Numerical Evaluation of Lightning Stress on High Voltage Substations

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Abstract: Especially the distribution network in the voltage range up to 30 kV without shielding wires is affected by direct atmospheric discharges. These discharges cause important stress to high voltage substations and their components. Therefore, a close examination of the influence of the spatial arrangement of the substation itself and its feeders, the rise time of the transient waveform of the incoming lightning overvoltage and the size of a medium voltage indoor substation in general were taken into account. This paper deals with the evaluation of the voltage stress at all network nodes of the substation. A variation of the substation arrangement itself such as feeder locations or feeder types is discussed. Furthermore, a number of parameters were analyzed like the amplitude, rise time, stress duration and high frequency content.

Keywords: Lightning, Modeling, Substation, Isolation Coordination, Overvoltage Stress, EMTP

I. Introduction

In the countryside of Austria more than 30.000 km of overhead lines in the voltage range of 10, 20 and 30 kV are located. This widespread overhead distribution network which is radially operated is responsible for a reliable electric power supply.

For several years investigations were conducted by the Institute and Research Institution of High Voltage Engineering at the Technical University Graz. The numerical evaluation of the transient stress in detail caused by atmospheric discharges close to substations [1] is part of a research project in cooperation with various utilities based on technical and economical reasons.

The above mentioned distribution network is in general not protected by shielding wires. In addition, areas with high lightning activities can be found in some regions of Austria. Up to 20.000 flashes a day have been recorded by the Austrian Lightning Detection and Information System [2]. This system gives a good basis for selecting substations in typical lightning areas. The negative current distribution (Fig. 1) has a median value of about 15 kA. Most strokes in the Austrian region transport a current between 7 and 12 kA.

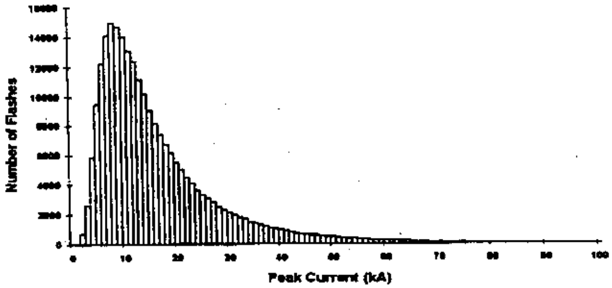

Fig. 1. Distribution of the current amplitudes 1995 [2]

II. Calculation parameters

Appropriate software, as well as representative circuit diagrams help to investigate this transient phenomena in substations. The basis for an evaluation of high frequency transients is a representative amplitude and rise time of the atmospheric discharge on one side and a well designed equivalent circuit diagram of the substation on the other side. Both have essential influence on the results to be evaluated.

In general, frequencies up to a few megahertz can be assumed [3]. Fig. 2 and Fig. 3 show how the lightning current shape influences the voltage stress in all network nodes (here superposed in one diagram).

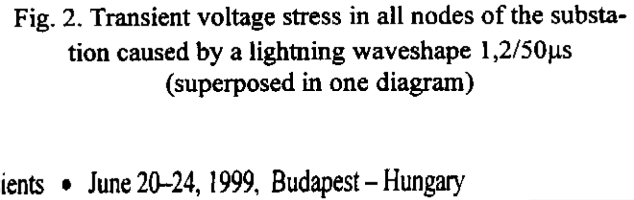

Fig. 2. Transient voltage stress in all nodes of the substation caused by a lightning waveshape 1,2/50µs (superposed in one diagram)

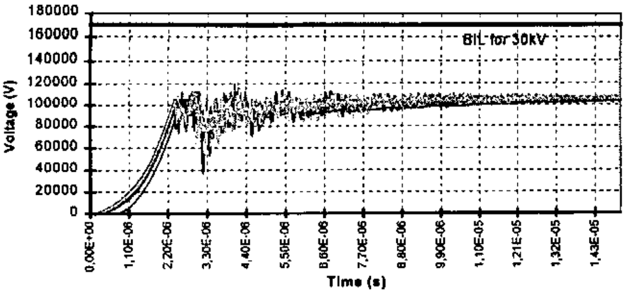

Fig. 3. Transient voltage stress in all nodes of the substation caused by a lightning waveshape 10/100µs (superposed in one diagram)

As one can see, a representative current or voltage shape has to be used in the calculations. In this case, the more critical waveshape with a rise time of 1,2 µs for the incoming overvoltage has been chosen. The amplitude of 2,7 MV equals an impulse current of 15 kA. For the overhead line outside of the substation a matching impedance of 370 Ω has been taken.

Since the beginning of this project, one typical indoor substation in the countryside of Austria provides the basis for several numerical evaluations[4]. Originally, this substation consisted of 5 sections of an insulated busbar in the center of the station with a total length of 9 m and three air-insulated buses of 3,2 m. Two of the buses lead to an overhead line and one leads to a cable connection for the power transformer. Later on, two feeders were added, one leads to a new built overhead line and the other one to a second power transformer. Both transformer feeders consist of a 75 m cable section. In the basic configuration, the substation is protected by three silicone-carbide arrestors with a nominal spark over voltage of 106 kV.

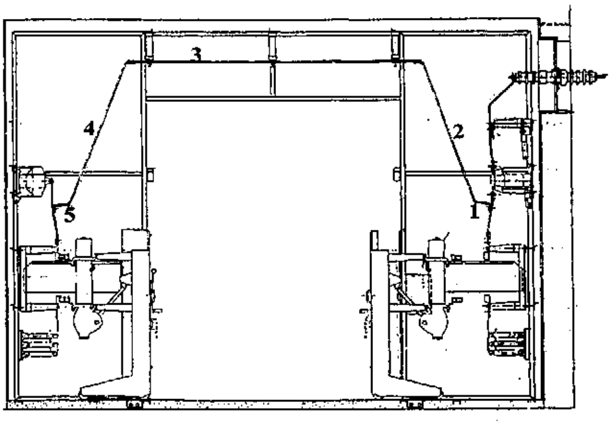

Fig. 4. Indoor substation with the overhead busbar divided in sections 1-5 for calculating the surge impedance

The commonly used equations for the propagation speed, length and the surge impedance were used to find the distributed line model for the input file of EMTP [5]. As shown in Fig. 4, the overhead busbar of the indoor substation is divided into 5 sections in order to calculate more accurate values for the surge impedance of the air-insulated busbar. The time step used for the numerical calculations corresponds to the highest expected frequency and the shortest section of a line. A transient voltage source equal to the double of the requested amplitude with an internal impedance equal to the surge impedance of the feeding line, simulates an infinite outgoing line for the reflected transient voltages in the substation.

For the numerical calculation the following parameters and elements representing the components of the substation were considered:

- Propagation speed of the air insulated lines and busbar $c_0 \approx 3{,}0 \cdot 10^8$ [m/s] and insulated lines $c_0 \approx 1{,}5 \cdot 10^8$ [m/s].
- Frequency range 10 kHz to 5 MHz.
- Shortest line-section 0,3 m.
- Time step of calculation 1 ns.
- Surge impedance for the air insulated busbar 240 - 370 Ω, for the insulated busbar and the cable 30 - 36 Ω.
- Lumped capacitance 30 pF - 1 nF for the voltage (*SpaWa*) and current (*StrWa*) transformers, insulating bushings (*DF*), switching devices *(LSA)*, power transformers.
- Silicone-carbide lightning arrestor (*ABL*) using the following non-linearity for the varistor:

Current	*Voltage*
25.	*55.E3*
80.	*65.E3*
250.	*75.E3*
500.	*82.E3*
1125.	*88.E3*
3750.	*100.E3*

- Basic Insulation Level (BIL) 170 kV for the 30 kV system.

III. Stress evaluation

A lightning strike or a back flashover very close to the substation is of interest for the stress evaluation of the high voltage insulation system. In the following section four types of substations are compared. The transient behavior of all network nodes is calculated and shown for each substation type.

Fig. 5 shows the basic configuration of the substation. For all calculations, one overhead line feeder (No.4) is connected to the transient voltage source representing the incoming lightning voltage. Transient results are shown in Fig. 2 and Fig. 3. In Fig. 2, a time delay of 0,5 μs at the transformer can be seen.

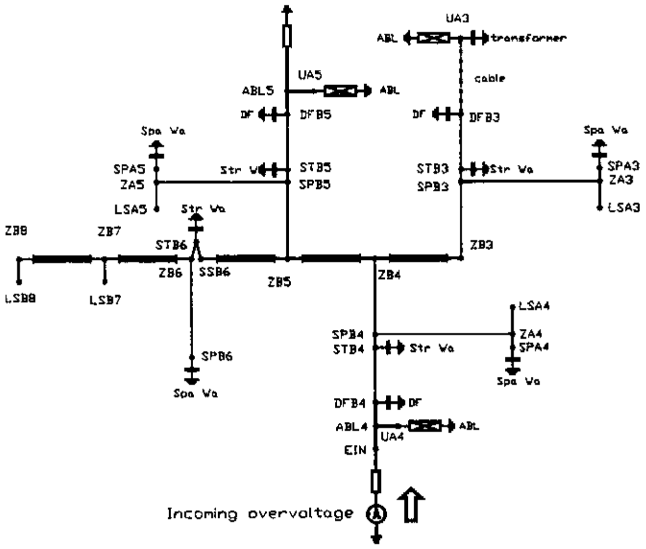

Fig. 5. Circuit diagram for the basic configuration of the substation (incoming overvoltage "⇑")

When the circuit state of the substation is changed as in Fig. 6, the transient behavior changes as well. In Fig. 7 a dominant frequency of 2,5 MHz can be seen in most of the network nodes when the transformer feeder is disconnected.

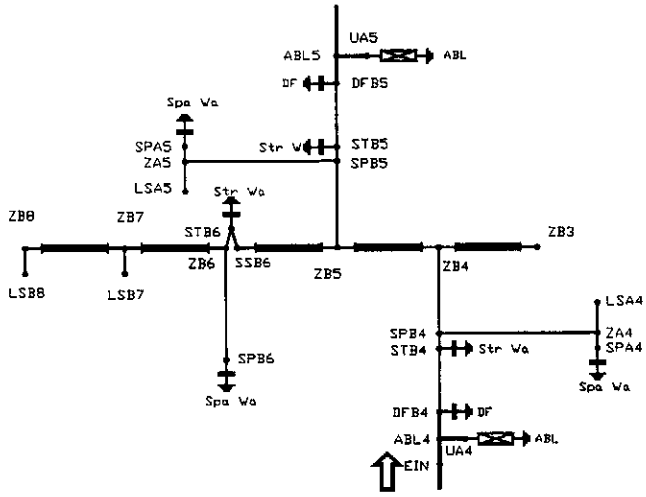

Fig. 6. Circuit diagram of the substation without the transformer feeder No.3, (incoming overvoltage "⇑")

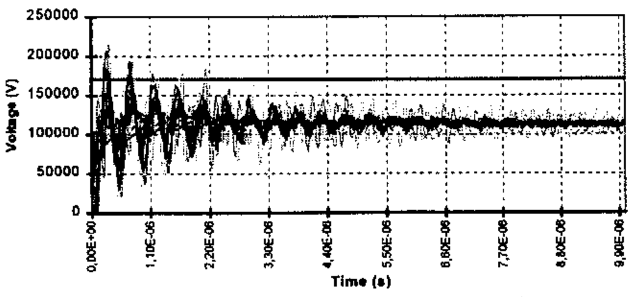

Fig. 7. Transient stress of the substation without a transformer feeder No.3

Comparing the results with Fig. 2, a number of the transient oscillations exceed the basic insulation level of 170 kV. Transient overstressing of the dielectric is caused by these peak values and these high oscillation frequencies in this configuration. In Fig. 8 the basic configuration with an additional overhead line feeder (No.7) is shown. A situation when an additional power supply is needed.

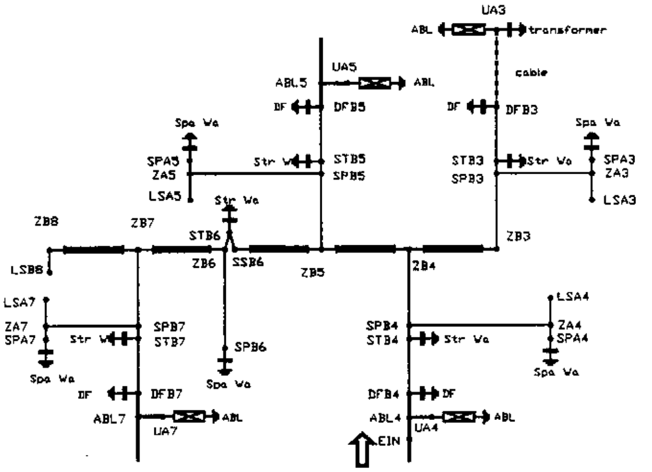

Fig. 8. Circuit diagram with an additional overhead line feeder No.7, (incoming overvoltage "⇑")

Again the transient results in all network nodes are shown. The results in Fig. 9 are very similar to the transient behavior of the basic configuration. The peak values are slightly lower, the mean value of all transients is significantly lower, which is caused by this additional feeder. This feeder helps to reduce the voltage stress in the substation.

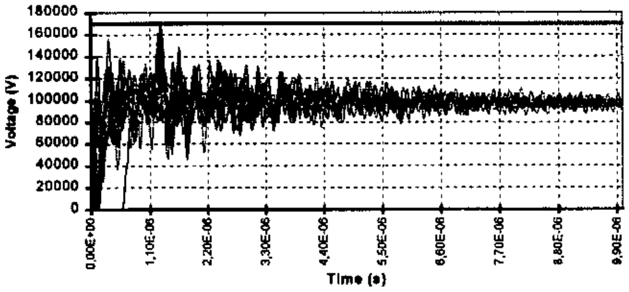

Fig. 9. Transient stress of the substation with one additional feeder No.7

Fig. 10 and Fig. 11 show an impression of the planned circuit state in this particular substation in future and the expected transients.

An overload or damage of an arrestor is one of the most critical situations for the insulation system of the substation. Assuming that the arrestor in the transformer feeder is damaged , the transient stress is shown in Fig. 12. Most node voltages can be kept under the critical value of 170 kV by the remaining two arrestors in the system. However, the voltage at the transformer exceeded the basic insulation level three times, with peak values up to 250 kV, stressing the insulation system of the power transformer.

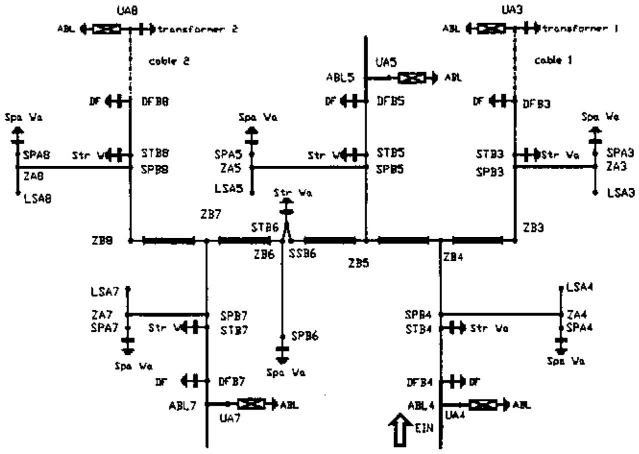

Fig. 10. Circuit diagram of the substation with two transformer feeders No.3, 8, and three overhead line feeders No.4, 5, 7, (incoming overvoltage "⇑")

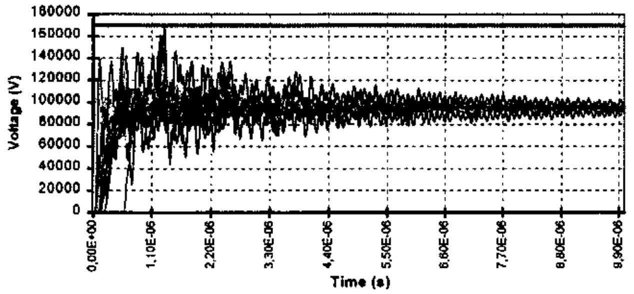

Fig. 11. Transient stress of the substation with two transformer feeders No.3, 8, and three overhead line feeders No.4, 5, 7

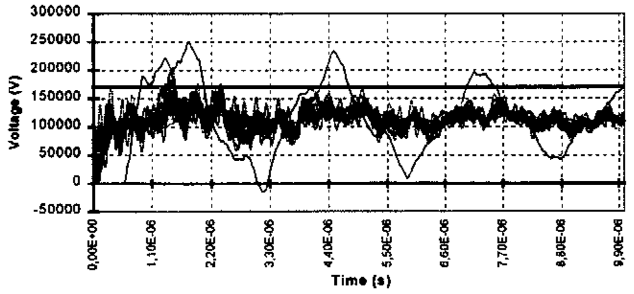

Fig. 12. Typical transient overstressing of the transformer No.3 caused by a damage of this arrestor

IV. Conclusions

To use numerical simulations as a tool to evaluate transient voltage stress in compact high voltage substations (e.g. 30 kV), a representative network model must be developed. In general, the expected frequencies in correlation to the shortest distributed line element have to be considered.

The type of the arrestor used in the network model has a significant influence on the transient node voltages because of the non linearity of the varistor. Therefore, testing a network model of this element must be based on measurements.

As a result of the work in the last few years, several aspects of the transient stress in the medium voltage system have been studied. The transient behavior of substations can be evaluated by plotting "all transients on one diagram". This diagram represents the total voltage stress of the substation. Stress duration and the remaining safety margin can be estimated easily. In addition, dominant peak values or dominant frequencies can be detected. Individual analysis of the peak values, the steepness and frequency content at each high voltage component (nodes) can be conducted to get detailed information.

As shown, the amplitudes of the transient stress are generally lower than the basic insulation level. But it has to be stated, that the safety margin is significantly decreased. A steepness for the incoming voltage with values lower than 2 µs has to be taken into account for realistic evaluations. In general, the rise time of the total transient stress increases to values of about 0,5 µs. An essential increase of the frequency range can be detected in the network nodes caused by the traveling waves on the short busbars and feeders.

As a final conclusion, the applied calculations help to find alternative measures to improve operating status by changing circuit states. In addition, different configurations can be evaluated in advance to support planning and design actions.

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