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**MODELING OF THE BEHAVIOR OF MEDIUM VOLTAGE
INSULATORS AGAINST LIGHTNING OVERVOLTAGES**

SÃO PAULO

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MIL TOM SHIGIHARA

**MODELING OF THE BEHAVIOR OF MEDIUM VOLTAGE
INSULATORS AGAINST LIGHTNING OVERVOLTAGES**

**Tese apresentada ao Programa de
Pós-Graduação em Energia do
Instituto de Energia e Ambiente da
Universidade de São Paulo para a
obtenção do título de Doutor em
Ciências.**

Orientador:

Prof. Dr. Alexandre Piantini

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**AUTORIZO A REPRODUÇÃO E DIVULGAÇÃO TOTAL OU PARCIAL
DESTE TRABALHO, POR QUALQUER MEIO CONVENCIONAL OU
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A FONTE.**

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Ata de defesa pública de Tese do(a) Senhor(a) Milton Shighihara no Programa: Energia, do(a) Instituto de Energia e Ambiente da Universidade de São Paulo.

Aos 05 dias do mês de outubro de 2015, no(a) São Paulo realizou-se a Defesa da Tese do(a) Senhor(a) Milton Shighihara, apresentada para a obtenção do título de Doutor intitulada:

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Após declarada aberta a sessão, o(a) Sr(a) Presidente passa a palavra ao candidato para exposição e a seguir aos examinadores para as devidas arguições que se desenvolvem nos termos regimentais. Em seguida, a Comissão Julgadora proclama o resultado:

Nome dos Participantes da Banca	Função	Sigla da CPG	Resultado
Alexandre Plantini	Presidente	IEE - USP	<u>APROVADO</u>
Ruy Alberto Corrêa Altafim	Titular	EESC - USP	<u>Approved</u>
Vladimir Alexander Rakov	Titular	UF - Externo	<u>Approved</u>
William Alexander Chisholm	Titular	Externo	<u>Approved</u>
Kazuo Yamamoto	Titular	Chubu - Externo	<u>Approved</u>

Resultado Final: APROVADO

Parecer da Comissão Julgadora *

Eu, Adriana Fatima Pelegrina, lavrei a presente ata, que assino juntamente com os(as) Senhores(as). São Paulo, aos 05 dias do mês de outubro de 2015.

Ruy Alberto Corrêa Altafim

Vladimir Alexander Rakov

William Alexander Chisholm

Kazuo Yamamoto

Alexandre Plantini

Presidente da Comissão Julgadora

* Obs: Se o candidato for reprovado por algum dos membros, o preenchimento do parecer é obrigatório.

A defesa foi homologada pela Comissão de Pós-Graduação em _____ e, portanto, o(a) aluno(a) faz jus ao título de Doutor em Ciências obtido no Programa Energia.

Presidente da Comissão de Pós-Graduação

Para a minha querida Cintia Tiemi,
e nossos filhos Luisa Ayumi e Samuel Hiro
nossos maiores tesouros

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“In the middle of difficulty lies opportunity”

Albert Einstein

ABSTRACT

SHIGIHARA, M. **Modeling of the behavior of medium voltage insulators against lightning overvoltages**. 2015. 94 p. Dissertation (PhD) – Graduate Program on Energy, Universidade de São Paulo, São Paulo, 2015.

Lightning causes important transient disturbances on transmission and distribution systems, with consequent damages to equipment, outages, and general decrease of the power quality. The assessment of the lightning dielectric strength of power equipment is generally based on tests performed using the standard lightning impulse voltage (1.2 / 50 μ s waveshape), although the characteristics of the lightning overvoltages depend on many parameters and may vary widely. The behavior of insulators when subject to non-standard impulses depends both on the voltage amplitude and waveshape, and therefore a reliable model is required to produce the corresponding volt-time curves. Although there is no method universally accepted for this purpose, one of the most used is the Disruptive Effect (DE) model, which is based on the integration method concept. The application of this model involves the estimation of some parameters for which different procedures have been proposed in the literature, as for instance the procedures by Darveniza and Vlastos, by Hileman, by Chowdhuri *et al.*, and by Ancajima *et al.* Tests of representative lightning overvoltages were performed to obtain the critical flashover overvoltages (CFO) and the volt-time curves of typical porcelain pin-type insulators considering three standard medium-voltage distribution classes (15 kV, 24 kV, and 36 kV) and five impulse voltage waveshapes, of both polarities. These tests provided data for the analyses of the insulators' behavior and the results obtained using the different procedures for estimating the DE parameters. It is shown that in some cases insulator flashover is not predicted. A new method is then developed and proposed for evaluating the dielectric behavior of MV insulators. The method is validated using the typical insulators of the three voltage classes and the five lightning impulse voltages considered, of positive and negative polarities. The calculated volt-time curves showed in general a good agreement with the measured results for all the cases studied. The mean difference between the measured and calculated times to breakdown, for all the cases considered, was about 1.3 μ s; while the

maximum difference was 4.0 μ s. The application of the proposed method to evaluate the occurrence of insulator flashovers in the shield wire line (SWL) system implemented in the State of Rondônia due to nearby lightning strikes supports previous conclusions that indicate that lightning has a significant impact on the SWL system performance in regions with high ground flash density.

Keywords: lightning flash, lightning overvoltages, impulse voltage tests, MV insulators, distribution systems, lightning protection.

RESUMO

SHIGIHARA, M. **Modelagem do comportamento de isoladores de média tensão contra sobretensões de impulsos atmosféricos**. 2015. 94 f. Tese (Doutorado em Ciências) - Programa de Pós-Graduação em Energia da Universidade de São Paulo, São Paulo, 2015.

Descargas atmosféricas produzem distúrbios transitórios significativos em sistemas de transmissão e distribuição, com consequentes danos em equipamentos, interrupções e redução geral na qualidade de energia elétrica. A avaliação da suportabilidade dielétrica frente às descargas atmosféricas do equipamento de potência é geralmente baseada em ensaios realizados usando o impulso atmosférico de tensão normalizada (forma de onda $1.2 / 50 \mu s$), contudo as características das sobretensões atmosféricas dependem de muitos parâmetros e podem variar amplamente. O comportamento dos isoladores quando sujeitos a impulsos não normalizados depende tanto da magnitude como da forma de onda da tensão, e então um modelo confiável é necessário para se obter as curvas tensão-tempo correspondentes. Embora não haja um método universalmente aceito para essa finalidade, um dos mais utilizados é o modelo de Efeito Disruptivo (DE), que é baseado no conceito do método de integração. A aplicação desse modelo envolve a estimativa de alguns parâmetros para os quais diferentes procedimentos têm sido propostos na literatura, como por exemplo, os procedimentos de Darveniza e Vlastos, de Hileman, de Chowdhuri *et al.* e de Ancajima *et al.* Ensaios de sobretensões atmosféricas representativas foram feitos para obter as tensões de descarga disruptiva (CFO) e as curvas de tensão-tempo de isoladores de porcelana típicos, tipo pino, considerando três classes de tensão de distribuição de média tensão (15 kV, 24 kV e 36 kV) e cinco formas de onda de impulso de tensão, de ambas as polaridades. Estes ensaios proporcionaram dados para as análises do comportamento dos isoladores e os resultados obtidos usando os diferentes procedimentos para estimar os parâmetros necessários para a aplicação do modelo do Efeito Disruptivo. É mostrado que em alguns casos a disrupção no isolador não é prevista por tais procedimentos. Um novo método é, então, desenvolvido e proposto para avaliar o comportamento dielétrico dos isoladores de média tensão. O método é validado usando os isoladores típicos das três classes de

tensão e as cinco formas de tensões de impulso atmosféricos consideradas, de polaridades positiva e negativa. As curvas tensão-tempo calculadas mostraram, em geral, boa concordância com os resultados medidos para todos os casos estudados. A diferença média entre os tempos de interrupção medidos e calculados, para todos os casos considerados, foi da ordem de 1,3 μ s; enquanto a máxima diferença foi de 4,0 μ s. A aplicação do método proposto para avaliar a ocorrência de interrupções em isoladores do Sistema de Cabo Para-raios Energizados (PRE), implementado no estado de Rondônia, devido a descargas atmosféricas indiretas, apoia as conclusões previamente obtidas que indicam que as descargas atmosféricas têm impacto significativo sobre o desempenho do sistema PRE em regiões com alta densidade de descargas para solo.

Palavras-chave: descargas atmosféricas, sobretensões atmosféricas, ensaios de impulso de tensão, isoladores de média tensão, sistema de distribuição de energia elétrica, proteção contra descargas atmosféricas.

LIST OF SYMBOLS

V'_{50}	50 % probability of producing a disruptive discharge from any type of lightning impulse voltage test
V'_{16}	16 % probability of producing a disruptive discharge from any type of lightning impulse voltage test
V_{50}	50 % probability of producing a disruptive discharge from standard lightning impulse voltage test
CFO	critical flashover and is the same V_{50} , i.e., 50 % probability of producing a disruptive discharge from standard lightning impulse voltage test
CFO_{15kV}	critical flashover and is the same of V_{50} , i.e., 50 % probability of producing a disruptive discharge from standard lightning impulse voltage test for 15 kV insulator
CFO_{24kV}	critical flashover and is the same of V_{50} , i.e., 50 % probability of producing a disruptive discharge from standard lightning impulse voltage test for 24 kV insulator
CFO_{36kV}	critical flashover and is the same of V_{50} , i.e., 50 % probability of producing a disruptive discharge from standard lightning impulse voltage test for 36 kV insulator
BIL	crest value of the voltage, namely basic insulation level and refers to 10 % probability of failure of the equipment when subject to the standard lightning impulse test
σ	standard deviation calculated as V'_{50} minus V'_{16}
σ^*	corrected standard deviation calculated considering the value of degree of freedom ν
DE	Disruptive Effect constant
σ_{DE}	relation between σ and DE , namely mean square deviation
$\sigma_{DE\%}$	percentage value of σ_{DE}

DE_C	critical Disruptive Effect value
SI	Severity Index
α	value calculated empirically from V×t test
ε_T	parameter used to estimate the optimum value of α
α^*	optimum value of α calculated from ε_T
DE^*	optimum value of DE calculated from α^*
t_{cj}	calculated time to breakdown considering measured peak voltage and the Ancajima <i>et al.</i> method.
t_{mj}	measured time to breakdown obtained from V×t test
ε_{tr}	mean of relative difference of time to breakdown
$\sigma_{\varepsilon_{tr}}$	standard deviation of ε_{tr}
$v(t)$	the instantaneous voltage stressing the dielectric at time t
V_0	the onset voltage, reference voltage or the minimum voltage to start the breakdown
t_0	the time at which $v(t_0) = V_0$
t_b	the time to breakdown
K	exponent that depends on the values of α , $v(t)$ and V_0 as proposed for Chowdhuri <i>et al.</i>
P	portion of samples
n	number of voltage level from multi-level test
γ	confidence interval
ν	number of degrees of freedom given by the number of voltage levels (n) minus one (used in the multi-level test)
k	value tabulated and depends on the values of P , γ and ν for one-sided tolerance limit factor of a normal distribution
M	number of voltage levels for volt-time test

m	total number of applications of the specific impulse voltage and polarity for volt-time test
$C_{m,2}$	two-by-two combination of the m number of impulse voltage profiles from the experimental V×t test
t_{bM}	value of the longest recorded time to breakdown between the m applications of volt-time test
$v(t_{bM})$	the voltage corresponding to the time t_{bM}
$p(V)$	normal cumulative distribution function
Δx	incremental length in the DE model
Δt	incremental time in the DE model
S	the gap length between the electrodes
δ	parameter that depends on the gap length characteristic
V_p	peak voltage
0_1	virtual origin
δt	the time interval between two successive points acquired by digitizer
d	distance of lightning stroke
LPM	leader progression model
R	resistance for short wavetails adjustment
R_1''	external front resistance, which controls the front-time
R_2''	external tail resistance
L	inductance for short wavetails
C_2	summation of the additional load capacitance, stray capacitance, and the insulator capacitance, which value is approximately C_2
PRE	cabos para-raios energizados
SWL	shield wire line
SWS	shield wire scheme

A, B weights of the characteristic curve proposed by Darveniza, Popolansky,
and Whitehead

w insulator length

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1 INTRODUCTION

Lightning causes strong transient disturbances on transmission and distribution systems, with consequent damages to equipment, outages, and general decrease of the power quality (CHOWDHURI; GROSS, 1967; COORAY; DE LA ROSA, 1986; YOKOYAMA; MIYAKE; FUKUI, 1989; NUCCI *et al.*, 1993; RACHIDI *et al.*, 1996; OBASE; PIANTINI; KANASHIRO, 2005; OBASE; PIANTINI; KANASHIRO, 2006; PIANTINI *et al.*, 2007; PIANTINI, 2008; PIANTINI; JANISZEWSKI, 2013). The overvoltages produced by lightning flashes usually have front times in the range $0.1 - 20 \mu\text{s}$ (IEEE Std 1313.2, 1999). The assessment of the lightning dielectric strength of power equipment is generally based on tests performed using the standard lightning impulse voltage ($1.2 / 50 \mu\text{s}$ waveshape), where the tolerances are $\pm 30 \%$ for the virtual front-time, $\pm 20 \%$ for the time to half-value, and $\pm 3 \%$ for the peak voltage (IEEE Std 4, 2013). However, the characteristics of these overvoltages depend on many parameters and may vary widely (DARVENIZA; VLASTOS, 1988; PIANTINI *et al.*, 2004; RAKOV; UMAN, 2007; PIANTINI, JANISZEWSKI, 2009).

As the insulator lightning impulse withstand capability depends both on the voltage amplitude and waveshape, the evaluation of its behavior when subject to non-standard impulses requires a model to produce the corresponding volt-time curves. Although there is no method universally accepted for this purpose, one of the most widely used is the Disruptive Effect model (WITZKE; BLISS, 1950a, 1950b), which is based on the integration method concept. The application of this model involves the estimation of some parameters, for which different procedures have been proposed in the literature (JONES, 1954; KIND, 1958; RUSCK, 1959; DARVENIZA; VLASTOS, 1988; CHOWDHURI; MISHRA; McCONNEL, 1997; HILEMAN, 1999; SAVADAMUTHU; UDAYAKUMAR; JAYASHANKAR, 2002; ANCAJIMA *et al.*, 2010; KRITHIKA; USA, 2015).

The features of breakdown in air have been studied since 1920s, when the impulse waveshapes of $1.5 / 40 \mu\text{s}$ and $1 / 50 \mu\text{s}$ were the standard lightning impulse voltages in the USA and Europe, respectively. These early studies of impulse characteristics were commonly carried out on air gaps with configurations combining spheres, rods, and planes (IEEE TASK FORCE 15.09, 1994). At that time, the studies of overvoltage waveshapes using instrumented

transmission lines showed that a large fraction of results had positive polarity, low amplitude, and short time to half value (CHISHOLM, 2010).

The AIEE Lightning and Insulator Subcommittee, in 1933, based on the experience with measurements of lightning overvoltages on overhead lines, and by consensus recommended three different waveshapes: $1 / 5 \mu\text{s}$, $1 / 10 \mu\text{s}$, and $1.5 / 40 \mu\text{s}$. The designation of the front-time was the time from zero to crest, in microseconds. In 1934, this Subcommittee reviewed the discrepancies of the 60-cycle and impulse voltage tests, and the four major electrical manufactures' laboratories (General Electric Company, Westinghouse Electric and Manufacturing Company, Ohio Brass Company, and Locke Insulator Company), which were best equipped, conducted a study of insulator and gap flashovers. The tests were carried out with the $1 / 5 \mu\text{s}$ and $1.5 / 40 \mu\text{s}$ waveshapes with the goal of determining and eliminating differences in insulator breakdown data from different sources in order to obtain reliable flashover data for standard insulators and gaps.

Kuffel and Abdullah, in 1966, studied the electrical features of the corona and the leader stroke preceding the impulse flashover of sphere-plane and rod-rod gaps up to 40 cm long, in atmospheric air. The studies were performed with both polarities and impulse voltage wavefronts between $2 \mu\text{s}$ and $300 \mu\text{s}$. The effect of the wavefront duration on the breakdown voltage was also studied. It was observed that for voltage front times shorter than $2 \mu\text{s}$, the breakdown in all gaps was preceded by a positive leader.

In 1973, Caldwell and Darveniza performed tests in various gaps and insulators with different types of impulse voltages, with front-times varying from 1.3 to $14.4 \mu\text{s}$, and times to half-value varying from 53 to $126 \mu\text{s}$, as well as with partially chopped and oscillatory waveshapes. The results, obtained from the application of the integration method, showed acceptable accuracy in reproducing the standard volt-time curves and for predicting breakdown data for steep-front and long-front impulses (times to breakdown from 50 ns to $25 \mu\text{s}$).

Grzybowski and Jacob, in 1990, presented results of a study on the flashover voltage characteristics of porcelain pin-type insulators (sizes of 5.5, 7.25, and 8.5 inch), 4-inch porcelain suspension insulators (one, two, three, and 4 units), 15 kV polymer suspension insulators (7 inch), wood crossarm, and porcelain suspension insulators plus wood crossarm, submitted to steep-front, short duration pulses. The authors found out that for the time to

breakdown of 1.2 μ s, the peak flashover voltage for steep-front waveshapes was 2 times higher than the lightning impulse standard *CFO* (critical flashover overvoltage) of the same insulator. They observed also that, for all types of insulators tested, for peak voltages higher than a certain value no further reduction of the time to breakdown was observed (with the increase of the voltage) less than approximately 120 ns. In addition, the authors noticed that for pulses with front time and time to half value of approximately 65 ns and 5 μ s, respectively; the flashover voltages under positive polarity were higher than those of negative polarity in the case of times to breakdown shorter than 250 ns.

The Guideline prepared by the CIGRE WG 33.07 (1992) illustrates the general trends in the dielectric strength as a function of the most important influencing parameters and gives methods and criteria for the evaluation of the strength. The work concluded that it is possible to extrapolate experimental data through modelling to evaluate the strength under non-standard lightning impulses with generally sufficient accuracy.

In 1996, the data of lightning induced voltages on an overhead line at a distance of 145 m from a rocket triggered lightning source, collected by Barker *et al.*, showed a median 1.6 / 4.1 μ s waveshape, similar to the 1 / 5 μ s waveshape selected by the AIEE from measurements in the 1920s (CHISHOLM, 2010).

Recently, Braz *et al.* (2014) evaluated the dielectric behavior of a typical medium-voltage (MV) insulator when subjected to non-standard voltage impulse waveshapes. The main methods to estimate the parameters necessary for the application of the Disruptive Effect model were compared. For the analysis, tests were performed on a pin-type porcelain insulator of 15 kV voltage class, applying the standard lightning impulse voltage waveshape and other selected waveshapes. The non-standard waves were chosen based on the characteristics of measured and calculated lightning overvoltages from reduced models and full-scale experiments. The assessment of the methods for determining the parameters of the Disruptive Effect model was based on comparisons between the measured volt-time data obtained from laboratory tests and those predicted by the methods considered, for each of the selected voltage waveshapes.

Various measurements of lightning overvoltages performed in reduced models and full scale systems indicate that the voltage waveshapes may vary widely. The knowledge of the behavior of distribution insulators under such non-standard waveshapes is essential for the

analysis of the lightning performance of power distribution lines. As already mentioned, one of the most commonly used methods for the prediction of volt-time curves of power system insulators is the Disruptive Effect Model. As suggested by Chisholm (2010), data of the 1920s and 1930s related to $1/5 \mu\text{s}$ impulse available in the literature can be used to refine the DE model for modern usage.

However, the existing procedures for estimating the parameters required for the application of the DE model for distribution insulators either involve the performance of tests with the standard lightning impulse voltage, as for example the procedure by Darveniza and Vlastos (1988), or the use of an equation which was derived based on tests performed in transmission line insulators, as for example the procedure by Hileman (1999).

1.1. Objective

The main objective of this research is to develop an accurate model to evaluate the behavior of medium voltage insulators under standard and non-standard lightning impulse voltages. The analyses comprises the following specific goals:

- to obtain the critical flashover overvoltages (*CFO*) and the volt-time curves for typical insulators of three standard medium-voltage distribution classes (15 kV, 24 kV, and 36 kV) considering five impulse voltage waveshapes, of positive and negative polarities, representative of lightning overvoltages;
- to develop, propose, and validate a procedure for estimating more accurately the values of the parameters required for the application of the Disruptive Effect model based on comparisons of the volt-time curves obtained from the tests and those predicted by the most important existing procedures, namely those proposed by Chowdhuri *et al.* (1997) and Ancajima *et al.* (2010);
- to develop, propose, and validate a general method, based on the application of the proposed procedure, for the analysis of the dielectric behavior of 15 kV, 24 kV, and 36 kV distribution insulators under non-standard lightning impulse voltages of positive and negative polarities;

- to compare and analyze the results predicted by the proposed method with those obtained by the Darveniza and Vlastos (1988) and Hileman (1999) methods, as well as with the volt-time curves obtained from the tests;
- to apply the proposed method to a practical and realistic situation. More precisely, the method is used to find out whether, for some specific combinations of line and lightning parameters, the overvoltages induced by lightning strikes in the vicinity of a non-conventional, low cost MV system implemented in the Amazon region, namely the shield wire scheme (SWS), cause insulator flashovers.

1.2. Outline of the Dissertation

This Dissertation is organized in six chapters. The first presents a short introduction, the objective, and the structure of this Dissertation.

The second chapter presents a chronological review about the Disruptive Effect (DE) model, widely applied in insulation coordination designs and in computational simulations. The main procedures for estimating the DE model parameters are presented.

The third chapter proposes a new method for estimating more accurately the values of the Disruptive Effect model parameters, based on comparisons of the volt-time curves obtained from tests and those predicted by other procedures.

The fourth chapter refers to the lightning impulse voltage tests, and presents some of the test circuits, the characteristics of the 15 kV, 24 kV, and 36 kV insulators, and the standard and non-standard waveshapes applied in the tests.

The fifth chapter presents, for the three standard medium-voltage distribution classes and the various impulse voltage waveshapes considered, of positive and negative polarities, the prospective value of the test voltage that has a 50% probability of producing a disruptive discharge. After presenting a parametric analysis, comparisons are provided between the experimentally derived volt-time curves and those predicted by the various procedures. Then, based on test results, a new and simple method for evaluating the dielectric behavior of MV insulators of the three voltage classes considered is proposed and validated.

In the sixth chapter the proposed method presented in chapter 5 is applied to a real system to evaluate the occurrence of insulator breakdown associated with induced voltages caused by lightning strikes close to a shield wire line (SWL) system implemented in the State of Rondônia, Brazil.

The final chapter presents the main conclusions and contributions of the work, as well as topics for future research.

2 THE DISRUPTIVE EFFECT MODEL

An insulator breakdown occurs randomly and is completely defined when the applied voltage is known between the interval t_0 (the instant of the time, where the instantaneous applied voltage $v(t)$ is greater than the onset voltage V_0) and the time to breakdown t_b (KUFFEL, E.; ZAENGL; KUFFEL, J., 2000). Therefore, the breakdown characteristics follow a normal distribution function as follows:

$$p(V) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(V-V'_{50})^2}{2\sigma^2}} \quad (1),$$

where V'_{50} and σ can be estimated from standardized tests:

- up-and-down tests (DIXON; MOOD, 1948; HAUSCHILD, MOSCH, 1992; IEC 60060-1, 2010);
- multiple-level tests (HAUSCHILD, MOSCH, 1992; IEC 60060-1, 2010);
- successive discharge tests (HAUSCHILD, MOSCH, 1992; IEC 60060-1, 2010).

Details of the test procedures are not covered in this dissertation, but they can be found in the specific standards of high-voltage tests such as IEC 60060-1 (2010).

Equation (1) can also be approximated by alternative distributions, including Weibull (1951), Gumbell (1935), or extreme-value distributions. These distributions are all very close to the normal cumulative distribution function for probability levels from 2% up to 98% (DARVENIZA, POPOLANSKY, WHITEHEAD, 1975; DAVIES *et al.*, 1988; CIGRE WG 33.07, 1992). Additional information about the statistical applications in high voltage can be found in Carrara and Yakov (1983), Hyltén-Cavallius and Chagas (1983), Carrara and Hauschild (1990), Hauschild and Mosch (1992), and Pavinatto *et al.* (2000).

The methods developed to assess the lightning impulse strength may be grouped in the following categories, according to the CIGRE WG 33.07 Report (1992):

- general physical models applied in gaseous, liquid, and solid insulations (KUFFEL; ZAENGL; KUFFEL, 2000);
- integration method (WITZKE; BLISS, 1950a, 1950b);
- simple formulae, based on data interpolation (DARVENIZA, POPOLANSKY, WHITEHEAD, 1975; CORTINA *et al.*, 1980; IEEE Std. 1243, 1997).

When a discharge heavily involves the insulator, the CIGRE WG 33.07 Report (1992) concludes that in order to predict the volt–time curve, the best accuracy is given by the integration method. This indicates that the breakdown process in gases is complex and involves various phases. Detailed descriptions of the breakdown phenomena can be found in (KUFFEL, E.; ZAENGL; KUFFEL, J., 2000; COORAY *et al.*, 2012).

2.1. DE model: review and some applications

In 1994, the Lightning and Insulator Subcommittee of the T&D Committee, Task Force 15.09 on Non-standard Lightning Voltage Waves, reviewed and summarized several studies on non-standard lightning overvoltage in two papers. One of the topics covered non-standard impulse waveshapes using the Disruptive Effect model, which is summarized as follows:

- Torok and Ramberg (1929) discuss the surge flashover mechanism influenced by factors such as applied voltage characteristics, electrical breakdown in air at atmospheric pressure, voltage electrostatic field, and the nature of electrodes. They introduced the term “active portion,” which refers to the region above the onset voltage V_0 in the volt–time curve that possibly leads to breakdown in the insulator under a voltage test;
- Hagenguth (1941) and Kind (1958) independently developed, in the USA and Germany, respectively, during the Cold War, similar methodologies to evaluate insulation strength. The basic concept was to use the equivalent area (“active portion,” constant area criteria, or “equal-area” criterion) above the onset voltage V_0 to assess the insulator’s breakdown strength on the basis of experimental records;
- Based on the integration method, Witzke and Bliss (1950a, 1950b) proposed the Disruptive Effect model, as follows:

$$DE = \int_{t_0}^{t_b} [v(t) - V_0]^K \cdot dt \quad (2),$$

where $v(t)$ is the voltage stressing the dielectric at time t , V_0 is the onset voltage, t_0 is the time at which $v(t_0) = V_0$, and t_b is the time to breakdown. Equation (2) was initially used to evaluate the effect of non-standard surge voltage waveshapes on oil-insulated transformers. They and Jones (1954) used this method in a particular case to assess the time to breakdown t_b , considering a simplified equation, $DE = \int_0^{t_b} [v(t)]^K \cdot dt$, where V_0 and t_0 were also simplified and conveniently considered zero. Gross, Bliss and Dillard (1952) defined the per-unit severity index (*SI*) or equivalent standard wave (*ESW*) concept as follows: “[...] *SI* of any given wave as the peak magnitude of a standard 1.5 / 40 μ s wave, which has the same *DE* value as the given wave [...]”. The waveshape of 1.5 / 40 μ s was the standard lightning voltage waveshape at that time in the USA;

- Rusck (1959) presented research covering the effects of non-standard voltage surges on insulators, which were basically classified in internal and external insulations. The author modeled the spark-gap as an extension of the electrodes and deduced a formula for the time to breakdown, taking into account the instantaneous voltage and the length of the gap. The final formula was written as, $DE = \int_0^{t_b} [v(t)]^3 \cdot dt$ which is similar to the one proposed by Witzke and Bliss and by Jones, assuming $K = 3$.
- In 1973, Caldwell and Darveniza presented the effect of non-standard waveshapes on the impulse strength of external insulation, both experimentally and analytically. The authors selected various types of waveshapes, including long-front waves, semi-chopped waves, and oscillatory waves, which were applied in typical air-gaps and insulators strings. A theoretical investigation was conducted on the basis of the selection the values of *DE* parameters. Subsequently, these analytical models were evaluated in order to predict V_{50} voltages and the volt–time curves for non-standard waveshapes. Thereafter, the $V \times t$ curves were compared with those experimental studies of leader propagation and pre-breakdown currents. Based on the results, they suggested a modification in the onset voltage as $V_0(t) = V_0 \left[1 + \frac{DE(t)}{DE(t_b)} \right]$ with $K = 1$, whereby the V_0 value depends on the breakdown process influence. $DE(t)$ is the instantaneous value of the disruptive effect, and $DE(t_b)$ is the full value of *DE* associated with the standard wave breakdown at the time t_b . Darveniza and Vlastos (1988) estimate *DE* by assuming $K = 1$ and $V_0 \approx 0.9 \times V_{50}$, where

V_{50} is the peak value of the standard lightning impulse voltage waveshape that has a 50 % probability of producing a disruptive discharge (also known as *CFO*, the critical flashover overvoltage, according to IEEE Std. 1410 (2010)). Their *DE* analysis showed that for small values of V_0 ($0 \leq V_0 \leq 0.5 \times V_{50}$), K is large ($K = 3-5$). If V_0 is large ($V_0 \sim 0.9 \times V_{50}$), K is equal to or lower than 1.

- Chowdhuri *et al.* (1997) proposed the following:

$$V_0 = V'_{50} - k \cdot \sigma \quad (3),$$

and

$$K = \alpha \cdot \frac{v(t)}{V_0} \quad (4),$$

where V'_{50} refers to the specific voltage stressing waveshape and Equation (3) is known as the lower tolerance limit, which follows a normal distribution. In Equation (3), σ is the standard deviation obtained from tests employing the multiple-level method (NBR 6936, 1992; IEC 60060-1, 2010; IEEE Std 4, 2013) and $\sigma = V'_{50} - V'_{16}$, where V'_{16} is the 16% probability of producing a disruptive discharge. $k = k(P, \gamma, \nu)$ is a factor obtained from the one-sided tolerance limit (OWEN, 1962; BEVINGTON; ROBINSON, 1980; MONTGOMERY; RUNGER, 2002), where P is the portion of the samples (assumed to be 0.999) greater than V_0 , γ is the confidence interval (assumed to be 0.95) and ν is the number of degrees of freedom given by the number of data points (n) minus one. The number of data points n corresponds to the number of voltage levels considered in the multiple-level tests. The parameter α depends on the type of air gap and waveshape.

After computing V_0 , α is derived from the two-by-two combination $C_{m,2}$ of the number of impulse voltage profiles from the experimental $V \times t$ characteristic (number of voltage levels m multiplied by the number of voltage applications for each level, giving a total of M). This calculation is performed to determine the *DE* constant and is computed in pairs.

The next step is to calculate the mean square deviation $\sigma_{DE\%}$, i.e., the relationship between the standard deviation σ_{DE} and mean *DE*, as shown in Equation (5). Each $\sigma_{DE\%}$ is computed by averaging *DE* from all voltage profiles obtained in the volt–time tests and for each α , which was previously calculated.

$$\sigma_{DE\%} = \frac{\sigma_{DE}}{DE} \cdot 100 \quad (5)$$

The best value of α is the one that leads to the minimum value of $\sigma_{DE\%}$;

- Hileman (1999) proposed a Severity Index (*SI*) for evaluating the surge voltage of non-standard waveshapes for self-restoring insulators. *SI* represents a measure of the severity of a surge on the insulation. *SI* can be used to determine the margin between maximum peak voltage and *CFO* or to establish the *CFO* for non-standard waveshapes for general use. The parameters involved in the calculation of the *SI* are measured peak voltage and *CFO* or basic insulation level (*BIL*). Alternative methods for estimating *SI* are based on a leader progression model (LPM) (DELLERA; GARBAGNATI, 1989, 1990) and DE model. With regard to the DE model, the authors proposed practical values of $K = 1.36$ and $V_0 = 0.77 \times CFO$ in order to estimate *DE* of non-standard waveshapes. The *DE* base (DE_C) value was determined using $DE_C = 1.1506 \times CFO^{1.36}$ (1 μ s base) and considered as the critical *DE* value for an air-porcelain insulator. The insulator breakdown occurs when the calculated *DE* is larger than DE_C .
- Ancajima *et al.* (2006) proposed a modification in the procedure for calculating V_0 , according to the following:

$$V_0 \leq V'_{50} - k \cdot \sigma^* \quad (6),$$

where,

$$\sigma^* = \sigma \cdot \sqrt{\frac{n}{n-2}} \quad (7).$$

In 2007, a new condition for determining V_0 was proposed by the authors, which stated that the value calculated from Equation (6) must also satisfy the following requirement:

$$V_0 \leq v(t_{bM}) \quad (8),$$

where $v(t_{bM})$ is the voltage corresponding to the longest recorded time to breakdown (t_{bM}) among M applications of $V \times t$, characteristic of a specific impulse voltage and polarity. This condition considered necessary because in some cases, particularly for impulse waveshapes with short tails, the breakdown voltage is smaller than V_0 derived from Equation (6). Fig. 1 illustrates an example of $v(t_{bM})$ during an impulse voltage test, where V_0 was calculated according to Equation (6).

Figure 1 - An example of $v(t_{bM})$ occurrence (15 kV class, 1.2 / 10 μ s waveshape, and positive polarity).

Based on tests performed on two composite insulators rated 3 kV d.c. used in Italian electric traction lines, Ancajima *et al.* (2010) showed that it is possible to predict the volt–time characteristics for short tail lightning impulses with satisfactory accuracy by assuming $K = 1$ and estimating V_0 and DE from flashover data obtained using a standard lightning impulse.

Concerning the DE model and *CFO* criteria, some application examples are as follows: the CENDAT/USP group has applied the DE model since the 1990s, based on Darveniza and Vlastos (1988), in order to evaluate the insulator disruption in distribution systems using the Alternative Transient Program (ATP) (OBASE *et al.*, 2005, 2006; PIANTINI *et al.*, 2012).

The measured input data used in the circuit designs were obtained from standard impulse voltage tests performed in the high-voltage laboratory. Braz *et al.* (2014) performed extensive tests using the various DE model procedures and the standard and non-standard impulse voltages applied to a 15 kV insulator. The authors compared the experimental records and those obtained using the main methods. They concluded that the method of Ancajima *et al.* (2010) exhibited the best adjustment between the measured and calculated times to breakdown; De Conti *et al.* (2010) investigated the actual insulation volt–time curves in the lightning-induced voltages of distribution lines and estimated the number of flashovers on an overhead wire due to nearby lightning strikes. The flashover mechanism was modeled on the basis of the DE model, and the *CFO* reference used was that recommended by IEEE Std. 1410 (2010). The results suggest to use a $1.2 \times CFO$ value, which is sufficient for estimating a realistic flashover rate, instead of a threshold level of $1.5 \times CFO$ in the considered case. This result was confirmed by statistical analyses using a Monte Carlo-based approach.

Lopes *et al.* (2013) presented and discussed the critical flashover voltage of the standard and 13 types of non-standard impulse voltage waveshapes of both polarities, in the distribution insulators. The tests were conducted using the up-and-down method, considering both dry and wet conditions. The authors discussed the influence of front and tail times on the basis of the V'_{50} values. The results assured that the standard impulse shape is adequate to represent some of the induced lightning voltage stresses in the dielectric tests and lightning studies. In addition, for a particular waveshape, the positive polarity V'_{50} under dry conditions is, in most cases, sufficient to set as the lowest V'_{50} level and no further testing is necessary.

Wang, Yu, and He (2014) built a model to accurately characterize the insulator breakdown process based on LPM, which was applied to typical porcelain and composite insulators under both negative and positive polarity impulses. The multiple-string-length insulator-breakdown experiments used in transmission lines were conducted under a short-tail impulse. The leader progression model was then developed utilizing voltage records, current data, and high-speed camera photos. Finally, the models were validated using PSCAD™/EMTDC™ software. Visacro and Silveira (2015a, 2015b) proposed a novel methodology in order to obtain the minimum electrode length of transmission lines on the basis of the design of tower-footing electrodes and assuming a defined outage rate of these transmission lines. The methodology was performed for direct strike currents (first-stroke) in order to assess the overvoltages. The

possibility of backflashover was determined using the DE model. The soil parameters, including resistivity and permittivity, were considered in the analysis.

Paulino *et al.* (2015) showed the influence of waveshape parameters from lightning-induced voltages (front-time and time-to-half value) by the ground resistivity, line length, and the distance between the flash and the line. The effect of the overvoltage waveshape, produced by indirect lightning in aerial distribution lines, was assessed using the DE model as the flashover criteria. The authors showed that the flashover rates significantly differ from those obtained when only the peak value is used as the flashover criterion, as recommended by IEEE Std. 1410 (2010).

2.2. DE model: estimation of its parameters and application on the basis of the method of Ancajima *et al.*

The DE model theory, as presented for Witzke and Bliss (1950a, 1950b), can be developed from a generalized insulation breakdown model, according to the theory described in the EPRI Red Book (2005) as follows:

In general, considering that a streamer or leader travels from one electrode to another with Δx step in time Δt ,

$$\Delta x = \delta \cdot [V(t) - V_0]^K \cdot \Delta t \quad (9),$$

where δ depends on the gap length, and when this gap is completely bridged at time t_b ,

$$S = \sum_{t_0}^{t_b} \delta \cdot [V(t) - V_0]^K \cdot \Delta t \quad (10),$$

where S is the gap length of the electrodes. In the limit, Equation (10) becomes

$$DE = \int_{t_0}^{t_b} [V(t) - V_0]^K \cdot dt \quad (11),$$

where for this condition, $DE = \frac{S}{\delta}$.

Because the DE model integration requires attention to several details, including the virtual origin, time to breakdown, and peak voltage, these values are derived using specific routines in Scilab workspace, version 5.3.3, 2007 (GOMEZ, 1999; CAMPBELL; CHANCELIER; NIKOUKHAH, 2006). This software is a free open-source package for scientific computation. The following items show the software's difficulties and their adopted solutions:

- peak voltage V_p : the maximum voltage value reached in each application considered. This study did not take into account the effect of oscillations at the maxima, emphasizing that the peak values obtained by the digitizer were very close to those calculated in the routines developed for the Scilab app. The relative difference in peak voltage between the calculated and measured values found in the tests was approximately 1%;
- virtual origin 0_1 : an impulse voltage waveshape commonly shows oscillations around the peak region. Furthermore, the voltage breakdown during the rise time causes significant variation in the virtual origin. Moreover, the virtual origin calculations refer to the maximum voltage at any peak (IEC 60060-1, 2010; IEEE Std. 4, 2013). This is important for evaluating the time to breakdown based on a full lightning impulse waveshape from a measured data profile. Thus, a constant value for the virtual origin was adopted from calculations at times t_{30} and t_{90} and voltages $0.3 \times V_p$ and $0.9 \times V_p$, respectively, all of which referred to as the representative full wave. Hence, the time corresponding to the virtual origin was determined through the ratio between the linear and angular coefficients, derived from the rectangular coordinates $(t_{30}, 0.3 \times V_p)$ and $(t_{90}, 0.9 \times V_p)$ using the linear extrapolation;
- time to breakdown t_b : the chopping time was determined by comparing the angular coefficient of the straight line obtained through the linear regression of ten successive points acquired by a digitizer with angle $\pi/2$. The time corresponding to the last of these ten points for which the ratio of the angular coefficient with $\pi/2$ is greater or equal than 0.999999 was considered as the time to breakdown.

Fig. 2 shows the block diagram used to compute DE and α , according to the method of Ancajima *et al.* (2010).

Figure 2 - Block diagram to calculate the values of α and DE .

Figs. 3 to 5 show the relationships between the parameters α and $\sigma_{DE\%}$ derived from the method of Ancajima *et al.* (2010) for the five negative and positive polarity impulse waveshapes from the voltage impulse tests performed in the 15 kV, 24 kV, and 36 kV voltage class insulators. Details of insulator types, assembled circuits, and waveshape types, applied in the tests, are described in Chapter 4. The curves presented in Fig. 3a show that the minimum $\sigma_{DE\%}$ values are well defined for 1.2 / 4 μ s and 1.2 / 10 μ s waveshapes but not for the other waveshapes. In the case of positive polarity, as shown in Fig. 3b, the values of α , corresponding to the minimum values of $\sigma_{DE\%}$, are reasonably well defined, except for the 7.5 / 30 μ s waveshape, whereby the variation of $\sigma_{DE\%}$ with α is relatively small in the range of interest ($\alpha < 0.6$).

Figure 3 - Relationship between parameters α and $\sigma_{DE}\%$ for the five impulse waveshapes (15 kV insulator).

a) Negative polarity

b) Positive polarity

With regard to the tests performed in the 24 kV insulator, Fig. 4a shows that the minimum $\sigma_{DE}\%$ values are not well defined only for the 7.5 / 30 μs waveshapes. Fig. 4b shows that the minimum $\sigma_{DE}\%$ values are well defined in all cases considered.

Figure 4 - Relationship between parameters α and $\sigma_{DE}\%$ for the five impulse waveshapes (24 kV insulator).

a) Negative polarity

b) Positive polarity

Fig 5, relevant to the tests conducted in the 36 kV insulator, indicates that the minimum $\sigma_{DE\%}$ values are well defined for the five impulse waveshapes considered. However, in some cases, as shown in Figs. 3 and 4, the minimum $\sigma_{DE\%}$ values are not well-defined, and for such cases an alternative methodology for the estimation of the DE parameters could lead to improved results. This observation motivated the development of the procedure described in Chapter 3.

Figure 5 - Relationship between parameters α and $\sigma_{DE\%}$ for the five impulse waveshapes (36 kV insulator).

a) Negative polarity

b) Positive polarity

3 A NEW METHOD FOR ESTIMATION OF THE PARAMETERS FOR THE APPLICATION OF THE DE MODEL

The evaluation of insulator disruption in electrical systems can be performed using *CFO* criteria or the DE model. The DE model is usually applied using the parameters derived according to the methods of Darveniza and Vlastos (1988) or Hileman (1999). More sophisticated procedures, such as those proposed by Chowdhuri *et al.* (1997) or Ancajima *et al.* (2010) require the performance of several tests.

In the methods of Chowdhuri *et al.* (1997) and Ancajima *et al.* (2010), the minimum mean square deviation $\sigma_{DE\%}$ value is used to “calibrate” an optimal volt–time curve based on the α value. Note that the parameter K is calculated according to Equation (4), and its value is directly proportional to the α value.

However, as shown in the curves presented in Figs. 3 to 5, in some cases α cannot be precisely determined and therefore an alternative technique for its estimation is proposed in this section.

This optimum α value depends on the measured and calculated times to breakdown (t_{mj} and t_{cj} , respectively). Subsequently, using the DE and V_0 values estimated according to Ancajima *et al.* (2010), the optimum α value is estimated on the basis of the following parameter:

$$\varepsilon_T = \frac{1}{M} \sum_{j=1}^M \frac{(t_{cj} - t_{mj})}{t_{mj}} \quad (12),$$

where j is the specific voltage level ($1 \leq j \leq M$) adopted for the construction of the volt–time curve.

In order to find the optimum α value, the bisection technique was adopted to solve (11), for a certain α range. The optimum value of α (α^*) corresponds to the value of ε_T closest to zero, which is found in the transition from negative to positive values. The lower limit corresponds to the maximum α for which insulation breakdown is not predicted; as the α value is not known a priori, the adopted range of α was from 0.01 to 1.

The optimum DE value (DE^*) was obtained using the calculated values of V_0 and α^* .

Figs. 6, 7, and 8 show, for the tests performed in the 15 kV, 24 kV, and 36 kV voltage class insulators, respectively, the relationships between α and ε_T for the five impulse voltage waveshapes, considering both polarities.

Figure 6 - Relationship between α and ε_T for the five impulse waveshapes.

(15 kV insulator)

a) Negative polarity

b) Positive polarity

Figure 7 - Relationship between α and ε_T for the five impulse waveshapes.

(24 kV insulator)

a) Negative polarity

b) Positive polarity

**Figure 8 - Relationship between α and ϵ_T for the five impulse waveshapes.
(36 kV insulator)**

a) Negative polarity

b) Positive polarity

Clearly, the optimum α values are well defined for all the waveshapes and polarities considered. In Chapter 5, the various procedures used to calculate the $V \times t$ curve are compared with one another, including the proposed method and those obtained from laboratory impulse tests.

4 HIGH-VOLTAGE LABORATORY TESTS

High-voltage laboratory tests were conducted at the High Voltage Laboratory of the Institute of Energy and Environment of the University of São Paulo (IEE-USP) using a Marx impulse generator with a maximum voltage of 3 MV, total energy of 225 kJ, and total capacitance of 50 nF. The capacitance, energy, and voltage corresponding to each of the 15 stages are 750 nF, 15 kJ, and 200 kV, respectively. Test assemblies and tolerances and the determination of the correction factors under ambient conditions were performed according to national and international standards (NBR 6936, 1992; IEC 60060-1, 2010; IEEE Std. 4, 2013).

Different combinations of resistors, capacitors and air-core inductors were used for the generation of the impulse voltage waveshapes considered in the tests. The general scheme of the lumped circuit used to generate these impulse waveshapes is illustrated in Fig. 9 (BRAZ, 2011).

Figure 9 - General lumped circuit scheme used to generate the high-voltage impulses of different waveshapes (adapted from BRAZ, 2011).

In Fig. 9, R is the resistance for the short wavetail adjustment, R_1'' is the external front resistance, which controls the front-time, R_2'' is the external tail resistance, L is the inductance for short wavetails (CARRUS *et al.*, 1999), and C_2 is derived by summing the additional load capacitance, stray capacitance, and insulator capacitance, which has a value of approximately C_2 . Table 1 shows the values of the circuit components of the impulse generator for the five test waveshapes.

Table 1 – Impulse generator circuit component values for the five test waveshapes (15 kV insulator) (BRAZ *et al.*, 2011).

Impulse Waveshape	Number of stages	R (Ω)	R ₁ '' (Ω)	R ₂ '' (Ω)	L (mH)	C ₂ (pF)
1.2 / 4 μ s	3	90	110	15	0.37	~2700
1.2 / 10 μ s	3	100	200	100	0.37	~2700
1.2 / 50 μ s	3	---	880	255	---	~300
3 / 10 μ s	5	---	800	10	0.63	~2300
7.5 / 30 μ s	15	---	180	4450	---	~1740

A general view of the test setup is shown in Fig. 10.

Figure 10 – Test setup (15 kV insulator, 7.5 / 30 μ s waveshape).

Fig. 11 shows examples of the components and arrangements performed in the tests.

Figure 11 – The test setup composed of resistors, air-core inductors, and high-voltage capacitors.

Each insulator was placed above a metal rod located vertically, 1.05 m above the metal grounded base, as shown in Fig. 12a (ABNT NBR 5032, 2004; IEC 60383-1, 1993). The tested insulators had voltage classes of 15 kV, 24 kV, and 36 kV, all pin-type and made of porcelain, typically used in distribution systems in Brazil, as shown in Figs. 12b, 12c, and 12d, respectively. The insulators subjected to impulse tests have the following characteristics according to their manufacturers:

- 15 kV class: Santa Terezinha, reference 1114, rated voltage of 15 kV, BIL of 95 kV, dry arc distance of 140 mm, leakage distance of 230 mm, negative V_{50} of 140 kV, and positive V_{50} of 115 kV;
- 24 kV class: Siklowatt, model PI25MN25-M, rated voltage of 25 kV, BIL of 125 kV, leakage distance of 318 mm, negative V_{50} of 170 kV, and positive V_{50} of 140 kV;
- 36 kV class: Santa Terezinha, reference 23105, rated voltage of 36 kV, BIL of 150 kV, dry arc distance of 240 mm, leakage distance of 530 mm, negative V_{50} of 265 kV, and positive V_{50} of 200 kV.

Figure 12 - (a) Pedestal used to support the pin-type insulator; (b) Sample of the 15 kV insulator; (c) Sample of the 24 kV insulator; and (d) Sample of the 36 kV insulator.

The capacitance measured for insulator of 15 kV class was about 20 pF and the dry arc distance measured for insulator of 24 kV class was 210 mm. Fig. 13 shows a detailed schematic of the tested insulators and their dimensions.

Figure 13 - Design of insulators: (a) 15 kV class; (b) 24 kV class; and (c) 36 kV class.

The selection of the impulse test waveshapes was based on lightning-induced voltage waveshapes measured in reduced-scale and full-scale systems (PIANTINI, 1997; PIANTINI *et al.*, 2004), considering, as illustrated for instance in Fig. 14.

Figure 14 - Examples of measured lightning-induced voltages (adapted from Piantini, 1997; and Piantini *et al.*, 2004).

Based on the waveshapes obtained in (PIANTINI, 1997; PIANTINI *et al.*, 2004), in order to obtain some representative non-standard unipolar waveshapes, suitable adjustments were made in the Marx impulse generator at the High Voltage Laboratory. A comparison between the 1.2 / 4 μs waveshape obtained in the laboratory and a lightning induced voltage measured in the full-scale system is shown in Fig. 15.

Figure 15 – Comparison between one of the measured lightning-induced voltages and the corresponding impulse voltage generated at the High-Voltage Laboratory at IEE/USP (1.2 / 4 μs waveshape, positive polarity) (adapted from BRAZ, 2011).

The lightning impulse voltage tests were performed for both polarities and under dry conditions for four representative non-standard waveshape types (1.2 / 4 μs , 1.2 / 10 μs , 3 / 10 μs , and 7.5 / 30 μs) and the standard waveshape (1.2 / 50 μs) as well.

Subsequently, for each type of impulse voltage waveshape selected, three different tests were conducted: up-and-down method, multiple-level method, and volt–time curves (NBR 6936, 1992; IEC 60060-1, 2010; IEEE Std. 4, 2013). Fig. 16 shows an example of the result of the multiple-level test application given as a normal cumulative distribution. Each point was obtained from the mean of 5 or 10 peak voltages at the same level.

Figure 16 - Example of the cumulative probability obtained in the multiple-level method test (15 kV insulator, 1.2/10 μ s waveshape, positive polarity).

In the straight linear portion of Fig. 16, the equation is given by $V_p(p) = 0.0964 p + 124.78$. This equation was obtained by linear regression. For this example, $V_{50} = 129.6$ kV and $\sigma = 3.3$ kV. Based on the method of Chowdhuri *et al.* (1997), the value of k is calculated for k (0.999, 0.95, 4), where $n = 5$ (number of voltage levels); thus, $v = 4$. Subsequently, based on Owen (1962), k is 7.509 and the minimum voltage to initiate breakdown is $V_0 = 104.8$ kV. Thus, for $V_0 = 104.8$ kV, the cumulative probability of disruption is only approximately 2.84×10^{-14} (2.84×10^{-12} %). For the method of Ancajima *et al.* (2010), the statistical onset voltage is 97.8 kV, but $v(t_{bM})$ is 75.5 kV, which means that the onset voltage must be the lower voltage, i.e., $V_0 = 75.5$ kV (cumulative probability of disruption is 1.06×10^{-58} %). Darveniza and Vlastos (1988) set the onset voltage as $0.9 \times CFO$, which implies $V_0 = 0.9 \times 112.8 = 101.5$ kV. Finally, in the method of Hileman, the onset value is calculated as $V_0 = 0.77 \times CFO$, which means $V_0 = 0.77 \times 112.8 = 86.9$ kV.

The up-and-down test was performed in order to estimate the initial value of V'_{50} of each waveshape type and polarity. This value of V'_{50} was used as a reference for the multiple-level

test, considering that the relative difference between the V'_{50} values for both tests was limited up to 3 %.

The volt–time test permits an evaluation of the relationship between the time to breakdown t_b and voltage level V_p , starting from a value close to the onset voltage V_0 . An estimation of the characteristic curve was proposed by Darveniza, Popolansky, and Whitehead (1975) and adopted by IEEE Std. 1243 (1997) as follows:

$$V_p(t_b) = \left(A + \frac{B}{t_b^{0.75}} \right) \cdot w \quad (13),$$

where the weights A and B can be calculated by regression, based on the measured $V \times t$ data, and w is the insulator length.

5 ANALYSIS OF DIFFERENT PROCEDURES AND A NEW PROPOSAL FOR THE EVALUATION OF THE DIELECTRIC STRENGTH OF MV DISTRIBUTION INSULATORS

This chapter is subdivided into three parts. Section 5.1 presents, for the three standard medium-voltage distribution classes (15 kV, 24 kV, and 36 kV) and the five positive and negative polarity impulse voltage waveshapes, the prospective test voltage value that has a 50% probability of producing a disruptive discharge (V'_{50}) and standard deviation (σ), obtained from multiple level tests. After presenting parametric analysis used to illustrate the influence of V_0 , α , and DE on the calculated volt–time curves, comparisons are provided between the experimentally derived volt–time curves and those predicted by the procedures proposed in Chowdhuri *et al.* (1997), in Ancajima *et al.* (2010), and in Chapter 3 of this dissertation.

Based on test results, in Section 5.2, a new and simple method is proposed for evaluating the dielectric behavior of MV insulators of the three voltage classes considered. A general equation, relevant for the standard waveshape (1.2 / 50 μ s), is provided, which relates the critical DE value with the insulator CFO . This critical value, used in conjunction with the proposed values of α and V_0 , allows one to obtain the insulator volt–time curves of the five positive and negative polarity waveshapes tested.

The proposed method is validated in Section 5.3 on the basis of comparisons of the predicted volt–time curves with those obtained from the tests and using the methods of Darveniza and Vlastos (1988) and Hileman (1999).

5.1. Comparisons between the procedures based on laboratory tests

This subsection presents comparisons between the mean relative differences in the times to breakdown, taking the measured values as reference, derived from the methods of Chowdhuri *et al.* (1997) and Ancajima *et al.* (2010), in addition to the one presented in Chapter 3.

Initially, for the three insulator voltage classes and the five positive and negative impulse voltage waveshapes considered, the parameters required for applying the DE model are

obtained according to the three methods. The calculated V'_{50} , V'_{16} , and σ values and the ratio σ/V'_{50} are also shown for each case. Parametric analysis is then performed to illustrate the influence of V_0 , α , and DE on the calculated volt–time curves. Finally, the measured volt–time curves are presented and compared with the curves predicted using the three methods.

5.1.1. 15 kV insulator

Table 2 shows a summary of the data obtained using the multiple-level method for the 15 kV insulator. The highest V'_{50} values were obtained for the shortest tail impulse (1.2 / 4 μ s waveshape), whereas the lowest values correspond to the impulses with longer wavetails (7.5 / 30 μ s and 1.2 / 50 μ s waveshapes).

Table 2 – Summary of data obtained from multiple-level method (15 kV class).

Waveshape	Polarity	n	V'_{50} (kV)	V'_{16} (kV)	σ (kV)	σ/V'_{50} (%)
1.2 / 4 μ s	Neg.	5	151.2	148.0	3.1	2.1
	Pos.	5	134.2	129.6	4.5	3.4
1.2 / 10 μ s	Neg.	5	146.9	142.7	4.2	2.9
	Pos.	5	129.6	126.3	3.3	2.5
1.2 / 50 μ s	Neg.	5	133.2	128.4	4.8	3.6
	Pos.	5	112.8	109.1	3.7	3.3
3 / 10 μ s	Neg.	5	140.6	137.0	3.7	2.6
	Pos.	5	117.6	114.4	3.2	2.7
7.5 / 30 μ s	Neg.	5	134.8	129.3	5.5	4.1
	Pos.	5	111.3	106.7	4.6	4.1

Tables 3 to 5 present the results obtained after applying the main methods for estimating the DE model parameters (Chowdhuri *et al.*, Ancajima *et al.*, as well as the one proposed in Chapter 3). As indicated in these tables, for the five positive and negative polarity impulse waveshapes, the α values remained in the range of 0.1 to 0.6.

Table 4 also shows the comparisons between the statistically calculated and $v(t_{bM})$ voltage values. The lower of these two values corresponds to the optimal onset voltage (V_0).

Table 3 – DE model parameters according to the method of Chowdhuri *et al.* (1997):
15 kV class.

Waveshape	Polarity	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	127.6	0.1762	6.93×10^{-6}
	Pos.	100.2	0.1391	9.00×10^{-6}
1.2 / 10 μ s	Neg.	115.3	0.2332	2.85×10^{-5}
	Pos.	105.0	0.2085	2.26×10^{-5}
1.2 / 50 μ s	Neg.	97.0	0.3457	5.81×10^{-4}
	Pos.	84.7	0.1883	4.40×10^{-5}
3 / 10 μ s	Neg.	113.2	0.2998	1.07×10^{-4}
	Pos.	93.7	0.2839	1.03×10^{-4}
7.5 / 30 μ s	Neg.	93.5	0.3519	9.95×10^{-4}
	Pos.	76.8	0.4519	6.53×10^{-3}

Table 4 – DE model parameters according to the method of Ancajima *et al.* (2010):
15 kV class.

Waveshape	Polarity	$V'_{50} \cdot k \cdot \sigma^*$ (kV)	$v(t_{bM})$ (kV)	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	120.7	69.6	69.6	0.1364	3.50×10^{-5}
	Pos.	90.3	68.6	68.6	0.1365	2.90×10^{-5}
1.2 / 10 μ s	Neg.	106.1	93.8	93.8	0.2569	1.17×10^{-4}
	Pos.	97.8	75.5	75.5	0.1666	3.98×10^{-5}
1.2 / 50 μ s	Neg.	86.5	137.7	86.5	0.3124	6.94×10^{-4}
	Pos.	76.5	114.7	76.5	0.1738	5.04×10^{-5}
3 / 10 μ s	Neg.	105.2	131.7	105.2	0.2918	1.44×10^{-4}
	Pos.	86.7	83.0	83.0	0.2809	1.91×10^{-4}
7.5 / 30 μ s	Neg.	81.5	131.1	81.5	0.2307	3.05×10^{-4}
	Pos.	66.7	105.0	66.7	0.3682	4.65×10^{-3}

Table 5 – DE model parameters according to the proposed method: 15 kV class.

Waveshape	Pol.	V_0 (kV)	α^*	DE^*
1.2 / 4 μ s	Neg.	69.6	0.1365	3.50×10^{-5}
	Pos.	68.6	0.1362	2.90×10^{-5}
1.2 / 10 μ s	Neg.	93.8	0.2570	1.17×10^{-4}
	Pos.	75.5	0.1657	3.98×10^{-5}
1.2 / 50 μ s	Neg.	86.5	0.3190	6.94×10^{-4}
	Pos.	76.5	0.1778	5.04×10^{-5}
3 / 10 μ s	Neg.	105.2	0.2967	1.44×10^{-4}
	Pos.	83.0	0.2824	1.91×10^{-4}
7.5 / 30 μ s	Neg.	81.5	0.2302	3.05×10^{-4}
	Pos.	66.7	0.3931	4.65×10^{-3}

Figs. 17 to 21 compare the volt–time curves obtained from the tests with the curves calculated according to the proposed procedure (i.e., using the values of DE^* and α^* indicated in Table 5) but considering different values for V_0 . All figures indicate that the time to breakdown increases with V_0 and, in the case of relatively high V_0 , breakdown may not be predicted at lower voltage levels.

Figure 17 - Influence of V_0 on the $V \times t$ curves for the 1.2 / 4 μ s waveshape (15 kV class).

a) Negative polarity

($DE^* = 3.50 \times 10^{-5}$ and $\alpha^* = 0.1365$)

b) Positive polarity

($DE^* = 2.90 \times 10^{-5}$ and $\alpha^* = 0.1362$)

Figure 18 - Influence of V_0 on the $V \times t$ curves for the 1.2 / 10 μs waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 1.17 \times 10^{-4} \text{ and } \alpha^* = 0.2570)$$

b) Positive polarity

$$(DE^* = 3.98 \times 10^{-5} \text{ and } \alpha^* = 0.1657)$$

Figure 19 - Influence of V_0 on the $V \times t$ curves for the 1.2 / 50 μs waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 6.94 \times 10^{-4} \text{ and } \alpha^* = 0.3190)$$

b) Positive polarity

$$(DE^* = 5.04 \times 10^{-5} \text{ and } \alpha^* = 0.1778)$$

(a)

(b)

Figure 20 - Influence of V_0 on the $V \times t$ curves for the 3 / 10 μ s waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 5.27 \times 10^{-5} \text{ and } \alpha^* = 0.2967)$$

b) Positive polarity

$$(DE^* = 1.91 \times 10^{-4} \text{ and } \alpha^* = 0.2824)$$

(a)

(b)

Figure 21 - Influence of V_0 on the $V \times t$ curves for the 7.5 / 30 μ s waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 3.05 \times 10^{-4} \text{ and } \alpha^* = 0.2302)$$

b) Positive polarity

$$(DE^* = 4.65 \times 10^{-3} \text{ and } \alpha^* = 0.3931)$$

To investigate the influence of the parameter α , the values of DE^* and V_0 were fixed, as indicated in Table 5, and the volt–time curves were obtained for different values of α , as shown in Figs. 22 to 26. For the same variation in α , a larger variation in the time to breakdown is observed when the lower values of α are considered. This behavior is clearly illustrated in Fig. 24a for the 1.2/50 μs negative polarity waveshape.

Figure 22 - Influence of α on the $V \times t$ curves for the 1.2 / 4 μs waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

$(DE^* = 3.50 \times 10^{-5} \text{ and } V_0 = 70 \text{ kV})$

$(DE^* = 2.90 \times 10^{-5} \text{ and } V_0 = 69 \text{ kV})$

Figure 23 - Influence of α on the $V \times t$ curves for the 1.2 / 10 μs waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

$(DE^* = 1.17 \times 10^{-4} \text{ and } V_0 = 94 \text{ kV})$

$(DE^* = 3.98 \times 10^{-5} \text{ and } V_0 = 76 \text{ kV})$

Figure 24 - Influence of α on the $V \times t$ curves for the 1.2 / 50 μs waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 6.94 \times 10^{-4} \text{ and } V_0 = 87 \text{ kV})$$

b) Positive polarity

$$(DE^* = 5.04 \times 10^{-5} \text{ and } V_0 = 77 \text{ kV})$$

Figure 25 - Influence of α on the $V \times t$ curves for the 3 / 10 μs waveshape (15 kV class).

a) Negative polarity

$$(DE^* = 5.27 \times 10^{-5} \text{ and } V_0 = 105 \text{ kV})$$

b) Positive polarity

$$(DE^* = 1.91 \times 10^{-4} \text{ and } V_0 = 83 \text{ kV})$$

Figure 26 - Influence of α on the $V \times t$ curves for the 7.5 / 30 μs waveshape (15 kV class).
a) Negative polarity ($DE^* = 3.05 \times 10^{-4}$ and $V_0 = 82$ kV)
b) Positive polarity ($DE^* = 4.65 \times 10^{-3}$ and $V_0 = 67$ kV)

Figs. 27 to 31 illustrate the effect of a DE variation on the time to breakdown. Analysis of the behavior of the volt–time curves shows that this effect is more pronounced when the DE range considered involves higher DE values, as illustrated in Fig. 28b (comparing, for example, the variations of the time to breakdown relative to curves $DE = 0.04 DE^*$ and $DE = 0.25 DE^*$ with the variations corresponding to the curves $DE = 1.0 DE^*$ and $DE = 1.5 DE^*$). The curves were obtained after setting α^* and V_0 to the values indicated in Table 5 and considering different values for DE . The lowest DE value adopted in the simulations, shown in detail in Fig. 28b, was the minimum value obtained from the tests for the V_0 and α values considered.

Figure 27 - Influence of DE on the $V \times t$ curves for the 1.2 / 4 μs waveshape (15 kV class).
a) Negative polarity ($V_0 = 70$ kV and $\alpha^* = 0.1365$)
b) Positive polarity ($V_0 = 69$ kV and $\alpha^* = 0.1362$)

Figure 28 - Influence of DE on the $V \times t$ curves for the 1.2 / 10 μs waveshape (15 kV class).

a) Negative polarity
($V_0 = 94$ kV and $\alpha^* = 0.2570$)

b) Positive polarity
($V_0 = 76$ kV and $\alpha^* = 0.1657$)

Figure 29 - Influence of DE on the $V \times t$ curves for the 1.2 / 50 μs waveshape (15 kV class).

a) Negative polarity
($V_0 = 87$ kV and $\alpha^* = 0.3190$)

b) Positive polarity
($V_0 = 77$ kV and $\alpha^* = 0.1778$)

Figure 30 - Influence of DE on the $V \times t$ curves for the 3 / 10 μs waveshape (15 kV class).

Figure 31 - Influence of DE on the $V \times t$ curves for the 7.5 / 30 μs waveshape (15 kV class).

Figs. 32 to 36 present a comparison of the experimentally derived volt–time curves and those predicted by the procedures proposed by Chowdhuri *et al.* (1997), Ancajima *et al.* (2010), and in Chapter 3 (identified as “Proposed Method” in the figures).

Figure 32 - Volt–time curve for the 1.2 / 4 μs waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

Figure 33 - Volt–time curve for the 1.2 / 10 μs waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 34 - Volt-time curve for the 1.2 / 50 μ s waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 35 - Volt-time curve for the 3 / 10 μ s waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

Figure 36 - Volt–time curve for the 7.5 / 30 μs waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

As shown in Figs. 32 to 36, the curves obtained using the three procedures are in general agreement with the insulator behavior when it is subjected to the various types of impulse voltages considered.

In most cases, the volt–time curves obtained using the method of Ancajima *et al.* (2010) and the proposed method have a similar behavior. The observed differences between the predicted times to breakdown are more evident in the 7.5 / 30 μs positive polarity waveshape case (Fig. 36b).

5.1.2. 24 kV insulator

Table 6 summarizes the measured data using the multiple-level method for the 24 kV insulator. The minimum and maximum values of the deviation σ/V'_{50} were found for the 1.2 / 4 μs and 7.5 / 30 μs , positive and negative polarity impulse waveshapes, respectively. As expected, the negative polarity V'_{50} values were always higher than the corresponding positive polarity values.

The DE parameters computed using the methods of Chowdhuri *et al.* (1997), Ancajima *et al.* (2010), and the one proposed here are shown in Tables 7, 8, and 9, respectively.

Table 6 – Summary of the values obtained using the multiple-level method (24 kV class).

Waveshape	Polarity	n	V'_{50} (kV)	V'_{16} (kV)	σ (kV)	σ/V'_{50} (%)
1.2 / 4 μ s	Neg.	5	199.3	195.8	3.4	1.7
	Pos.	5	183.0	174.2	8.8	4.8
1.2 / 10 μ s	Neg.	5	169.4	166.1	3.3	1.9
	Pos.	5	146.4	139.6	6.8	4.6
1.2 / 50 μ s	Neg.	5	164.4	162.0	2.4	1.5
	Pos.	5	142.9	136.9	6.0	4.2
3 / 10 μ s	Neg.	5	176.1	169.7	6.4	3.7
	Pos.	5	142.3	137.7	4.6	3.3
7.5 / 30 μ s	Neg.	5	171.8	160.9	10.9	6.3
	Pos.	5	135.2	128.4	6.8	5.0

Table 7 – DE model parameters according to the method of Chowdhuri *et al.* (1997): 24 kV class.

Waveshape	Polarity	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	167.6	0.2128	1.60×10^{-05}
	Pos.	102.2	0.1358	2.70×10^{-05}
1.2 / 10 μ s	Neg.	139.3	0.3110	1.72×10^{-04}
	Pos.	84.0	0.1571	1.00×10^{-04}
1.2 / 50 μ s	Neg.	142.0	0.3086	9.60×10^{-05}
	Pos.	87.7	0.1655	9.20×10^{-05}
3 / 10 μ s	Neg.	116.8	0.2472	1.82×10^{-04}
	Pos.	99.6	0.1523	3.40×10^{-05}
7.5 / 30 μ s	Neg.	71.5	0.2481	4.21×10^{-03}
	Pos.	72.4	0.1991	4.02×10^{-04}

Table 8 – DE model parameters according to the method of Ancajima *et al.* (2010):
24 kV class.

Waveshape	Polarity	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	127.8	0.2010	4.36×10^{-05}
	Pos.	78.7	0.1138	3.78×10^{-05}
1.2 / 10 μ s	Neg.	130.6	0.2989	2.08×10^{-04}
	Pos.	65.8	0.1245	1.12×10^{-04}
1.2 / 50 μ s	Neg.	135.5	0.3084	1.26×10^{-04}
	Pos.	71.6	0.1376	1.05×10^{-04}
3 / 10 μ s	Neg.	99.6	0.2194	2.43×10^{-04}
	Pos.	87.2	0.1536	5.51×10^{-05}
7.5 / 30 μ s	Neg.	42.4	0.1619	1.05×10^{-02}
	Pos.	54.2	0.1526	4.98×10^{-04}

Table 9 – DE model parameters according to the proposed method: 24 kV class.

Waveshape	Pol.	V_0 (kV)	α^*	DE^*
1.2 / 4 μ s	Neg.	127.8	0.2086	4.36×10^{-05}
	Pos.	78.7	0.1133	3.78×10^{-05}
1.2 / 10 μ s	Neg.	130.6	0.3133	2.08×10^{-04}
	Pos.	65.8	0.1298	1.12×10^{-04}
1.2 / 50 μ s	Neg.	135.5	0.3243	1.26×10^{-04}
	Pos.	71.6	0.1329	1.05×10^{-04}
3 / 10 μ s	Neg.	99.6	0.2395	2.43×10^{-04}
	Pos.	87.2	0.1648	5.51×10^{-05}
7.5 / 30 μ s	Neg.	42.4	0.1622	1.05×10^{-02}
	Pos.	54.2	0.1718	4.98×10^{-04}

Figs. 37, 38, and 39 illustrate the influences of V_0 , α , and DE on the volt–time curves. The optimal α and DE values are shown in Table 9. As expected, the influences of these parameters are similar to those observed in the case of the 15 kV class insulator.

Figure 37 - Influence of V_0 on the $V \times t$ curves for the 1.2 / 4 μ s waveshape (24 kV class).

a) Negative polarity

$$(DE^* = 4.36 \times 10^{-5} \text{ and } \alpha^* = 0.2086)$$

b) Positive polarity

$$(DE^* = 3.78 \times 10^{-5} \text{ and } \alpha^* = 0.1133)$$

Figure 38 - Influence of α on the $V \times t$ curves for the 1.2 / 50 μ s waveshape (24 kV class).

a) Negative polarity

$$(DE^* = 1.26 \times 10^{-4} \text{ and } V_0 = 136 \text{ kV})$$

b) Positive polarity

$$(DE^* = 1.05 \times 10^{-5} \text{ and } V_0 = 72 \text{ kV})$$

Figure 39 - Influence of DE on the $V \times t$ curves for the 1.2 / 10 μs waveshape (24 kV class).

a) Negative polarity

($V_0 = 131 \text{ kV}$ and $\alpha^* = 0.3133$)

b) Positive polarity

($V_0 = 66 \text{ kV}$ and $\alpha^* = 0.1298$)

Based on the DE parameter values shown in Tables 7–9, Figs. 40–44 compare, for the five positive and negative polarity impulse voltage waveshapes, the experimentally derived volt–time curves with those predicted using the methods in Chowdhuri *et al.* (1997), in Ancajima *et al.* (2010), and in Chapter 3.

Figure 40 - Volt–time curve for 1.2 / 4 μs waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 41 - Volt-time curve for 1.2 / 10 μ s waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 42 - Volt-time curve for 1.2 / 50 μ s waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 43 - Volt–time curve for 3 / 10 μ s waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 44 - Volt–time curve for 7.5 / 30 μ s waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

As in the case of the 15 kV insulator, Figs. 40–44 demonstrate that the curves calculated according to the three procedures are in general agreement with the insulator behavior for the five impulse voltage waveshapes considered.

5.1.3. 36 kV insulator

The data obtained from the multiple-level method for the 36 kV insulator are presented in Table 10.

The DE parameters computed from the method of Chowdhuri *et al.* (1997), the method of Ancajima *et al.* (2010), and the one proposed here are shown in Tables 11, 12, and 13, respectively.

Table 10 – Summary of the data obtained using the multiple-level method (36 kV class).

Waveshape	Polarity	n	V'_{50} (kV)	V'_{16} (kV)	σ (kV)	σ/V'_{50} (%)
1.2 / 4 μ s	Neg.	5	301.1	295.2	5.9	2.0
	Pos.	5	271.1	266.9	4.2	1.5
1.2 / 10 μ s	Neg.	5	284.0	277.4	6.6	2.3
	Pos.	5	235.0	231.4	3.7	1.6
1.2 / 50 μ s	Neg.	5	276.4	269.6	6.8	2.5
	Pos.	5	235.4	228.6	6.8	2.9
3 / 10 μ s	Neg.	5	275.7	270.4	5.2	1.9
	Pos.	5	237.1	229.5	7.6	3.2
7.5 / 30 μ s	Neg.	5	263.0	249.7	13.3	5.1
	Pos.	5	228.7	214.8	14.0	6.1

Table 11 – DE model parameters according to the method of Chowdhuri *et al.* (1997):
36 kV class.

Waveshape	Polarity	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	256.5	0.3551	1.12×10^{-04}
	Pos.	239.7	0.4314	5.59×10^{-04}
1.2 / 10 μ s	Neg.	234.5	0.3548	2.30×10^{-04}
	Pos.	207.4	0.2064	3.40×10^{-05}
1.2 / 50 μ s	Neg.	225.1	0.4219	8.13×10^{-04}
	Pos.	184.6	0.2742	1.83×10^{-04}
3 / 10 μ s	Neg.	236.3	0.3197	1.24×10^{-04}
	Pos.	180.1	0.2205	8.60×10^{-05}
7.5 / 30 μ s	Neg.	163.1	0.4465	1.87×10^{-02}
	Pos.	123.7	0.1831	2.63×10^{-04}

Table 12 – DE model parameters according to the method of Ancajima *et al.* (2010):
36 kV class.

Waveshape	Polarity	V_0 (kV)	α	DE
1.2 / 4 μ s	Neg.	160.0	0.2703	5.87×10^{-04}
	Pos.	160.0	0.1909	7.67×10^{-05}
1.2 / 10 μ s	Neg.	127.7	0.2345	1.24×10^{-03}
	Pos.	61.8	0.0806	1.40×10^{-04}
1.2 / 50 μ s	Neg.	210.2	0.4079	1.15×10^{-03}
	Pos.	169.9	0.2630	2.40×10^{-04}
3 / 10 μ s	Neg.	224.9	0.3180	1.67×10^{-04}
	Pos.	140.4	0.1966	1.73×10^{-04}
7.5 / 30 μ s	Neg.	134.0	0.3436	1.30×10^{-02}
	Pos.	93.2	0.1454	3.65×10^{-04}

Table 13 – DE model parameters according to the proposed method: 36 kV class.

Waveshape	Pol.	V_0 (kV)	α^*	DE^*
1.2 / 4 μ s	Neg.	160.0	0.2730	5.87×10^{-04}
	Pos.	160.0	0.3059	7.67×10^{-05}
1.2 / 10 μ s	Neg.	127.7	0.2366	1.24×10^{-03}
	Pos.	61.8	0.0788	1.40×10^{-04}
1.2 / 50 μ s	Neg.	210.2	0.4154	1.15×10^{-03}
	Pos.	169.9	0.2603	2.40×10^{-04}
3 / 10 μ s	Neg.	224.9	0.3675	1.67×10^{-04}
	Pos.	140.4	0.2024	1.73×10^{-04}
7.5 / 30 μ s	Neg.	134.0	0.3217	1.30×10^{-02}
	Pos.	93.2	0.1508	3.65×10^{-04}

Figs. 45, 46, and 47 illustrate the influences of V_0 , α , and DE , respectively, on the volt–time curves. As expected, such influences are similar to those observed for the 15 kV and 24 kV insulators.

Figure 45 - Influence of V_0 on the $V \times t$ curves for the 1.2 / 4 μs waveshape (36 kV class).

a) Negative polarity

$$(DE^* = 5.87 \times 10^{-4} \text{ and } \alpha^* = 0.2730)$$

b) Positive polarity

$$(DE^* = 7.67 \times 10^{-5} \text{ and } \alpha^* = 0.3059)$$

Figure 46 - Influence of α on the $V \times t$ curves for the 1.2 / 50 μs waveshape (36 kV class).

a) Negative polarity

$$(DE^* = 1.15 \times 10^{-03} \text{ and } V_0 = 210 \text{ kV})$$

b) Positive polarity

$$(DE^* = 2.40 \times 10^{-04} \text{ and } V_0 = 170 \text{ kV})$$

Figure 47 - Influence of DE on the $V \times t$ curves for the 1.2 / 10 μs waveshape (36 kV class).

a) Negative polarity

$(V_0 = 128 \text{ kV and } \alpha^* = 0.2366)$

b) Positive polarity

$(V_0 = 62 \text{ kV and } \alpha^* = 0.0788)$

Figs. 48–52 show a comparison of the experimentally derived volt–time curves with the curves predicted using the method of Chowdhuri *et al.* (1997), the method of Ancajima *et al.* (2010), and the method presented in Chapter 3 for the five positive and negative polarity impulse voltage waveshapes. The estimated parameters presented in Tables 11–13 were used to calculate the volt–time curves according to the three methods.

Figure 48 - Volt–time curve for 1.2 / 4 μs waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

Figure 49 - Volt–time curve for 1.2 / 10 μs waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

Figure 50 - Volt–time curve for 1.2 / 50 μs waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 51 – Volt–time curve for 3 / 10 μ s waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 52 – Volt–time curve for 7.5 / 30 μ s waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

As in the previous cases (15 kV and 24 kV insulators), Figs. 48–52 show that the curves calculated according to the three procedures are in general agreement with the insulator behavior for the five impulse voltage waveshapes considered. However, the method of Chowdhuri *et al.* (1997) does not predict the insulator breakdown occurrence for the lower voltage levels for the 1.2 / 4 μ s waveshape of both polarities. The reason for this discrepancy is related to the parameter V_0 , calculated according to the method of Chowdhuri *et al.* (1997) (240 kV and 257 kV for the positive and negative polarities, respectively, which are too high for this impulse waveshape). As pointed out by Ancajima *et al.* (2007), the estimation of V_0

should be made taking into account the parameter $v(t_{bM})$, which is defined as the voltage corresponding to the longest recorded time to breakdown. That is, if $v(t_{bM})$ is lower than the estimated value for V_0 , $V_0 = v(t_{bM})$. For the 1.2 / 4 μ s impulse waveshape, the same value for $v(t_{bM})$ (160 kV) was obtained for the positive and negative polarities. This example clearly illustrates the importance of this parameter, particularly in the case of very short tail lightning impulses as in the 1.2 / 4 μ s waveshape.

5.1.4. Analysis

Comparisons were made between the methods used to estimate the parameters for applying the DE model (Chowdhuri *et al.* (1997), Ancajima *et al.* (2010), and the one presented in Chapter 3), taking into account the absolute differences between the measured and calculated times to breakdown. The mean relative difference in time to breakdown, ε_{tr} , was calculated for each method and for each voltage waveshape and polarity as a function of the M voltage levels as follows:

$$\varepsilon_{tr} = \frac{1}{M} \sum_{j=1}^M \frac{|t_{cj} - t_{mj}|}{t_{mj}}. \quad (14).$$

The corresponding standard deviation ($\sigma_{\varepsilon_{tr}}$) was also calculated for each voltage waveshape and polarity.

Comparisons between the mean relative differences in the time to breakdown of the three methods, taking the measured values as reference, are presented in Tables 14–16. Tables 14, 15, and 16 show the comparisons relevant to the 15 kV, 24 kV, and 36 kV insulators, respectively. The method presented in Chapter 3 is identified as “Proposed” in the tables.

Table 14 – Comparisons between the derived mean relative differences in times to breakdown (ε_{tr}) according to the three methods (15 kV class).

Waveshape	Polarity	$\varepsilon_{tr} \pm \sigma_{\varepsilon_{tr}}$		
		Chowdhuri <i>et al.</i>	Ancajima <i>et al.</i>	Proposed
1.2 / 4 μ s	Neg.	0.08 $\pm$ 0.06	0.04 $\pm$ 0.03	0.04 $\pm$ 0.03
	Pos.	0.05 $\pm$ 0.08	0.04 $\pm$ 0.05	0.04 $\pm$ 0.05
1.2 / 10 μ s	Neg.	0.09 $\pm$ 0.07	0.07 $\pm$ 0.06	0.07 $\pm$ 0.06
	Pos.	0.03 $\pm$ 0.02	0.03 $\pm$ 0.02	0.03 $\pm$ 0.02
1.2 / 50 μ s	Neg.	0.07 $\pm$ 0.06	0.07 $\pm$ 0.06	0.05 $\pm$ 0.03
	Pos.	0.07 $\pm$ 0.05	0.08 $\pm$ 0.06	0.05 $\pm$ 0.03
3 / 10 μ s	Neg.	0.06 $\pm$ 0.03	0.07 $\pm$ 0.03	0.07 $\pm$ 0.02
	Pos.	0.03 $\pm$ 0.01	0.03 $\pm$ 0.01	0.03 $\pm$ 0.01
7.5 / 30 μ s	Neg.	0.09 $\pm$ 0.09	0.10 $\pm$ 0.11	0.10 $\pm$ 0.11
	Pos.	0.16 $\pm$ 0.09	0.16 $\pm$ 0.09	0.11 $\pm$ 0.06

Table 15 – Comparisons between the derived mean relative differences in times to breakdown (ϵ_{tr}) according to the three methods (24 kV class).

Waveshape	Polarity	$\epsilon_{tr} \pm \sigma_{\epsilon_{tr}}$		
		Chowdhuri <i>et al.</i>	Ancajima <i>et al.</i>	Proposed
1.2 / 4 μ s	Neg.	0.06 $\pm$ 0.05	0.05 $\pm$ 0.05	0.06 $\pm$ 0.03
	Pos.	0.06 $\pm$ 0.04	0.05 $\pm$ 0.04	0.05 $\pm$ 0.03
1.2 / 10 μ s	Neg.	0.14 $\pm$ 0.06	0.14 $\pm$ 0.06	0.07 $\pm$ 0.06
	Pos.	0.11 $\pm$ 0.10	0.12 $\pm$ 0.10	0.08 $\pm$ 0.05
1.2 / 50 μ s	Neg.	0.14 $\pm$ 0.11	0.14 $\pm$ 0.11	0.12 $\pm$ 0.06
	Pos.	0.05 $\pm$ 0.04	0.05 $\pm$ 0.04	0.04 $\pm$ 0.02
3 / 10 μ s	Neg.	0.16 $\pm$ 0.13	0.16 $\pm$ 0.12	0.11 $\pm$ 0.06
	Pos.	0.10 $\pm$ 0.09	0.09 $\pm$ 0.09	0.10 $\pm$ 0.03
7.5 / 30 μ s	Neg.	0.21 $\pm$ 0.18	0.21 $\pm$ 0.18	0.21 $\pm$ 0.18
	Pos.	0.20 $\pm$ 0.15	0.20 $\pm$ 0.15	0.13 $\pm$ 0.05

Table 16 – Comparisons between the derived mean relative differences in times to breakdown (ϵ_{tr}) according to the three methods (36 kV class).

Waveshape	Polarity	$\epsilon_{tr} \pm \sigma_{\epsilon_{tr}}$		
		Chowdhuri <i>et al.</i>	Ancajima <i>et al.</i>	Proposed
1.2 / 4 μ s	Neg.	0.07 $\pm$ 0.07	0.06 $\pm$ 0.07	0.07 $\pm$ 0.05
	Pos.	0.13 $\pm$ 0.01	0.08 $\pm$ 0.06	0.09 $\pm$ 0.05
1.2 / 10 μ s	Neg.	0.08 $\pm$ 0.07	0.08 $\pm$ 0.06	0.08 $\pm$ 0.06
	Pos.	0.10 $\pm$ 0.09	0.08 $\pm$ 0.09	0.08 $\pm$ 0.06
1.2 / 50 μ s	Neg.	0.14 $\pm$ 0.06	0.14 $\pm$ 0.06	0.11 $\pm$ 0.09
	Pos.	0.16 $\pm$ 0.15	0.17 $\pm$ 0.15	0.13 $\pm$ 0.07
3 / 10 μ s	Neg.	0.11 $\pm$ 0.09	0.10 $\pm$ 0.08	0.09 $\pm$ 0.09
	Pos.	0.11 $\pm$ 0.09	0.10 $\pm$ 0.08	0.09 $\pm$ 0.09
7.5 / 30 μ s	Neg.	0.29 $\pm$ 0.16	0.30 $\pm$ 0.16	0.11 $\pm$ 0.07
	Pos.	0.18 $\pm$ 0.17	0.18 $\pm$ 0.17	0.15 $\pm$ 0.14

In most cases, as shown in Tables 14–16, the proposed method leads to better agreement between the measured and calculated times to breakdown. However, in some cases, either the method of Chowdhuri *et al.* (1997) or the method of Ancajima *et al.* (2010) exhibits slightly lower values of ε_{tr} , as shown, for example, in the case of the 1.2 / 4 μ s negative polarity waveshape (24 kV insulator).

5.2. A new proposal for evaluating the dielectric behavior of MV insulators

Analysis of the distribution lines' lightning performance requires an understanding of the line insulator behavior. Ideally, the dielectric strength should be evaluated using a simple and reliable model. Two procedures for the application of the DE method, which are often used for such analysis, are those proposed by Darveniza and Vlastos (1988) and by Hileman (1999). However, the former requires laboratory tests for determining the critical value of DE (DE_C), that is, the minimum value of DE that leads to breakdown. By its turn, the latter adopts parameters intended to be applied in transmission systems and it would be necessary to check whether its application to distribution insulators leads to acceptable results.

These facts motivated the development of the proposal described in this section, which is a new and simple method for evaluating the dielectric behavior of MV insulators of the three voltage classes considered, on the basis of the test results. A general equation is developed that relates the critical DE value with the insulator CFO , relevant to the standard waveshape (1.2 / 50 μ s). This critical value, used in conjunction with the proposed values for α and V_0 , allows one to obtain the insulator volt–time curves for the five positive and negative polarity waveshapes adopted in the tests. The goal is to provide a method that is suitable for the three voltage levels and that does not require laboratory tests.

Initially, based on the test results and parametric analysis, α , V_0 , and DE_C values that lead to volt–time curves for the five impulse waveshapes that are in close agreement with the measured ones were determined for each insulator and polarity. These parameter values are presented in Table 17.

Table 17 – DE parameters suitable for obtaining the five impulse waveshape volt–time curves for each insulation class and polarity.

Polarity	Class	DE_C	α	V_0 (kV)	CFO (kV)
Negative	15 kV	0.00033	0.28	$0.63 \times CFO$	133.2
	24 kV	0.00030	0.20	$0.50 \times CFO$	164.4
	36 kV	0.00055	0.30	$0.63 \times CFO$	276.4
Positive	15 kV	0.00085	0.22	$0.70 \times CFO$	112.8
	24 kV	0.00022	0.19	$0.56 \times CFO$	142.9
	36 kV	0.00036	0.21	$0.53 \times CFO$	235.4

Following this, a more general set of parameters was obtained, which also led to relatively good agreement between the measured and calculated volt–time curves. The advantage in relation to the parameters shown in Table 17 is that, both for V_0 and α , the same value can be used for all the impulse waveshapes considered, independent of polarity, as shown in Table 18.

Table 18 – DE parameters suitable for obtaining the five impulse waveshape volt–time curves for each insulation class and polarity (assuming constant values for α and the ratio V_0/CFO).

Polarity	Class	DE_C	α	V_0 (kV)	CFO (kV)
Negative	15 kV	0.00020	0.24	$0.60 \times CFO$	133.2
	24 kV	0.00027	0.24	$0.60 \times CFO$	164.4
	36 kV	0.00025	0.24	$0.60 \times CFO$	276.4
Positive	15 kV	0.00027	0.24	$0.60 \times CFO$	112.8
	24 kV	0.00044	0.24	$0.60 \times CFO$	142.9
	36 kV	0.00035	0.24	$0.60 \times CFO$	235.4

After fixing α and the ratio V_0/CFO , the next step was to obtain an equation relating DE_C and CFO that would result in acceptable agreement between the measured and calculated volt–

time curves for each insulation class and polarity. The relationship between these two parameters is shown in Fig. 53.

Figure 53 - Relationship between DE_C and CFO for the three insulation classes.

To assure quality results for the lower and upper insulation classes and to obtain a simple equation, two straight lines were considered, one for each polarity, passing through the points corresponding to the 15 kV and 36 kV insulation classes. Therefore, the following equation was derived to express DE_C as a function of CFO (in kV):

$$DE_C(CFO) = 1.535 \times 10^{-4} + 3.492 \times 10^{-7} \times CFO + p \times (4.290 \times 10^{-5} + 3.034 \times 10^{-7} \times CFO) \quad (15),$$

$$\text{where } \begin{cases} p = 0 \text{ for the negative polarity;} \\ p = 1 \text{ for the positive polarity.} \end{cases}$$

The proposed method for evaluating the MV insulator dielectric behavior, i.e., the method for obtaining the volt–time curves for lightning overvoltages, consists, thus, in the following set of parameters: $\alpha = 0.24$, $V_0 = 0.60 \times CFO$, and the relation between DE_C and CFO given by equation (14).

5.3. Comparisons between measured and calculated volt–time curves

To validate the proposed method, this section presents a comparison between the predicted and measured volt–time curves for the five positive and negative polarity voltage impulse waveshapes. In addition, the results obtained using the methods of Darveniza and Vlastos (1988) and Hileman (1999), are also considered in the comparative analysis.

Tables 19 and 20 show the derived DE model parameters according to the methods of Darveniza and Vlastos (1988) and Hileman (1999), respectively.

Table 19 – DE model parameters according to the method of Darveniza and Vlastos (1988).

Class	Polarity	V_0 (kV)	DE_C (kV· μ s)	$\sigma_{DE\%}$
15 kV	Neg.	119.9	43.0	20
	Pos.	101.5	47.7	17
24 kV	Neg.	148.0	42.9	33
	Pos.	128.6	78.8	23
36 kV	Neg.	248.8	63.0	31
	Pos.	211.9	95.5	17

Table 20 – DE model parameters according to the method of Hileman (1999).

Class	Polarity	V_0 (kV)	DE_C
15 kV	Neg.	102.6	10.7
	Pos.	86.9	8.6
24 kV	Neg.	126.6	10.0
	Pos.	110.0	8.3
36 kV	Neg.	212.8	28.9
	Pos.	181.3	23.3

5.3.1. 15 kV insulator

Figs. 54–58 show the derived volt–time curves from the tests and calculations based on the three methods considered in the analysis.

Figure 54 – Volt–time curves for the 1.2 / 4 μs impulse waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

Figure 55 - Volt–time curves for the 1.2 / 10 μs impulse waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 56 - Volt–time curves for the 1.2 / 50 μ s impulse waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 57 - Volt–time curves for the 3 / 10 μ s impulse waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

Figure 58 - Volt–time curves for the 7.5 / 30 μs impulse waveshape (15 kV class).

a) Negative polarity

b) Positive polarity

As shown in Fig. 54a and Fig. 55a, the method of Hileman (1999) does not predict insulator breakdown for any voltage levels for the 1.2 / 4 μs and 1.2 / 10 μs negative polarity waveshapes. For the 1.2 / 4 μs and 1.2 / 10 μs positive polarity waveshapes (Figs. 54b and 55b, respectively) and for the 3 / 10 μs waveshape of both polarities (Fig. 57), the method does not predict insulator breakdown at lower voltages.

In general, the volt–time curves obtained using the method of Darveniza and Vlastos (1988) are in good agreement with the measured results. However, as shown in Figs. 54, 55, and 57b, this method does not predict insulator breakdown for the lower voltage levels for the 1.2 / 4 μs and 1.2 / 10 μs waveshapes of both polarities and the 3 / 10 μs waveshape of positive polarity.

In general, the curves calculated using the proposed method are in good agreement with the measured results for the five positive and negative polarity impulse waveshapes considered. The maximum observed difference between the measured and calculated times to breakdown was 3.5 μs for the 7.5 / 30 μs negative polarity waveshape (Fig. 58a).

5.3.2. 24 kV insulator

Figs. 59–63 show the experimentally derived and calculated volt–time curves using the three methods considered in the analysis.

Figure 59 - Volt–time curves for the 1.2 / 4 μs impulse waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

Figure 60 - Volt–time curves for the 1.2 / 10 μs impulse waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 61 - Volt-time curves for the 1.2 / 50 μ s impulse waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 62 - Volt-time curves for the 3 / 10 μ s impulse waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

Figure 63 - Volt–time curves for the 7.5 / 30 μs impulse waveshape (24 kV class).

a) Negative polarity

b) Positive polarity

The method of Hileman (1999) predicts a closer agreement with the measured values in comparison with the results relevant to the 15 kV insulator. However, it does not predict insulator breakdown for the lower voltage levels for the 1.2 / 4 μs waveshape of both polarities (Fig. 59) and the 1.2 / 10 μs waveshape of positive polarity (Fig. 60b).

By its turn, as in the case corresponding to the 15 kV insulator, the volt–time curves obtained using the method of Darveniza and Vlastos (1988) have also are in good agreement with the measured results. However, this result does not predict insulator breakdown for the lower voltage levels in the case of the 1.2 / 10 μs waveshape of positive polarity (Fig. 60b).

As in the previous case (15 kV insulator), the curves calculated using the proposed method are also in relatively good agreement with the measured results for the five positive and negative polarity impulse waveshapes considered. The maximum observed difference between the measured and calculated times to breakdown was 4.0 μs for the 7.5 / 30 μs negative polarity waveshape (Fig. 63a).

5.3.3. 36 kV insulator

Figs. 64–68 present the experimentally derived and theoretically calculated volt–time curves based on the three methods considered in the analysis.

Figure 64 - Volt–time curves for the 1.2 / 4 μs impulse waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

Figure 65 - Volt–time curves for the 1.2 / 10 μs impulse waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 66 - Volt-time curves for the 1.2 / 50 μ s impulse waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

(a)

(b)

Figure 67 - Volt-time curves for the 3 / 10 μ s impulse waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

Figure 68 - Volt–time curves for the 7.5 / 30 μs impulse waveshape (36 kV class).

a) Negative polarity

b) Positive polarity

The method of Hileman (1999) does not predict insulator flashover for the 1.2 / 4 μs negative polarity waveshape, as shown in Fig. 64a. Insulator breakdown is not predicted at the lower voltage levels of the following waveshapes: 1.2 / 4 μs of positive polarity, 1.2 / 10 μs of negative polarity, 3 / 10 μs of both polarities, and 7.5 / 30 μs of positive polarity.

As observed in the case of the 15 kV and 24 kV insulation classes, the volt–time curves derived from the method of Darveniza and Vlastos (1988) are in good agreement with the measured results. However, insulator breakdown is not predicted at the lower voltage levels in the case of the 1.2 / 10 μs and 7.5 / 30 μs impulse waveshapes of positive polarity and for the 3 / 10 μs waveshape of both polarities.

As in the other insulation classes, the calculated curves using the proposed method are in good agreement with the measured results for the five positive and negative polarity impulse waveshapes considered. The maximum observed difference between the measured and calculated times to breakdown was 2.2 μs for the 1.2 / 50 μs negative polarity waveshape (Fig. 66a).

5.3.4. Analysis

Table 21 presents, for each insulation class and polarity of the five impulse waveshapes, the absolute values of the maximum differences between the calculated times to breakdown, according to the three methods considered, and the values obtained from the tests. Besides the maximum time differences observed for each impulse waveshape, Table 21 lists the mean and standard deviation corresponding to each method for the three insulation classes.

Table 21 – Absolute values of the maximum differences between the calculated times to breakdown according to the three methods and the values obtained from the tests (μs).

Class		15 kV			24 kV			36 kV		
Waveshape	Pol.	Darv. ¹	Hil. ²	NP ³	Darv. ¹	Hil. ²	NP ³	Darv. ¹	Hil. ²	NP ³
1.2 / 4 μs	Neg.	0.3*	**	0.5	0.5	1.0*	0.6	0.4	**	0.3
	Pos.	0.2*	1.4*	0.3	0.6	0.4*	1.2	0.6*	1.6*	0.8
1.2 / 10 μs	Neg.	0.3*	**	0.1	0.7	2.5	0.7	1.4	4.1*	1.6
	Pos.	0.1*	4.2*	3.4	0.8*	0.7*	1.9	0.2	6.8	1.4
1.2 / 50 μs	Neg.	0.5	3.6	0.9	0.5	3.2	0.5	1.8	9.8	2.2
	Pos.	0.2	3.8	0.3	0.4	0.9	1.0	0.6	6.8	1.6
3 / 10 μs	Neg.	0.4	3.3*	0.8	0.7	1.8	1.0	1.0*	3.9*	1.0
	Pos.	0.4*	2.4*	0.2	0.8	1.2	0.5	0.7*	2.7*	1.8
7.5 / 30 μs	Neg.	2.0	3.9	3.5	2.2	3.0	4.0	2.2	5.8	1.9
	Pos.	1.8	3.8	2.8	2.2	2.7	1.4	1.8*	5.0*	1.5
Mean (μs)		0.6	3.3	1.3	0.9	1.7	1.3	1.1	5.2	1.4
Standard deviation (μs)		0.7	0.9	1.3	0.6	1.0	1.0	0.7	2.3	0.5

¹Darv.: Darveniza and Vlastos (1988)

²Hil.: Hileman (1999)

³NP: New proposal (described in section 5.2)

*insulator breakdown is not predicted for the lower voltage levels

**insulator breakdown is not predicted

Note that each point displayed in the “measured” volt–time curves refers to the mean peak value of five voltage applications. For illustration, Fig. 69 shows not only the mean values but also all the measured points from the tests performed using the 7.5 / 30 μ s impulse waveshape for the voltage classes of 15 kV (positive polarity) and 24 kV (negative polarity). Therefore, Figs. 69a and 69b correspond to Figs. 58b and 63b, respectively. The only difference between them is that Fig. 69 displays all the measured points, and not only the mean value corresponding to each test voltage level.

Figure 69 - Volt–time curves for the 7.5 / 30 μ s impulse waveshape.

a) 15 kV class, positive polarity

b) 24 kV class, negative polarity

Wide variations in the time to breakdown may occur, particularly for the impulse voltages with long front times, such as the 7.5 / 30 μ s waveshape. Variations in voltage also occurs as breakdown may take place on the front, i.e., before the voltage reaches its peak. Therefore, although five impulses were applied at each voltage level, in the case of different times to breakdown (on the wave front), the breakdown voltages will be different and, hence, the points corresponding to this prospective voltage do not appear at the same level on the graphic. Flashovers do not always occur at lower voltages, but if they do, they usually occur on the wave tail. For instance, at a fixed (low) voltage level, 167 kV in Fig. 69b, flashover may take place in just one or two of the five applications, in which case the number of points on the volt–time curve at this voltage level will be less than five.

In Fig. 69a, the mean value of the measured time to breakdown corresponding to the lowest voltage level (120 kV) was approximately 11.7 μs , but the minimum and maximum values measured were 9.6 μs and 16.9 μs , respectively. Considering the proposed method, the difference between the measured (mean value) and calculated times to breakdown was approximately 2.8 μs . However, if the difference considered is that between the calculated and the closest measured value, the value reduces to 0.6 μs .

The method of Hileman (1999), which was formulated for application to transmission line insulator chains, can be used to predict insulator flashovers for the standard waveshape and the three distribution voltage classes considered. The maximum difference between the measured and calculated times to breakdown was 9.8 μs , which was observed for the 36 kV insulator. In most of the tests performed with the 7.5 / 30 μs waveshape, flashover was predicted. However, that was not the case for various voltage levels when the insulator was subjected to impulses with short tails (1.2 / 4 μs , 1.2 / 10 μs , and 3 / 10 μs waveshapes).

In general, the volt–time curves derived from the method by Darveniza and Vlastos (1988) are in good agreement with the measured results for the three insulation classes. However, insulator breakdown is not always predicted at lower voltages for the 1.2 / 4 μs , 1.2 / 10 μs , 3 / 10 μs and 7.5 / 30 μs impulse waveshapes.

In general, the curves derived from the proposed method are in good agreement with the measured results for the five positive and negative polarity impulse waveshapes and the three insulation classes considered. The maximum difference observed between the measured and calculated times to breakdown was 4.0 μs for the 7.5 / 30 μs negative polarity waveshape. This result demonstrates the suitability of the proposed method.

6 APPLICATION

The proposed method was applied to evaluate the occurrence of insulator flashovers in the three-phase scheme adopted in the shield wire line (SWL) system implemented in the State of Rondônia, Brazil, due to nearby lightning strikes. The SWL system uses two insulated shield wires of the 230 kV transmission line as two phases of a three-phase system; the ground is taken as the third phase (RAMOS, 2010). The so-called Extended Rusck Model - ERM (PIANTINI, JANISZEWSKI, 2009) was applied to assess the lightning-induced voltages.

6.1. Calculation of lightning-induced overvoltages

The Extended Rusck Model - ERM (PIANTINI, JANISZEWSKI, 2009) was applied in the present research to assess the lightning induced overvoltages (PIANTINI, SHIGIHARA, RAMOS, 2014). ERM represents an extension of the model by Rusck (1958), supported by IEEE Std. 1410 (2010), but, unlike the original model, its features can account for situations of practical interest. In the original formulation (RUSCK, 1958), the lengths of the line and of the stroke channel are assumed to be infinite, only straight lines can be considered, and realistic configurations cannot be taken into account. On the other hand, the ERM allows also to consider the incidence of lightning flashes to nearby elevated objects and the occurrence of upward leaders. The case of a line with various sections of different directions can also be taken into account, as well as the presences of a multigrounded neutral or shield wire and equipment such as transformers and surge arresters (PIANTINI, JANISZEWSKI, 2009).

The model was validated through several comparisons using reduced- and full-scale experiments (PIANTINI, JANISZEWSKI, 2009, 2012). Figs. 70 and 71 show examples of comparisons between the measured and calculated lightning-induced voltages applying ERM.

Figure 70 – Example of comparison between measured and calculated induced voltages.

(a) Induced voltages

(b) stroke current at the top of the tower

(adapted from Piantini and Janiszewski (2009)).

Figure 71 – Measured and calculated (using ERM) induced voltages: reduced-scale model. (a) Induced voltages and (b) the measured current and straight line approximation superimposed (adapted from Piantini and Janiszewski (2012)).

6.2. Brief description of SWS technology in Rondônia

In the Amazon region, the existence of small towns and villages located relatively close to transmission lines, but far from the sub-transmission and electricity distribution systems is not uncommon. The use of conventional medium-voltage lines for supplying power to these communities is sometimes not feasible because of economic reasons.

A nonconventional and low-cost alternative, conceived by Iliceto (1983, 1989), namely the shield wire scheme (SWS), has been applied in the State of Rondônia, Brazil, since 1995. Loads greater than 4 MVA can be supplied with SWS, and the insertion of this technology in the regional scenario has provided energy to more than 40,000 people (RAMOS *et al.*, 2007). Fig. 72 shows the three-phase scheme of the SWL system implemented in Rondônia.

Figure 72 – Three-phase scheme of the SWL technology implemented in Rondônia.

CB: circuit breaker; R and L: third phase resistor and reactor, respectively (adapted from Ramos *et al.* (2007)).

The Brazilian experience with the SWS is highly positive, but lightning has a great impact on the system operational performance and is responsible for most of the reported power outages.

The effect of the overvoltages resulting from direct strikes to the two SWL systems implemented in Rondônia (SMQ and AQJR) was examined in Ramos (2011).

With regard to SWL SMQ, the average conductor height is 21.5 m, i.e., more than twice the height of a typical 36 kV line. Although SWLs are located in regions dominated by pastures, there are tall trees close to some sections of the line. These trees provide some shielding to the conductors and reduce the line exposure to direct strokes; however, on the other hand, lightning may occur very close to the line; therefore, the induced overvoltages can reach sufficiently high levels to cause insulator flashovers. This chapter evaluates, in a simple SWS configuration, the induced overvoltages produced by nearby strokes on SWL SMQ.

6.3. Standard lightning impulse tests on SWL, simulations, and results

The impulse tests were performed at the high-voltage laboratory, and the measured critical impulse flashover overvoltages (*CFO*) of SWL, referred to the reference atmospheric conditions, were 277 kV and 281 kV for the positive and negative polarities, respectively. These values refer to the rod–rod electrode distance of 330 mm. Fig. 73 shows the mounted test setup for evaluating *CFO*, which applies to the standard lightning impulse voltage. The tests were performed according to the Brazilian Standards (NBR 6936, 1992; NBR 5032, 2004; NBR 15123, 2014).

The overvoltage calculations were performed assuming a stroke current with triangular waveshape, amplitude of 30 kA, front-time of 2 μ s, time to zero of 160 μ s, and propagation velocity equal to 30 % of light in free space. The soil resistivity and relative permittivity were assumed equal to 4000 Ω .m and 10, respectively. The line length adopted in the simulations was 2000 m.

Based on the new method proposed in item 5.2, the DE_C value, as a function of *CFO*, was calculated for each polarity (Table 22).

Figure 73 – Test setup: (a) Illustrative test setup; (b) Illustrative rod–rod air gap breakdown (RAMOS, 2010).

Table 22 – DE parameters for the SWS, with DE_C estimated according to Equation (14).

Waveshape	Polarity	CFO (kV)	V_0 (kV)	DE_C
1.2 / 50 μ	Neg.	281	168.6	2.52×10^{-4}
	Pos.	277	166.2	3.77×10^{-4}

To obtain the volt-time curves for both polarities, the overvoltage presented Fig. 74 was calculated using ERM and used as input data to assess the volt-time curves. The overvoltage was computed at the insulator closest to the stroke location assuming a distance of 200 m between the line and the lightning strike point.

Figure 74 – Example of lightning-induced voltage at the insulator closest to the stroke location for a distance of 200 m between the line and the lightning strike point (PIANTINI, SHIGIHARA, RAMOS, 2014).

In order to illustrate the application of the method, Fig. 75 shows a comparison of the volt-time curves of both polarities, obtained using the proposed method and the data shown in Table 22. The simulations were performed assuming voltages with the waveshape shown in Fig. 74, but with different peak values (from 260 kV to 422 kV). The application of the proposed method, as illustrated in Fig. 75, shows that the time to breakdown are longer for positive polarity than for negative polarity.

Figure 75 – Volt-time curves - SWL (34.5 kV class).

Fig. 76 shows the voltages at the insulator closest to the stroke location considering lightning-induced voltages of three different distances: 150 m, 180 m, and 200 m. The insulator behavior was evaluated using the proposed method, as described in item 5.2.

Figure 76 – Examples of lightning-induced voltages at the insulator closest to the stroke location ($CFO = 281$ kV).

Fig. 76 indicates that, for the conditions considered, the incidence of lightning to distances (d) shorter than about 200 m from the SWL can cause line flashovers. This result supports the conclusion obtained in Ramos *et al.* (2007, 2011), that lightning has a significant impact on the SWL system performance in regions with high ground flash density. As discussed in (PIANTINI, SHIGIHARA, RAMOS, 2014), SWLs are more prone to lightning-caused flashovers in comparison with conventional power distribution lines. Because their conductors are at a higher position, they tend to be struck more often and, additionally the magnitudes of the lightning-induced voltages by nearby strokes tend to be higher.

7 CONCLUSIONS

The focus of this dissertation was on the development and validation of a model for the evaluation of the behavior of medium-voltage distribution insulators under standard and non-standard lightning impulse voltages.

Impulse voltage tests were carried out on typical porcelain pin-type medium-voltage insulators of three distribution classes (15 kV, 24 kV, and 36 kV). Five impulse voltage waveshapes of positive and negative polarities were adopted, including the standard lightning impulse voltage. The tests aimed at obtaining the values of the critical flashover overvoltages (*CFO*) and the volt-time curves.

Two commonly used procedures for estimating the parameters of the Disruptive Effect model - Chowdhuri *et al.* (1997) and Ancajima *et al.* (2010) - were analyzed and new procedure was proposed. A parametric analysis was performed to illustrate the influence of the DE parameters on the calculated volt-time curves and the measured volt-time curves were presented and compared with the curves predicted using the three methods.

Then, a new method for evaluating the dielectric behavior of MV insulators of the three voltage classes considered was proposed and its validation confirmed based on comparisons with the experimentally derived volt-time curves and those predicted by the various procedures.

The main conclusions of the present work may be summarized as:

- in all cases, the measured peak voltage of negative polarity were always higher than the positive polarity. The *CFO* corresponding to the 24 kV insulator is about 25 % higher than that of the 15 kV insulator; the *CFO* corresponding to the 36 kV insulator is about 65 % higher than that of the 25 kV insulator. These relationships are valid for both polarities. In addition, the ratio between the *CFOs* of the negative and positive polarities is about 1.15 for the three voltage classes considered. The maximum relative standard deviation, considering all tests performed, was lower than 6.3%;
- the DE parameters estimated using the procedures by Chowdhuri *et al.* (1997) and by Ancajima *et al.* (2010) can be used to predict the insulator times to breakdown for all the impulse waveshape considered, although in some cases the method of Chowdhuri *et al.*

(1997) does not predict flashovers for the lower voltage levels. However, both procedures require the performance of tests for each impulse waveshape;

- the volt-time characteristics predicted using the method by Darveniza and Vlastos (1988) presents, in general, a good agreement with the measured results for the three insulation classes. This method uses the standard lightning impulse voltage test as reference to predict the occurrence of insulator flashovers under different types of waveshapes. However, insulator breakdown is not always predicted for the lower voltage levels. Moreover, for the application of the method, tests using the standard lightning impulse voltage (1.2 / 50 μ s) must be performed in order to estimate the value of the critical DE value (DE_C);
- the method by Hileman (1999), which was conceived for application to transmission line insulators, can be applied to predict insulator flashovers for the standard waveshape for the three distribution voltage classes considered. However, in various cases the occurrence of flashover was not predicted for the lower voltage levels. For some impulse waveshapes and polarities, flashovers were not predicted for any of the voltage levels considered.
- the new method proposed for predicting insulator volt-time curves was validated using typical porcelain pin-type insulators of the three voltage classes and the five lightning impulse voltages considered, of positive and negative polarities. The curves showed in general a good agreement with the measured results for all the cases studied. The mean difference between the measured and calculated times to breakdown, for all the cases considered, was about 1.3 μ s; the maximum difference was 4.0 μ s for the 7.5 / 30 μ s negative polarity waveshape;
- the application of the proposed method to evaluate the occurrence of insulator flashovers in the shield wire line (SWL) system implemented in the State of Rondônia due to nearby lightning strikes supports previous conclusions that indicate that lightning has a significant impact on the SWL system performance in regions with high ground flash density.

The main contributions of this research are:

- obtainment of the volt-time data corresponding to four non-standard impulse voltage waveshapes representative of lightning overvoltages, for insulators of three MV distribution voltage classes (15 kV, 24 kV, and 36 kV);
- an improved method for estimating more accurately the values of the parameters required for the application of the Disruptive Effect model;
- a new, simple, and suitable method for evaluating the dielectric behavior of MV insulators for engineering applications;
- a general equation that can be used to estimate DE_C based on the insulator CFO relevant to the standard lightning impulse waveshape (1.2 / 50 μ s).

The following topics deserve further investigation:

- validated of the proposed method for insulators with different *CFOs*, shapes, and materials (for instance, composite material);
- development of a model that can be applied to bipolar waveshapes.

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