Simulation of Lightning Overvoltages in Electrical Power Systems

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Abstract - **Lightning strikes to overhead transmission lines cause travelling waves which propagate along the overhead line and enter substations where they cause overvoltages which can pose a risk to any items of equipment connected, such as cables or transformers. With the use of metal-oxide arresters, these overvoltages are reduced to values which, taking into account an adequate safety margin, are below the electric strength of the electrical devices applied. The paper describes the fundamental relations for calculating lightning overvoltages, the models used for the investigations, and presents as an example the results obtained from a simulation process using the NETOMAC digital simulation program [1].**

Keywords: Insulation Co-ordination, Overvoltages, Lightning, Surge Arresters, Modelling, NETOMAC

I. TYPES OF LIGHTNING STRESSES

In the calculation of overvoltages which occur after lightning strikes to overhead power transmission lines, a distinction is drawn between three types of lightning strikes:

A. Remote strikes

Remote strikes do not occur in the immediate vicinity of the switchgear. These remote strikes result in travelling waves which are simulated by a lightning impulse voltage with a front time of 1.2 µs and a time to half-value of 50 µs. The travelling waves propagate towards the switchgear, and it is assumed that the amplitudes occurring are below the flashover voltage of the insulators of the overhead power transmission line. Therefore, remote strikes do not lead to any flashovers at the overhead line insulators in the immediate vicinity of the switchgear. The amplitude of these remote strikes (90 % withstand voltage) can be calculated from the 50 % flashover voltage of the insulators, taking into account the standard deviation of $\sigma = 0.03$ for lightning impulse voltages [2]:

$$U_{90} = U_{50} \cdot (1+1{,}3 \cdot \sigma) \qquad (1)$$

As a typical example, the simulation of a remote strike with an amplitude of 1600 kV for a 230 kV system is illustrated in Fig. 1a).

B. Strikes to towers

Lightning strikes which directly strike towers increase the potential of the towers affected and can, dependent on the level of the tower footing resistance and the electric strength of the overhead line insulators, lead to backward flashovers from the tower to an overhead line conductor. These backward flashovers cause travelling waves which propagate via the overhead line towards the switchgear. The simulation of these strikes takes into account the concave wave shape during rise which is described in [3] with a time to half-value of approximately 100 µs. For the amplitude of the lightning strike current, the maximum value of 200 kA for lightning strikes on level ground has been assumed as the worst case [3]. Fig. 1b) illustrates such a lightning strike current with an amplitude of 200 kA.

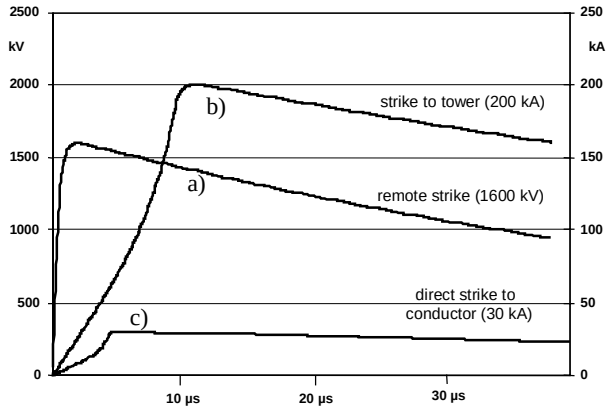

Fig. 1. Simulation of lightning currents and voltages

C. Nearby direct strikes to overhead line conductors

The current amplitudes of the lightning strikes which strike an overhead line conductor are influenced very considerably by the tower geometry and the shielding effect of the overhead earth wires. High towers with wide conductor spacing and considerable angles of protection from the overhead earth wires lead to higher lightning strike currents in the event of direct strikes to the overhead line conductor. Thus, the amplitudes of the lightning strike currents are therefore calculated as a function of the tower geometry for overhead transmission lines. Usually, the lightning strike currents are within a range of approximately 10 kA to 60 kA. Similarly to strikes to towers, a concave wave shape occurs during the rise, with

a time to half-value of approximately 100 µs. As an example of the waveform, Fig. 1c) illustrates a lightning strike current of 30 kA.

II. MAXIMUM LIGHTNING CURRENTS IN CASE OF DIRECT STRIKES TO AN OVERHEAD LINE

The amplitude of the maximum lightning strike current which can directly strike an overhead line conductor depends very largely on the tower geometry. The calculation of these currents is based on the geophysical model illustrated in Fig. 2 [3, 4].

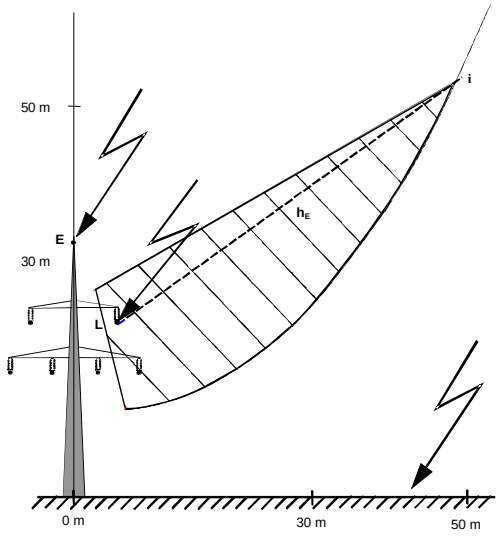

Fig. 2. Electrogeometric model of a tower to calculate maximum direct lightning strikes

Dependent on the tower data, such as the height above ground of the overhead line conductor and the overhead earth wire, and the deflection of the overhead line conductor in relation to the overhead earth wire, a parabola can be plotted which represents a curve of equal distances from the overhead conductor and from ground. Thus, lightning strikes on the right of this parabola will always strike earth, and lightning strikes on the left of this parabola will strike the tower. In order to determine the portion of this area which concerns direct strikes to the overhead line conductor, the mid-perpendicular of the straight line connecting overhead earth wire (E) and overhead line conductor (L) is plotted. Only the hatched area enclosed by the mid-perpendicular and the parabola can be considered as possible area for direct lightning strikes to the overhead line conductor. The maximum possible lightning strike current I in the event of direct strikes to the overhead line conductor can therefore be calculated by means of the following relationship

$$h_E = 8 \cdot I^{0,65} \qquad (2)$$

where h_E is determined by the length of the overhead line conductor section (L) and point of intersection (i) of the mid-perpendicular with the parabola.

III. FLASHOVER MODEL OF INSULATORS

The flashover characteristic of insulators is described with the 50 % flashover voltage. Fig. 3 illustrates the standardised characteristic of such a 50% flashover voltage as a function of time. Accordingly, high voltages which are present for a short time or low voltages which are present over long periods lead to flashover at the test object for half of the impulses induced with this voltage. For simulation of the flashover characteristic of insulators, the Kind design criterion [5] is applied for calculations with NETOMAC. When the voltage present at the insulator exceeds a reference value U_∞, derived from the 50 % flashover voltage of the insulators, calculation of the voltage-time area F is commenced.

$$U = U_\infty + \sqrt{2 \cdot S \cdot F} \qquad (3)$$

When the defined limit value for voltage-time area F is exceeded, flashover of the insulator takes place.

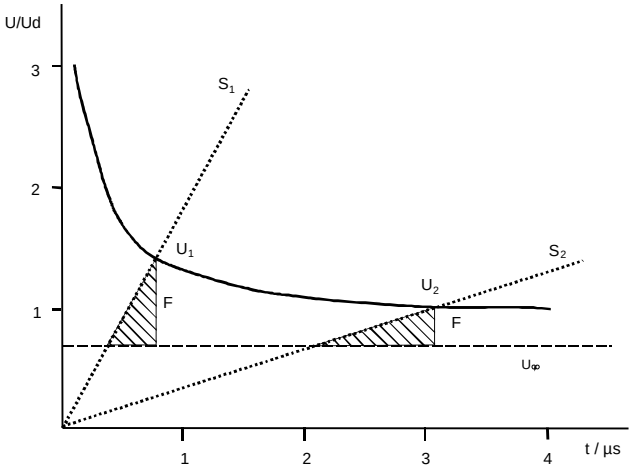

Fig. 3. Sparkover voltage versus time of an insulator

IV. TRAVELLING WAVE MODEL OF EQUIPMENT

In the calculation of lightning overvoltages, it is necessary to take account of the propagation time of these overvoltages, the reflection at open ends, and the refraction on transition to surge impedances of differing magnitudes. Thus, simulation of lightning overvoltages requires emulation of the items of electrical equipment, such as overhead transmission lines, overhead earth wires, towers and switchgear, as travelling wave conductors. In the case of a travelling wave model, the items of equipment are not simulated as a concentrated impedance, but are described by their surge impedance Z, speed of propagation v and length l. Travelling waves propagate in air or gaseous insulants at the velocity of light c (v = 300 m/µs). In the case of exposed conductive parts with solid insulation (for example, cables), the speed of propagation is less (XLPE cables, v ≈ 200 m/µs, oil-impregnated paper cables, v ≈ 160 m/µs), and depends on the level of the

relative dielectric constant ε_r.

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (4)$$

The surge impedance Z describes the high-frequency behaviour of the items of equipment and can be calculated with the relationship:

$$Z = \frac{1}{v \cdot C'} \quad (5)$$

where $Z = \sqrt{L'/C'}$

$$v = \frac{1}{\sqrt{L' \cdot C'}}$$

C' = capacitance per km
L' = inductance per km

The surge impedance depends inter alia on the level of the phase-to-earth capacitance, which is in turn affected by the height above ground. For overhead lines and overhead earth wires, the resultant surge impedance can be calculated with the relationship:

$$Z = 60 \cdot \ln \frac{2 \cdot h}{r} \quad (6)$$

where h describes the suspension height above ground, and r is the equivalent radius of the conductor. In addition to this simplified simulation, which is quite adequate in the vast majority of cases for investigation into lightning voltage stress on equipment, the travelling wave conductor can also be simulated in NETOMAC with the use of the Marti model [6]. Here, the reducing influence of the coupling between the phases of a system and the frequency-dependent damping on the lightning stress are taken into account. The surge impedances of the switchgear can be calculated with relationship (5). In the calculation of lightning overvoltages, the elements of the switchgear, such as current transformers, potential transformers, circuit-breakers, etc., are not simulated individually. While the slight differences in the surge impedances of the individual items of equipment are perceptible in the refraction characteristics of the incoming travelling wave, they have only slight influence on the result of the calculations. In contrast to investigations of very fast transient phenomena, such as disconnector switching, it is sufficient when calculating lightning overvoltages to use a mean surge impedance for certain sections, such as busbars or outgoing feeder bays. The calculation of the surge impedances for the towers is derived from relationship (6), where a weighted average radius r_{av} over the entire tower height h is taken into account [7].

$$Z_{av} = 60 \cdot \ln \left(\sqrt{2} \cdot \frac{\sqrt{h^2 + r_{av}^2}}{r_{av}} \right) \quad (7)$$

V. REMEDIAL MEASURES AGAINST LIGHTNING OVERVOLTAGES

The current amplitudes of the lightning strikes which can strike an overhead line conductor directly are influenced very considerably by the tower geometry and shielding action of the overhead earth wires. Thus, it is a general rule that high towers with wide conductor spacing and large angles of protection of the overhead earth wires lead to higher lightning strike currents in the event of direct strikes to the overhead line conductor. Above all, in regions susceptible to frequent thunderstorms, it is possible by suitable choice of tower configuration for the maximum possible lightning strike current amplitudes to be significantly reduced in the event of direct strikes to overhead line conductor (for example, two overhead earth wires and arrangement of the overhead earth wires extending as nearly vertically as possible past the overhead line conductors).

Lightning strikes to towers lead to an increase of the tower's potential, which is essentially determined by the tower footing resistance. If this potential exceeds the electric strength of the insulators, backward flashovers occur across the insulators which, especially when they occur in the direct vicinity of the switchgear, can cause high overvoltages and overvoltages with high rates of change. Here, linking the last towers to the switchgear earthing system as a remedial measure is a suitable method of significantly reducing the tower footing resistance and of preventing backward flashovers across the insulators of these towers. For economic reasons however, this measure is generally restricted to portal and first tower seen from the substation.

The use of arcing horns on the insulators can also influence the flashover characteristic. If several systems are arranged on a tower, the insulators of one of these systems can be equipped with arcing horns, so that flashovers will occur preferably in this system, dependent on the clearance distance set. In areas subject to frequent thunderstorms, this measure is advisable, since in the event of a tower being struck, backward flashovers will be restricted to one system of the power transmission line and total failures of the power transmission system will be prevented.

In addition to the structural alternatives previously mentioned, the use of line surge arresters to improve transmission line lightning performance or to avoid double circuit outages has increased over the last years. The number and location of surge arresters installed on a particular line depends on many factors, such as: desired improvements, lightning activity of the region, line construction, tower footing resistance, arrester characteristic.

Beside this specific application, the installation of surge arresters in a substation is an effective method of limiting transient overvoltages, for example switching overvoltages or lightning overvoltages [8].

Today, metal-oxide surge arresters are predominantly used, which limit the overvoltages occurring by virtue of their non-linear characteristic (residual voltage

characteristic). The dimensioning criteria for selection of the arresters are, in addition to the maximum operating voltage U_m , the method of neutral-point connection of the system and the resultant earth fault factor. On the basis of this system data, it is possible to select arresters described by their continuous operating voltage U_c, the rated voltage U_r and the residual voltage characteristic.

In order to make optimum use of the protection characteristic of the surge arresters, it will be necessary, particularly on account of the lightning stresses, to install them as close as possible to the objects to be protected, such as transformers or shunt reactors. In order to protect switchgear from incoming lightning overvoltages, surge arresters are installed in the incoming or outgoing feeder bays of overhead power transmission lines. The transitions from overhead line to cable are also protected by surge arresters in order to prevent unacceptably high overvoltages caused by reflected travelling waves at the transition point from cable (low surge impedance) to overhead line (high surge impedance).

If operation of unloaded overhead lines or mixed overhead line / cable feeders (open end) is possible in a system over an extended period of time, the installation of surge arresters at the end of the transmission link will also be necessary in order to limit overvoltages caused by total reflection of the travelling surge at the open end.

VI. CALCULATION OF LIGHTNING OVER-VOLTAGES USING NETOMAC

Following the above general explanations, this section will describe the results of a calculation of lightning overvoltages with the NETOMAC digital simulation program, using the example of a 230 kV GIS (**G**as-**I**nsulated **S**ubstation).

For modelling the substation and the overhead lines the graphical user interface NETCAD® (NETOMAC Computer Aided Design) is used. NETCAD is a quick, easy-to-use drawing tool for drafting, editing and documenting electrical systems and control structures. Additionally NETCAD is used for developing and modelling libraries for special simulation tasks e.g. for calculation of lightning overvoltages.

In addition to well-known CAD facilities such as copying, shifting, rotating, zooming, etc., the system also provides a large library of symbols containing all elements of the NETOMAC program in the form of symbols. The user prepares his network diagrams and block diagrams through the graphical connection of library symbols. Fig. 4 shows a network element being selected from the symbol library "Lightning Overvoltages".

Data is entered by means of templates which are object-related and contain detailed help in plain text as well as in abbreviated form. There is also a facility for combining groups of related symbols to produce new, original symbols in the form of macro-models and adding them to the program symbol library or the user's own libraries. It is possible, for example, to combine complex control structures or sub-networks, comprising a large number of different items of equipment, into new symbols. As a result of this hierarchical configurability, depending on the requirements and using the same data, the system allows a choice to be made as to how complexly or how clearly a system should be presented.

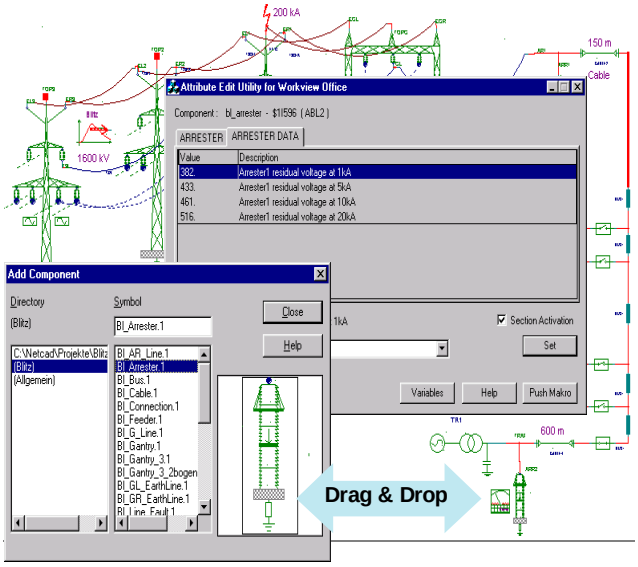

Fig. 4. Selecting network elements by Drag & Drop

Individual components can be activated and deactivated and linked to any point in the system. Thus, it is possible to show and simulate the behavior of different tower configurations as travelling wave models anywhere in the network.

The NETCAD library for the calculation of lightning overvoltages contains several models of different types of towers, gantries, arresters, transformers, overhead lines, cable sections or substation components.

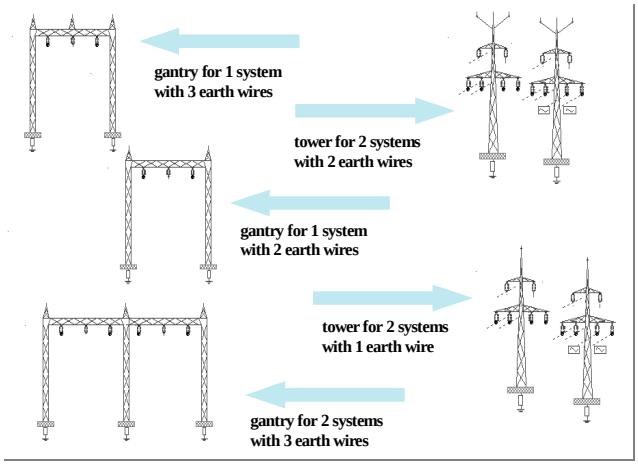

Fig. 5. Library for modelling overhead lines

For simulating lightning currents or impulse voltage wave shapes, models of the current and voltage sources are also included in this library. Fig. 5 shows as an example some overhead line models of this library. Fig. 6 shows the components to model a switch gear.

All components like bus connections, transformers, generators or cable sections are modelled as travelling wave models.

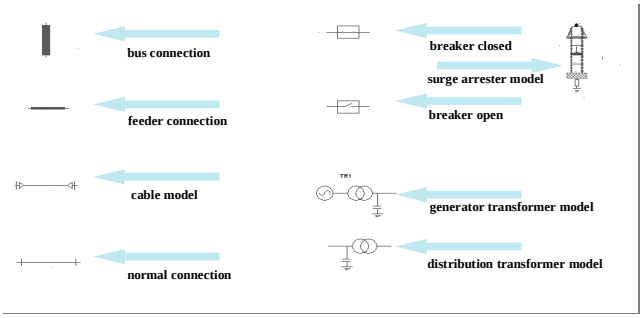

Fig. 6. Models for switch gear components

Fig. 7 shows the symbols of the current and voltage source models for the simulation of the lightning currents and impulse voltage wave shapes. Dependent on the source type (voltage source, current source), the fault location and network settings, variants of calculations are possible. The library also includes special measurement equipment. As an example Fig. 7 shows the current, voltage and the energy of an arrester caused by a lightning strike.

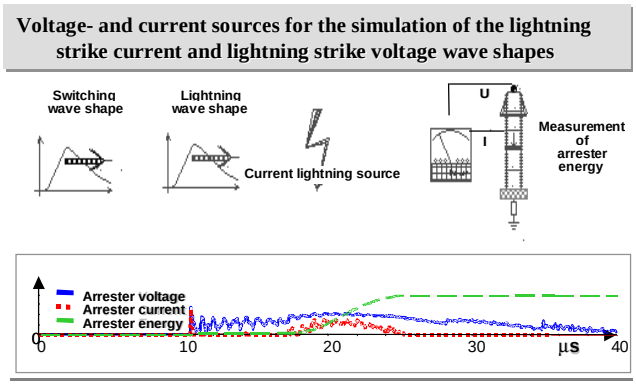

Fig. 7. Voltage- and current sources used to simulate lightning phenomena

The NETCAD user interface is an open system. For this it is possible to implement new models in graphical form to enlarge the extent of the library step by step. The use of the graphical libraries make it possible to model a detailed system easily and dealing effectively with a wide variety of problems:

- Automatic modeling of the current and voltage sources for simulation of lightning currents and impulse voltage wave shapes.
- Modeling of different tower configurations as a travelling wave model.
- Simulation of the flashover characteristic of the insulators.
- In the case of special problems (for example, influence of coupling of the three phases or frequency-dependent damping, a Marti model is implemented in NETOMAC.

Fig. 8 shows the simplified equivalent circuit diagram of the 230 kV system configuration examined. Simulated are the first three towers of the overhead line connections and their cable links to the substation. The substation, including the outgoing transformer bays, is also simulated according to its travelling wave characteristics. The transformer bays are taken into account with their surge capacitance between the high-voltage connection and ground. For protection of the items of equipment, metal-oxide arresters are installed at the point of overhead line to cable transition and at the transformer terminals on the 230 kV side.

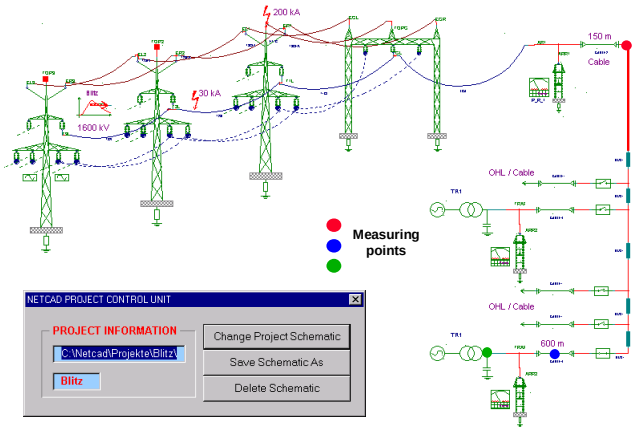

Fig. 8. Example for a lightning study of a 230 kV GIS

The purpose of the investigation is the calculation of overvoltages which, following lightning strikes to the overhead line, occur at various locations of the substation, the cable connections and at the terminals of the transformers on the high-voltage side. The results are also used for the selection of suitable surge arresters for protection from unacceptably high lightning overvoltages. In these calculations, the three different types of lightning strikes as described at the beginning (remote strikes, strikes to one of the first towers and direct strikes to the overhead line conductor) are simulated, taking into account the most unfavourable configuration of the substation. The highest stresses generally occur when the substation is operated in a dead-end configuration, that is, one system of an overhead line supplies only one transformer.

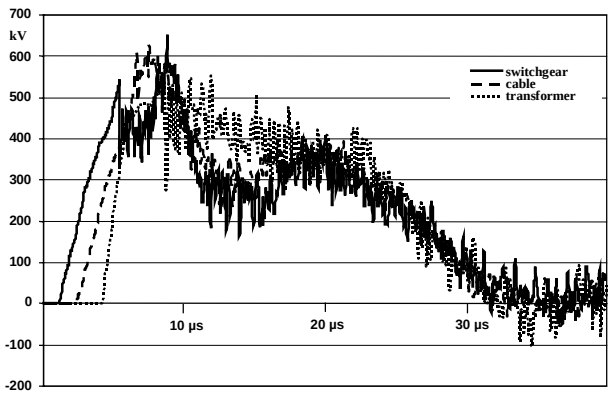

Fig. 9. Lightning voltage stresses following a direct strike to the overhead line conductor in the vicinity of tower 1

The effectiveness of the surge arrester protection concept is checked by comparison of the maximum voltages occurring with the permissible value for the **B**asic **I**nsulation **L**evel (BIL) of the equipment, taking account of a safety margin (S) specified in the Standard [2].

The calculated lightning stresses for switchgear, cables and transformer following a direct lightning strike of 30 kA to the overhead line conductor in the vicinity of tower 1 are presented in Fig. 9. For the substation, the dead-end configuration illustrated in Fig. 7 is taken into account in these calculations. As an example of the action of the surge arresters, Fig. 10 illustrates the current and voltage stress on the transformer arrester following the direct strike to the overhead line conductor described.

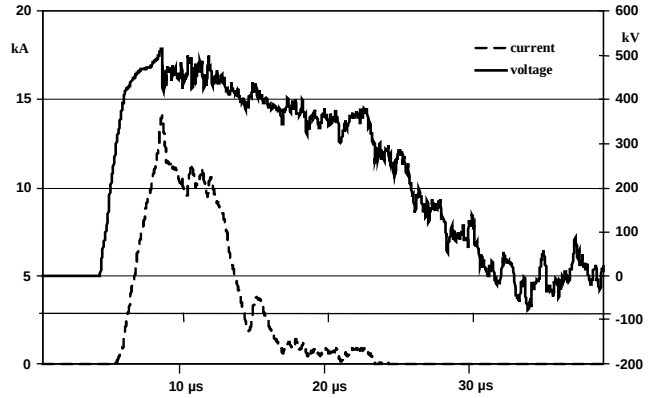

Fig. 10. Current and voltage applied at transformer arrester

For the example described, a basic insulation level of BIL = 1050 kV has been specified for the switchgear and cables, and of BIL = 900 kV for the terminals on the high-voltage side of the transformers. The results show that, with the present surge arrester design, the specified voltage stresses of BIL/S = 1050 kV/1.15 = 913 kV for switchgear and cables, and of BIL/S = 900 kV/1.15 = 783 kV for the transformers are clearly maintained.

VII. SUMMARY

Calculation of lightning overvoltages necessitates simulation of the electrical equipment, such as for example overhead transmission lines, cables, towers and substations as travelling wave model. Simulation of remote strikes reproduces lightning strike voltages corresponding to the standardised 1.2/50 µs impulse voltage, while lightning strike currents in the case of strikes to towers or direct strikes to the overhead line conductor possess a concave wave shape. The peak values of the lightning strike currents in the case of direct strikes to the overhead line conductor are determined essentially by the tower geometry and the shielding effect of the overhead earth wires, and are determined individually for each substation.

The flashover characteristic of the insulators is described by a voltage-time area, i.e. the Kind design criterion.
The effect of coupling between the individual phases of a three-phase system, as well as the frequency-dependent damping, can be simulated for special cases by the use of a Marti model.

For calculations of lightning overvoltages with the NETOMAC simulation program, macro modules are used which, by simple application, make it possible to deal effectively with a wide variety of problems, such as in the design of substations, in the development of new equipment, or in the system operation of large power converters (HVDC transmission). Based on the results of the calculations it is possible, for example, to ascertain the quantity and optimum location of surge arresters for a substation design, or to calculate voltage stresses on items of equipment and to determine suitable remedial measures where the specific limit values are exceeded.

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