Insulation Coordination for Lightning Transients Based on Energy Spectral Density

J. L. Reis, J. G. Rolim, A. B. Fernandes

***Abstract*-- Traditionally insulation coordination studies are based on classic methods such as probabilistic methods for self-restoring insulation and deterministic methods for non-self-restoring insulation. The tests applied by manufacturers in order to evaluate the insulation strength are classified into two groups: basic switching level (BSL) and basic impulse level (BIL). In this work, the main subject is overvoltage on transformers caused by lightning, consequently only the BIL value is analyzed. Probabilistic methods are based on the statistical approach of the lightning. After the incoming surges generated by lightning reach the surge arresters in a substation, they suffer a decrease in amplitude and travel toward transformers. The value of overvoltage (stress) at the terminal of the transformer is compared with its insulation dielectric strength in order to guarantee that the BIL value is higher than the stress. However, in the overvoltage signal there are various components in different frequencies, each one with distinct energy. The main objective in this work is to analyze the transformer insulation from the viewpoint of the energy spectral density of the signal. Power transformers have a frequency response characterized by multiple resonance points. This behavior is considered in the method described in this paper and simulations applied to the model of a real system are used to present an example of application.**

***Keywords*: Insulation Coordination, Fast Front Transients, Spectral Density, Digital Simulation, Transformer Modeling, Vector Fitting.**

I. INTRODUCTION

Classical methods for insulation coordination of non-self-restoring insulation, such as the transformer, are based on a deterministic approach. This approach compares overvoltage stress with insulation strength. The Basic Impulse Level (BIL) of the transformer insulation is specified according to the transformer voltage rating and to the maximum overvoltage that may occur. This work proposes a more accurate analysis, which considers the energy spectral density of the overvoltage signal and the frequency response of the transformer, especially its internal resonance points. This work shows that a simple evaluation of overvoltage amplitude could be not enough to define the transformer insulation safety margins.

In section II the classical theory of insulation coordination and the main concepts of energy spectral density are reviewed. In section III the modeling of a real system used for an example of application of the proposed approach is described. The simulations of some real cases are presented in section IV and the conclusions in section V.

II. CLASSICAL INSULATION COORDINATION AND ENERGY SPECTRAL DENSITY

In studies of lightning overvoltage, it is necessary to estimate the highest stress that may occur on the terminals of apparatus. Firstly, surges are simulated directly on the transmission line conductors (shielding failure) and on its shield wire. Frequently, the highest overvoltages are due backflashovers (flashover due to lightning striking towers or shield wires) [1]. When this happens, the insulator strings gaps are broken and the surge travels toward de substation.

The overvoltage level is influenced by atmospheric conditions, by the instant of impact of the surge (on transmission line) on the voltage wave, the tower footing impedance, among other aspects. These uncertainties lead to the statistical representation of overvoltages with medium value and standard deviation according to Gaussian distribution. The behavior of insulation is similar, but dependent of other factors like, time of crest, time of tail, type of tower, etc.. One convolution between stress (overvoltage) and strength (insulation) is necessary. This convolution is shown in Fig 1. The risk of failure R can be expressed by (1) [2]:

$$R = \int_0^\infty f(V_a)G(V_w)dV \quad (1)$$

Where $f(V_a)$ and $G(V_w)$ are the probability distribution function of stresses and the probability density function of strengths, respectively. This method of calculating the risk of failure is called statistical approach of insulation coordination.

When the risk of failure is zero, the shaded area in Fig. 1 does not exist and the method is called deterministic insulation coordination, usually applied to non-self-restoring insulations like that of transformers.

When a deterministic method is applied, usually the maximum overvoltage should not exceed 0.85 BIL of the transformer. This margin of safety (15%) is important because when the insulation gets old, its properties suffer degradation.

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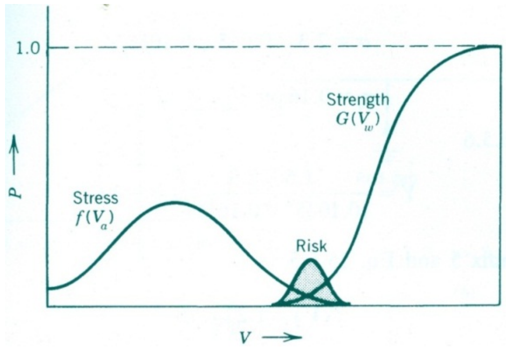

Fig. 1. Risk of failure (shaded area, much enlarged) by convoluting stress and strength data. Source: Reference [2].

The study of insulation coordination based on energy spectral density (ESD) uses the Parseval identity theory, well-known in signal processing.

The spectrum of frequencies $F(\omega)$, of a temporal signal, $f(t)$ is obtained by the application of the Fourier Transform,

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \quad (2)$$

Through the application of Fourier Transform (FT), a continuous signal is represented by a sum of complex exponentials. The inverse transform shown in (3) allows recovering the temporal signal from its FT.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{j\omega t} d\omega \quad (3)$$

According to the Parseval's identity theory (4), the energy of the temporal signal $f(t)$ may also be obtained from the energy of its frequency components:

$$E = \int_{-\infty}^{\infty} f^2(t) dt = \int_{-\infty}^{\infty} |F(\omega)|^2 d\omega \quad (4)$$

Where $|F(\omega)|^2$ represents the module of ESD, in $[(V.s)^2]$.

The next subsections will show the ESD for standard tests on transformers and the frequency domain severity factor, which will be one parameter to evaluate the insulation on transformers.

A. ESD for Standard Tests

The standard tests that are applied in transformers are [14]:

- Full Impulse with time of crest of 1.2µs and time of tail of 50µs (BIL) - This test corresponds to the exposition of insulation to lightning surges;
- Full Impulse with time of crest of 100µs an time of tail of 1000µs (BSL – Basic Switching Level) - This test corresponds to the exposition of insulation to switching surges;
- Chopped Wave Impulse with time until crest of 2, 3 and 5µs - This wave models the exposition of the insulation to very fast transients and usually is more severe than the previous two.

The Fig. 2 and 3 shows this wave forms:

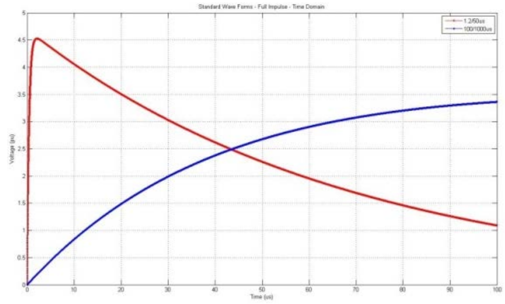

Fig. 2. Wave 1,2/50µs and 100/1000µs (standards tests).

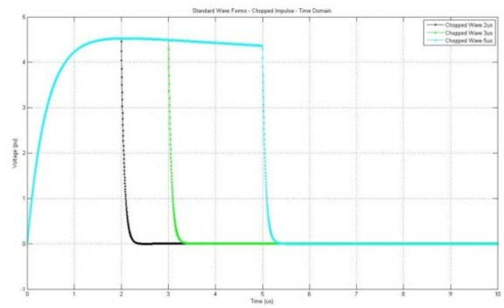

Fig. 3. Chopped Waves (standards tests).

The ESD corresponding to these standard signals can be considered the strength of insulation in each frequency (covered by manufacturer tests) and will be compared with the signals that reach the transformer terminal in simulation studies. This approach was initially proposed by a Joint Work Group (JWG A2/C4-03) of Cigré-Brazil [4].

Fig. 4 show the ESD of the signals used in these standard tests. The maximum values in each frequency are used to form an envelope curve, represented in pink in Fig. 4. The envelope is defined by the maximum stress in laboratory applied tests at each frequency point in a wide band frequency range. The envelope will be used for comparison with the ESD of overvoltage signal obtained on the transformer terminal.

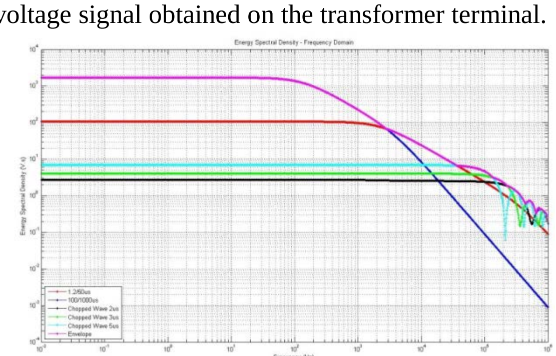

Fig. 4. ESD for standards tests and envelope.

B. Frequency Domain Severity Factor

The frequency domain severity factor (FDSF), proposed for evaluating switching transients [4] is proposed here to evaluate the severity of the overvoltage signals to the insulation for lightning. For determining its value, the ESD of the overvoltage signal is divided by the envelope of standard tests (Fig. 4), point to point in each frequency.

If FDSF ≤ 1, the insulation of transformer is considered safe (covered by tests). On the contrary, if FDSF > 1, the insulation is not safe. If this happens, the insulation of the system under analysis has to be improved. One method to solve this problem is improving the locations (or increasing the number) of surge arrester or decreases its residual voltages, choosing a lower rating.

Fig. 5 shows an example for FDSF evaluation. It can be observed that the limit of FDSD is exceeded by the red curve (phase A) around 70.0 kHz. In this case, the insulation may not withstand the stress caused by the overvoltage.

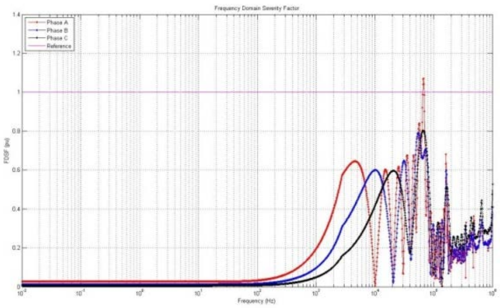

Fig. 5. FDSF for three phases of the signal.

The method of evaluating insulations using ESD is more reliable than the traditional deterministic method for insulation coordination. The traditional approach considers amplitude but does not quantify the frequencies present in the overvoltage and its duration. The Energy Spectral Density provides additional information, when quantify the signal energy. It will be shown that there are cases where traditional method would guarantee that insulation is safe, but when the new approach taking into account the ESD is applied, the conclusion is different.

III. PROPOSED SYSTEM AND USED MODELS

The test system represented in Fig. 6 is part of a real 230kV substation of *Eletrobrás Eletrosul Company*. This system has five transmission line bays, one transfer circuit breaker bay and one transformer bay. The objective is to evaluate the overvoltages that may reach the transformer. The data about apparatus are real and provided by the manufacturers. All the parameters and models used are suited for lightning overvoltage studies. These models are described in the next subsections.

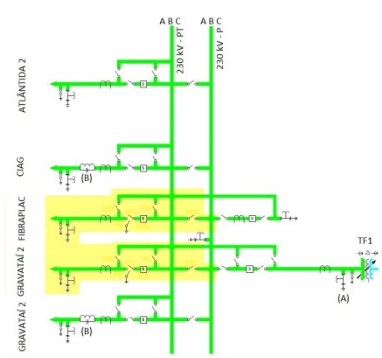

Fig. 6. Real system (Eletrobrás Eletrosul Company, transmission lines highlighted are operated by Company).

A. Transmission Lines

The tower impedance, the tower footing impedance and insulator strings are considered part of transmission line. In the sequence each part of transmission line will be commented.

Firstly, for studies of lightning transients it is necessary to represent each span of transmission line through distributed parameters. In this case, four spans of each transmission line have been modeled. The model used was *Bergeron* [5], which considers frequency constant distributed parameters. The modal model was used for calculating de series impedance matrix, shunt capacitive matrix and propagation constant matrix, considering a perfect transposition in all spans. Therefore, the mutual impedance between phase conductors and shielding conductors are equal and the series impedance matrix is symmetrical. In the line parameter calculations, the problems with return ground impedance of Carson [6] can occur when high frequencies are considered. The earth has a behavior of dielectric with high frequencies and high earth's resistivity [7]. If this happen, the Carson's equation is not valid. But, in this system the value of earth's resistivity is 410 Ω.m and the model can be used.

The tower impedance was calculated based on the tower form. The impedance of cylindrical and conical towers (see Fig. 7) was calculated by the application of (5) or (6) [3]:

$$Z = 60\left[ln\left(2\sqrt{2}\frac{h}{r}\right) - 1\right] \quad \text{Cylindrical tower (5)}$$

$$Z = 60ln\left[\sqrt{2}\sqrt{\left(\frac{h}{r}\right)^2 + 1}\right] \quad \text{Conical tower (6)}$$

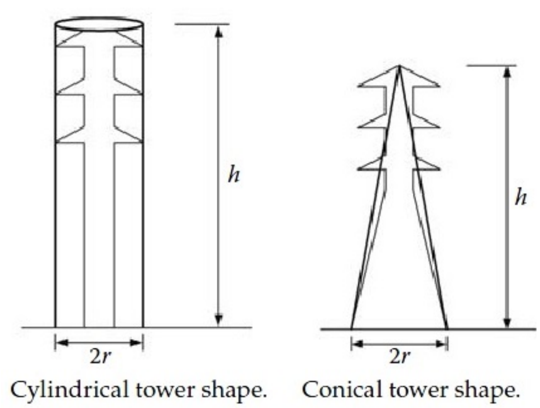

Fig. 7. Tower forms for calculating tower impedance.
Source: Reference [3]

The tower footing impedance was considered 15Ω according to data of overhead lines design. The insulator string was modeled as a controlled voltage switch in parallel with a capacitor that represents the equivalent capacitance of the insulator string. The capacitance of each insulator is 80pF and the capacitance of the full string depends on the amount of discs or insulators [8]. The backflashover happens when the voltage through the insulator string exceeds its strength. This is determinated for evaluating curve Vxt of insulator string.

Equation (7) shows the relation between voltage flashover and insulator length [8]:

$$V_{v-t} = K_1 + \frac{K_2}{t^{0.75}} \qquad (7)$$

Where:
V_{v-t}= Flashover voltage, kV;
$K_1 = 400L$;
$K_2 = 710L$;
L = Insulator length, m;
t = elapsed time after lightning stroke, µs.

After lightning strike hits the shield wire, the flashover voltage is calculated using (7) and the voltage reference for closing the switch of insulator string model is set for each insulator string in each phase. Fig. 8 shows the complete model.

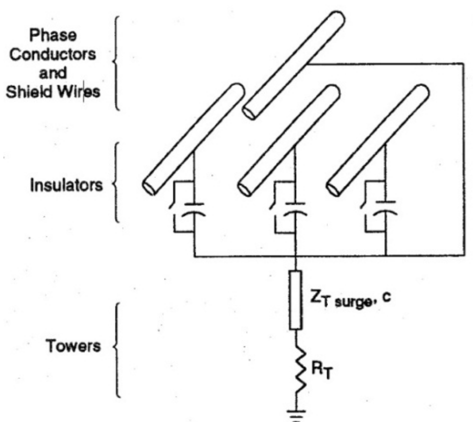

Fig. 8. Complete model for transmission line.
Source: Reference [8]

B. Apparatus

Other apparatus like circuit breakers, capacitive and magnetic voltage transformers, current transformers, disconnect switches and bus supporting insulators also are part of system and need to be modeled. In high frequencies, the capacitive behavior is more pronounced than the inductive behavior, thus the previously cited apparatus have been represented in this work by a capacitance lumped to ground, whose value depends on the voltage level. Tab. I show some capacitance values for this apparatus [8]. The capacitance of line straps is 250pF.

The values presented in Table I for 400 kV have been applied to model the test system used in this work (230kV). All intersections of system where an apparatus is installed have been represented. The correct distances between apparatus are considered in the substation modeling.

The *Bergeron* model (transmission line) has been used to model the sections between apparatus, to consider the overvoltage reflections.

TABLE I
SOME CAPACITANCES LUMPED TO GROUND
SOURCE: REFERENCE [8]

Equipment	Capacitance-to-Ground		
	115kV	***400kV***	***765kV***
Disconnector Switch	100 pF	200 pF	160 pF
Circuit Breaker	100 pF	150 pF	600 pF
Bus Support Insulator	80 pF	120 pF	150 pF
Capacitive Voltage Transformer	8000 pF	5000 pF	4000 pF
Magnetic Voltage Transformer	500 pF	550 pF	600 pF
Current Transformer	250 pF	680 pF	800 pF

C. Stroke Current

The stroke current was represented by a slope-ramp source type 13 of ATP (Alternative Transients Program – EMTP type program) [13]. This type of source is mathematically represented by a double exponential, as shown in (8):

$$i(t) = A_0\left(e^{-\alpha t} - e^{-\beta t}\right) \qquad (8)$$

Where:
$i(t)$= stroke current, A;
A_0= amplitude, A;
α= rise time coefficient, 1/s;
β= decay time coefficient, 1/s.

The simulation of stroke currents on shield wires in the first span causes the worst stresses when backflashovers happens, but in fourth spans also was simulated for comparing. Lightning strikes directly on phase conductor (shielding failure) were simulated in each span of each transmission line. Stroke currents on shield wires, were simulated only on first and fourth spans. The value of stroke current was calculated by Love's geometric method [1].

D. Surge Arrester

The surge arresters should be modeled by dynamic and dependent-frequencies models, especially when there is interest in their behavior in high frequencies. These models consider the non-linearity of the resistance of metallic elements (ZnO) and also the phase displacement between residual voltage and discharge current. The IEEE model [9] is used in this work. It is represented in the Fig. 9 and its parameters can be calculated by (9-13). A disadvantage of this model is the necessity of constructive data about the metallic elements. In this case, it was provided by the manufacturer.

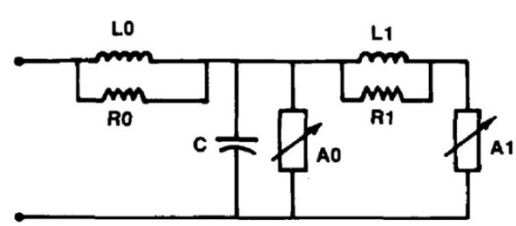

Fig. 9. The IEEE Model.
Source: Reference [9]

$$L_0 = 0.2\frac{d}{n}, \mu H \quad (9) \qquad R_0 = 100\frac{d}{n}, \Omega \quad (10)$$

$$L_1 = 15\frac{d}{n}, \mu H \quad (11) \qquad R_1 = 65\frac{d}{n}, \Omega \quad (12)$$

$$C = 100\frac{n}{d}, \text{pF} \quad (13)$$

The values A_0 and A_1 represent nonlinear resistors and are obtained from the curve in Fig. 10.

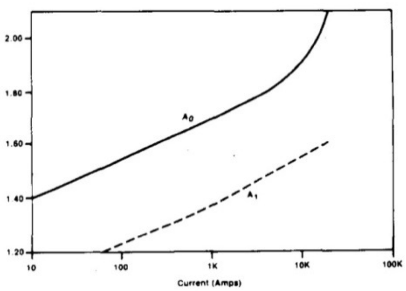

Fig. 10. Nonlinear Resistances.
Source: Reference [9]

E. Transformer

The main objective of this work is to simulate and analyze the overvoltage in the power transformer terminal. The transformer was represented considering its points of resonance obtained from its frequency response test – a wide band model.

The frequency response analysis (FRA) is also used for determining coil dislocation during transportation through the comparison of the test results in the laboratory and at the substation.

The results of the frequency response test may also be used to obtain an analytical model of the transformer, which can be in the frequency domain (transfer function) or time domain (an RLC circuit). An efficient method to find a transformer wide band model is through the application of the *Vector Fitting* routine [10]. This routine synthetizes one RLC network [11] from a rational transfer function $f(s)$ also calculated using the *Vector Fitting*. The rational function is fitted with objective of approximating it to the transformer frequency response obtained from measurements. The rational function can be observed in (14). It is very important that this function be strictly proper (N>M).

$$f(s) = \frac{a_0 + a_1 s + a_2 s^2 + \cdots + a_M s^M}{b_0 + ba_1 s + b_2 s^2 + \cdots + b_N s^N} \quad (14)$$

The function being fitted has one realization in state space that can be observed:

$$y(s) = Y_{fit}(s)u(s) \quad (15)$$

$$y(s) = [C(sI - A)^{-1}B + D + sE]u(s) \quad (16)$$

$$G(s) = [C(sI - A)^{-1}B + D + sE] \quad (17)$$

The criteria for stopping the iterative process of the routine [10] is the medium square error. At the end, the routine provides a circuit that approximates the original transfer function (frequency response). An example of RLC network, that synthetizes its realization is shown in Fig. 11 and can be calculated according (18-25).

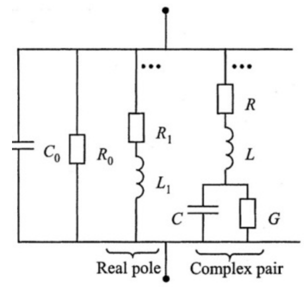

Fig. 11. RLC Network.
Source: Reference [11]

$$C_0 = E \quad (18) \qquad R_0 = \frac{1}{D} \quad (19)$$

$$R_1 = -\frac{A}{C} \quad (20) \qquad L_1 = \frac{1}{C} \quad (21)$$

$$L = \frac{1}{2C'} \quad (22)$$

$$R = (-2A' + 2(C'A' + C''A'')L)L \quad (23)$$

$$\frac{1}{C} = (A'^2 + A''^2 + 2(C'A' + C''A'')R)L \quad (24)$$

$$G = -2(C'A' + C''A'')CL \quad (25)$$

The amount of RLC elements depends on the order of the fitted transfer function. In some cases, the number of poles and zeros may be very high, makes difficult the implementation of the model as an electric circuit in digital program.

IV. Results

Some simulations were carried out for evaluating the energy spectral density of the overvoltage signals that may reach the transformer shown in Fig. 6 due to lightning strikes.

Firstly, the surges that would be applied in the transmission line (shield wire or phase conductors) were chosen. For incidence on phase conductors, the amplitude of the surges was calculated according to the Love's geometric model and profile tower. For incidence on shield wires, the *Berger's Data* were used [12].

The simulated surges were:

- Positives strokes: 35kA 22/230µs and 250kA 3.5/230µs;
- Negative strokes: 30kA 5.5/75µs and 80kA 1.8/75µs;
- Critical Strokes: 350kA 0.2/50µs;
- Shielding Failure Strokes: according each profile tower with 0.5/50µs.

Altogether, 49 cases were simulated.

Some results are shown in Table II and Table III. As shown in Table II, when only the BIL criterion is verified, all these tests respect the safety margins.

TABLE II
RESULTS FOR CLASSICAL INSULATION COORDINATION

N°	CASE	VTMAX [KV]	BIL MARGIN [%]	BACKFLASHOVER
3	SF_S3_FIB	393.44	53.71	NO
10	PS_250_S4_ATL2	198.87	76.60	YES
14	PS_250_S1_CIAG	477.85	43.78	YES
22	PS_250_S1_GRAC2	347.79	59.08	NO
34	PS_250_S4_FIB	387.36	54.43	YES
38	PS_250_S1_GRAC1	441.08	48.11	YES
42	PS_250_S4_GRAC1	390.36	54.08	YES
49	CS_300_S1_GRAC1	450.46	47.00	YES

TABLE III
RESULTS FOR ENERGY SPECTRAL DENSITY (SAME CASES)

N°	CASE	FDSFMAX	FDSF MARGIN [%]	FCRITICAL [KHz]
3	SF_S3_FIB	0.8957	10.43	4.777
10	PS_250_S4_ATL2	0.984	1.6	1607
14	PS_250_S1_CIAG	0.9906	0.94	4.832
22	PS_250_S1_GRAC2	1.001	-0.1	1025
34	PS_250_S4_FIB	0.9566	4.34	3.844
38	PS_250_S1_GRAC1	1.047	-4.7	2000
42	PS_250_S4_GRAC1	1.02	-2	1025
49	CS_300_S1_GRAC1	7.891	-689.1	1866

On the other hand, when the FDSF method is applied, the results show that the insulation could fail in cases 22, 38, 42 and 49.

Legends for Examples:

Case 3 - SF_S3_FIB: Shielding Failure Stroke for third span of transmission line Fibraplac;

Case 42 - PS_250_S4_ATL2: Positive Stroke with 250kA 3.5/230μs for fourth span of transmission line Atlântida 2;

Case 49 - CS_300_S1_GRAC1: Critical Stroke with 300kA 0.2/50μs for first span of transmission line Gravataí 2 Circuit 1.

The overvoltage curves for cases number 3, 38 and 49 are shown in Fig. 12-17:

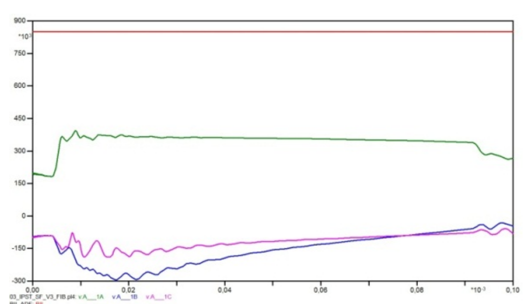

Fig. 12 – Overvoltages versus BIL (case 3)

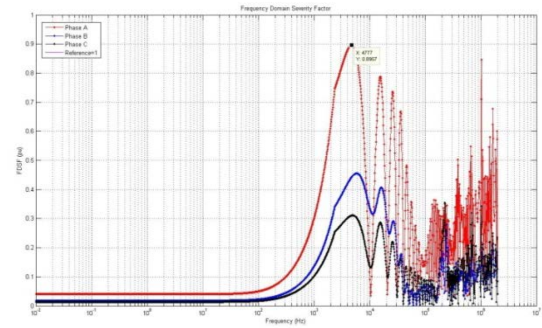

Fig. 13 – FDSF (case 3)

Fig. 12 shows that the maximum overvoltage value occurs in phase “A” (green color). This is justified because the lightning stroke was applied on phase “A” conductor (shielding failure). This peak overvoltage was 53.71% lower than BIL (red color). It can be observed in Fig. 13 that the FDSF curve of phase A is higher than the ones of other phases.

The FDSF safety margin in this case is only 10.43%, much smaller than the BIL margin (>53% as shown in Table II).

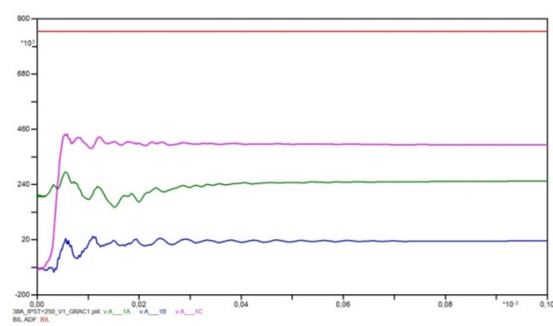

Fig. 14 – Overvoltages versus BIL (case 38)

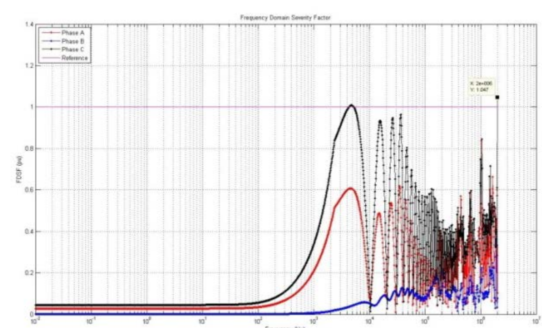

Fig. 15 – FDSF (case 38)

The results obtained in case 38 in time and frequency analysis are shown in Fig. 14 and 15. In this case the maximum overvoltage occurs in phase “C” and its value is higher than in case 3, because the amplitude of applied surge was higher and the backflashover happened first in phase “C”. The BIL margin was 48.11% using classical approach.

Can be observed 2 points across the frequency range, that exceed the threshold value of FDSF (=1.0). The more critical one exceeds in 4.7% the FDSF limit, at 2 MHz.

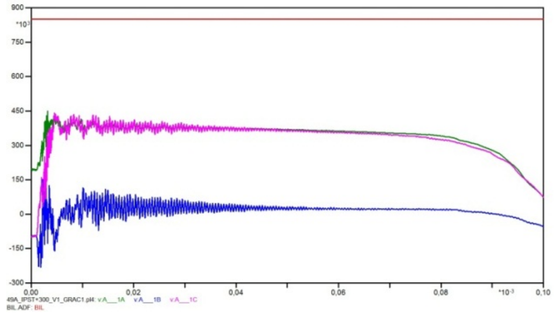

Fig. 16 – Overvoltages versus BIL (case 49)

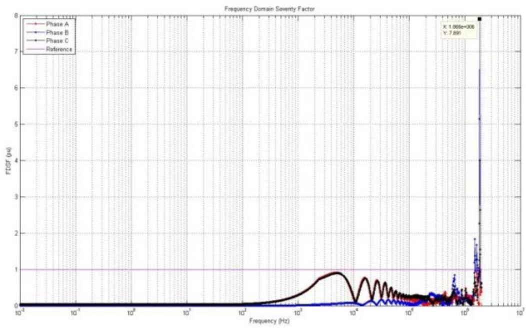

Fig. 17 – FDSF (case 49)

In case 49, a several frequencies were excited, as can be observed in Fig. 16 (until 40μs). This case suffered a more critical surge, for this reason the overvoltage had a higher magnitude. The same rule is valid for backflashover (phase "A" and "C" happen almost at the same time). Various critical frequencies can be observed in Fig. 17. These critical frequencies and resonance points are between 1.4 and 2 MHz. The FDSF limit (1.0) was exceeded in various points, but the highest was 689.1% above the limit. It was observed that all overvoltages has a good safety margin when only the BIL criterion (deterministic method) is considered, but when the frequency domain severity factor (FDSF) is verified, this is not true.

V. Conclusions

The approach described in this paper aims to evaluate if the transformer insulation withstands overvoltages caused by lightning strikes. After various simulations through a digital program, some conclusions are pointed out:

a The positive strokes with amplitude of 250kA with 3.5/230μs cause more critical stresses;

b The negative strokes with amplitude of 80kA with 1.8/75μs also cause backflashover;

c The frequency domain severity factor (FDSF) limit also was exceeded without backflashover;

d Different critical frequencies were obtained in different cases;

e Strokes with fast front time are more critical;

f Shielding failure strokes need to be evaluated.

Although positive strokes have less probability of occurring, they should be considered (conclusion a).

Strokes with less amplitude can also cause backflashover, which depends on the time of crest (conclusion b).

Shielding failure typically has a less amplitude of surge because the lightning strokes amplitude is lower. Usually this type of surge is not taken into consideration in classic insulation coordination studies, because its probability of causing backflashover is low, and so the strength of insulation is guaranteed. But, using the approach of ESD/FDSF, this is not true (conclusion c and f).

Strokes with fast front time are more critical because they have components in a wider range of frequencies, increasing the chances of having a component coinciding with a transformer resonance point.

The parameters of transmission lines, such as surge impedance and tower footing impedance are important for this evaluation. Various transmission lines on substation satisfy the BIL criterion, but not necessarily the FDSF.

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VI. References

[1] A. H. Hileman, *Insulation Coordination for Power Systems*, CRC Press Taylor & Francis Group, 1998.

[2] A. Greenwood, *Electrical Transients in Power Systems*, Second Edition, Wiley Intersciense, 1991.

[3] J. A. Martinez-Velasco, *Power System Transients – Parameter Determination*, CRC Press Taylor & Francis Group, 2010.

[4] JWG A2/C4-03, "Interaction between Transformers and the Power System with focus in high frequency electromagnetic transients" , Brazilian Working Group, Cigré-Brazil, 2005.

[5] H.W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks", IEEE Trans. on Power Apparatus Systems, Vol. PAS-88, N° 4, pp. 388-399, 1969

[6] J. R. Carson, "Wave Propagation on Overhead Wires with Ground Return", Bell System Technical Journal, vol. 5, pp. 539-554, 1926.

[7] A. Deri, G. Tevan, A. Semlyen and A. Castanheira, "The Complex Ground Return Plane, A Simplified Model for Homogeneous and Multi-Layer Earth Return", IEEE Trans. Power Apparatus and Systems, Vol. PAS-100, n°8, pp. 3686-3693, 1981.

[8] IEEE PES Special Publication, "Modeling Guidelines for Fast Front Transients", Modeling and Analysis of System Transient Using Digital Programs, Working Group 15.08.09, 1998.

[9] IEEE Working Group 3.4.11, "Modeling of Metal Oxide Surge Arresters", Application of Surge Protective Devices Subcommittee, Surge Protective Devices Committee, 1992.

[10] B. Gustavsen and A. Semlyen, "Rational Approximation of Frequency Domain Responses By Vector Fitting", IEEE Trans. on Power Delivery, vol. 14, n° 3, pp. 1052-1061, 1999.

[11] B. Gustavsen, "Computer Code for Rational Approximation of Frequency Dependent Admittance Matrices", IEEE Trans. on Power Delivery, vol. 17, n° 4, pp. 1093-1098, 2002.

[12] K. Berger, R. B. Anderson and H. Kroninger, "Parameters of the Lightning Stroke", ELECTRA, 41, pp. 23-37. 1975.

[13] ATPDrawn Rulebook, VII.C.3.

[14] IEC 60076-3, Power Transformers – Part 3: Insulation levels, dielectric tests and external clearances in air, Second Edition, 2000.