

Insulation co-ordination —

Part 4: Computational guide to insulation co-ordination and modelling of electrical networks

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National foreword

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The UK participation in its preparation was entrusted to Technical Committee GEL/28, Insulation coordination, which has the responsibility to:

- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
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Insulation co-ordination –

Part 4:
Computational guide to insulation co-ordination
and modelling of electrical networks



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INSULATION CO-ORDINATION –

Part 4: Computational guide to insulation co-ordination and modelling of electrical networks

FOREWORD

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IEC 60071-4, which is a technical report, has been prepared by IEC technical committee 28: Insulation co-ordination.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
28/156/DTR	28/158/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard
- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this technical report may be issued at a later date.

INSULATION CO-ORDINATION –

Part 4: Computational guide to insulation co-ordination and modelling of electrical networks

1 Scope and object

This technical report gives guidance on conducting insulation co-ordination studies which propose internationally recognized recommendations

- for the numerical modelling of electrical systems, and
- for the implementation of deterministic and probabilistic methods adapted to the use of numerical programmes.

Its object is to give information in terms of methods, modelling and examples, allowing for the application of the approaches presented in IEC 60071-2, and for the selection of insulation levels of equipment or installations, as defined in IEC 60071-1.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1:1989, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:1993, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2:1996, *Insulation co-ordination – Part 2: Application guide*

IEC 60076-8:1997, *Power transformers – Part 8: Application guide*

IEC 60099-4:1991, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems* ¹

IEC 61233:1994, *High-voltage alternating current circuit-breakers – Inductive load switching*

3 Terms and definitions

For the purposes of this document, the following terms and definitions, in addition to those contained in IEC 60071-1, apply.

NOTE Certain references are taken from the IEC Multilingual Dictionary[1] ².

¹ A consolidated edition exists, published in 2001, which incorporates the current edition, plus its amendment 1 (1998) and amendment 2 (2001).

² References in square brackets refer to the bibliography.

3.1

backfeeding

refers to the conditions of supplying a high-voltage overhead line or cable through a transformer from the low-voltage side

3.2

back flashover

flashover of phase-to-earth insulation resulting from a lightning strike to towers and shielding wires [1]

3.3

back flashover rate

number of back flashovers of a line per 100 km per year

3.4

closing of capacitive load

essentially closing of capacitor banks but also closing of any other capacitive load

3.5

critical current

minimum lightning current that induces a flashover on a line

NOTE The critical current of the line is the smallest critical current among all injection points.

3.6

direct lightning strike

lightning striking a component of the network, for example, conductor, tower, or substation equipment [1]

3.7

energization

connecting or reconnecting to a source an element of a power system which has no stored energy

3.8

fault clearing

interruption of the short-circuit condition on a system

3.9

limit distance

distance from the substation after which no overvoltage resulting from a lightning stroke gives rise to an impinging surge dangerous for the substation's equipment

3.10

line dropping

disconnection of the line by opening the last circuit-breaker

3.11

line fault application

application of a line short-circuit on a system

3.12

load rejection

opening of a line breaker during normal power flow causing a certain amount of load to be unsupplied

NOTE From a temporary overvoltage point of view, the worst case occurs when the remote circuit-breaker of a long line transmitting a significant part of the supply of a power station is opened.

3.13**line re-energization**

opening and fast closing of the line circuit-breaker as the consequence of a fault or a relay maloperation

NOTE With respect to line energization, trapped charges should be taken into account.

3.14**maximum shielding current**

maximum lightning current that can hit a phase conductor on a line protected by shielding wires

3.15**parallel line resonance**

overvoltage appearing on an unenergized shunt reactor compensated circuit due to capacitive coupling with a parallel energized circuit

3.16**point-on-cycle controlled switching**

energization of capacitive load at the instant that the voltage is zero across the circuit-breaker contacts thus eliminating the switching transient

NOTE De-energization of inductive load ensures a long and weak power arc at zero-current crossing thus eliminating the risk of re-strike and re-ignition.

3.17**representative lightning stroke current**

minimum value of lightning current at a specific point of impact which produces overvoltages that the equipment has to withstand; it is deduced from experience

3.18**slow-front overvoltage flashover rate**

number of flashovers of a line per 100 km per year due to slow-front overvoltages

3.19**switching resistor**

resistance inserted to match the surge impedance of the line in order to limit the switching surge magnitude launched from the source

3.20**switching of inductive and capacitive current**

includes interruption of starting current of motors, interruption of inductive current when interrupting the magnetizing current of a transformer or when switching off a shunt reactor, switching and operation of arc furnaces and their transformer, switching of unloaded cables and of capacitor banks, interruption of current by high-voltage fuses

(See 2.3.3.4 in IEC 60071-2)

3.21**uneven breaker pole operations**

operation caused by one or two breaker poles stuck during opening or closing of the circuit-breaker

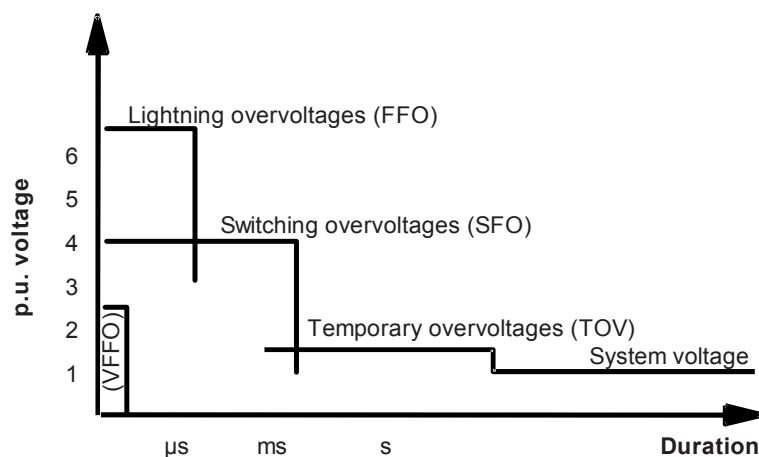
4 List of symbols and acronyms

AIS	Air-insulated substation
BFO	Back flashover
BFR	Back flashover rate
EGM	Electro-geometric model
FACTS	Flexible alternating current transmission systems
FFO	Fast-front overvoltages
GIS	Gas-insulated system
HVDC	High-voltage d.c.
LIWV	Lightning impulse withstand voltage
MOA	Metal oxide surge arrester
SFO	Slow-front overvoltages
SIWV	Switching impulse withstand voltage
SFOFR	Slow-front overvoltage flashover rate
TOV	Temporary overvoltages
TRV	Transient recovery voltage
VFFO	Very-fast-front overvoltages
Z_s (or Z_c)	Surge (or characteristic) impedance
I_c	Critical current
I_m	Maximum shielding current

In addition, refer to 1.3 of IEC 60071-2 as well as the list of symbols in [4].

5 Types of overvoltages

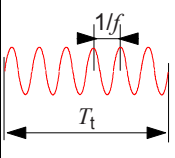
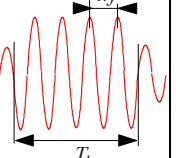
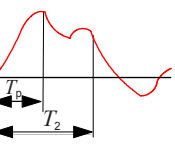
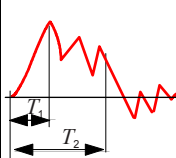
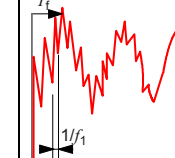
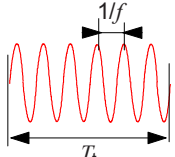
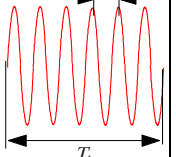
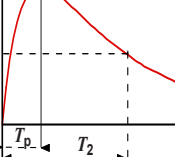
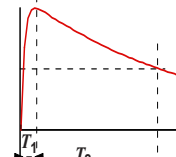
Table 1, extracted from IEC 60071-1, and Figure 1, detail the characteristics of all types of overvoltages.



IEC 763/04

Figure 1 – Types of overvoltages (excepted very-fast-front overvoltages)

Table 1 – Classes and shapes of overvoltages – Standard voltage shapes and standard withstand tests

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	$f = 50 \text{ Hz or } 60 \text{ Hz}$ $T_t \geq 3\,600 \text{ s}$	$10 \text{ Hz} < f < 500 \text{ Hz}$ $0,03 \text{ s} \leq T_t \leq 3\,600 \text{ s}$	$20 \mu\text{s} < T_p \leq 5\,000 \mu\text{s}$ $T_2 \leq 20 \text{ ms}$	$0,1 \mu\text{s} < T_1 \leq 20 \mu\text{s}$ $T_2 \leq 300 \mu\text{s}$	$3 \text{ ns} < T_t \leq 100 \text{ ns}$ $0,3 \text{ MHz} < f_1 < 100 \text{ MHz}$ $30 \text{ kHz} < f_2 < 300 \text{ kHz}$
Standard voltage shapes	 $f = 50 \text{ Hz or } 60 \text{ Hz}$ T_t ¹⁾	 $48 \text{ Hz} \leq f \leq 62 \text{ Hz}$ $T_t = 60 \text{ s}$	 $T_p = 250 \mu\text{s}$ $T_2 = 2\,500 \mu\text{s}$	 $T_1 = 1,2 \mu\text{s}$ $T_2 = 50 \mu\text{s}$	¹⁾
Standard withstand test	¹⁾	Short-duration power frequency test	Switching impulse test	Lightning impulse test	¹⁾

¹⁾ To be specified by the relevant apparatus committees.

6 Types of studies

For range I voltage level (U_m up to 245 kV), SFO are generally not critical while the FFO due to lightning have to be carefully considered. However, for higher voltage levels, SFO become of major importance, specifically in the UHV range, while FFO become in many cases less critical.

TOV have to be studied for all system voltage levels. Table 2 provides a list of events and the most critical types of overvoltages generated.

Table 2 – Correspondence between events and most critical types of overvoltages generated

	Temporary overvoltages TOV	Transient overvoltages		
		Slow-front overvoltages SFO	Fast-front overvoltages FFO	Very-fast-front overvoltages VFFO
Load rejection (see 2.3.2.2 in IEC 60071-2)	X			
Transformer energization	X	X		
Parallel line resonance	X			
Uneven breaker poles	X			
Backfeeding	X			
Line fault application (see 2.3.3.2 in IEC 60071-2)	X	X		
Fault clearing (see 2.3.3.2 in IEC 60071-2)	X	X		
Line energization (see 2.3.3.1 in IEC 60071-2)	X	X		
Line re-energization	X	X		
Line dropping	X	X		
AIS busbar switching			X	1)
Switching of inductive and capacitive current (see 2.3.3.4 in IEC 60071-2)	X	X	X	
Back flashover			X	
Direct lightning stroke (see 2.3.3.5 in IEC 60071-2)			X	
Switching inside GIS substation				X
SF ₆ circuit-breaker inductive and capacitive current switching	X	X	X	1)
Flashover in GIS substation				X
Vacuum circuit-breaker switching			X	X

1) In the case of short distance busbars and low damping, very-fast-front overvoltages can also occur.

6.1 Temporary overvoltages (TOV)

Temporary overvoltages are of importance when determining stresses on equipment related to power-frequency withstand voltage in particular for the energy capability of MOA. TOV can stress transformers and shunt reactors as a consequence of over fluxing. Ferro-resonance is a particular type of TOV which is not studied in this report.

6.2 Slow-front overvoltages (SFO)

Slow-front overvoltages play a role in determining the energy duty of surge arresters and in the selection of required withstand voltages of equipment as well as the air gap insulation for transmission line towers.

SFO studies require the investigation of possible network configurations and switching conditions that result in overvoltages exceeding the withstand values mentioned above. In decreasing order of importance, events which have to be considered typically are line re-energization, line energization, line fault application, fault clearing, capacitive load closing and inductive load opening (from the reactor's point of view). In reactive current switching, the

circuit-breaker may break down after the final clearance due to excessive dv/dt . A dielectric breakdown across the circuit-breaker before a quarter cycle of the power frequency after the final clearance is known as re-ignition, but a dielectric breakdown across the CB after the quarter cycle of the power frequency following the final clearance is known as restrike. Circuit-breaker restrike generates high SFO.

NOTE There is no withstand value specified for range I equipment.

6.3 Fast-front overvoltages (FFO)

They are essentially produced by lightning strokes. Their magnitude is much larger than other kinds of overvoltages.

FFO are therefore critical for all voltage levels, and it is essential to mitigate them with protective devices, i.e. mainly surge arresters. Fast-front overvoltages are studied to determine the risk of equipment failure and therefore to select their required withstand level in relation to protective device configuration and tower earthing, and to evaluate line and station performance.

NOTE Vacuum breakers can cause overvoltages in the fast-front range because of current chopping and restrike.

6.4 Very-fast-front overvoltages (VFFO)

Very-fast-front overvoltages are important for protection against high-touch voltages and internal flashover in GIS enclosures. VFFOs appear under switching conditions in GIS (see [3]) or when operating vacuum circuit-breakers in medium-voltage systems.

Pre-striking GIS disconnector and SF₆ circuit-breaker re-ignition would produce VFFO. Normally, these VFFOs can be avoided by point-on-cycle (POC) switching but analysis is required to cater for the control relay malfunction.

7 Representation of network components and numerical considerations

7.1 General

Simplified methods for the evaluation of each type of overvoltage are presented briefly in 8.1, 9.1 and 10.1, respectively. They do not require a precise modelling of each component. However, when it is necessary to determine accurately overvoltages or overvoltages for which simplified methods cannot deal, detailed analysis with detailed models are required. These models representing the components of the system to be used in studies depend on the type of overvoltage being considered. After numerical considerations, this clause presents, for each type of overvoltage, the models which are adequate for representing each component.

7.2 Numerical considerations

7.2.1 Initialization before calculation of transients

The solution of a transient phenomenon is dependent on the initial conditions with which the transient is started. Some simulations may be performed with zero initial conditions, i.e. with some particular cases of lightning surge studies, but there are many cases for which the simulation must be started from power-frequency steady-state conditions. In most cases, this issue is solved internally by simulation tools.

However, there is presently no digital tool which can calculate the initial solution for the most general case, although some programmes can perform an initialization with harmonics for some simple cases. The initial solution with harmonics can be obtained using simple approaches. The simplest one is known as the "brute-force" approach: the simulation is started without performing any initial calculation and carried out long enough to let the transients settle down to steady-state conditions. This approach can have a reasonable accuracy, but its convergence will be very slow if the network has components with light damping.

A more efficient method is to perform an approximate linear a.c. steady-state solution with non-linear branches disconnected or represented by linearized models.

7.2.2 Time step

The time step has to be coherent with the highest frequency phenomenon appearing in the system during the transient under consideration. A value of one-tenth of the period corresponding to the highest frequency is advised.

The time step has to be lower than the travel time of any of the propagation elements of the network. A value of half this travel time is advised.

The correctness of the time step may be verified by the method presented in [5] which involves comparing the result given with the time step and half of the time step. If the two results are equivalent, the first value of the time step is considered small enough.

7.2.3 Duration of the simulation

The duration time must be sufficiently long to ensure that the maximum overvoltages are recorded in the simulation results. In particular, propagation times and reflections must be taken into account. For TOV, it is necessary to cover a time interval sufficient to permit an accurate calculation of energy in surge arresters.

7.2.4 Numerical oscillations

Numerical oscillations can be related to:

- numerical methods applied for the calculation of the transient, particularly the integration method applied in the solver in the case of time-domain calculation,
- the intrinsic unstable character of the modelling of the system for given values of parameters.

When oscillations occur in a simulation case, one has to check if they are related to physical phenomena or not. If the oscillations depend on the time step or are not damped, they may be numerical.

In programmes using the trapezoidal rule, a resistance may be included in parallel with inductances (Figure 2) to damp numerical oscillation which may occur when a current is injected into it, as shown in the following diagrams [29].

According to [29], this resistance may not have a detrimental effect on the amplitude-frequency response of the inductance but introduces a phase error. Based on an acceptable phase error at power frequency, [38] proposes to use the following criteria:

$$5,4 \times \frac{2 \times L}{\Delta t} \leq R_{\text{dampL}} \leq 9,4 \times \frac{2 \times L}{\Delta t}$$

Numerical oscillations can also appear in a capacitance current if an abrupt change is applied to the voltage between the terminals of the capacitor, in a programme using trapezoidal rule but is seldom a problem in practical studies. To damp these oscillations a resistance may be included in series with the capacitance (Figure 3).

Reference [29] proposes using

$$R_{\text{dampC}} = 0,15 \times \frac{\Delta t}{2 \times C}$$

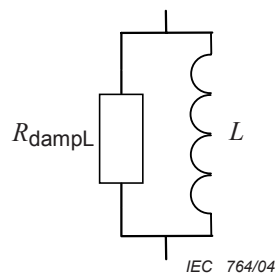


Figure 2 – Damping resistor applied to an inductance

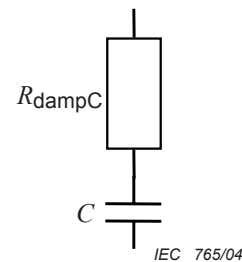


Figure 3 – Damping resistor applied to a capacitance

It is also possible to apply the backward Euler rule for a few time steps to damp the oscillation [29].

7.2.5 Data representation for output

Care should be taken to avoid inopportune filtering of the results of calculation during preparation of these results for output. This may happen, for example, if the time step used for the representation of the output is not small enough and hides some oscillations occurring between two samples.

7.2.6 Non-linear elements

The number of elements representing the piecewise non-linearity must be large enough to accurately represent the element, especially for the data around the "knee point" and produce credible results. Non-linear elements can cause numeric inaccuracies due to methods used for time-domain resolution.

Attention must be paid to the assumptions made for values during steady state, as one can see in the following example (Figure 4).

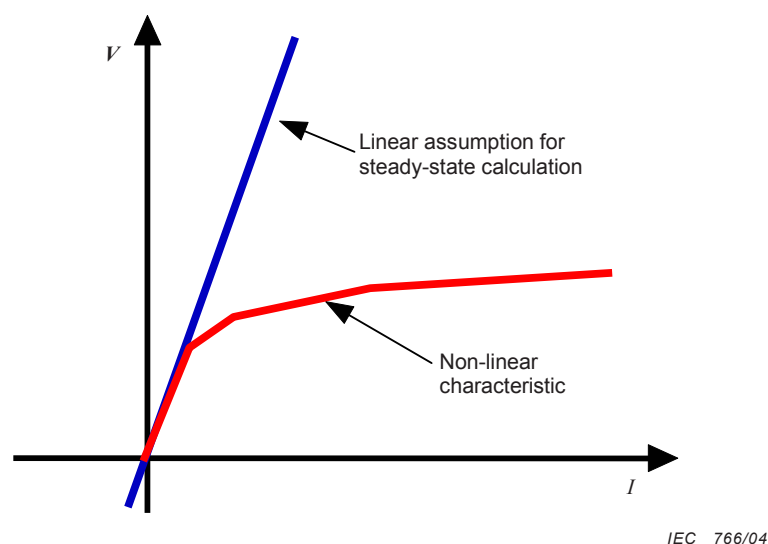


Figure 4 – Example of assumption for the steady-state calculation of a non-linear element

7.3 Representation of overhead lines and underground cables

Many alternatives exist to represent overhead lines and underground cables. Table 3 gives a summary of the models which are most commonly used. Details on modelling are given in Annex A.

Table 3 – Application and limitation of current overhead line and underground cable models

Name	Applications	Limitations
1 – Exact Pi model	Initialization	
2 – Nominal Pi model	Initialization Transients	- Initialization at one frequency only - Choice of number of cells - Trapezoidal rule problem, due to first capacitance
3 – Travelling wave model with constant transform matrix	Transients	- Choice of frequency for calculation of model - Reflections due to lumped impedances representing the losses - In most cases discrepancies due to real approximation of the coefficients of the transfer matrix - Approximations in calculation of historical terms due to time step $\frac{\text{Time step}}{\text{Propagation time for each mode}} \leq 1/2$
4 – Frequency-dependent model with constant transform matrix	Transients	- Transfer matrix is frequency-dependent for cables and multiphase conductors at low frequencies - Coefficients of the transfer matrix are in many cases approximated as real coefficients - Time-step limitations
5 – Frequency-dependent model with frequency-dependent transform matrix	Transients	- Coefficients of the transfer matrix are in many cases approximated as real coefficients - Time-step limitations
6 – Phase domain model	Transient and initialization	Phase-domain line modelling is currently not very popular. One advantage may be to avoid approximating the co-efficients of the transfer matrix as real

When modelling cables, care should be taken to represent carefully cross-bonding (more generally sheath arrangements of cables). Damping of oscillations are in general difficult to simulate in the case of cables, particularly because of the representation of the shunt losses.

7.4 Representation of network components when computing temporary overvoltages

Most of the models described in this subclause are presented in more detail in [2].

7.4.1 Power supply

a) Positive- and zero-sequence RLC circuit

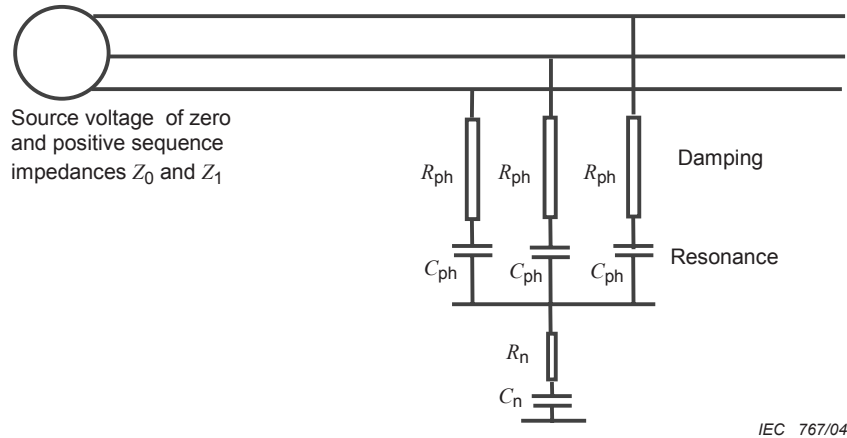


Figure 5 – AC-voltage equivalent circuit

In Figure 5, Z_0 and Z_1 are respectively the zero and positive-sequence impedance of the source.

$$Z_0 = R_0 + jL_0 \times 2\pi f, \quad \text{and} \quad Z_1 = R_1 + jL_1 \times 2\pi f,$$

To compute Z_0 and Z_1 , one can assume that they are mostly inductive, i.e. $Z_0 \approx jL_0 \times 2\pi f$, and $Z_1 \approx jL_1 \times 2\pi f$, with f the power frequency. L_0 and L_1 are calculated from the values of single-phase and three-phase short-circuit currents and by the formula:

$$\frac{Z_0}{Z_1} = \frac{3 \times I_{3\text{ph-sc}}}{I_{1\text{ph-sc}}} - 2$$

R_0 and R_1 are then computed from the inductances by the relationship $L/R = \tau$, the time constant. Resonance capacitors are determined from the zero- and positive-sequence resonance frequencies (both of these frequencies are obtained from measurements) by:

$$\begin{cases} C_1 = \frac{1}{L_1 \omega_1^2} \\ C_0 = \frac{1}{L_0 \omega_0^2} \end{cases}$$

Zero- and positive-sequence values

$$\begin{cases} C_{\text{ph}} = \frac{1}{L_1 \omega_1^2} \\ C_n = \frac{3}{L_0 \omega_0^2 - L_1 \omega_1^2} \end{cases}$$

Phase and neutral values

Then the damping resistors are given by:

$$\begin{cases} R_1 = k \sqrt{\frac{L_1}{C_1}} \\ R_0 = k \sqrt{\frac{L_0}{C_0}} \end{cases} \quad \begin{cases} R_{ph} = kL_1\omega_1 \\ R_n = \frac{k}{3}(L_0\omega_0 - L_1\omega_1) \end{cases}$$

Zero and positive sequence values Phase and neutral values

The factor k defines the level of attenuation and is deduced from measurements.

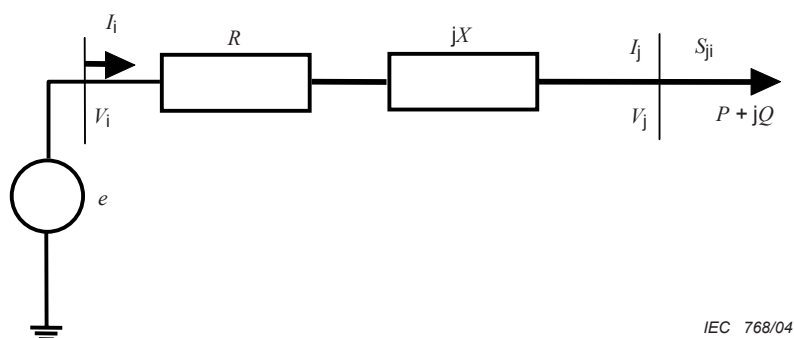
The pulsations ω_0 and ω_1 are estimated from measurements. Reference [63] proposes for instance to evaluate the resonance frequencies of the network from the overvoltages obtained when energizing a transformer. When a transformer is energized its magnetic core saturates and therefore highly distorted currents occur, which provide harmonic peaks on the overvoltage.

b) Synchronous machine

Modelling is based on the simulation of the equations in the direct and quadrature axes. Saturation, excitation and mechanical torque must be represented. It is also important to represent voltage and speed control. The parameters are frequency-dependent, but this dependency is complex to model and for the transients considered is often not important. The effect of the capacitances is negligible.

c) Dynamic source model [55]

This model is adapted to represent a source with a fluctuating frequency. It permits the representation of a network bypassing the difficulty of modelling the synchronous machine by using the results of a transient stability programme (see Figure 6).



IEC 768/04

Figure 6 – Dynamic source modelling

The quantities P , Q , V_j and δ_j are functions of time. They are obtained from measurements or from transient stability studies. This model provides a way to calculate for each time step the amplitude and the phase of the Thevenin equivalent source of the system.

We have

$$Z = R + jX$$

$$S_{ji} = -(P + jQ) = P_{ji} + jQ_{ji}$$

$$P = -P_{ji} = (R \times V_i V_j \cos\delta - X V_i V_j \sin\delta - R V_j^2) / (R^2 + X^2)$$

$$Q = -Q_{ji} = (X x V_i V_j \cos \delta - R_i V_j \sin \delta - X V_j^2) / (R^2 + X^2)$$

where

$$\delta = \delta_i - \delta_j$$

$$\delta_i = \angle V_i \text{ and } \delta_j = \angle V_j$$

$$R_e(V_i) = x = V_i \cos \delta$$

$$I_m(V_i) = y = V_i \sin \delta$$

$$R x + X y = a = (R^2 + X^2)(P/V_j) + R V_j$$

$$X x - R y = b = (R^2 + X^2)(Q/V_j) + X V_j$$

$$x = (a R + b X) / (R^2 + X^2)$$

$$y = (a X - b R) / (R^2 + X^2)$$

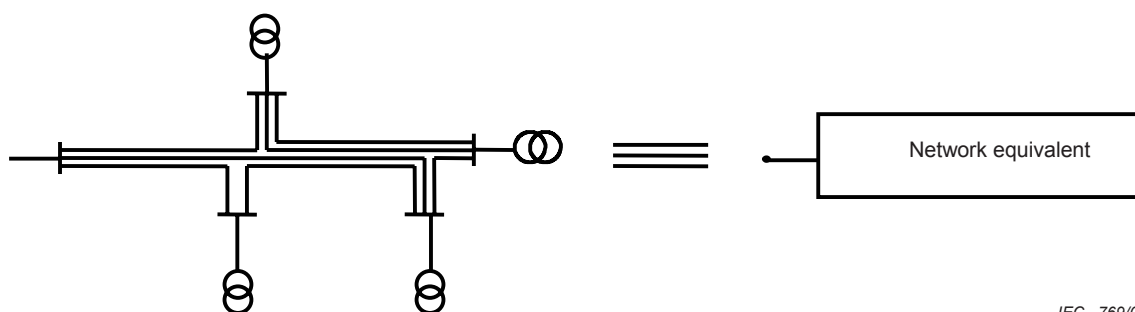
$$V_i = (x^2 + y^2)^{0.5}$$

$$\delta = \arctan(y/x) \text{ with } -\pi < \delta < \pi$$

The voltage of the equivalent source is given by $e = V_i(t) \cos[2\pi f t + \delta_i(t)]$.

7.4.2 Linear network equivalent

A linear portion of the network can be reduced in order to gain calculation speed by network reduction routines. The fitting between the real network and the reduced one may be made up to 1 kHz, which is the frequency range of interest for TOV. The aim is to calculate an equivalent circuit which has the same frequency response as the detailed network (typically up to 1 kHz), from the nodes connected to the portion of the system represented in detail (see Figure 7).



IEC 769/04

Figure 7 – Linear network equivalent

7.4.3 Overhead lines and underground cables

When representing overhead lines it is of importance to take into account the frequency dependence of the zero-sequence parameters. Asymmetry has to be considered as well. Shielding wires may be eliminated assuming zero voltage on these wires.

It is possible to use models 2, 3, 4 and 5 of 7.3. When using model 2 (nominal Pi model) the recommendations of the subclause above have to be taken into consideration.

7.4.3.1 Recommendations for the use of the Pi-model

The number of Pi-sections required to represent the line correctly is directly related to the frequency of the oscillation which can be expected during transient. The highest frequency [17] which can be represented by a Pi-cell, the corresponding length of which is l , is given by the following formula:

$$f_{\max} = \frac{1}{\pi l \sqrt{LC}}$$

where L and C are respectively the inductance and the capacitance per unit length.

Reference [5] considers that if a frequency f has to be represented, the line length corresponding to a Pi-cell should be smaller than:

$$l = \frac{v}{5 \times f_{\max}}$$

where v is the velocity of electromagnetic wave given by:

$$v = \frac{1}{\sqrt{LC}}$$

If the line is switched immediately in parallel to a capacitance of the feeding system side, this leads to an infinite current due to the direct connection of two capacitors if the two initial voltages are different. To avoid this problem, a resistor in the order of the surge impedance of the line should be connected in series with the first shunt capacitance of the first Pi-cell.

7.4.4 Tower

When analysing a fault application overvoltage, overhead line towers are represented as a single electrical node because of their small impedance and admittance.

Towers can be neglected.

7.4.5 Corona effect

A corona effect is not represented in most of the TOV studies because overvoltages observed in these studies are too small and do not reach the ionization threshold, except for very long lines and bad environmental conditions, for example, humidity and altitude.

7.4.6 Air gap, line insulator

It is not common to represent air gaps when studying TOV.

7.4.7 Busbar

Busbars are not represented individually because their length is negligible compared with wave lengths involved in this type of study. Major busbars can be represented by lump capacitances.

7.4.8 Transformers and shunt reactors

At TOV frequencies, transformers react as inductive elements. Capacitances do not have to be considered. Saturation of the magnetizing inductance, residual flux and losses (copper and magnetizing) play an important role in TOV generation and damping. Inductance and resistance are obtained from measurements or estimated from computer programmes. See IEC 60076-8 or [8].

Non-saturated shunt reactors are easy to represent by an inductance, since losses which are very low can be neglected. If TOV amplitude is large enough to lead to the saturation of the shunt reactors, then the remarks about transformers can be applied.

The design of the core plays a fundamental role since it affects the zero sequence of the transformer. A three-limbed design involves a lower zero-sequence impedance. In fact, in a three-leg transformer the zero-sequence flux closes its path through the tank, and therefore the relevant zero-sequence reluctance is higher with respect to the five-leg transformer (or the shell-type core). The inductance is in inverse proportion with respect to reluctance, thus the zero-sequence inductance of a three-leg transformer is lower than that of a five-leg one.

The above depends on the winding connection, i.e. on the vector group and the earthing of the neutral. The zero sequence is open for both unearthed star- and delta-winding connection, since these kinds of connection do not allow the flow of zero-sequence current. Thus, in practice, the different performance of a three-leg transformer with respect to a five-leg one is of concern for a star-earthed winding connection.

In this particular configuration, when, for instance, a transformer is seen from its star-earthed winding terminals and, on the other side, there is only a star-unearthed winding, the three-leg transformer has a performance which is markedly different to a five-leg one, since, from a modelling point of view, the three-leg transformer acts as a five-leg transformer but is equipped with an additional fictitious delta winding which takes into account the low zero-sequence inductance (for a five-leg transformer the zero sequence is open in this case). When a transformer is seen from its star-earthed winding terminals, yet there is only a delta winding, the three-leg transformer has a performance which is slightly different from a five-leg one, since, from a modelling point of view, the three-leg transformer acts as a five-leg transformer but equipped with an additional fictitious delta winding which takes into account the slightly lower zero-sequence inductance. Reference to this aspect can be found in [50] or in [66].

7.4.9 Unoperated circuit-breaker and disconnector

An open circuit-breaker is generally represented as a dead-end element, but in some studies circuit-breaker grading capacitance may be required for open-circuit breakers, especially if ferro-resonance is considered. A closed circuit-breaker is represented as a single electric node.

7.4.10 Substation and tower earthing electrodes

If the representation of an earthing electrode is required, it may be modelled as a resistor representing the low-frequency earth resistance for small current.

7.4.11 Lightning stroke

If it is necessary to simulate a short-circuit (or flashover) caused by lightning, it can be modelled by a short-circuit with a closing switch.

7.4.12 Surge arresters

There are some cases where surge arresters have to be modelled:

- if their damping effect has to be taken into account;
- if their energy withstand is analysed;
- if TOV amplitude exceeds the rated voltage of a metal-oxide arrester or the sparkover voltage of an arrester with gap;
- if the studied TOV is associated with a slow front transient overvoltage;
- when sacrificial arresters are used to limit the amplitude of TOV.

In these cases, a non-linear resistor is enough to represent the influence of the arrester on TOV.

7.4.13 Loads

The main problem for the representation of loads is to know their parameters. If the only known parameters are active and reactive powers, then it is advised (see [2]) to perform two TOV studies, one with series-RL loads, one with parallel-RL loads. If the two studies show a big difference between the two models, then more data about loads should be obtained in order to use a more accurate model.

The presence of motors in loads may modify short-circuit power and frequency response.

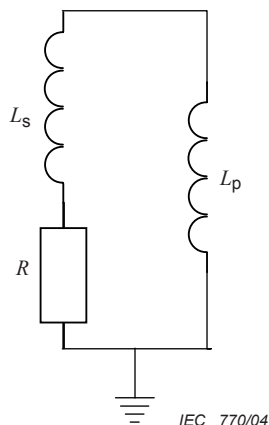


Figure 8 – Representation of load in [56]

Reference [56], which deals with harmonics calculation, proposes approaching the issue of load modelling using three methods:

- Method 1 – The equivalent reactance of the load is neglected, by considering it infinite. The load is equivalent to a resistance $R = U^2/P$, where U is the nominal voltage and P the active power controlled by the load.
- Method 2 – The equivalent resistance of the load is calculated as above but it is associated with an inductance in parallel with it. The reactance is estimated based on the number of motors in service, their installed unitary power and their installed reactance.
- Method 3 – Over a frequency range corresponding to frequencies between the 5th and the 20th harmonics, the load can be represented by an inductance L_s in series with a resistance R , the two of them being connected in parallel with an inductance L_p such that

$$R = \frac{U^2}{P_{50}}$$

$$L_s = 2,3 \times 10^{-4} R$$

$$L_p = \frac{R}{100 \times \pi(6,7 \times \tan \varphi_{50} - 0,74)}$$

with $\varphi_{50} = Q_{50}/P_{50}$.

P_{50} and Q_{50} are respectively the active and reactive power absorbed at nominal frequency by the overall load.

7.4.14 Filters and capacitors

It is important for TOV to represent them. They are represented by lumped R , L , C elements. Examples of installations can be found in IEC 60071-5 [64] for HVDC applications.

7.4.15 Other equipment

Devices such as FACTS or HVDC that can modify power flows or inject harmonics have to be accurately represented, especially their control. The action of protection systems has to be taken into account in order to get realistic scenarios.

7.5 Representation of network components when computing slow-front overvoltages

7.5.1 Power supply

7.5.1.1 Source network representation

According to [57], the characteristics listed below have a major effect on the overvoltages and must be modelled correctly.

- Power-frequency impedance.
- Surge impedance as seen from the energizing bus.
- Behaviour of the source at the major natural frequencies of the whole system (switched lines included).

Reference [57] makes the following general recommendations to model the sources adequately in line energization and line re-energization studies.

- Parts of the source network at a lower voltage level with respect to that of the switched line may be disregarded apart from their contribution to the short-circuit power.
- It is generally sufficient to represent the lines, at least in meshed systems, up to two busbars back from the energizing bus; the remaining part of the system may be represented by its short-circuit reactance in parallel with its surge-impedance.

7.5.1.2 Synchronous machine

For slow front overvoltage computation, synchronous machines are modelled as shown in Figure 9.

C (external capacitance of the overall system) must be calculated, taking into account what is connected to the machine. This capacitance is of secondary importance in the case of slow-front overvoltage computing.

The transition from subtransient to transient and to synchronous reactance is only of importance for the decay of short-circuit current [5].

When modelling the external behaviour of a synchronous machine only, $R(f)$ can often be represented by a constant, independent of frequency.

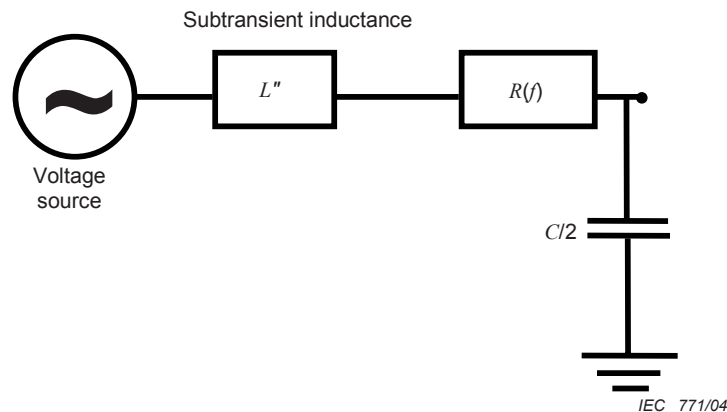


Figure 9 – Representation of the synchronous machine

7.5.2 Overhead lines

7.5.2.1 Trapped charge

This is used to simulate a high-speed reclosure condition. Completely different behaviour is expected when the line is equipped with shunt reactors, which implies a free oscillation of the trapped charges, in contrast with uncompensated lines without magnetic transformers for which trapped charges decay exponentially without free oscillations.

When a circuit-breaker opens an overhead line sequentially without current chopping, polarity of trapped charges on each phase is positive, negative and positive, or negative, positive and negative. Magnitude of trapped charge on the last phase to open corresponds to 1 p.u. However, the voltage magnitude corresponding to trapped charge on the first phase to open becomes larger than 1 p.u. and can reach more than 1,3 p.u. This voltage increase is caused by capacitive coupling between phases [53]. For single-circuit OHL, this voltage rise is a function of C_1/C_0 . For double-circuit OHL, the voltage rise is a function of C_1/C_0 and of the coupling from the adjacent circuit. On the other hand, magnitude of the voltage on the second phase to open is smaller than 1 p.u. This phenomena has been confirmed by field tests. Of course, trapped charges decay with time. To simplify the simulation for high-speed reclosing, it is assumed in many cases that the trapped charges are +1 p.u. –1 p.u. and +1 p.u. or –1 p.u. +1 p.u. and –1 p.u. However, care should be taken that in the case of reclosing after a single phase-to-earth fault, trapped charges on the healthy phases may be higher than 1 p.u., depending on the earthing of the neutral. In the case of a single-phase reclosing, the trapped charge is smaller than 1 p.u.

7.5.2.2 Line model

Models 3, 4 and 5 of 7.3 may be used.

7.5.3 Tower

As the tower's equivalent capacitance to the line can be considered negligible when compared to the capacitance of the line, they need not be represented in the study, except when a flashover occurs at a tower. In this case the tower is represented by a resistance equal to the tower footing resistance for SFO studies, if necessary (because a fault application overvoltage is little affected by the tower footing resistance).

7.5.4 Corona effect

In most of the cases, slow-front overvoltages are too low to induce corona effects.

7.5.5 Underground cable

Models 3, 4 and 5 of 7.3 may be used.

Cross-bonding and earthing have to be carefully taken into account. All conductors (core, sheath, armour and additional conductors) must be represented. Reference [58] provides a large presentation of solutions generally adopted for underground cable cross-bonding and earthing.

7.5.6 Air gap, line insulator

7.5.6.1 Flashover trigger

For a first approximation, one can assume that the gap flashes as soon as its voltage reaches a given value. Once the flashing condition has been verified, several possibilities exist to represent the flashover process.

7.5.6.2 Flashover process

7.5.6.2.1 Ideal switch

An air gap, once the flashing condition has been verified, can be simply represented by an ideal switch which closes in one time step. If the time step is not too small, this model is quite representative.

7.5.6.2.2 Voltage source

In the case of a study using a very small time step, the last model can lead to excessively high overvoltages due to a value too high of dV/dt . One can then model the flashing of an air gap by a voltage source which decays progressively from the initial voltage to zero in a given time, equal to several time steps.

7.5.6.2.3 Use of inductance

For a study using a small time step, the air gap may be represented by a small inductance (for example, 1 $\mu\text{H/m}$) in a series with an ideal switch which closes in one time step.

7.5.7 Busbar

Busbars are not represented individually because their impedance and admittance are too small to influence the transient response. Important sets of busbars can be represented as a single lumped capacitance. Small busbar sections (the travel time of which represents few time steps) can be represented as a lumped capacitance.

7.5.8 Transformer

A power-frequency model must be used, taking into account non-linearity, losses, remnant flux and primary-secondary stray capacitances. In some cases it is important to model accurately the capacitances to get a correct resonant behaviour (energization of a transformer from a short line). A frequency-dependent transformer model would be of interest but in most practical cases the knowledge of the transformer parameters does not permit an accurate representation of the transformer.

7.5.9 Open circuit-breaker

An open circuit-breaker is represented as a dead-end element. A grading capacitor, in parallel with the breaker contacts, can also be included when possible.

7.5.10 Circuit-breaker

Breakers are important in SFO as most of these are generated during switching operations. Depending on the type of phenomena that are being studied, a different model for the breaker should be used.

7.5.10.1 Ideal switch (closing and opening)

As a first approximation, a breaker can be considered as either an infinite resistance (open breaker) or a null resistance (closed breaker), changing from one to the other in a time step in case of closing, as well as when its current reaches zero in case of opening.

Several improvements have been proposed to this model:

- The possibility to chop non-zero current when the current drops under a given value. This data is difficult to obtain; it depends on the current value and the characteristics of the load. This feature can be very useful when simulating the interruption of inductive currents [14].
- A high-frequency current property (see IEC 61233). A value of dI/dt which is too high prevents the breaker from opening. This data is also difficult to obtain.
- Restriking possibility. This model includes a computation routine to determine when the breaker will restrike after it has opened. The routine may be a simple comparison of the longitudinal voltage versus time and a TRV shape.
- Statistical switch. The closing times of the three phases of the breaker have a great influence on the generated overvoltage. Two parameters are taken into account. First, the closing command may happen at any time, which means anywhere on the power-frequency sine. Then the three phases, which are supposed to receive the command at the same time, respond to this command with a random delay due to mechanical dispersions and pre-strikes. The strategy the most commonly adopted is as follows: the closing command is supposed to be uniformly distributed on the sine and real closing times are supposed to be around it, with a Gaussian probability. This double distribution is illustrated in Figure 10. If the transient behaviour of the system is symmetric in terms of polarities, one can limit the excursion of the switching order time to under one-third of a power voltage period. Concerning the Gaussian distributions, the standard deviation of the inter-phase time distribution is not always known. A value of 0,8 ms to 2 ms may be used as a typical value. IEC 62271-100 [65]. allows 5 ms.

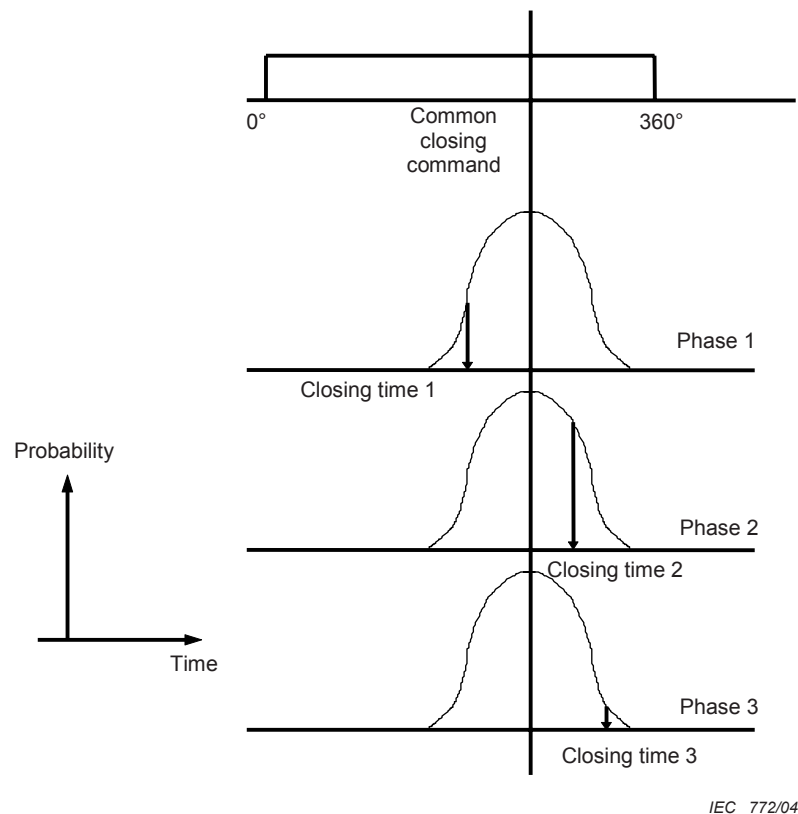


Figure 10 – Diagram showing double distribution used for statistical switches

It is a simplification to assume that the closing command is unique for the three phases. If a particular breaker is studied and if data are available, three different closing commands can be given, as described in [20].

7.5.10.2 Arc model based on the physics of the circuit-breaker

This sophisticated model tries to simulate the physics of the circuit-breaker as closely as possible. It is much more complicated than the ideal switch, and its parameters can be difficult to obtain. It is not required for most studies but it is useful for an accurate representation of restrike phenomena in cases such as breaker explosion investigations.

Most mathematical models are based on energy balances between the electric arc and the surrounding environment when the current drops to zero. The two equations most used are the Mayr and Cassie equations [13]. More details are given in Annex B.

A simplified model may be used if the effect of arc voltage only is considered [5]. Statistical characteristics can be added to this model in the same manner as above.

7.5.11 Metal-oxide surge arrester

A MOA is represented as a non-linear resistor, using its 30/80 μs characteristics (IEC 60060-1). The surge arrester's benchmarks are 0,5 kA, 1 kA and 2 kA.

7.5.12 Substation and tower earthing electrodes

If the representation of the earthing electrode is required, it may be modelled as a resistor representing the low-frequency earth resistance for small current.

7.5.13 Network equivalent

A model similar to the one given in 7.4.2 may be used but covering a higher frequency range (up to 20 kHz).

7.6 Representation of network components when computing fast-front transients

7.6.1 Power supply – voltage source

The power-frequency voltage, at the inception time of a lightning stroke, can be represented as a power-frequency voltage source and an adaptation resistor in series (value $[R] = [Z_s]$, surge impedance matrix).

The relative polarities of the lightning stroke and the initial line voltage are of importance. It is necessary to investigate both polarities. In some specific configurations, several values of initial line voltage need to be considered.

7.6.2 Overhead transmission line and underground cable

7.6.2.1 Line or cable close to the lightning stroke inception point

If a complex model is to be implemented, approximately 2 000 m of overhead line must be accurately modelled. In the case of underground cables, especially when the remote end of the cable is under open-circuit conditions, invaded surge may produce high overvoltages due to positive multi-reflections at both ends. Therefore, use of a cable model with full length is recommended.

7.6.2.2 Line or cable far from the lightning stroke inception point

If reflections are not to be considered, the line can be terminated in its equivalent characteristic surge impedance in the phase domain.

7.6.3 Tower

A tower is commonly represented as a radiating structure [4]; as a lossless propagation line with constant characteristics; as a propagation line with damped inductance; or as an equivalent inductance.

7.6.3.1 Lossless propagation line with constant parameters

Wagner and Hileman [15] have proposed the expression below to calculate the surge impedance of a cone:

$$Z_{pyl} = 60 \times \ln \frac{H\sqrt{2}}{r_{pyl}}$$

where:

H is the height of the cone equivalent to the tower;

r_{pyl} is the tower base radius.

Chisholm, Chow and Srivastava have discovered that the impedance depends on the direction of injection. However, they propose the use of an average impedance Z_{av} [18]:

$$Z_{av} = 60 \times \ln(\cot \theta / 2)$$

where $\theta = \tan^{-1}(r(h)/h)$, h is the height along the tower and $r(h)$ is the tower radius at a height of h .

They propose the following practical simplification:

$$Z_{av} = 60 \times \ln[\cot(0,5 \times \tan^{-1}(r_{avg}/H_t))]$$

with:

$$r_{avg} = \frac{r_1 h_2 + r_2 (h_1 + h_2) + r_3 h_1}{h_1 + h_2}$$

where:

r_1 is the tower top radius;

r_2 is the tower mid-section radius;

r_3 is the tower base radius;

h_1 is the height from base to mid-section;

h_2 is the height from mid-section to top;

$H_t = h_1 + h_2$.

7.6.3.2 Propagation line with damped inductance

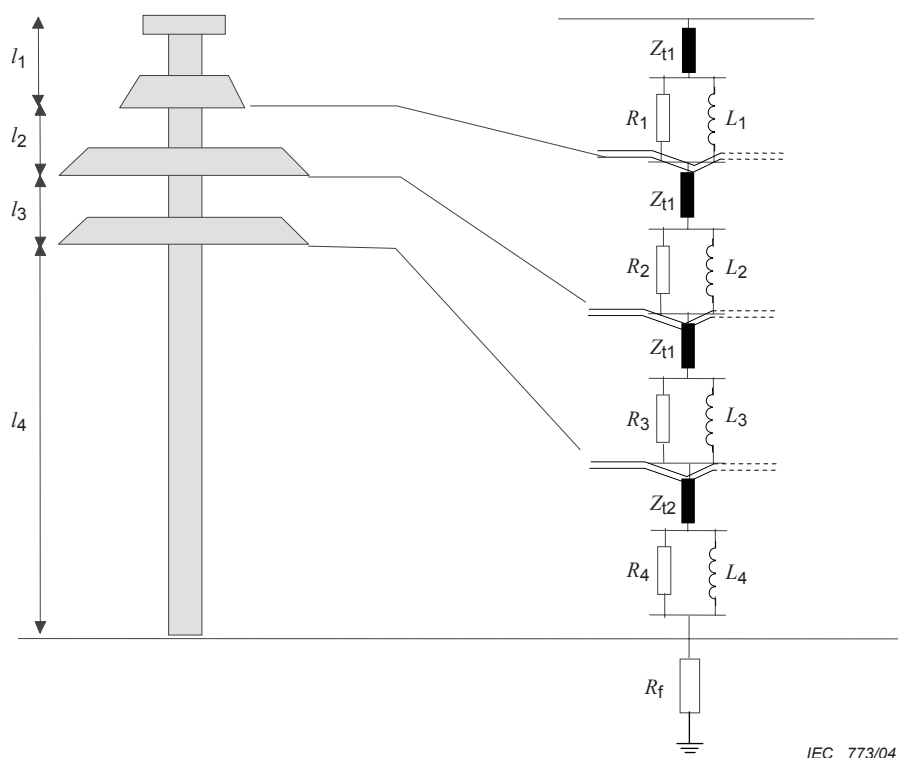


Figure 11 – Multi-story transmission tower [16], $H = l_1 + l_2 + l_3 + l_4$

A model for a multi-story transmission tower [16] has been developed on the basis of measurements on a 500 kV transmission tower equipped with shield wires (see Figure 11). This model consists of four sections divided at the upper, middle and lower phase cross-arm positions. Each section consists of a lossless transmission line in series with an inductance in parallel with a damping resistance. The impedance depends on the direction of the lightning current in air. The model considers the most severe condition. The parameters of the corresponding electrical model are calculated using the following rules:

Surge impedance: (upper part) $Z_{t1} = Z_{t2} = Z_{t3} = 220 \, \Omega$ (lower part) $Z_{t4} = 150 \, \Omega$

Surge propagation velocity: $v_t = v_{t1} = v_{t2} = v_{t3} = v_{t4} = 300 \, \text{m}/\mu\text{s}$

Time constant (travel time on tower $\times 2$): $\tau = 2 \times H/v_t$

Attenuation is constant along the tower: $\gamma = 0,8944$

Damping resistance per unit length of upper part: $r_1 = 2 \times Z_{t1} \ln(\gamma/(l_1 + l_2 + l_3))$

Damping resistance per unit length of lower part: $r_2 = 2 \times Z_{t4} \ln(\gamma/l_4)$

$R_1 = r_1 l_1$, $R_2 = r_1 l_2$, $R_3 = r_1 l_3$, $R_4 = r_2 l_4$ where l_1 , l_2 , l_3 and l_4 are real length.

Inductance in parallel with a damping resistance: $L_1 = R_1 \tau$, $L_2 = R_2 \tau$, $L_3 = R_3 \tau$, $L_4 = R_4 \tau$.

7.6.3.3 Inductive branch

A value of 1 μH per metre can be used.

7.6.3.4 Cross-arm representation

Because of their short length, propagation in cross arms cannot be represented easily in FFO studies. Cross arms have been represented as short, electrical transmission lines with open-circuit ends [4], [18], including the effect of doubling of the overvoltage at the end of the cross arm.

Therefore, in this respect, a cross arm may be modelled as a lossless propagation line with constant parameters or an equivalent inductance (1 $\mu\text{H}/\text{m}$); this last representation does not give the effect of doubling of the overvoltage at the end of the cross arm before flashover.

7.6.3.5 Travel time

Some experiments [18], [19] have shown that travel time is longer than the tower height divided by the speed of light in a vacuum but it is reasonable to ignore the additional path length in practical studies. The additional contribution due to the propagation from the shield wire may be considered [4].

7.6.4 Corona effect

The corona effect [45] [4] involves an increase in the line capacitance due to the ionization of the air around the conductor. This effect appears both between phase and ground and between phases. Most of the models account for the phase-to-ground corona effect.

Since this effect tends to reduce the steepness of the impinging surge, it is a conservative approximation to neglect it. There are many proposals on the methods to simulate corona effect. The next subclause presents one of them.

7.6.4.1 Discrete components model

The corona effect can be represented using discrete classical components. This is achieved by dividing the line into sections of a given length and connecting one or two branches containing a diode, a capacitor and a d.c. voltage source to each section. The source represents the voltage above which the corona begins to appear, the capacitor represents the additional capacitance of the line due to the corona and the diode is an artifice which facilitates the connection of the capacitor only when the voltage reaches the d.c. source value. This model is only valid for one polarity of overvoltages, i.e. positive, in the example shown in Figure 12.

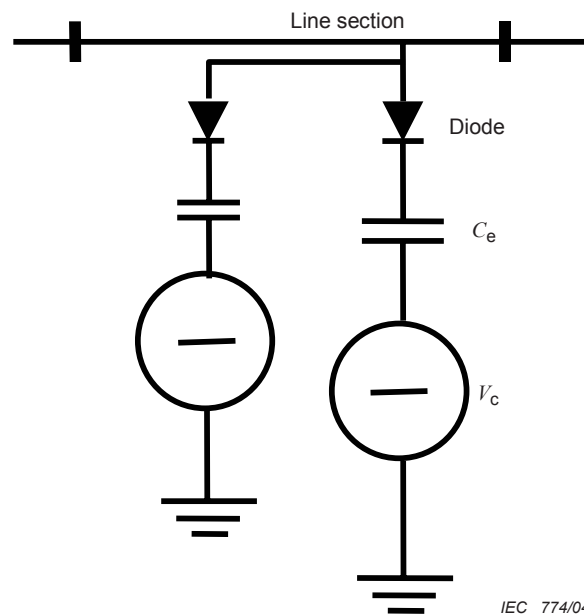


Figure 12 – Example of a corona branch model

For the computation process, this model is both time- and memory-consuming because it requires dividing the line into many small lengths. For this reason, it is recommended that the model only be used in the most stressed part of the network, i.e. 500 m from the stroke inception point.

7.6.4.2 Parameter values

Parameter values can be found in Clause F.1 of IEC 60071-2, in [21], [24] and in 5.6 of [4]. It must be noted that parameters for the corona effect depend on the geometry of the line (i.e. conductor radius, number of sub-conductors per bundle), polarity and even on the waveform of the transient. Reference [4] proposes a method to evaluate the reduction of steepness due to the corona effect of an impinging surge.

7.6.5 Air gap, line insulator

7.6.5.1 Flashover trigger

7.6.5.1.1 Voltage threshold

An assumption that the gap flashes as soon as its voltage reaches a given value is not recommended for this type of studies.

7.6.5.1.2 Volt-time curve [4], [10] (Figure 13)

The instant of breakdown is considered as being the point of intersection of $U(t)$ with the volt-time curve of the insulation. $U(t)$ is the voltage between the two terminals of the air gap versus time. The knowledge of the performance of insulation under the stress of the standard lightning impulse is, however, not sufficient to predict the performance of the insulation exposed to any non-standard impulse. Furthermore, it is not always correct to assume that flashover will occur when a voltage wave just exceeds the volt-time curve at any time. The experimental volt-time characteristic is only adequate for relating the peak of the standard impulse voltage to the time of flashover. For a non-standard impulse, a more accurate determination of the time of flashover may be obtained using the two models presented below.

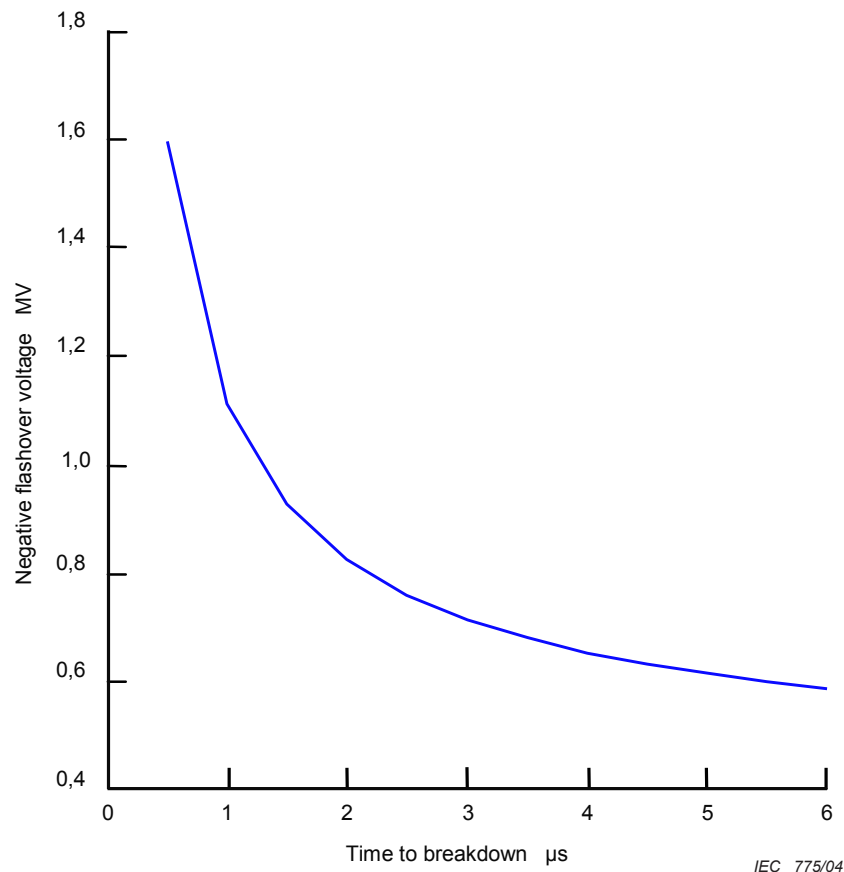


Figure 13 –Example of volt-time curve

7.6.5.1.3 Air gap model using the area criterion [4], [30]

The area criterion involves determining the instant of breakdown using a formula of the type described below. The method allows the applied waveform to be taken into account.

$$\text{Integrate}(t) = \int_{T_0}^t (U(\tau) - U_0)^k d\tau$$

Flashover occurs when $\text{Integrate}(t)$ becomes equal to DE (constant):

$U(t)$ is the voltage applied at time t , to the terminals of the air gap.

U_0 is a minimum voltage to be exceeded before any breakdown process can start or continue.

k and U_0 and DE are constants corresponding to an air-gap configuration and overvoltage polarity.

T_0 is the time from which $U(\tau) > U_0$.

The parameters U_0 , k and DE are determined by using the voltage-time curve.

This model is valid for impulses of either positive or negative polarity but does not apply in case of oscillation, when the voltage between the terminals decreases below U_0 after having being greater than U_0 .

The model is recommended for air gaps smaller than 1,2 m.

In [59] standard impulse tests have been used to evaluate some sets of parameters U_0 , k , DE which were used to predict the performance of the insulation stressed by non-standard data and to make some comparison with experimental data. The sets of parameters corresponding to the different configurations considered are presented in Table 4 below.

Table 4 – Values of U_0 , k , DE for different configurations proposed by [59]

Gap (cm) – Test object – Polarity	k	U_0 kV	DE
56 – rod-rod – +	1	306	4,9
56 – rod-plan – +	1	252,2	306,5
114 – rod-rod – +	1	577,5	641,2
8 – insulators ¹ – +	1	643	369,3
56 – rod-rod – –	1	391,6	240,1
56 – rod-plan – –	0,47	590	7,947
114 – rod-rod – –	1	825,8	427,5
8 – insulators – –	1	638,7	525,4
NOTE An eight-unit string of 254 mm × 146 mm suspension insulators mounted in a geometry similar to that of a steel tower.			

7.6.5.1.4 Air-gap model based on the leader propagation representation [4], [30]

The physics of discharge in large air gaps, i.e. air gaps greater than 1 m, has proved that the breakdown in large air gaps involves three successive phases: corona inception (t_i), streamer propagation (t_s) and leader propagation (t_l).

Leader propagation models are based on the numerical representation of these three stages.

a) Breakdown process

When the voltage applied to the air gap exceeds the corona inception voltage, streamers propagate and cross the gap after a time t_s , if the voltage remains high enough.

When the streamers have crossed the gap, the leaders develop rapidly, with speed being dependent on the applied voltage. The streamers and the leaders can develop from one or two electrodes. The breakdown occurs when the leader has crossed the gap or when the two leaders have met. The time to breakdown can be calculated by:

$$t_c = t_i + t_s + t_l$$

t_i being the time before streamers exist. It can be neglected for practical purposes.

b) Calculation of t_s (streamer propagation time)

An approximation made in most models is that the streamer phase is completed when the voltage applied reaches a value leading to an average gradient E equal to E_{50} (average field for U_{50}).

c) Calculation of t_l (leader propagation time)

The leader velocity $v_l(t)$ can be calculated using the following formula [4]:

$$v_l(t) = g(u(t), d_g) (u(t) - U_0(d_g - l_l)) / (d_g - l_l)$$

Where g and U_0 are some functions, d_g and l_l correspond to the gap length and the leader length respectively; $u(t)$ is the absolute value of the actual voltage in the gap. The model considers an equivalent leader propagating from one electrode even if two leaders exist in reality.

It is considered that the leader stops if $u(t)$ drops below $U_0(d_g - l_l)$. As a practical application, two types of formula have been proposed for the calculation of the velocity of the leader: