SIMULATION OF THE TRANSIENT VOLTAGES IN THE AUXILIARY POWER NETWORK OF A LARGE POWER PLANT IN CASE OF A DIRECT LIGHTNING STRIKE TO THE HIGH-VOLTAGE OVERHEAD TRANSMISSION LINE

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ABSTRACT

Large power plants can be endangered by lightning strikes with possible consequences regarding their safety and availability. A special scenario is a lightning strike to the HV overhead transmission line close to the power plant's connection to the power grid. If then additionally a so-called shielding failure of the overhead ground wire on top of the overhead transmission line is assumed, i.e. the lightning strikes directly into a phase conductor, this is an extreme electromagnetic disturbance.

The paper deals with the numerical simulation of such a lightning strike and the consequences on the components of the power plant's auxiliary power network connected to different voltage levels.

1 INTRODUCTION

In the latest years there was an increasing number of reports of failures in large power plants and in the HV power grid due to lightning incidents. Those incidents are not new, and they were also existing in the past. However, due to the increasing sensitivity of the society and due to the increasing instability of the power grid, those incidents become an increasing importance for power utilities.

A certain failure mode in a northern European power plant was the final reason, to investigate such an incident. It is assumed, that the lightning strikes close to the power plant directly to the HV overhead transmission line representing the connection to the power grid. It is further assumed, that the lightning strikes directly into a phase conductor and not into the overhead ground wire on top of the overhead transmission line, i.e. there is a dangerous shielding failure.

The lightning surge voltages and currents occurring on the HV overhead transmission line are transformed to the different voltage levels of the auxiliary power network of the power plant, with that endangering the connected electrical components which are important for the safety of the plant. These transformations are investigated based on detailed numerical simulations.

2 DEFINITION OF THE SOURCE OF DAMAGE

The existing withstand impulse voltage levels of the components can not be used as the sources of damage for the investigation. With the requirements given in [1] experimental tests may be performed for these components. However, for numerical simulations of the coupling mechanisms via individual components (e.g. transformers) another definition of the source of damage is necessary.

This definition is found in the lightning protection standardization. At the point of strike a lightning current is fed in directly, with that representing the source of damage as a current source. The definitions are given in IEC 62305-1:2006 [2] in combination with IEC 81/335/CDV (IEC 62305-1 Edition 2):2009 [3], the latter defining a third lightning current component.

We choose the lightning protection level I (LPL I) for the investigation, with that the following three different lightning current components have to be considered for the simulation:

Positive first stroke
Lightning current amplitude: 200 kA
Average current's front steepness: 20 kA/µs
Front time: 10 µs
Decay time to half value: 350 µs

Negative first stroke
Lightning current amplitude: 100 kA
Average current's front steepness: 100 kA/µs
Front time: 1 µs
Decay time to half value: 200 µs

Negative subsequent stroke
Lightning current amplitude: 50 kA
Average current's front steepness: 200 kA/µs
Front time: 0,25 µs
Decay time to half value: 100 µs

As mentioned, it is assumed, that for the investigated HV overhead transmission line a so-called shielding failure according to IEC 60099-5 [4] exists, i.e. the lightning protection measures of the overhead transmission line (overhead ground wire, air termination system of the outdoor switchyard, etc.) fail . This leads as a consequence to a direct strike to a phase conductor of the overhead transmission line with the highest lightning current parameters.

3 DEFINITION OF A TYPICAL POWER PLANT ARRANGEMENT

The typical arrangement of the power plant used for the calculation contains all typical components, loads and protection measures at the different voltage levels of the auxiliary power network:

- The connecting lines (HV and LV) are varied with different lenghts and cross-sections.
- A surge arrester is installed at the 400 kV side of the high voltage substation to protect the power plant against lightning surges from the power grid.
- Very close to that is the 420 kV / 27 kV machine transformer (1070 MVA).
- On the secondary side of this transformer (27 kV, representing the generator power frequency voltage) there are another surge arrester and a HV capacitor (10 … 100 nF), the second for protection against high frequency disturbances created by the generator.
- An auxiliary power transformer 27 kV / 10 kV reduces the voltage to the highest internal voltage level for the most powerful auxiliary components, e.g. pump drives. In the typical arrangement these loads are generally simulated with two different motors: 250 kW and 2450 kW.
- The majority of the auxiliary components (smaller motors, heaters, ventils, I&C-systems) is connected to a 0.4 kV voltage level. This level is supplied via a further auxiliary power transformer 10 kV / 0.4 kV. For simulating the loads, simple high-ohmic resistances are used.

4 HF-MODELS FOR THE ELEMENTS OF THE AUXILIARY POWER NETWORK

Selection and defining the parameters of the models for the auxiliary power network have a special importance for the calculation. For some components satisfying models exist (e.g. as from [5, 6, 7]). For other components those models and their parameters are not available, neither from standards nor from manufacturers, so that they must be elaborated for this purpose.

The models should be valid in the lightning-relevant frequency range, which is assumed here from 10 Hz up to 10 MHz; however the dominating part of the electromagnetic coupling is concentrated between 10 kHz and 1 MHz.

Because of the fact, that the lightning strike occurs to a phase conductor, a single-phase equivalent circuit is sufficient. Therefore also only single-phase models of the elements are required. We calculate the longitudinal voltage (common mode) caused by the lightning strike, i.e. the voltage between the active conductor and the earthing system or the equipotentialization system, resp. Therefore, the modelling of geometrically large structures, like sections of the HV overhead transmission line, masts of the line, etc., has to consider travelling waves phenomena, if their length exceeds $s_{\max}$ [5]:

$$s_{\max} = \frac{v}{5 \cdot f_{\max}} \tag{1}$$

v: speed of propagation (in case of overhead transmission lines approx. the speed of light v = 300 m/µs);

$f_{\max}$: highest expected frequency.

If $f_{\max}$ is taken conservatively to 3 MHz, all elements longer than 20 m have to be modelled as travelling wave lines or as a circuit with more than one π-section.

4.1 HV overhead transmission line

The modelling includes, as mentioned above, only one single phase. Based on the geometrical data, the HV overhead transmission lines are modelled generally as lossy lines [6]. However, the parallel resistance can be always neglected, because the dielectric material air can be assumed to be absolutely lossless (G’ = 0). Furthermore, for frequencies higher than 1 kHz also the series resistance can be neglected, because the inductive part of the series impedance definitely dominates (R’ = 0).

The characteristic impedance Z_L of the phase conductor or the conductor bundle is given as [7]:

$$Z_L = 60 \cdot \Omega \cdot \ln\left(\frac{2 \cdot h}{r_E}\right) \tag{2}$$

$$r_E = \sqrt[n]{r \cdot n \cdot (r_b)^{n-1}} \tag{3}$$

h: height of the phase conductor (bundle) above ground;

r_b: radius of the bundle;

r: radius of the conductor;

n: number of conductors in the bundle (in case of a single conductor n = 1 and with that $r_E = r$).

The travelling wave run time can be calculated from the length of the conductor section and the speed of propagation given above. The ground surface is assumed to be a perfectly conductive plane [8].

4.2 Masts and isolators of HV overhead transmission lines

Masts and mast arms of the HV overhead transmission line are modelled as travelling wave lines having the shape of a cone. The characteristic impedance is given as [6]:

$$Z_M = 60 \cdot \Omega \cdot \ln\left(\frac{\sqrt{2} \cdot h}{r}\right) \qquad (4)$$

h: height of the conductor fixing at the mast;
r: radius of the mast base.

For typical masts of HV overhead transmission lines the characteristic impedance is 150 … 250 Ω. The travelling wave run time for the mast follows from the height of the mast arm above ground level (for the mast arm from its length from the mast to the isolator) and the speed of propagation given above.

The isolators of the HV overhead transmission line are generally assumed to be ideal. Only in case of their breakdown as a consequence of a lightning surge voltage, i.e. if the breakdown voltage is reached, a model is necessary.

According to IEC 60071-2 Annex G [7] the breakdown voltage of isolators of a HV overhead transmission line for a lightning impulse voltage with 1.2 µs front time can be estimated as:

$$\frac{U_{d/50}}{kV} = 700 \cdot \frac{d}{m} \qquad (5)$$

d: length of the isolator (distance between the electrodes).

For impulse voltages with even higher voltage steepness, the breakdown voltage will further increase. A conversion of the breakdown voltage level valid for the standardized impulse withstand voltage 1.2/50 µs for a more steeper impulse voltage is possible for gaseous insulating materials using the constant-area-criterion [9]. The calculations show, that at least in case of the negative subsequent stroke the front times of the impulse voltages across the isolators are smaller than for the standardized impulse withstand voltage 1.2/50 µs. With that, due to the “time delay” of the breakdown (flash-over) at the isolator, higher levels of the lightning surge voltages in the downstream electrical installations occur.

If the flash-over is reached, i.e. the conditions for the breakdown are given, according to IEC 60071-4 [6] the isolator of the HV overhead transmission line can be modelled as an ideal switch for a lightning impulse voltage threat. This ideal switch closes within one time step.

The consequent current increase is limited by the inductance of the electric arc. Therefore an inductance of approx. 1 µH/m is connected in series to the ideal switch.

4.3 Earthing systems and earthing impedances

Earthing systems in the outdoor sections of large power plants can be assumed to be mainly “ideal”, i.e. the connections of electrical components to the ideal earth are low-impedant. This is also valid for the elements of a HV outdoor substation. We assume always a value of $R_{E/S} = 1\ \Omega$ for these connections.

The masts of the HV overhead transmission line outside the power plant area are earthed via a simple ohmic resistance. This is in accordance with simple estimations [6]. Always a value of $R_{E/M} = 10\ \Omega$ is taken.

The equipotentialization system within the structures of the power plant can also be handled as “ideal”, because the reinforcements of walls and ceilings are incorporated. Consequently, if electrical components are connected to the equipotentialization system, only the inductance of the connecting leads (usually copper cables with 70 mm^2 cross section) exists, taken into account with 1 µH/m.

4.4 Surge arresters

The surge arresters used on the HV level are metal-oxide varistors. The following investigations take into account up-to-date gapless arresters. Furthermore it is assumed, that the transformer to be protected is within the (limited) protective distance of the surge arrester. However, these protective devices are not dimensioned for the scenario given in chapter 2: a direct strike to a phase conductor in the close vicinity of the surge arrester. Therefore, three important effects have to be considered for the simulations:

1. Current-voltage characteristic curve:
   For the varistors used the current-voltage characteristic curve is known (Fig. 1). The basic behaviour depends especially on the disc area. If the residual voltage of a varistor is known for a certain current value (e.g. 10 kA), then for a known disc area the entire slope of the current-voltage characteristic curve can be given. The varistors are conveniently simulated as current-controlled voltage sources with a continuous characteristic curve (Fig. 2).
2. Energy absorption capability and failure performance of the varistor:
   For the calculation it is assumed, that approx. 5 times the long duration current impulse (2 ms) is impressed within a time duration of a few milliseconds, leading to a destruction of the surge arrester and finally to an electric arc at the place of installation [10].
3. External flash-over at the arrester housing:
   It occurs based on the breakdown characteristic curve similar to the isolator (see chapter 4.2).

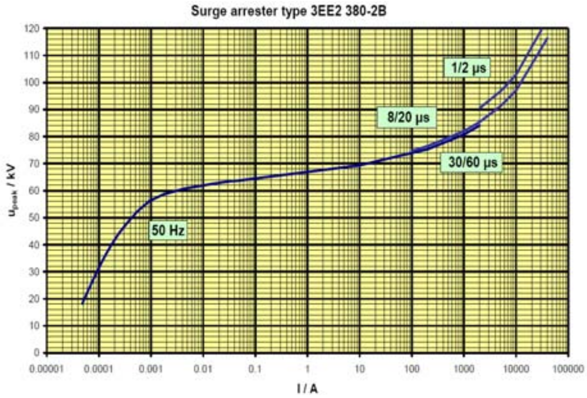

Figure 1: Characteristic curve of a 27 kV-surge arrester.

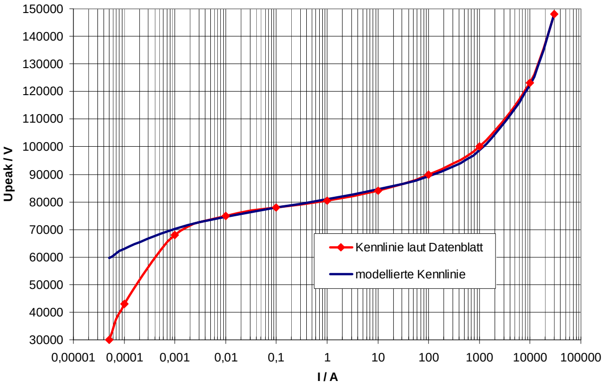

Figure 2: Characteristic curve of a 27 kV-surge arrester – comparison of data sheet and model.

The simulations with different installation conditions and with the three lightning current components (chapter 2) show different reactions of the stressed surge arrester:

- The arrester is not overloaded energetically and the conditions for an external flash-over are not given: The residual voltage of the arrester is given by the characteristic curve of the varistor.
- The arrester is overloaded energetically, but the conditions for an external flash-over are not given: The residual voltage of the arrester is given by the the electric arc voltage, after the arrester has blown out.
- For the arrester the conditions for an external flash-over are given, shortly before it is overloaded energetically: The residual voltage of the arrester is given by the the electric arc voltage, after the external flash-over occurred.

The described reactions of the surge arrester lead to differently high lightning surge voltages in the downstream electrical installations. For the investigation of the maximum insulation stress there, the worst-case results have to be used.

4.5 Transformers

As mentioned above, for transformers, even if models are proposed in standards [5, 6], the parameters for those models are usually not available. Therefore, for some typical transformers used for this investigation the transfer functions were measured experimentally. The transfer function is based on the electric quadrupole theory and is measured using the frequency response analysis. Important parameters are (1) the capacitance of the primary winding to earth, (2) the capacitance of the secondary winding to earth, (3) the capacitance of the primary winding to the secondary winding, and (4) the self inductances of the primary and secondary winding conductors.

The measurements include (1) a sinusoidal input over a wide frequency range and (2) an impulse input (i.e. wide-band source), both at the primary side. The output was measured at the secondary side of the transformers.

For the sinusoidal input the frequency range was determined with approx. 2000 supporting points being distributed logarithmically. The input generator was a voltage source with 10 V_{pp} and variable frequency. Based on the comparatively low voltage level small deviations are to be expected in the lower frequency range, which nevertheless can be neglected. Reason for that are the nonlinearity and the voltage dependency of the magnetic iron core, being valid up to approx. 10 kHz. Above this frequency limit the magnetic iron core is almost field-free and, consequently, without any influence.

The impulse input with 400 V was used to verify the results in the frequency and the time domain with a second wide band measurement.

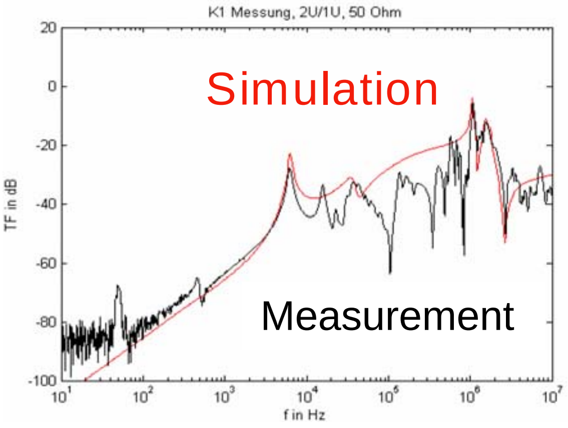

Figure 3: Voltage amplitude spectrum for a typical machine transformer (BBC GM 100 990) - according to [5, 6].

Based on these results as a first approach the models given in the report of the CIGRE Study Committee 33 [5] and in the Draft Technical Report of IEC TC 28 [6] were used to describe the coupling primary side vs. secondary side. However, these models turned out as not exact enough and therefore not sufficient for this investigation (Fig. 3). As a consequence for an entire simulation deviations up to more than 50 % were found in the final result.

Secondly the components were simulated via a lattice network. With that, a good correlation of both the amplitude spectrum and the phase shift between the measured (Fig. 4) and the simulated (Fig. 5) results were found. Based on these findings, all models for describing the surge transfer impedance and the damping of the transformers were developed with that method.

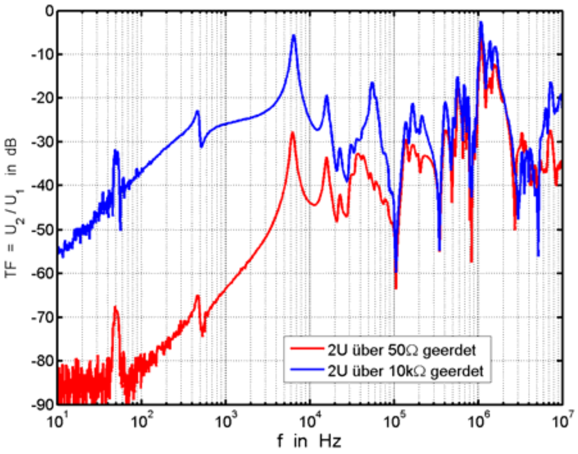

Figure 4: Amplitude spectrum for a typical machine transformer (BBC GM 100 990) – measurement.

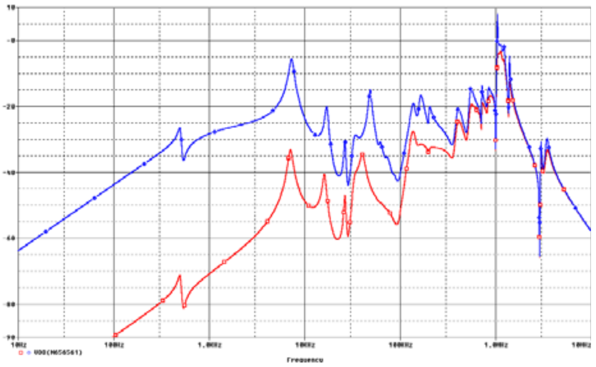

Figure 5: Amplitude spectrum for a typical machine transformer (BBC GM 100 990) – simulation with a lattice network.

4.6 Cables

Based on the data for the geometry and the dielectric materials also the cables are simulated as generally lossy lines, similar to the HV overhead transmission lines. Certainly, in the interesting frequency range the parallel resistance can be neglected again (G’ = 0).

In case of shielded MV cables the single phase conductors may have separate individual shields. This has to be considered as two equivalent circuits. The internal circuit consists of the single phase conductor and the inner shield’s surface, the external circuit is built by the outer shield’s surface and the surrounding equipotentialization system. Therefore, it is necessary to simulate a MV cable as two coupled travelling wave lines having different characteristic impedances. Adequate equations for the inductance and capacitance per unit length of the internal circuit (circular conductor in a concentric cylinder) and the external circuit (circular conductor above a conductive plane) are given for instance in [11, 12].

4.7 Generators and motors

The approach for the main generator of the power plant as well as for the motor-driven 10 kV loads is comparable to what is performed for the transformers. Similar to chapter 4.5 also for these components the transfer functions and models were determined.

5 SIMULATION RESULTS

The numerical simulations are conducted with a network analysis program (SPICE code). As already mentioned, there are different threats defined by the three lightning current components. Due to the fact, that the three components differ both in the transported energy and in the time slope, it is important to assess the current impulse with the largest threat. Therefore the simulations are to be performed for all three lightning current components.

Additionally the operational mode of the power plant is important for the simulation. Usually, if the generator is connected to the power grid, it is parallel to the auxiliary power network from the lightning impact point-of-view. The generator therefore works as some kind of low-pass filter. Here, the negative first stroke leads to the highest disturbances in the 10 kV and 400 V voltage levels. In case of a disconnected generator, i.e. the auxiliary power system of the power plant is supplied itself via the HV overhead transmission line, the negative subsequent stroke with its higher frequencies represents the worst threat.

Generally, a power plant is a complex arrangement of cascaded resonant circuits with a wide range of characteristic frequencies (see Fig. 6). Each load or transformer already forms an individual resonant circuit by itself, creating additional resonant circuits with the connecting leads. All these resonant circuits are dependent on each other, and influence themselves. Therefore, independent parameter analysis, e.g. the investigation of a variation of a connecting lead, can not be evaluated separately, but only in connection with other parameters. Conclusions for an optimum level of a certain parameter can not be formulated fundamentally, but only by trend, because each parameter depends on a wide variation of the others.

Back coupling from downstream voltage levels to the next higher voltage level are usually very low, so that they can be neglected for a first approach. Furthermore each transformer creates a damping to the next voltage level. The value of attenuation is given by its capacitive transfer characteristic in the higher frequency range, not by its classical transmission ratio. Therefore, the effective attenuation for a disturbance may be less than the given transmission ratio, so that, from a relative point-of-view, the disturbance is more dominant on the lower voltage levels. Kind and number of electrical loads on the different voltage levels, especially on the next higher voltage level, also influence the disturbance. Generally either high-power motors or a high number of motors act as a further attenuation.

The simulation results are demonstrated shortly on the basis of two examples. Fig. 6 shows the result of a lightning strike – negative subsequent stroke - 25 m away from the power plant at the different voltage levels – three loads with different power on the 10 kV level, 20 loads on the 400 V level. The power plant's generator is connected to the power grid. After 1.52 µs a flash-over occurs at the last isolator of the HV overhead transmission line. Some 0.1 µs later a flash-over at the primary surge arrester follows. Both electric arcs absorb the major part of the lightning current's energy. Therefore, for 10 kV loads the highest transient surge voltages are 14.2 kV at time 7.94 µs and for the 400 V loads we get only 216 V at time 6.98 µs. However, it must be mentioned that in other load cases the voltages may be remarkably higher. Further simulations show, that the transient surge voltages increase remarkably, if the surge arrester is not present or the electric arcs as a consequence of the flash-overs at the isolator and the surge arrester are not considered.

The second scenario shows the influence of a cable length on the oscillation behaviour and the maximum level of the lightning surge voltage (Fig. 7). In this case the length of the 10 kV cable between the auxiliary power transformer and the 10 kV busbar is varied from 5 m up to 250 m in steps of 5 m. The oscillation behaviour of the transient surge voltage dependent on the cable length can be clearly seen, both at the 10 kV level and at the 400 V level.

The simulations show, that the transient surge voltages generally are within the acceptable limits for the different voltage levels for each moment, if the surge arresters are present and the electric arcs at the isolators and arresters are considered. However, if the flash-over at the arrester ahead of the machine transformer is not considered, the transient surge voltages at the 10 kV level increase by a factor of 4. With that they are outside the given limits for cables and loads.

6 CONCLUSION

To analyse transient lightning surge voltages as a consequence of a direct lightning strike to a phase conductor bundle of the HV overhead transmission line close to a power plant, numerical simulations are conducted for a typical auxiliary power network. The simulations contain all typical components of an auxiliary power network at the different voltage levels. The models for the simulation are either taken from standards (e.g. lightning currents, transmission lines, earthing impedances) or are elaborated on the basis of measurements at typical components (e.g. transformers, generators, motors) and developed on the basis of existing models with extended performance description (e.g. surge arresters).

For different parameters and parameter combinations (lightning threat, power plant's operational mode, cable or lead lengths) numerical simulations are conducted with a network analysis program. The results of these simulations are discussed.

7 REFERENCES

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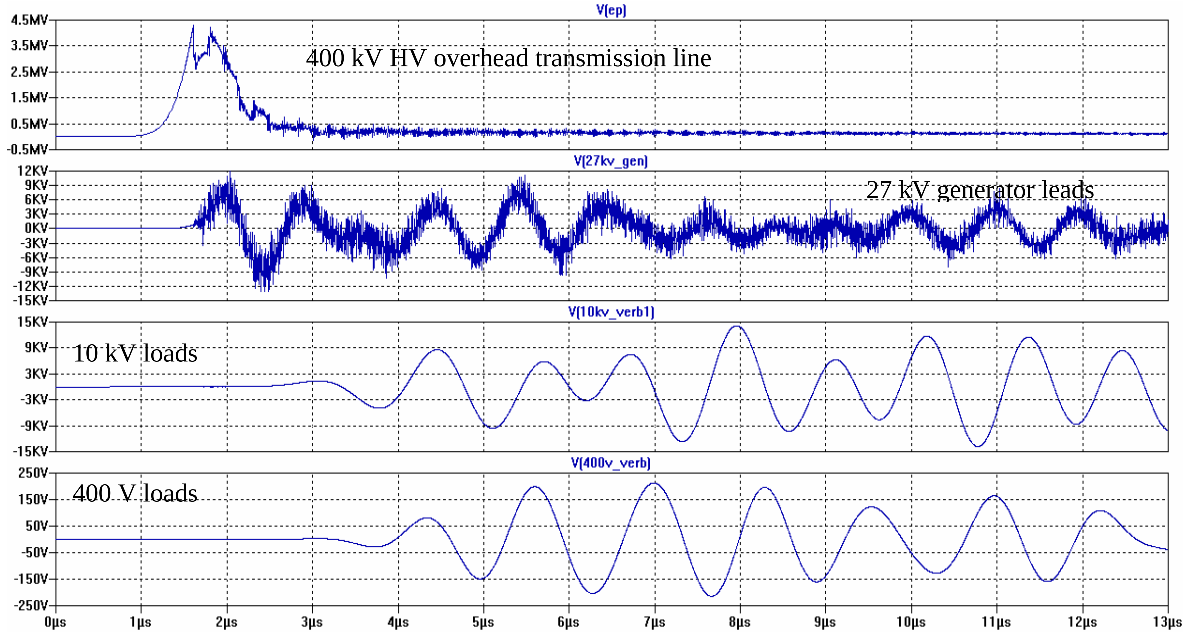

Figure 6: Wave shapes of transient surge voltages at different locations and at different voltage levels for a given power plant's operation (generator connected to power grid); line-to-ground power frequency voltage not displayed.

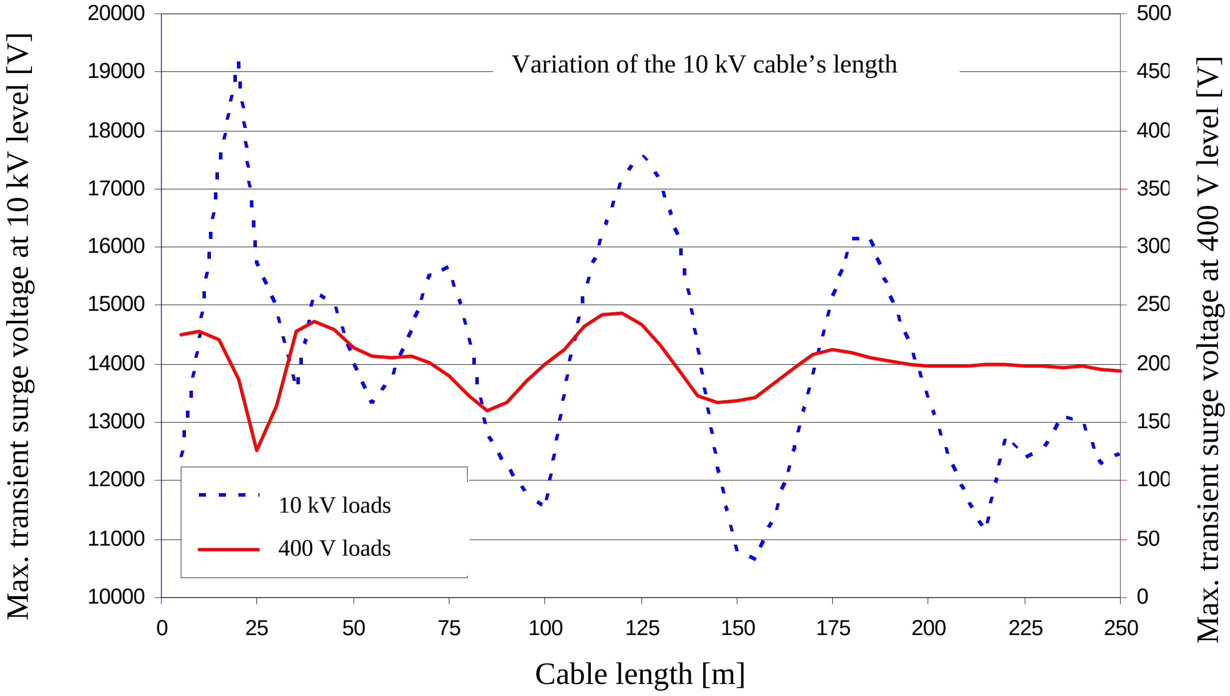

Figure 7: Transient surge voltages for 10 kV and 400 V loads depending on the length of the 10 kV cable between auxiliary power transformer and busbar.