltage due to operation can be applied at the terminal of the transformer winding. Numerical Fourier transform and modal analysis are used to obtain the solution in the frequency domain [9].

III. FREQUENCY DOMAIN ANALYSIS AND FDSF

In order to verify the frequency range that is taken into account in the standard dielectric tests, an analysis of their frequency spectrum was performed and afterwards compared with the frequency spectrum of the switching simulated curve. The frequency spectrum of the standard full lightning impulse and chopped waves, represented as double exponential wave shapes, were calculated with their corresponding crest levels according to the BIL specifications of each transformer [10].

In the frequency range of standard dielectric tests, some important transient overvoltages may will not be represented and will not be considered during the design. This fact may explain some transformer failure [2]. A comparison between the spectrum frequency of the simulated overvoltage and the standard wave shapes of dielectric tests is obtained to check whether the voltage level determined by the switching case is into the safety margin covered in the standard tests [3].

Taking into account that the standard energy associated with a wave signal *f(t)* is defined by,

$$E = \int_{-\infty}^{\infty} f^2(t)\ dt \tag{1}$$

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Applying Parseval's theorem,

$$E = \int_{-\infty}^{\infty} f^2(t)\ dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left|F(\omega)\right|^2 d\omega \qquad (2)$$

The energy spectral density (ESD) of the wave *f(t)* within the frequency spectrum is defined as the square of the magnitude of the Fourier transform of the signal,

$$\left|F(\omega)\right|^2 = F(\omega)\cdot F^*(\omega) = \left|\int_{-\infty}^{\infty} f\ \ (t)\ e^{-j\omega t} dt\right|^2 \qquad (3)$$

where ω is the angular frequency, $F(\omega)$ is the Fourier transform of $f(t)$ and $F^*(\omega)$ is its complex conjugate. For voltage signals, ESD is expressed in V^2sHz^{-1} or $(Vs)^2$. The energy spectral density of a signal represents the energy per unit frequency and shows the relative amount of energy of the different components of frequency. The energy spectral density describes how the energy of a wave is distributed along frequency.

The Cigre JWG A2/C4.39 has used the parameter called Frequency Domain Severity Factor (FDSF). This parameter is defined as the ratio of the energy spectral density calculated from the transient analysis to the energy spectral density associated with the standard impulse test waves. To make sure that the switching transients will be represented by the standard impulse waves, the FDSF should be lower than unit considering the maximum values of these standard impulse test waves for each frequency. These values give rise to an envelope curve, which represents the limit to be considered in the transient phenomenon [3].

The determination of the FDSF depends on the studied transient phenomenon and the point at which analysis is performed. Therefore the calculation of the FDSF in points along winding is needed to make sure that standard dielectric tests take into account the associated overvoltages from the studied transient phenomenon. In this paper, the FDSF is calculated in the internal nodes of HV winding during the switching operation.

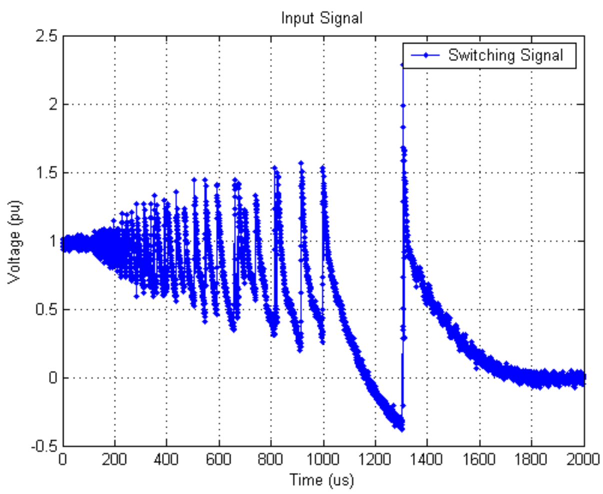

Figure 1. Transient voltage applied in the terminal HV winding during the opening of the switching operation according to ping test [1].

IV. APPLICATION AND RESULTS

The proposed study was applied to a theoretical design of a transformer. Figure 1 shows the waveform of the transient voltage that is applied in the HV winding terminal to study the response of the transformer when a switching operation according to ping test is carried out [1]. Figure 2 shows the frequency spectrum of standard full lightning impulse and chopped wave considering different time to chopping from 2 µs to 6 µs and the envelope of all curves.

The comparison of the ESD of the envelope curve from the dielectric tests with the ESD of the transient voltage applied to the transformer due to the disconnection switching operation is shown in Fig. 3. Figure 4 shows the comparison of the FDSF of the transient voltage in the HV winding terminal with the FDSF of the dielectric tests wave envelope, outside transformer terminals.

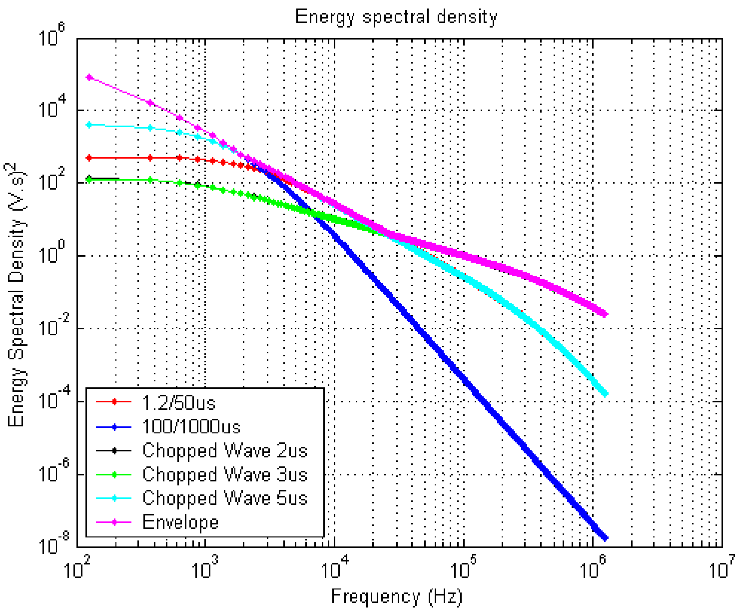

Figure 2. Energy spectral density (ESD) of the standard impulse test waves and the envelope of all curves.

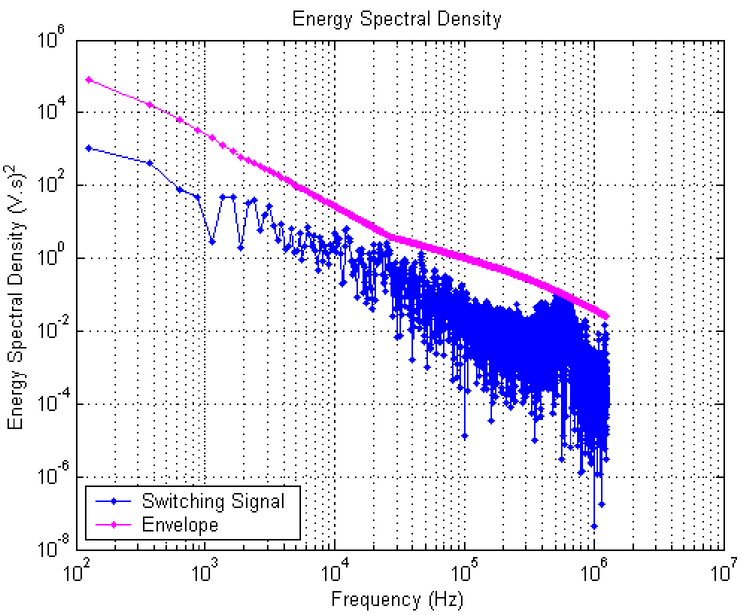

Figure 3. Comparison of the energy spectral density (ESD) of the transient voltage applied to the transformer with the energy spectral density of the standard impulse wave envelope.

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Figure 5 shows the comparison of the FDSF of internal transient voltage along all nodes of the HV winding with the FDSF of the dielectric tests wave envelope.

According to Fig. 3 and Fig. 4, the transformer is able to withstand transient voltage generated by the switching operation. However, Fig. 5 shows that one or more frequencies of the applied voltage coincide with some transformer internal resonance. This frequency is about 100 kHz and the resulting voltage amplification, in internal (inside transformer) points is bigger than the standard dielectric strength (values bigger than unit).

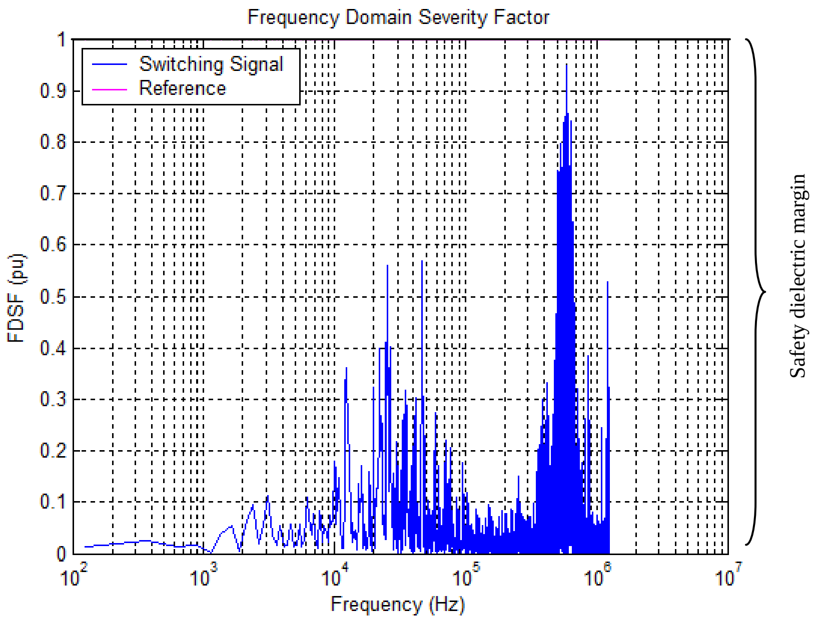

Figure 4. FDSF of the switching voltage in the HV winding terminal compared with the FDSF of the dielectric tests wave envelope **outside** transformer.

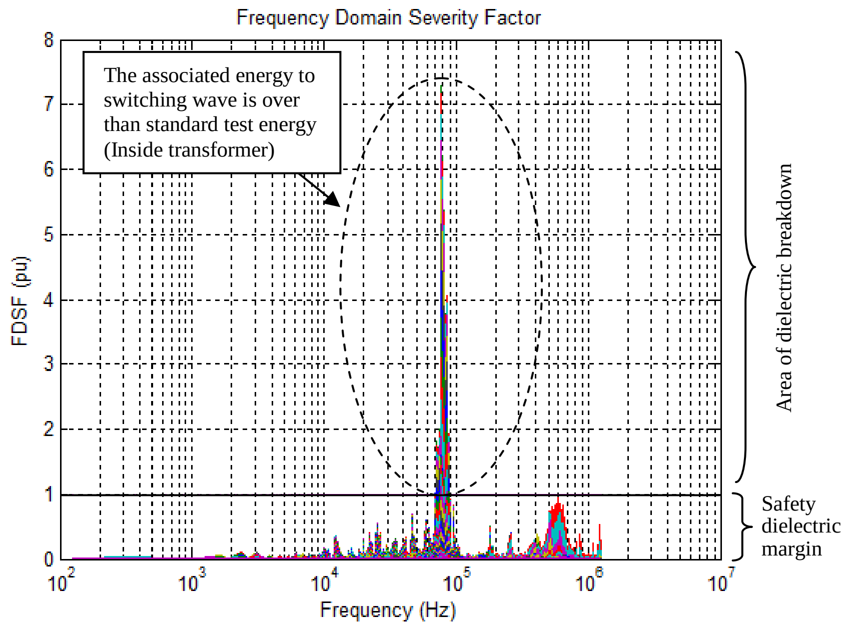

Figure 5. FDSF of internal switching voltage along all nodes of the HV winding compared with the FDSF of the dielectric tests wave envelope **inside** transformer.

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V. CONCLUSION

Transformers are well designed to withstand all dielectric tests up to the limit of the standards wave envelope. Failures in the insulation system of power transformers are produced when one or more frequencies of the applied voltage coincide with some transformer internal resonance. In this case the resulting voltage amplification in this internal point may lead to the transformer failure. Therefore, this paper shows that the information given by the FDSF can help to evaluate the severity of voltage supported by the transformer during transient performance. Moreover, the study here highlights how the risk of destructive voltage excursion during switching operation is different depending on if it is assessed outside or inside the transformer in general.

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