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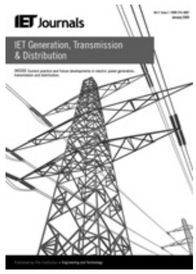

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Investigation on new mitigation method for lightning overvoltages in high-voltage power substations

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Abstract: In the present study, simulations of the lightning overvoltages propagation phenomenon in a typical 380 kV SF6 gas-insulated substation are presented. Influence of surge arresters installation on maximum-generated overvoltage peak values is illustrated. A new overvoltage mitigating passive device in a form of a high-voltage (HV) L–C filter is proposed. A process of its development and research is explained along with a simulation results. As demonstrated, the proposed device can be used in HV networks as an alternative or additional improvement for lightning overvoltages mitigation purposes. All simulations have been conducted using Matlab Simulink as well as EMTP/ATP software packages

1 Introduction

In high-voltage (HV) power systems, Insulation Coordination studies are needed in order to minimise the probability of equipment failure because of the lightning or switching surges' hazards. Proper surge arresters as well as installation of other mitigation devices are essential from the point of view of reliable working conditions of the transmission and distribution networks. It is difficult to measure such overvoltages because of operational, technological and last but not least – economical issues. However, over the years reliable methods of computational analyses have been developed, which allow one to determine possible overvoltage waveforms in case of different scenarios, such as lightning surges or transformer switching operations.

Lightning overvoltages are categorised as fast transients, which cover a frequency range from 10 kHz up to 1 MHz [1–3]. They are caused by lightning strokes to the transmission line, either into the phase wire (direct stroke) or into the shield wire, which causes a flashover along the insulator string (backflashover (BF)). As result a high overvoltage wave is generated, which propagates along the network leading to acceleration of the insulation ageing processes and in most severe conditions even failures of machines and apparatuses. Since this is very complex phenomenon, modelling of such events requires special attention to multiple wave reflections and nonlinear effects. This is the reason why computer models for lightning studies are more complex in comparison to those used during load flow or slow-front surges studies, for example, temporary or switching overvoltages. Maximum overvoltage peak values can appear in various locations of the studied network and are dependent of many factors such as layout of the transmission line, structure footing resistances, lengths and cross-sectional areas of HV cables and the most important – presence or not of surge arresters. Determination of their ratings and the appropriate installation locations are the most crucial issues from the point of view of insulation coordination analyses. Specific protection margins have to be fulfilled for different system voltage levels in relation to the basic insulation level (BIL), which is the maximum lightning impulse withstand voltage for a given system voltage. For networks with nominal voltage rated at $U_{\mathrm{N}} = 380$ kV, the BIL is standardised to 1425 kV [1].

A review of overvoltages that can be generated in HV power systems is given, focusing on their frequency spectra. Furthermore, special attention is attributed to lightning overvoltages and their modelling principles. Moreover, a new overvoltage mitigation method for 380 kV substations is presented. A HV passive L–C filter is integrated in the models and found as an alternative or additional solution for SF_6 gas insulated surge arresters that are usually localised at the transmission line entrance of a GIS substation. The development and research process is described. Moreover, simulation results for various lightning scenarios are presented in a form of comparisons of configurations with additional SF_6 surge arresters or with the proposed new HV L–C filter.

2 Fast transients in HV power systems

Transient overvoltages in power systems are mainly characterised by their magnitude, rise time and frequency spectrum and are generated during various types of switching as well as lightning events. According to international standards, they are classified divided into groups by their frequency spectra [1]. Low-frequency transients are caused by load rejection, earth and phase-to-phase faults as well as ferroresonance effects. Their magnitudes can reach values aboutd 2.0 p.u. and frequency is in the range of 10–500 Hz. High-frequency transients are divided into three sub-groups: slow-front, fast-front and very-fast-front transients. Slow-front transients are generated during line, capacitor or transformer switching (both energisation and de-energisation) and are strongly dependent of the type of system earthing and load switched. For past few years, there are various methods used for overvoltage mitigation, such as surge arresters, *R–C* filters or series connected *R–L* chokes, as presented in [4]. Very-fast-front transients have also a switching origin; however, they are caused by disconnector or circuit breaker operations inside the GIS substation. During the contacts' closing or opening an electric arc ignites multiple times generating overvoltage wave that propagates along the GIS busbars. Magnitude of overvoltages can reach values as high as 2.5 pu and frequency is in the range of 300 kHz up to 100 MHz.

This paper is focused on fast-front transients, which are generated by lightning strokes to the overhead transmission lines or earthing wires of the substations. The frequency spectrum during this phenomenon is in the range of 20 kHz up to 1 MHz. Overvoltage waves generated by lightning strokes are of a significant concern in HV power systems' engineering mostly due to the fact, that they are a potential danger to electrical machines and apparatus. However, appropriate measures on insulation coordination can successfully provide sufficient protection margins and minimise probability of failure.

Various current shapes can be selected for the lightning overvoltage studies and they have an impact on generated overvoltages. In this paper, CIGRE waveshapes were utilised according to [2]. Two different scenarios are specified [5, 6] (Fig. 1):

- Stroke to phase wire – direct stroke – 30 kA – based on Eriksson's modified electro-geometric model (DS) [5],
- Stroke to shield wire causing current flash across the insulator string –*BF*.

As it is shown in Fig. 1*a*, in case of the direct stroke into the phase wire, an overvoltage wave is injected into the phase conductors and propagates into the system [7–9]. During the BF scenario (Fig. 1*b*), an overvoltage wave is generated at the tower structure [10]. Owing to the inductive voltage drop and air ionisation around the insulator string, the current flashes from the tower structure to the phase wire. Multiple wave reflections from the tower base are also possible [3]. Since this phenomenon has a very complex nature [11], it requires different modelling techniques for either transmission lines, GIS busbars or substation apparatuses, which is described in detail in Section 4.

Today the most common overvoltage mitigation devices in HV systems are surge arresters, both air and SF_6 gas insulated types [5, 12]. Thanks to their non-linear voltage–current (*U–I*) characteristic they limit overvoltages below maximum acceptable levels. However, installation of additional SF_6 surge arresters is not always the most suitable solution from the economical point of view. Thus, a new method for mitigation of lightning overvoltages was developed. It is proposed to use passive HV *L–C* components at the entrance of a substation (located directly at the portal tower) as an alternative solution for additional SF_6 surge arrester. Its development and research process is described in Section 3.

3 HV L–C filter – improvement of the lightning protection

GIS substations are protected against switching and lightning overvoltages by means of surge arresters. The protective levels of the arresters are selected, so that the overvoltages appearing at the protected elements are lower than the corresponding insulation coordination levels. In insulation coordination practice air insulated surge (AIS) arresters are obligatory at the gantry of the substation. In most of the

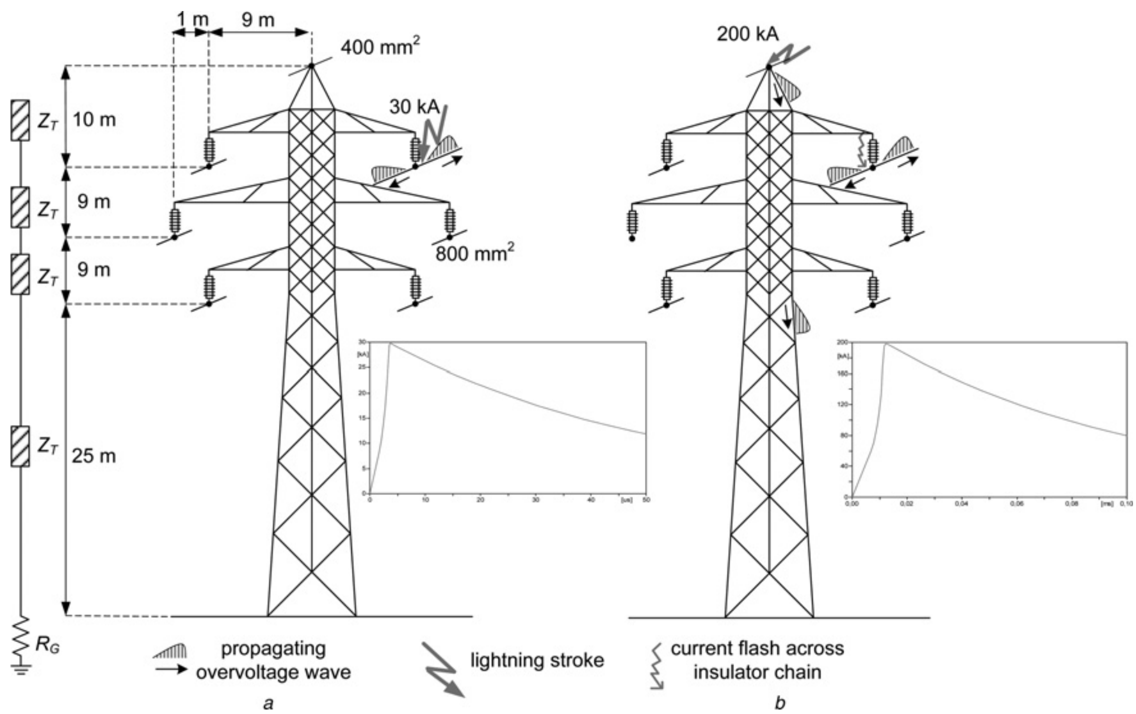

Fig. 1 *Phenomenon representation for lightning strokes*

a Direct stroke

b Back–Flashover, Z_T – tower surge impedance, R_G – tower-footing resistance cases, also the GIS surge arresters installed at the transformer terminals are needed. Other surge arresters, which can be installed within the GIS substation, are optional. The optional surge arresters are in some cases required to limit the voltage level within the substation to a value, which is below the insulation levels of the equipment. It can be the case when some crucial parameters of the substation cannot be adjusted accordingly to the insulation coordination practice, for example, if the tower footing resistance exceeds the required level.

The need for optional surge arresters is demonstrated with case-by-case analyses. Based on such analyses, in some of the cases, optional surge arresters can be replaced by an alternative and cheaper solution – the HV L–C filter. The reactive-type filter is intended to suppress lightning transients caused by both types: direct strokes in transmission lines and BFs on tower insulators. It consists of high-frequency (HF) filter elements – inductance L and capacitance C according to Fig. 2. Since it is utilised as a power line carrier (PLC) equipment, it does not have a negative influence on system steady-state conditions.

The impact of the parameters of the filter components on the overvoltage mitigation properties have been investigated in a typical HV 380 kV GIS substation. The study includes the following cases: lighting stroke to shield wire with BF to the phase wire (at towers 2 and 3) as well as direct stroke to a phase wire (at 50 and 300 m distance from the tower closest to the substation). For each of the cases, voltages in following three points were calculated: transformer terminal, GIS entrance and GIS exit (Fig. 5). For each of the above cases, different surge arresters combinations have been assumed. The overvoltages were calculated assuming the filter parameters within a given range: $L = 40\ldots400\ \mu$H, with step: 10 μH (37 values), and $C = 2\ldots40$ nF, with step: 2 nF (20 values) – 740 calculations for each scenario and surge arrester's combination. For each of the L–C filter's parameters combination, the overvoltages were calculated in the selected point of substation. Based on that the following ranges of L and C values were obtained providing overvoltages, which are below 80% of BIL (1140 kV): L = 260–400 μH, $C = 4$ nF. Summarised simulation results are illustrated in Fig. 3. Maximum overvoltage peak values are presented in case of direct stroke as well as BF scenarios. The study was done in a parametric manner for different parameters of capacitances and inductances of the HV L–C filter. Based on Fig. 3 it can be concluded, that the most effective mitigation properties are achieved with the following values of main coil and coupling capacitors: L = 315 μH and $C = 4.7$ nF, respectively. For these parameters, all overvoltage peak values are well below the BIL (1425 kV for $U_N = 380$ kV), which is marked in Fig. 3*b* as a red grid. It needs to be added that the filter composed on the elements given above is characterised by a parallel stray capacitance of the main coil, which leads to the internal resonance of the coil in range of 400 – 1000 kHz. This capacitance was included in the simulations to make sure it will not lead to any resonance leading to overvoltages increase. Since the highest overvoltage will arise at the L-terminal of the filter, it has to be protected with a surge arrester rated at $U_r = 25$ kV with maximum energy absorption equal to 225 kJ. Those parameters provide sufficient performance of the entire set-up both in steady-state and short-circuit conditions. Energy absorbed by the 25 kV surge arresters is well below the acceptable level due to the fact that the transient overvoltage at the main coil last for only few μs. The parasitic capacitance of the 25 kV surge arrester is negligible and does not have to be included.

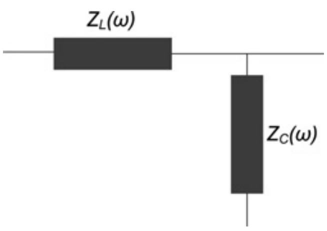

Fig. 2 *HF L–C filter representation*

$Z_L(\omega)$ – HF inductive element (main coil's parallel stray capacitance included), $Z_C(\omega)$ – HF capacitive element

4 Modelling principles for fast transients analyses

This section presents modelling techniques for various elements of HV power systems in the domain of HF transient states. The studied network (simulation scenarios and results in Section 5) consists of overhead transmission line, HV cables, GIS substation with surge arresters and power transformer. Detailed modelling techniques, which were used according to international standards and guidelines as well as research papers, are presented below.

The incoming overhead transmission line consists of two sets of three phase systems – thus six phase conductors were introduced with two wires per bundle (40 cm spacing). Additionally, one shielding wire was modelled for BF scenario consideration. Since the lightning phenomena are resulting in HF waveforms, the simulation model has to consider travelling waves effects [8]. Thus, a frequency-dependent line model (JMarti) was selected for this study [13–15]. According to the layout and dimensions illustrated in Fig. 1, five last spans (400 m each, 6 m sag) before the HV cable compound were modelled using LCC – line/cable constants subroutine in EMTP/ATP software package [16]. Since corona effect results in additional damping, it was not considered in the study for the worst case conditions [3].

The insulator strings are represented by the Leader Progression Model [3, 17, 18], which considers an equivalent leader that propagates along the insulator, from the tower structure to the phase wire. BF occurs when the leader length reaches length of the insulator gap (assumed to 4.5 m). The leader velocity and its propagation are described by a formula (1)

$$\frac{\mathrm{d}L}{\mathrm{d}t} = K \cdot u(t) \cdot \left(\frac{u(t)}{(g - L)} - E_0 \right) \tag{1}$$

where $K = 1.2\ \mathrm{m^2/(kV^2 \cdot s)}$ – the constant, $E_0 = 520$ kV/m – the average gradient voltage, $u(t)$ – the voltage across the gap (kV), $g = 4.5$ m – the gap length, L – the leader length (m).

Since the overvoltage wave that is generated can reflect from the tower base, the structure with its footing resistance has to be also employed in the model. For the tower structure, lossless distributed line was selected and modelled by means of surge impedance Z_T equal to 172 Ω, wave propagation speed of 290 m/μs and an associated height according to Fig. 1 (53 m). The tower footing resistance R_G can be modelled according to various

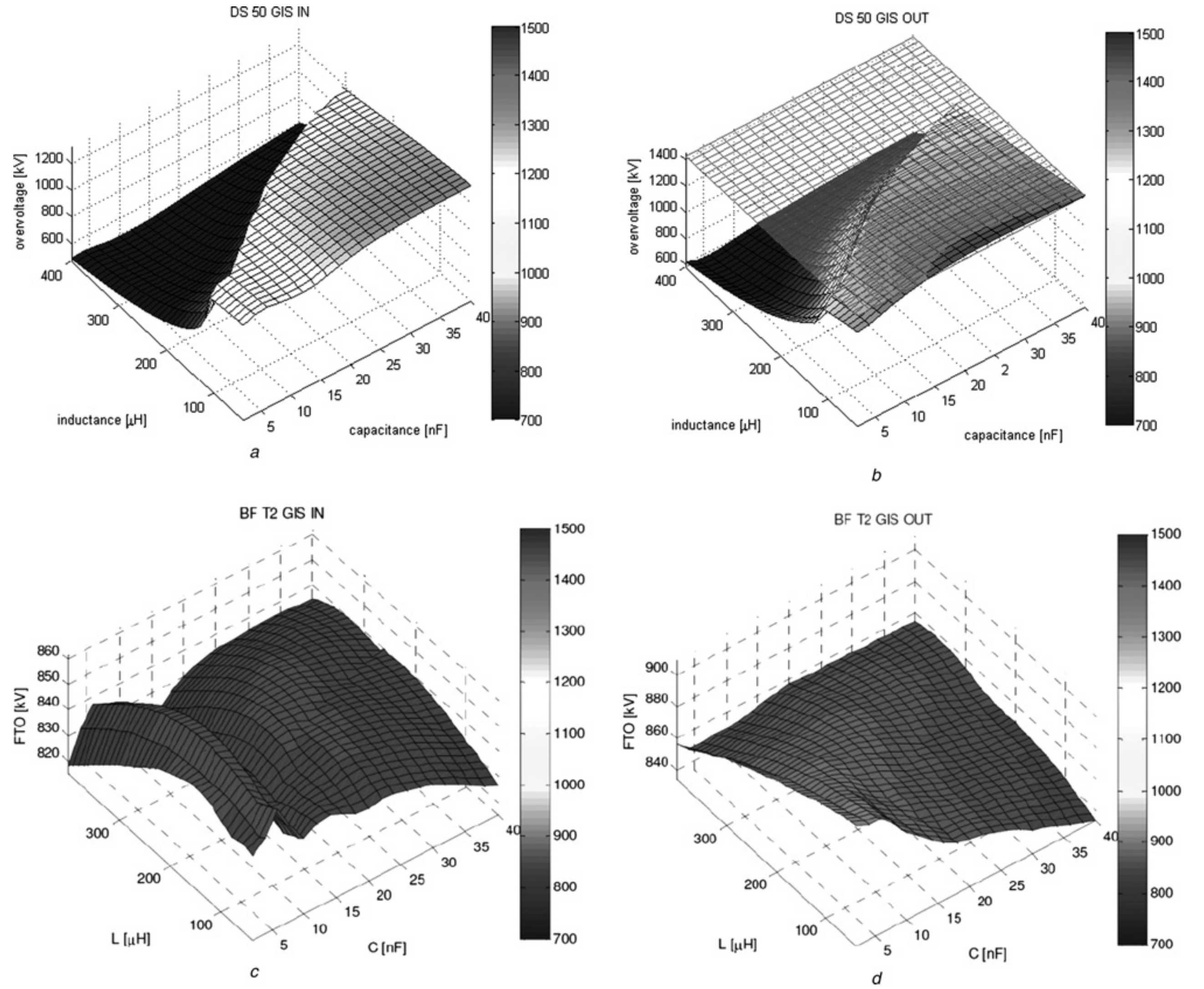

Fig. 3 *Fast transients overvoltages (FTO)*

L–C filter parametric study, GIS IN – GIS substation entrance, GIS OUT – GIS substation exit
(*a*, *b*) direct stroke, (*c*, *d*) BF

approaches, which includes complex effects of the soil ionisation that results in decrease of equivalent total footing resistance. In this paper, for the worst case conditions it was assumed to be a constant value of 50 Ω for towers and 1 Ω for the portal tower, which is the nearest one to the cable compound.

There are two sets of HV cables in the studied system, both 2500 mm^2. First one interconnects the overhead transmission line with the 380 kV GIS substation (5 km) and the second is located between GIS busbars and power transformer's HV side (0.2 km). Frequency-dependent elements with LCC subroutine have been used [19]. Both sets of cables were arranged into a flat formation, 1 m underground with 0.3 m spacing between each single-core cable.

Substation apparatus and busbars also require to be modelled as frequency-dependent elements, both distributed, such as surge impedances and lumped – in the case of phase-to-phase and phase-to-ground capacitances, as presented in Table 1.

As mentioned in the introduction, nowadays surge arresters are the first line of defence against lightning overvoltages [20, 21]. According to the international standards and guidelines, they are represented by means of non-linear *U–I* characteristic at 8/20 µs current surge, similarly for air and SF_6 gas insulated ones, as visible in Fig. 4. Additionally, phase-to-ground capacitances and lead lengths have been added, 25 pF/phase and 1 µH/m, respectively. The model was used according to [3].

5 Studied scenarios

The studied 380 kV network consists of two parallel incoming transmission lines, a GIS substation and HV cables that interconnect the GIS substation with overhead lines (5 km) and the GIS substation with power transformer

Table 1 Substation apparatus data

Apparatus	Parameters
GIS busbars	$Z = 60\ \Omega$, $v = 290$ m/µs
310 MVA transformer	
HV kV terminals	2000 pF
circuit breaker	50 pF
GIS spacer	15 pF

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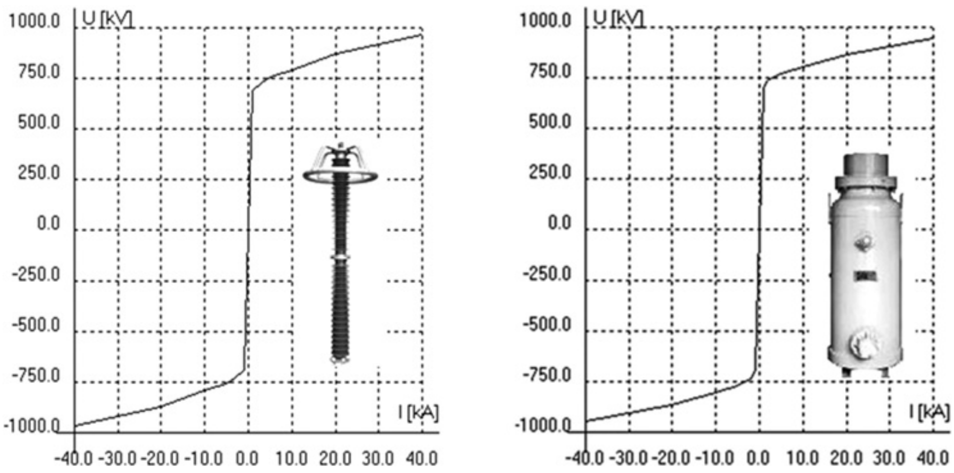

Fig. 4 *Voltage–current characteristics at 8/20 µs current impulse for surge arresters*

a Air insulated (AIS)
b SF_6 gas insulated (GIS)

(0.2 km). An air insulated surge arrester is installed at the portal tower, whereas gas insulated surge arresters are connected at the GIS substation and HV terminals of 310 MVA transformer (Fig. 5). A new solution has also been introduced. It was proposed to install a passive overvoltage mitigating device at the portal tower (Fig. 5), comprising a HV L–C filter.

Lightning strokes occurring at the overhead transmission lines incoming at the 380 kV GIS substation have been simulated by means of CIGRE wave shape. Two different scenarios and lightning current magnitudes were used:

- direct stroke to the phase wire with 30 kA current,
- stroke to shield wire causing BF across the insulator string to the phase wire with 200 kA current.

Current magnitudes were calculated to be as high as possible in order to reflect the worst case conditions. For each case, maximum overvoltage peak values have been calculated and compared with the BIL of 1425 kV.

The objective of these studies was to analyse the influence of HV L–C filter on overvoltages in a typical power network as well as to select such parameters, which are the most appropriate for mitigation of Fast Transients in a GIS substation. Detailed scope of work with surge arresters and L–C filter arrangements is presented in Table 2.

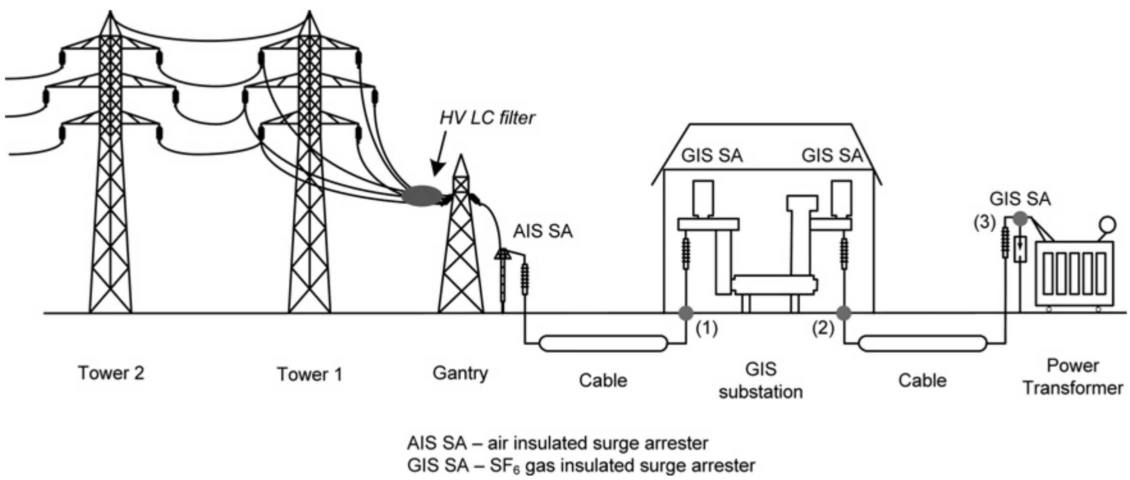

Fig. 5 *General network overview*

(1) GIS entrance
(2) GIS exit
(3) HV transformer terminals

Table 2 Scope of work

Overvoltage mitigation device	Run 1 – Fig. 7*a*	Run 2 – Fig. 7*b*	Run 3 – Fig. 7*c*	Run 4 – Fig. 7*d*
AIS surge arrester	connected	connected	connected	connected
L–C filter	connected	not connected	connected	not connected
GIS surge arrester at substation entrance	not connected	connected	not connected	not connected
GIS surge arrester at substation exit	not connected	connected	not connected	not connected
GIS surge arrester at Transformer HV terminals	not connected	connected	connected	connected

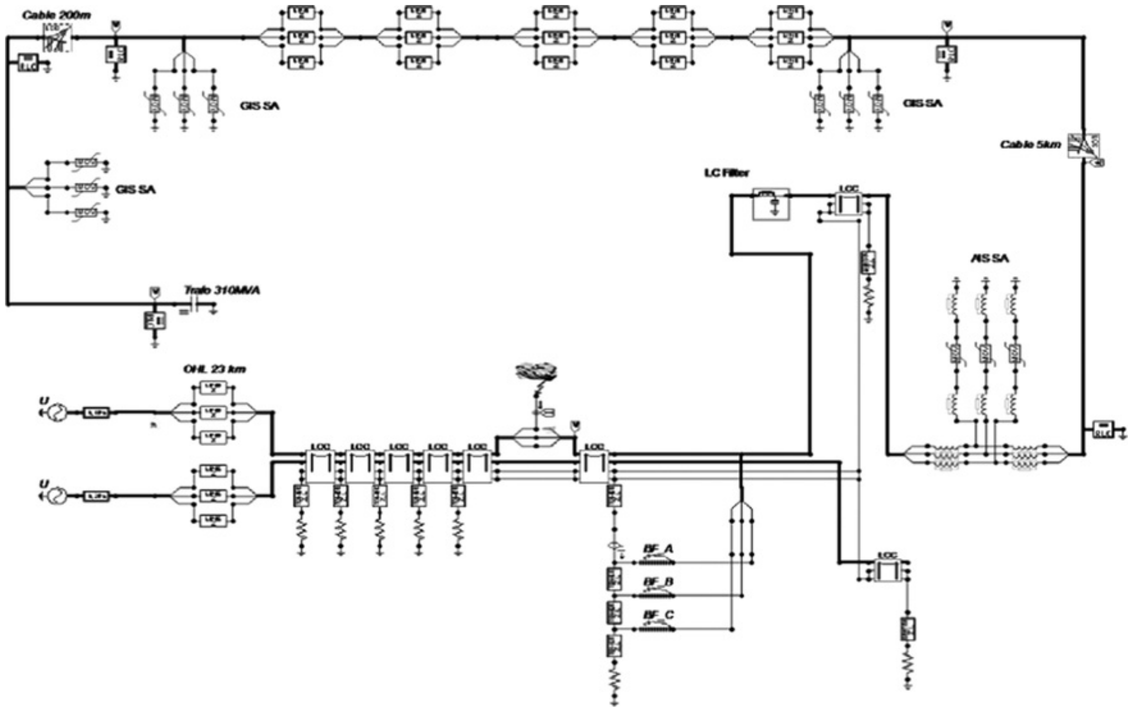

Fig. 6 *Typical 380 kV GIS substation EMTP/ATP model (corresponding to Fig. 5)*

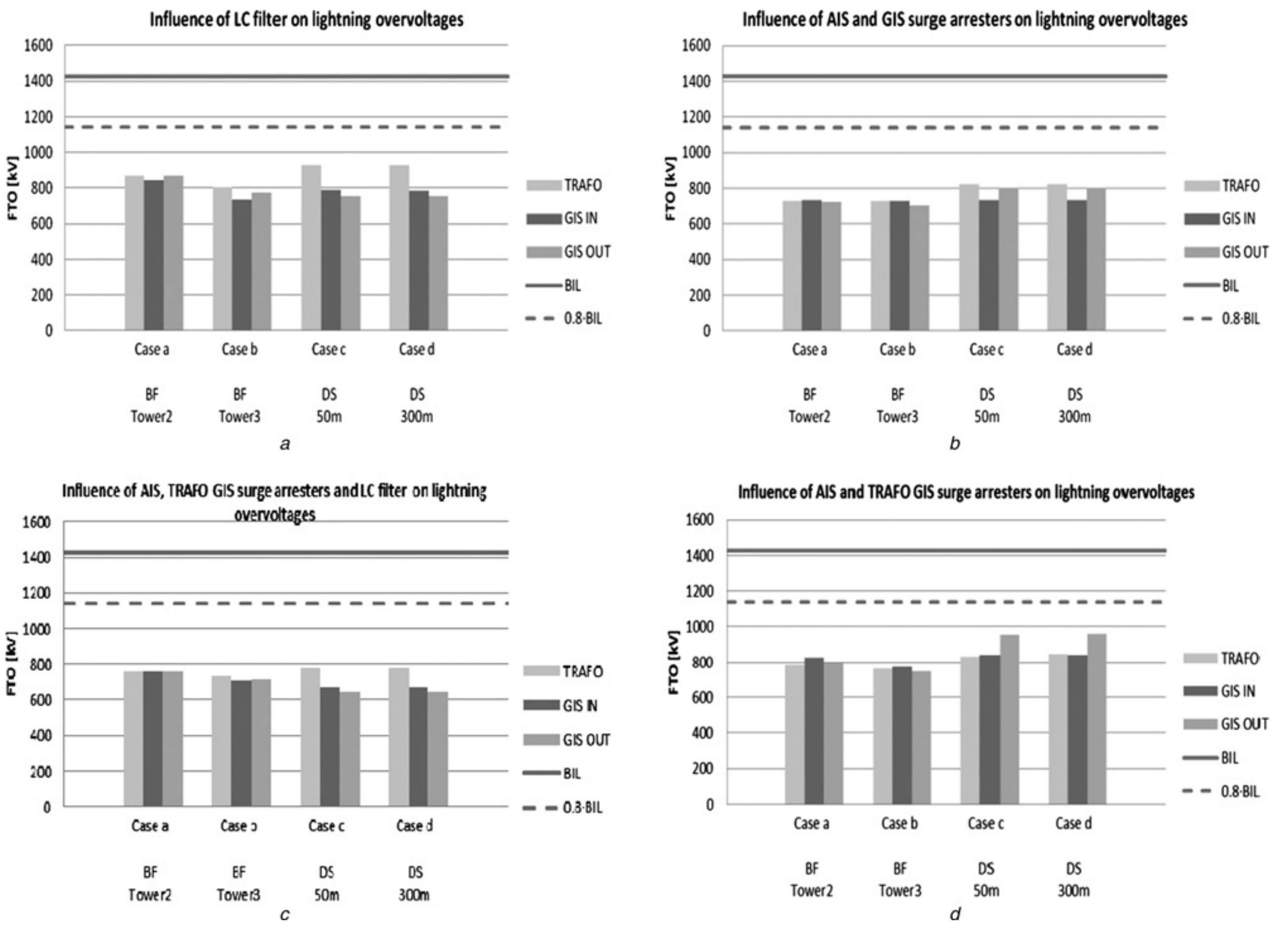

Fig. 7 *Fast transient maximum overvoltage peak values*

a Run 1
b Run 2
c Run 3
d Run 4

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The parameter optimisation analysis was performed for a typical 380 kV GIS substation in which the HV filter has been applied in order to mitigate fast transients caused by lightning strokes. The HV L–C filter has been located between overhead line (OHL) and HV cables, directly at the portal tower according to Fig. 5. For each of the above cases, voltages in three points were observed: at the transformer terminal (TRAFO), the GIS entrance (GIS IN) and the GIS exit (GIS OUT).

The EMTP/ATP model of the 380 kV power network and GIS substation involved in the simulations is shown in Fig. 6. The maximum overvoltage peak values for the simulated cases are summarised in Fig. 7 (Run 1–Run 4).

The following scenarios with respect to the scope of work from Table 2 have been considered:

- BF Tower 2 – BF at tower 2,
- BT Tower 3 – BF at tower 3,
- DS 50 m – direct stroke 50 m from tower 1,
- DS 300 m – direct stroke 300 m from tower 1.

Overvoltages have been calculated at the three points of consideration and for different surge arresters combinations as presented in Table 2 with reference to diagram illustrated in Fig. 5. Calculated EMTP/ATP simulation waveforms are presented in Figs 8 to 10 as typical case – Run 1.

It has been determined that in the system studied, it is potentially possible to omit the installation of GIS surge arresters in the power system. When only the GIS surge arresters within the GIS substation are omitted (i.e. when the only surge arresters are: the AIS SA at the gantry and the GIS SA at the transformer terminal), the overvoltages remain below the insulation coordination level (80% of BIL). Hence, the GIS surge arresters within the GIS substation of interest are optional.

For further reduction of the overvoltages and for improvement of the insulation coordination margin, the HV L–C filter can be applied. The reduction of the overvoltage amplitude is substantial for direct strokes, for which the insulation coordination level is exceeded if only the AIS surge arrester at the gantry is applied. In this case, the insulation coordination margin can be achieved by adding the GIS surge arrester at the transformer terminal. The proposed additional solution is a passive element consisting of a line trap main coil (L) and a coupling capacitor (C). It has been proven that the proposed filter provides better insulation coordination margins.

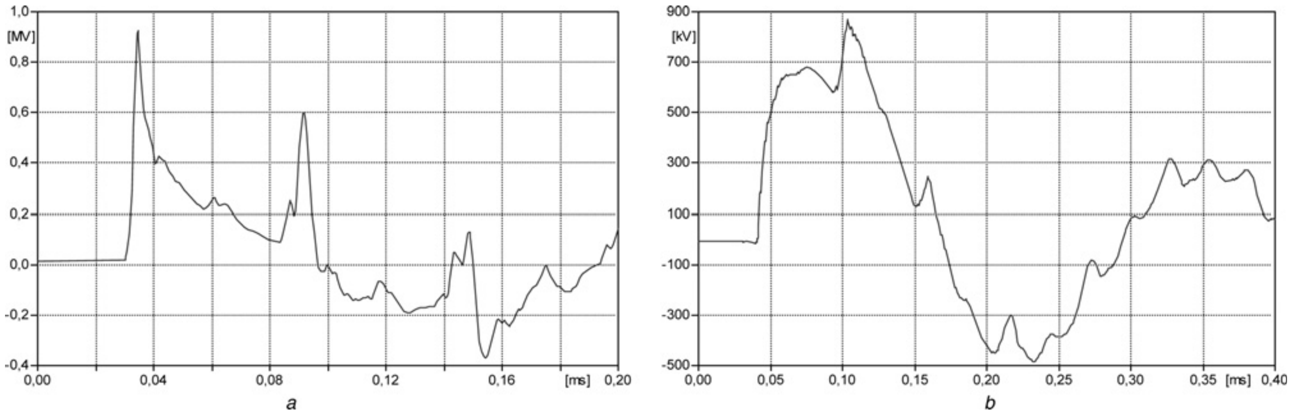


Fig. 8 *Overvoltage waveforms at GIS entrance*

a Direct stroke for Run 1
b BF for Run 1

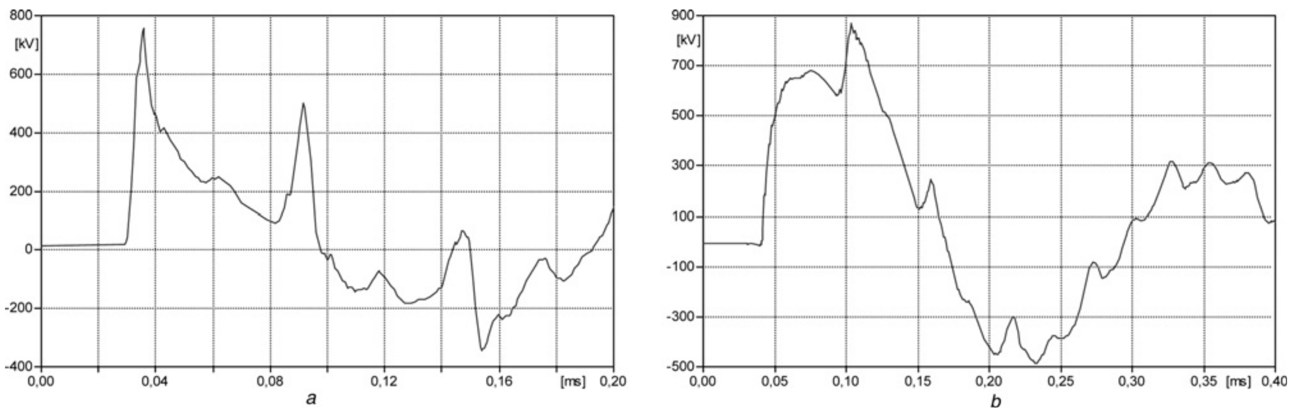
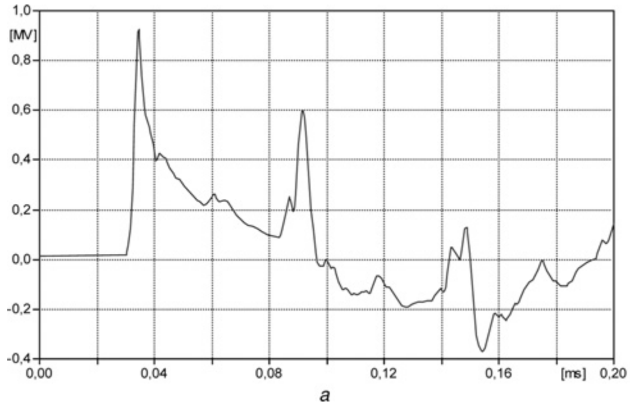


Fig. 9 *Overvoltage waveforms at GIS exit*

a Direct stroke for Run 1
b BF for Run 1



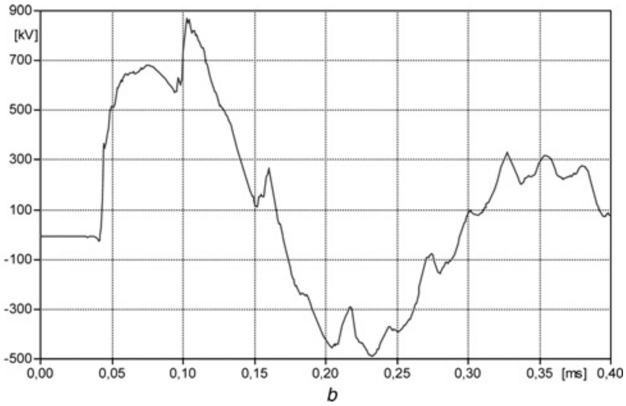


Fig. 10 *Overvoltage waveforms at transformer HV side*
a Direct stroke for Run 1
b BF for Run 1

6 Conclusions

The Insulation Coordination study for a typical system consisting of 380 kV GIS substation interconnected by HV cables has been performed using the EMTP/ATP software. BF and direct stroke scenarios for lightning overvoltage analyses were studied. The overvoltages have been calculated at essential points of the substation: at the transformer HV terminal, substation entrance and substation exit.

An alternative solution to the use of an additional GIS surge arrester has been proposed. The passive element consisting of a line trap main coil and a coupling capacitor installed at the portal tower have been introduced. It should be noted that when the HV L–C filter was installed the lightning overvoltages were kept below the BIL, especially in the worst cases where all GIS surge arresters in the power system were not installed. The present paper shows calculations for one particular system. However, considering the proposed solution for other substations and systems will require separate insulation coordination studies to validate its performance for specific conditions.

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