A PROCEDURE TO EVALUATE THE RISK OF FAILURE OF DISTRIBUTION TRANSFORMERS INSULATION DUE TO LIGHTNING INDUCED VOLTAGES

Gustavo P. LOPES
Federal University of Itajubá – Brazil
gustavo@lat-efei.org.br

Manuel L. B. MARTINEZ
Federal University of Itajubá – Brazil
martinez@lat-efei.org.br

Alberto BORGHETTI
University of Bologna – Italy
alberto.borghetti@unibo.it

Fabio NAPOLITANO
University of Bologna – Italy
fabio.napolitano@unibo.it

Carlo Alberto NUCCI
University of Bologna – Italy
carloalberto.nucci@unibo.it

Juliana I. L. UCHOA
AES Sul – Brazil
juliana.uchoa@aes.com

Gilnei J. G. DOS SANTOS
AES Sul – Brazil
gilnei.santos@aes.com

Donorvan R. FAGUNDES
AES Sul – Brazil
donorvan.fagundes@aes.com

ABSTRACT

The aim of the paper is to assess the risk of insulation failure of distribution transformers connected to overhead distribution due to indirect lightning induced voltages. The annual frequencies of occurrence of dangerous voltages are evaluated through a Monte Carlo procedure and by using the LIOV-EMTP code for the calculation of the Lightning Electromagnetic Pulse (LEMP) and its effects on the multi-conductor line. The probability of distribution transformers insulation to withstand the stresses caused by lightning overvoltages is inferred from the results of experimental test.

INTRODUCTION

The Brazilian distribution company AES Sul serves regions characterized by high keraunic levels throughout MV networks mainly composed by overhead lines and, therefore, it currently promotes several projects in order to improve the quality of service, reducing the probability of lightning caused faults and their effects on the customers.

A neutral resonant grounding device (e.g. [1]) is investigated as a possible standard neutral ground treatment in distribution networks that are generally working with solid grounded neutral. The neutral resonant grounding allows the system operation also in presence of a permanent phase-to-ground fault without the opening of the three-pole circuit breakers at the substation. In these conditions, as a consequence of the increase of the voltage in the sound conductors, the rated voltage of all surge arresters installed in the feeder must be increased with respect to the one chosen for the surge arresters installed with solid grounded neutral. This motivates the development and implementation of a specific procedure for the assessment of the lightning performance of energized MV overhead lines aimed at minimizing the number of required surge arresters [2].

Moreover, a compact overhead line configuration is expected to be adopted. The typical compact design is characterized by insulated covered conductors (without shield) and a close upper unenergized wire that has the main function of sustaining periodical spacers of the phase conductors (e.g. [3,4]). The analysis presented in [5] has shown that the compact configuration has some advantages with respect to the conventional one for the protection against indirect lightning events. These advantages are tangible if the upper wire – whose main function is of sustaining periodical spacers of the phase conductors – is periodically grounded. The contribution of the upper wire to the protection against direct lightning is disregarded as the insulation between the upper wire and covered conductors, around 215 kV that reduces to 95 kV in case of damaged insulation, is not considered sufficient.

Both the analytic studies previously described have been carried out by suitably adapting the Monte Carlo based procedure presented in [6] and [7], which is also included in the new edition of IEEE Std. 1410 [8].

Besides, the statistical analysis is complemented with an experimental activity, carried out at the LAT-EFEI high voltage laboratory, in order to provide an improved estimation of the statistical withstand capability of the network apparatus with particular reference to the MV/LV transformers.

This paper presents a procedure in order to evaluate the risk of failure of distribution transformers submitted to lightning induced voltages.

The paper is structured as follows: the next section is devoted to the description of the experimental tests, the following section describes the statistical procedure adopted to infer the probability density function (pdf) of the induced voltages at the transformer location and the risk of failure assessment. The paper is concluded by the description of the research aspects that will be investigated in the following phases of the research project.

EXPERIMENTAL TESTS ON DISTRIBUTION TRANSFORMERS

As described in [9], Progressive Impulse Tests (PIT) have been performed on a set of 45 brand new and repaired distribution transformers in order to evaluate their surge withstanding capability. A PIT consists on applying the standard lightning impulse 1.2 x 50 µs from the minimum amplitude of 30 kV up to 80 % of the BIL, increasing the peak voltage in 10 kV steps every shot. The obtained waveshapes are then classified in 4 types of winding conditions: from Type 1 (sound insulation) to Type 4 (short circuit between the winding and the tank). In this paper the analysis will be focused on Type 3 winding condition that refers to the case in which both current and voltage waveshapes present sparks signals which denote an incipient insulation failure. Fig. 1 shows an example of the recorded waveshapes of voltage and current with the sparks indicated by arrows. Type 3 result was observed on 27 transformers.

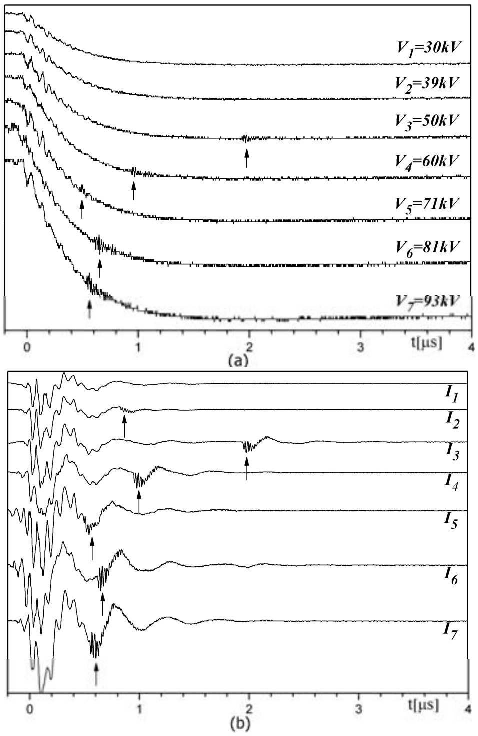

Fig. 1 Example of PIT Type 3 winding condition with spark signals on a) voltage and b) current wave shapes.

STATISTICAL EVALUATION OF THE LIGHTNING PERFORMANCE

As described in [6], the procedure for the calculation of the lightning performance starts with the generation of a large number of events (30 000 for the cases presented is paper) each characterized by the values of the lightning current parameters (amplitude and time to peak) in agreement with the log-normal distributions recommended in [10] for the first strokes of negative downward flashes and by the coordinates of the perspective stroke location at ground in the absence of the line, uniformly distributed in an area *A* around the line large enough to include all the events that could cause induced voltages higher than the assumed minimum dangerous level. In this paper, we make reference to a 2 km long line matched at both terminations and to a 6×4 km rectangular area *A* around it. The length of the line is chosen so to adequately represent the coupling between the lightning electromagnetic pulse (LEMP) and the line conductors. Due to the symmetry of the geometry, the considered stroke locations are distributed in a quarter of the area around the line. The direct strikes to the line have been identified by using the electrogeometric model with the lightning striking distance formula adopted in [8]. For each of the indirect events, the maximum amplitude of the induced voltages along the line is evaluated and the events able to cause a dangerous overvoltage are identified by a time domain simulation calculated by using the LIOV-EMTP code [10], [11] with the application of the LEMP analytical formulation presented in [12].

The lightning performance is usually represented by the graph with the insulation level in the *x*-axis and the expected annual number of dangerous events F_p in the *y*-axis. F_p is given by

$$F_p = \frac{n}{n_{tot}} A\, N_g \qquad (1)$$

where n_{tot} is the number randomly generated events, n is the number of the dangerous events, i.e. the events generating induced voltages higher than the value in abscissa, A is the area around the line and N_g is the annual ground flash density (in this paper we have assumed 1 event/km^2/yr).

For indirect lightning, the cumulative density function (cdf), i.e. n/n_{tot}, would depend on the value of A. F_p is independent of such a value if A is chosen wide enough in order to collect all the lightning events that produce overvoltages higher than the minimum value considered in the abscissa of the graph. The minimum voltage level is chosen in order to be lower than the expected insulation level of the line and of the connected components (in particular of the transformers).

We here consider two different compact line configurations (indicated with the 15 kV and 25 kV values respectively). As shown in Fig. 2 the two configurations are characterized by different distances between the covered conductors and the upper wire. As the distance between the upper wire and the ground is kept unchanged in the two configurations, the number of direct lightning events is almost the same (namely 0.3 events per year on a 2 km-long line). All the direct events produce a flashover. The upper wire is assumed grounded at every 50 m and the ground conductivity is assumed equal to 1 mS/m. Fig. 3 compares the F_p graphs obtained for the two different configurations for a 2 km-long line.

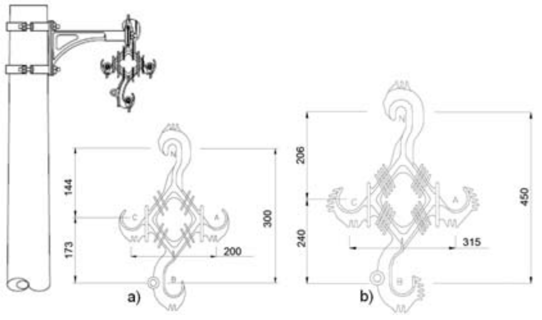

Fig. 2 Compact configuration with insulation class equal to: a) 15 kV and b) 25 kV (dimensions in millimetres).

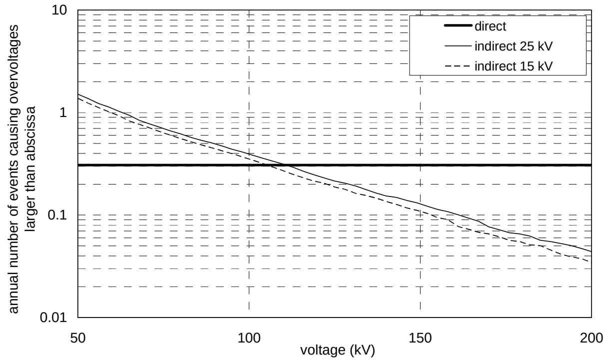

Fig. 3 Comparison between the lightning performance calculated for the two compact line configurations illustrated in Fig. 2.

RISK OF FAILURE ASSESSMENT

The typical procedure for the evaluation of the risk of failure due to lightning of a transformer connected to a line is based on the calculation of two functions: the pdf of the expected overvoltages at the transformer location and the cdf of distribution transformers insulation to withstand the stresses caused by lightning overvoltages. The risk of failure is obtained multiplying these two functions, integrating the result in a voltage range and multiplying the result for the expected annual number of dangerous events nd (e.g. [13]).

For induced voltages, the pdf at the chosen location can be calculated by the following equation

$$f_p = \frac{\Delta n}{n'_{tot}} \tag{2}$$

where Δn is the number of indirect events generating induced voltages with amplitudes from V to $V+\Delta V$ and n'_{tot} is the number of dangerous events, i.e. the events that generate overvoltages higher than the chosen minimum value. For a line length L and area A sufficiently large, (2) is independent of both the values of L and A.

The expected annual number of dangerous events n_d is calculated by

$$n_d = \frac{n'_{tot}}{n_{tot}} A\, N_g \tag{3}$$

Fig. 4 shows, for the 25 kV compact line, the stroke locations of the indirect events that induce overvoltages greater than 50 kV in the middle of a 2 km-long line, where the distribution transformer is supposed to be connected. Fig. 5 compares, for the two line configuration, the indirect lightning performance of the lines at the point of connection of the distribution transformer, while Fig. 6 shows the corresponding pdf. According to Fig. 6, the induced stresses are virtually the same, independent of the line rated voltage 15 or 25 kV. Indeed, the expected annual number of dangerous events n_d is a bit larger for 25 kV lines, 0.52 vs 0.45.

The risk is evaluated as the expected number of transformer failures

$$R = n_d \int_{V_0}^{\infty} f_p(V) P(V)\, dV \tag{4}$$

where $P(V)$ is the transformer failure probability and V_0 is the minimum induced voltage level assumed to be dangerous.

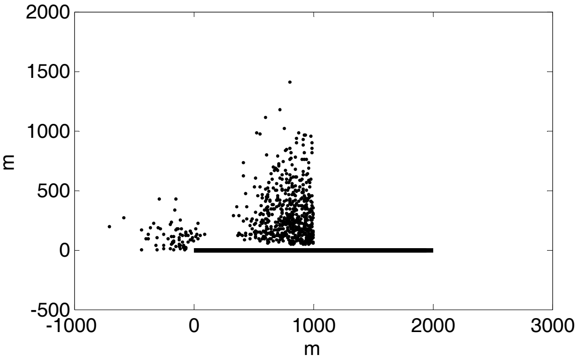

Fig. 4 Stroke locations of the generated events that produce induced overvoltages greater than 50 kV at the central point of a 25 kV compact line.

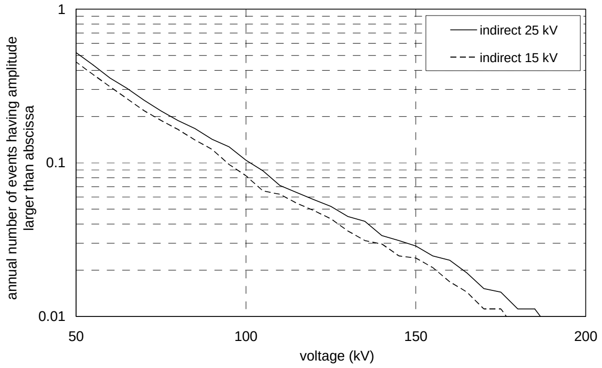

Fig. 5 Comparison between the indirect lightning for the central point of the compact lines.

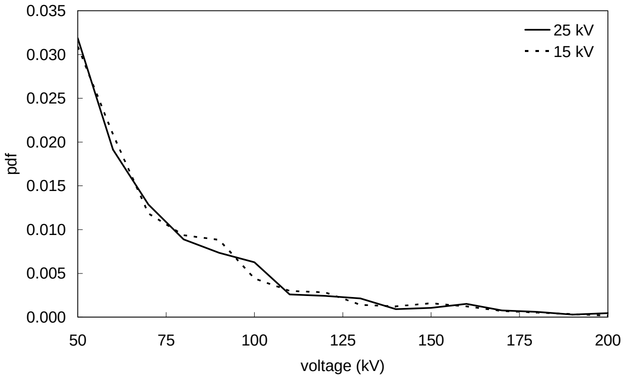

Fig. 6 Comparison between the pdf of the lightning induced overvoltages estimated for the central point of the compact lines.

For unprotected 15 kV class transformers, assuming a failure probability with mean value 110 kV and standard deviation 12 kV (corresponding to a BIL of 95 kV), the relevant risk is 6%; the risk of failure is represented by the grey area in Fig. 7. For 25 kV class transformers, assuming mean value 140 kV and the same standard deviation (BIL 125 kV), the risk is 3%.

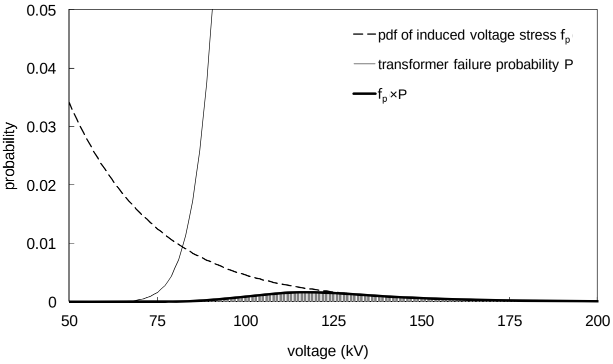

Fig. 7 Risks of failure for lightning induced overvoltages for 15 kV transformers.

Type 3 risk of failure for induced overvoltages for 25 kV transformers may be assessed by assuming mean value equal to 68 kV and standard deviation of 12 kV, which results in a risk of failure of around 30%.

CONCLUSIONS

The paper has described a procedure for the assessment of the risk of insulation failure of distribution transformers connected to overhead distribution due to indirect lightning induced voltages. The probability of distribution transformers insulation to withstand the lightning originated stresses has been inferred from the results of experimental test, while the annual frequencies of occurrence of dangerous voltages have been evaluated through a Monte Carlo procedure and by using the LIOV-EMTP code for the calculation of the Lightning Electromagnetic Pulse (LEMP) and its effects on the multi-conductor line, which allows to take into account realistic and complex network configurations. The proposed procedure allows to evaluate the risk of failure for indirect lightning events that in some cases, i.e. low insulation level, may represent the main cause of distribution transformer failures. The induced overvoltage stresses are quite similar for both the considered lines, which means that lower voltage transformers may experience a failure rate larger than higher voltage transformers, if they are not adequately protected by surge arresters or by other surge protective devices. It is worth noting that the industrial frequency voltage, which is always superimposed to the calculated stresses for both lines types, is expected not to modify the results due to its null average value.

REFERENCES

[1] K.M. Winter, 2005, "The RCC ground fault neutralizer – a novel scheme for fast earth-fault protection", *Proceedings 18th Int. Conf. on Electricity Distribution CIRED*, Turin, Italy.

[2] A. Borghetti, F. Napolitano, C.A. Nucci, M.L.B. Martinez, G.P. Lopes, J.I.L. Uchoa, 2012, "Protection systems against lightning-originated overvoltages in resonant grounded power distribution systems", *Proceedings International Conference on Lightning Protection (ICLP)*, Vienna, Austria.

[3] J B Wareing, 2005, "Covered Conductor Systems for Distribution", Report no. 5925, EA Technology.

[4] M. Oosthuizen, R. Lategan, 2010, “Hendrix Covered Conductor Manual”, Document, Western Power.

[5] F. Napolitano, A. Borghetti, D. Messori, C.A. Nucci, M.L.B. Martinez, G.P. Lopes, J.I.L. Uchoa, 2012, "Assessment of the Lightning Performance of Compact Overhead Distribution Lines", *Proceedings CIGRE SC C4 Colloquium*, Hakodate, Japan.

[6] A. Borghetti, C. A. Nucci, M. Paolone, 2007, "An improved procedure for the assessment of overhead line indirect lightning performance and its comparison with the IEEE Std. 1410 method", *IEEE Trans. Power Del.* vol. 22, 684-692.

[7] A. Borghetti, C.A. Nucci, M. Paolone, 2009, "Indirect-lightning performance of overhead distribution networks with complex topology", *IEEE Trans. Power Del.* vol. 24, 2206-2213.

[8] IEEE Working Group on the Lightning Performance of Distribution Lines, 2011, "IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines", IEEE Std 1410-2010.

[9] G.P. Lopes, M.L.B. Martinez, R.Salustiano, I.P. Faria, V.G.C. Telles, 2012, "A methodology to predict the lightning insulation strength for distribution transformers by applications of reduced lightning standard impulse voltages", *Conference Publications of ISEI.*

[10] R.B. Anderson, A.J. Eriksson, 1980, "Lightning parameters for engineering applications", *Electra*, vol. 69, 65-102.

[10] C.A. Nucci and F. Rachidi, 2003, “Interaction of electromagnetic fields with electrical networks generated by lightning” in *The Lightning Flash: Physical and Engineering Aspects*, V. Cooray, Ed. IEE - Power and Energy Series 34, pp. 425–478.

[11] C.A. Nucci and F. Rachidi, “Lightning protection of medium voltage lines,” in *Lightning Protection*, IEE Power and Energy series 58, 2010.

[12] F. Napolitano, 2011, "An analytical formulation of the electromagnetic field generated by lightning return strokes", *IEEE Trans. Electromagn. Compat.* vol. 53 (1), 108-113.

[13] L.O. Barthold, L. Paris, 1970, "The Probabilistic Approach to Insulation Coordination", *Electra*, No 13.