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New Method of Protection against Lightning Overvoltages for High Voltage GIS Substations

***Abstract**. In the present paper simulations of the lightning overvoltages propagation phenomenon in a typical 420 kV SF6 GIS substations are presented. A new overvoltage mitigating passive device in a form of a high-voltage 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 and ATP/EMTP software.*

***Streszczenie**. W artykule przedstawiono symulacje wyładowań atmosferycznych i propagacji fali przepięciowej w typowych stacjach GIS. Zaprezentowano możliwość zapewnienia dodatkowej ochrony przeciwprzepięciowej poprzez ograniczenie maksymalnej wartości przepięć za pomocą filtru L-C. Proponowane rozwiązanie może być użyte jako alternatywne lub spełniające dodatkową ochronę przeciwprzepięciową. Symulacje przeprowadzono przy użyciu programów MATLAB i ATP/EMTP. (**Nowa metoda na ograniczenie przepięć piorunowych w stacjach typu GIS**).*

Keywords: insulation coordination, GIS substation, lightning overvoltages, L-C filter, ATP/EMTP, MATLAB Simulink.
Słowa kluczowe: koordynacja izolacji, stacja typu GIS, przepięcia piorunowe, filtr dolno-przepustowy, ATP/EMTP, MATLAB Simulink.

Introduction

In high voltage power systems, insulation coordination studies are needed in order to minimize the probability of equipment failure due to 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 due to operational, technological and economic issues. However, over the years reliable methods of computational analyses have been developed, which allow one to determine possible overvoltage waveforms for different scenario, including lightning surges or transformer switching operations.

Lightning overvoltages are categorized as Fast Transients, which cover a frequency range from 100 kHz up to 100 MHz [1]. They are caused by lightning strokes to the transmission line, either into the phase wire (direct stroke) or to the shield wire, which causes a flashover along the insulator chain (back-flash). As a 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. Adequate modeling 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, like e.g. temporary or switching overvoltages. Maximum overvoltage peak values can appear in various locations of the network studied and are dependent of many factors the like layout of the transmission line, the layout of the substation, structure footing resistances, lengths and cross sectional areas of high voltage cables and the most important – presence or not of surge arresters as well as the surge arresters location. Determination of the surge arresters 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_N = 420 kV, the BIL is standardized to 1425 kV [1–3].

In the paper, a review of overvoltages which can be generated in a high voltage power system is given, focusing on their frequency spectrum. Furthermore, special attention is attributed to lightning overvoltages and their modeling principles. Moreover, a new overvoltage mitigation method for 400 kV substations is presented. A high voltage passive L-C filter is integrated in the models and proposed as an alternative or additional solution for SF_6 gas insulated surge arresters that are usually localized at the transmission line entrance of a GIS substation. In the paper, the development and the optimization process of the L-C filter is described. Moreover, simulation results for various lightning scenarios are presented in a form of comparison of configurations with additional SF_6 surge arresters or with the proposed new high voltage L-C filter.

Lightning overvoltages in high voltage power systems

Transient overvoltages in power systems are mainly characterized 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 and divided into groups by their frequency spectrum [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 around 2.0 p.u. and frequency is in the range of 10 to 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 energization and de-energization) and are strongly dependent of the type of system earthing and load switched. 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 p.u. and frequency is in the range of 100 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 high voltage 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 minimize probability of failure.

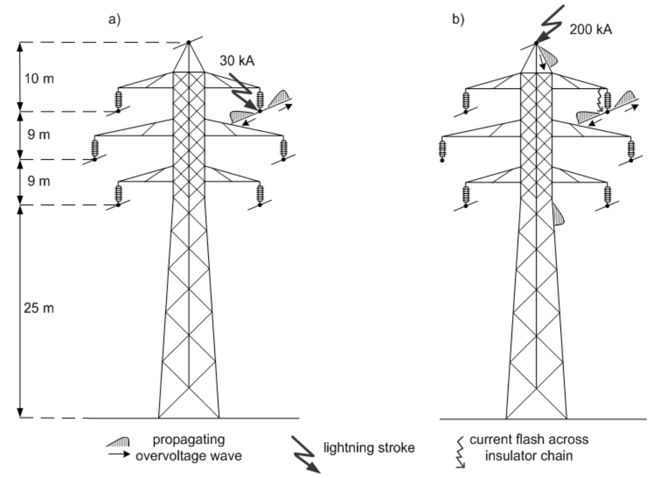

Fig.1. Direct stroke (a) and back-flash (b) phenomenon representation

For the lightning overvoltage studies, two different scenarios are specified [4–6] (Fig. 1):

- stroke to phase wire – direct stroke (DS),
- stroke to shield wire causing current flash across the insulator chain – back-flash (BF).

As it is shown in Figure 1a, 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]. During the back-flash scenario (Fig. 1b), an overvoltage wave is generated at the tower structure [10]. Due to the inductive voltage drop and air ionization around the insulator chain, the current flashes from the tower structure to the phase wire.

Nowadays the most common overvoltage mitigation devices in high voltage systems are surge arresters; both air and SF_6 gas insulated types [5, 8]. Thanks to their nonlinear voltage-current *(U-I)* characteristic they limit overvoltages below maximum acceptable levels. However, installation of additional SF_6 surge arresters has a significant economical impact. Thus, a new method for mitigation of lightning overvoltages was developed. It is proposed to use passive high voltage L-C components at the entrance of a substation (located directly at the portal tower) as an alternative solution for additional SF_6-insulated surge arresters.

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 AIS (air insulated) surge arresters are obligatory at the gantry of the substation. In most of the cases, also the GIS surge arresters installed at the transformer terminals is 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, e.g. if the tower footing resistance exceeds the required level.

The need for optional surge arresters is determined with case-by-case analyses. Based on such analyses, in some of the cases, optional surge arresters can be replaced by an alternative and cost-efficient solution – the high voltage L-C filter. The reactive type filter is intended to suppress lightning transients caused by both types: direct strokes into transmission lines and back-flashes on tower insulators. It consists of high frequency (HF) filter elements – inductance L and capacitance C according to Figure 2.

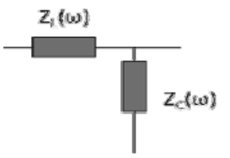

Fig.2. High frequency (HF) L-C filter representation; $Z_L(\omega)$ – HF inductive element (main coil's parallel stray capacitance included), $Z_C(\omega)$ – HF capacitive element

The impact of the parameters of the filter components on the overvoltage mitigation properties has been investigated for a typical HV 420 kV GIS substation. The study covered the following cases: lighting stroke to shield wire with back-flash to the phase wire (at towers 2 and 3) as well as direct stroke to a phase wire (at 50 m 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. 4).

The overvoltages were calculated assuming the filter parameters within a given range: L = 40...400 µH, with step: 10 µH (37 values), and C = 2...40 nF, with step: 2 nF (20 values) – 740 calculations for each scenario and surge arrester's combination. For each of the L-C filter parameters combination, the overvoltages were calculated in the selected point of substation. Based on that two 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. Summarized simulation results are illustrated in Figure 3.

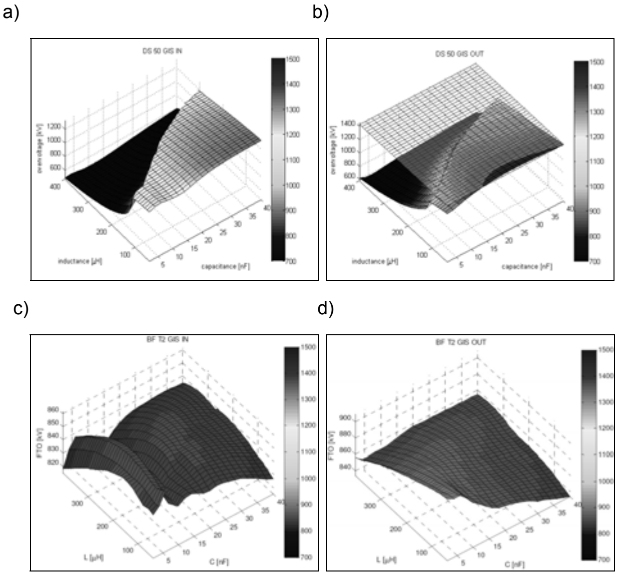

Fig.3. Fast transients overvoltages (FTO), L-C filter parametric study, GIS IN – GIS substation entrance, GIS OUT – GIS substation exit, direct stroke (a-b), back-flash (c-d)

Maximum overvoltage peak values are presented in case of the direct stroke as well as back-flash scenarios. The study was done in a parametric manner for different parameters of capacitances and inductances of the HV L-C filter. Based on Figure 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 = 420 kV), which is marked in Figure 3b as grey grid.

It needs to be added that the filter composed of the elements given above is characterized by a parallel stray capacitance of the main coil, which leads to the internal resonance of the coil in the range of 400÷1000 kHz. This capacitance was included in the simulations to make sure it will not lead to a resonant overvoltages increase.

Modeling principles for Fast Transients analyses

This section presents modeling techniques for various elements of high voltage power systems in the domain of high frequency transient states. The network studied (Fig. 4) consists of overhead transmission line, HV cables, GIS substation with surge arresters and power transformer. Detailed modeling 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 6 phase conductors were introduced with 2 wires per bundle. Additionally, one shielding wire was modeled for back-flash scenario consideration. Since the lightning phenomena are resulting in high frequency waveforms, the simulation model has to consider travelling waves effects [3]. Thus, a frequency dependent line model (*JMarti*) was selected for this study using LCC – Line/Cable Constants subroutine in ATP/EMTP software package [9]. The insulator chains are represented by the Leader Progression Model, which considers an equivalent leader that propagates along the insulator, from the tower structure to the phase wire. Back-flash occurs when the leader length reaches length of the insulator gap (assumed to 7 m) in specific time equal to that of real leaders. The leader velocity and it's propagation are described by a formula (1) according to [3]:

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

where: K – constant [m^2/((kV)^2· s)], E_0 – average gradient voltage [kV/m], $u(t)$ – voltage across the gap [kV], g – gap length [m], L – leader length [m].

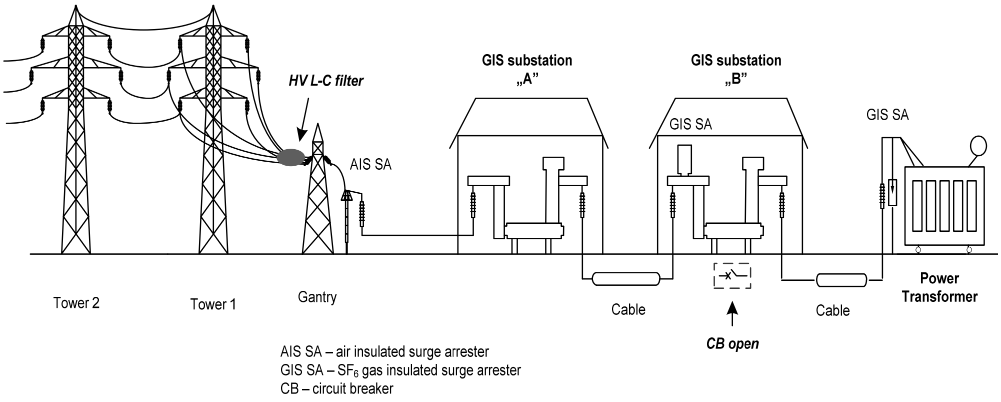

Fig.4. General network overview

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 modeled by means of surge impedance Z_T equal to 72 Ω, wave propagation speed of 290 m/µs and an associated height according to Figure 1 (53 m). The tower footing resistance was set to 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 420 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 Line/Cable Constants subroutine have been used. 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 has to be modeled as frequency dependent elements, both distributed, like surge impedances, and lumped – in the case of phase-to-phase and phase-to-ground capacitances, as presented in Table 1.

Table 1. Substation apparatus data [3]

Apparatus	Parameters
GIS busbars	Z = 60 Ω, v = 290 m/µs
power transformer 400 kV terminals	2000 pF
circuit breaker	50 pF
GIS spacer	15 pF

Nowadays surge arresters are the first line of defense against lightning overvoltages [8]. According to the international standards and guidelines, they are represented by means of nonlinear voltage-current (U-I) characteristic at 8/20 µs current surge, similarly for air and SF$_6$ gas insulated ones. Additionally, phase-to-ground capacitances and lead lengths have been added, 25 pF/phase and 1 µH/m respectively.

ATP/EMTP simulation results and analyses

The studied 420 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 (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 the power transformer (Fig. 4). A new solution has also been introduced. It was proposed to install a passive overvoltage mitigating device at the portal tower (Fig. 4) [10], comprising a high voltage L-C filter.

Lightning strokes occurring at the overhead transmission lines incoming at the 420 kV GIS substation have been simulated by means of CIGRE wave shape [2].

Two different scenarios and lightning current magnitudes were used:

- direct stroke to the phase wire with 30 kA current,
- stroke to shield wire causing back-flash across the insulator chain to the phase wire with 312 kA current (insulator chains lengths equal to 7 m).

Table 2. Scope of work

Overvoltage mitigation device	Combination 1	Combination 2
AIS surge arrester	connected	connected
L-C filter	connected	**not** connected
GIS surge arrester at substation entrance	**not** connected	connected
GIS surge arrester at substation exit	**not** connected	connected
GIS surge arrester at Transformer HV terminals	**not** connected	connected

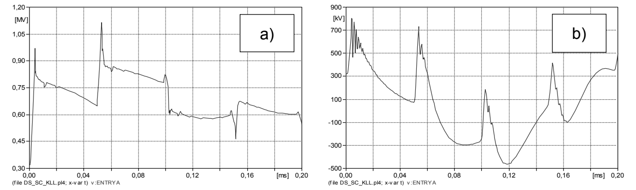

Fig.5. Voltage at GIS S/S "A" entrance, direct stroke, *L-C* filter not connected (a), *L-C* filter connected (b)

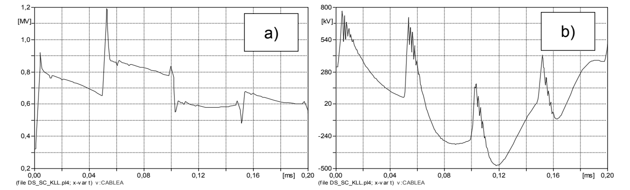

Fig.6. Voltage at GIS S/S "A" connection to the cable, direct stroke, *L-C* filter not connected (a), *L-C* filter connected (b)

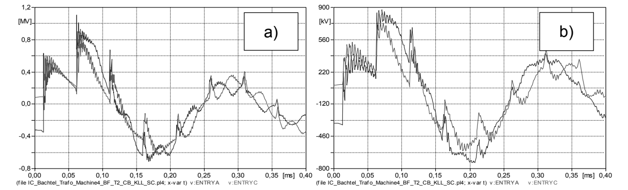

Fig.7. Voltage at GIS S/S "A" entrance, back-flash, *L-C* filter not connected (a), *L-C* filter connected (b)

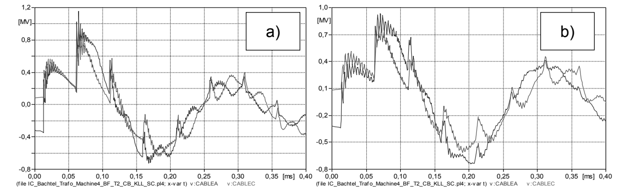

Fig.8. Voltage at GIS S/S "A" connection to the cable, back-flash, *L-C* filter not connected (a), *L-C* filter connected (b)

Conclusions

The Insulation Coordination study for a typical system consisting of two 420 kV GIS substations interconnected by a HV cable has been performed using the ATP/EMTP software. Back-flash and direct stroke scenarios for lightning overvoltage analysis were studied. The overvoltages were calculated in various points of the system. The main goals of the simulations were to investigate and determine on effectiveness of the *L-C* filter solution for mitigation of overvoltages occurring during lightning strokes as alternative solution for GIS surge arrester.

A 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 with the HV *L-C* filter installed, lightning overvoltages are significantly reduced, especially in the worst cases where line circuit breakers in the substation were opened.

Hence, it is suggested to use the proposed solution as an additional transients mitigation device.

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