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Transient electromagnetic simulations of substation earth grid for improving lightning withstand performance of a large power transformer

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Abstract: This paper demonstrates the results from detailed studies of the physical layout of a substation earthing grid. The particular layout of a 400/150 kV substation is modelled in details in MATLAB by means of a thin-wire approach originally developed by J.H.Richmond in 1974 for NASA. A model of the surge arresters, the incoming overhead line and the transfomer is implemented in EMTDC/PSCAD and interconnected with the MATLAB simulation model of the earthing system in an iterative manner. Six different layout approaches for the earth grid in the vicinity of the surge arrester downconductor connections are analyzed with respect to lightning overvoltage at the transformer bushings and it is shown clearly that the layout of the grounding system in the vicinity of the surge arrester down conductors plays an important role for the magnitude of the transformer bushing overvoltage during lightnings striking the incoming overhead line.

1 INTRODUCTION

On the 18th of June 2002 a heavy thunderstorm swept over North-Jutland in Denmark resulting in a serious fault in Energinet.dk's 400/150kV transformer placed at the Nordjyllandsværket 400 kV transformer station (NVV5). According to Energinet.dk, the fault was caused by a lightning transient on the 150 kV transmission grid. Apparently the transient lightning voltage exceeded the LIWL of the transformer.

This incident has caused speculations within Energinet.dk about the effectiveness of the lightning protection of the transformers now used at Energinet.dk's power stations. The possibility of this happening again to any of the other power transformers in Eltra's possession is likewise of major concern. The main concern of the project is to make a simulation model of that part of the substation which surrounds the transformer, see Fig. 1, and to simulate a double exponential lightning impulse current directly on a phase line, which will propagate towards the transformer in the form of a travelling wave. The main emphasis will be put on investigating the overvoltage distribution in the system with respect to the LIWL of the transformer and to simulate the components that are most likely to have caused the exceeding of the LIWL and thereby the damage of the transformer. These are the 150 kV surge arresters, the earth grid with respect to GPR and the transformer itself. The 150 kV overhead line between the 150 kV substation, NVV3, and the 400 kV substation, NVV5, is included in the simulation. The results will then be used to determine a possible weakness in the overall overvoltage protection design.

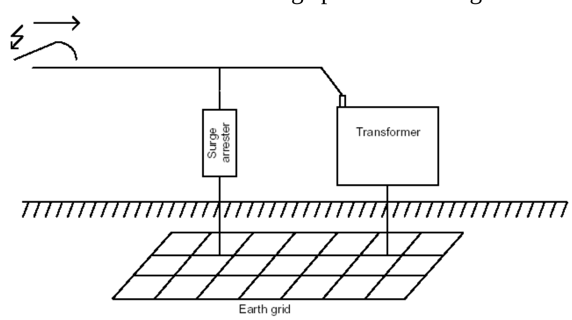

Fig. 1. Overview of the system, with the overhead line, the surge arrester, the transformer and the earth grid

This paper focusses on the role of the earth grid and presents the results from a detailled study of the earth grid layout in the vicinity of the surge arrester downconductor connections to the earth grid. The original layout and six possible improvements of the earth grid are analysed with respect to overvoltage magnitude at the transformer bushing and it is clearly shown that the earth grid layout in the vicinity of the surge arresters plays an important role in the overall lightning protection. Further details can be found in ref. [1] which is a Masters Thesis elaborated by K.E. Einarsdottir, E. Andresson and J.M. Rasmussen and [2].

2 MODELLING OF SYSTEM

The system shown in figure 1 is modelled using PSCAD/EMTDC with the following use of models:

2.1 ASEA Autotransformer model

The transformer must be modeled sufficiently to posses terminal properties, which reflects its high frequency behaviour sufficiently to achieve realistic results of overvoltage stresses. Normally [3], transformers are modeled as a single capacitance from line terminal to ground. More detailed models are normally used for studying the internal voltage distribution of the windings. This work uses an approach originally proposed by [4] which represents each phase winding as one single winding possessing capacitive, inductive and resistive behaviour.

2.2 ZnO surge arrester

The non-linear surge arrester dynamics are modeled using the approach proposed by [5], which is a simplified model of the IEEE model with model parameters described as proposed in [6], [7]. Figure 2 shows the Fernandez approach.

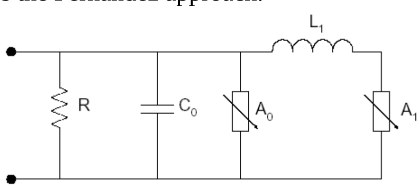

Fig. 2. The model proposed by Fernandez

Surge arrester downconductor is modelled as an inductive lumped element with an inductance of L = 52 nH.

2.3 Earth grid

The purpose of making a model of the earth system is to calculate the voltage between the surge arrester ground terminal and the neutral point of the transformer, which results from a difference in GPR under the two components, when a lightning current surges through the surge arrester into the earth grid. An electromagnetic field approach is the best choice when the need for calculation of transient voltages between points of the earth grid is present [8]. The earth grid model is a transient electromagnetic program written in the C-based programming language of MATLAB. It is based on the thin wire structure program originally written in Fortran code by J. H. Richmond, [9], [10]. The model performs an electromagnetic analysis on wire structures in the complex frequency domain, based on closed form expressions and Simpson's rule of integration for the solution of electromagnetic fields. Its function is to determine the electric near fields at the surface of the wire structure, due to the longitudinal current flowing in each section of the wire. The electric field calculation is then used to determine the dynamic impedance, both self and mutual, of the wire structure in order to determine the current distribution in the overall grid. The grid is divided into segments and the current distribution is approximated by defining every two segments as a dipole with a piecewizesinusoidal current distribution given with sinusoidal expansion functions, as it is very close to the natural current distribution on a perfectly conducting thin wire. A sinusoidal dipole is used as a test source, as this is probably the only finite line source with simple closed-form expressions for the near-zone fields, and the mutual impedances between two sinusoidal dipoles may be determined from exponential integrals [10], pp. 7. The thin wire approach has been used by L. Grcev et al. [11] [12] [13] [8] [14] to determine the electric fields in earth grids caused by lightning surge currents. L. Grcev refers to Richmond's thin wire program in [12], pp.394, but he additionally includes image theory in his model to account for reflections due to interface of air and earth, as this is not included in Richmond's program. L. Grcev also describes in his articles how to implement an injected current, also not included in Richmond's program. As Richmond's thin wire program was not specifically designed for calculating electromagnetic fields in earth grids, the program needed to be adapted to the problem presented in this report. All unnecessary functions to the presented problem have been eliminated from the program, which now has the main function of calculating antenna problems in a homogeneous conducting medium. Reflections of the electric field due to the interface of air and earth have been taken into consideration with the modified image theory, and to make injection of surge current possible, the modifications suggested by L. Grcev have been implemented in the program. Only the front time of the current wave is of interest as this provides the highest frequency and thereby the highest electric fields. All simulations are therefore made in the frequency domain, using the frequency corresponding to the desired current front time at each time, and a conversion of the current wave from the time-domain to the frequency domain by Fourier transforms is therefore not needed. The basic model (before implementing modified image theory and injection current) has been verified thoroughly with results presented in Richmond's notes [9]. After implementation of modified image theory and the injection current, the model was verified by comparing results with the results presented in [12] with very good agreement. The following assumptions and limitations are made in the model of the earth grid:

1. The wire structure is made of straight cylindrical metallic conductors.
2. The wire is subject to the thin wire approximation, and the conductor radius is therefore assumed much smaller than the wavelength, with wire length much greater than the wire radius (At least 30 times greater [9], pp.12]).
3. Image theory is applied to compensate for the effects of a ground plane, i.e. the interface between air and earth is taken into consideration. This limits the frequency range of the model to a few megahertz [13]
4. The media of earth and air are assumed homogeneous with a horizontal ground plane boundary between them.
5. The current on wire ends is assumed to be zero.
6. For accuracy, the longest wire segment should not greatly exceed 1/4 wavelength, [10].
7. Soil ionization is not taken into consideration.

The MATLAB made program is called TEMP and details can be found in [1] and [2]. Verification is performed against a 15 m long horizontal electrode and a 60x60 m meshed earth grid and excellent agreement is found between results published in [13], see [1] and [2].

2.4 The total system

The total system is modeled in the PSCAD/EMTDC software. The total system is used to determine the limits of the lightning current which can cause the voltage from phase to neutral on the transformer U_{trafo} to exceed the LIWL, i.e. 650 kV taking GPR into consideration. The voltage, U_{trafo}, is the sum of the residual voltage across the surge arrester, U_{arr}, and the voltage between the surge arrester ground terminal and the transformer neutral point, U_{st}. The resistance, R_{st}, between the surge arrester ground terminal and the transformer neutral point is calculated iteratively in TEMP in MATLAB for each simulation.

The earth grid is modeled in every detail according to construction drawing. The layout is shown in fig. 3, which is an output file created by TEMP. A unique feature is implemented in TEMP, which checks all electrical connections of the grid for inconsistency.

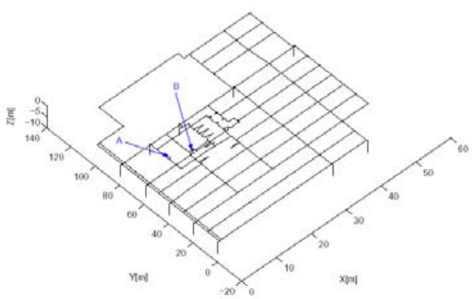

Fig. 3. TEMP output file showing earth grid layout. A is surge arrester round terminal location and B transformer neutral point location.

The calculations in TEMP are made with a fixed value of the soil resistivity, and it is therefore only possible to model a homogeneous soil for the whole grid. The soil under the surge arrester and in the nearest vicinity is most critical, as the electric field density is strongest at the feed point and decays very fast exponentially over a few meters distance. Fig. 4 shows the electric field at the feed point and the closest surroundings using resistivity ρ=1000 Ωm, $I_{lightning}$ = 10 kA with a front time of 1 μs. The location of the transformer neutral point and the injection point below the surge arrester are shown with the capital letter, **A** for surge arrester and **B** for transformer. The electrical field distribution gives by integration the voltage between chosen points. The soil relative permittivity may vary with different types of soil and water content in the app. range 4 – 20 according to [15]. The permittivity of the soil affects the calculated dynamic resistance R_{St} very little.

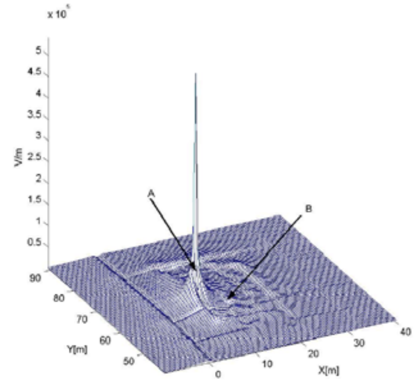

Fig. 4. A plot from TEMP showing E-field distribution between points A (surge arrester) and B (transformer)

2.5 Simulation Parameters

The parameters which can be varied in the total simulation model in PSCAD are:

- The soil resistivity of the transmission line model
- The dynamic earth grid resistance, R_{st}
- The parameters for the lightning surge, i.e the front time and the amplitude.

Grcev states in his article [13], pp.1776, that the value for the dynamic resistance only depends on the geometry of the earth grid, the applied frequency, i.e the front time of the lightning current, and the characteristics of the soil. Simulations were made with fixed values for resistivity and relative permittivity of the soil. Varying the amplitude of the input current as an iteration process in the TEMP program gave no change in the resistance value, R_{st}. TEMP calculates the resistance, R_{st}, using as an input the front time of the lightning current, the soil resistivity and the soil permittivity. A new value for the resistance, R_{st}, between the surge arrester ground terminal and the transformer neutral point was therefore determined for each new value of the soil resistivity and lightning current front time. The lightning current in the PSCAD simulation model was then gradually increased until the LIWL of the transformer was exceeded, and the current, I_{arr}, through the surge arrester was then measured. Then the current, I_{arr}, was used as an input with the fixed soil resistivity and lightning current front time in TEMP, and the voltage, U_{st}, was the output. TEMP determines the voltage, U_{st}, by integrating the electric field on a path between the surge arrester and the transformer. This voltage occurs due to difference in GPR between the two components. A sketch showing the GPR under the surge arrester ground terminal and the transformer neutral point with respect to infinite ground is shown in Fig. 5, where GPR_{diff} is equal to U_{st}.

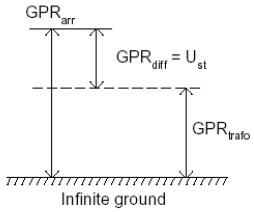

Fig. 5. The voltage, U_{st} is shown as GPR_{diff} as it is the difference in GPR under the transformer, GPR_{trafo}, and the surge arresters, GPR_{arr}.

3 RESULTS OF SIMULATIONS

This section shows simulation results for the overvoltage at the power transformer LV bushing as a function of lightning current magnitude, front steepness and soil resistivity. Section 3.1 shows results from the original layout of the earth grid and the following sections shows how six different earth grid layout proposals are affecting the overvoltage at the transformer bushing.

3.1 Original layout of earth grid (figure 3)

The simulations were split up in three main parts with soil resistivity of 100, 350 and 1000 Ωm and each with four different front times of the lightning current, i.e 0.5, 1, 4 and 8 µs. A soil resistivity of 100 Ωm was used in the first simulation, and the amplitude limits of the lightning current was determined for the four different front times. The same procedure was used for a soil resistivity of 350 and 1000 Ωm. The results from all the simulations are shown in tables below. The results, i.e resistance, R_{st}, the amplitude of the lightning current, the voltage at the terminal of the transformer and the voltage, U_{st} are listed in three tables. Table 1 lists the results with lightning currents with a front time of 0.5 µs for three different soil resistivities. Table. 2, 3 and 4 lists results using lightning currents front times of 1, 4 and 8 µs. Only the front time and the amplitude is of interest with respect to the lightning surge current, as the purpose is to determine the limits of different lightning currents which cause the voltage from phase to neutral on the transformer to exceed the LIWL = 650 kV of the transformer on the 150 kV side, when the voltage, U_{st}, is taken into consideration.

Front Time 0.5 μs and Soil Resistivity 100, 350 and 1000 Ωm

Resistivity, ρ [Ωm]	R_{st} [Ω]	$I_{lightning}$ [kA]	I_{arr} [kA]	U_{trafo} [kV]	U_{st} [kV]
100	24.7	10.5	8.8	659	259
350	49.0	7	5.3	664	260
1000	82.8	5	3.3	650	272

Table 1. Simulation results for a lightning with a front time of 0,5 µs. $I_{lightning}$ is the amplitude of the lightning current needed for the voltage U_{trafo} to exceed the LIWL = 650 kV of the transformer.

Front Time 1 μs and Soil Resistivity 100, 350 and 1000 Ωm

Resistivity, ρ [Ωm]	R_{st} [Ω]	$I_{lightning}$ [kA]	I_{arr} [kA]	U_{trafo} [kV]	U_{st} [kV]
100	18.1	13	11.2	655	203
350	35.1	8.5	6.8	662	239
1000	45.2	7.5	5.7	668	258

Table 2. Simulation results for a lightning with a front time of 1,0 µs. $I_{lightning}$ is the amplitude of the lightning current needed for the voltage U_{trafo} to exceed the LIWL = 650 kV of the transformer.

Front Time 4 μs and Soil Resistivity 100, 350 and 1000 Ωm

Resistivity, ρ [Ωm]	R_{st} [Ω]	$I_{lightning}$ [kA]	I_{arr} [kA]	U_{trafo} [kV]	U_{st} [kV]
100	8.9	31.5	18.8	650	167
350	11.4	27.5	15.7	653	179
1000	12.4	26	14.8	652	184

Table 3. Simulation results for a lightning with a front time of 4,0 µs. $I_{lightning}$ is the amplitude of the lightning current needed for the voltage U_{trafo} to exceed the LIWL = 650 kV of the transformer.

Front Time 8 μs and Soil Resistivity 100, 350 and 1000 Ωm

Resistivity, ρ [Ωm]	R_{st} [Ω]	$I_{lightning}$ [kA]	I_{arr} [kA]	U_{trafo} [kV]	U_{st} [kV]
100	5.3	61.5	30.8	651	163
350	6.0	58	28.4	651	170
1000	6.5	57	27.3	654	177

Table 4. Simulation results for a lightning with a front time of 8,0 µs. $I_{lightning}$ is the amplitude of the lightning current needed for the voltage U_{trafo} to exceed the LIWL = 650 kV of the transformer.

The simulation results of the total system showed that the resistance, R_{st}, between the surge arrester ground terminal and the transformer neutral point increases with higher soil resistivity and faster front times of the lightning current. A slower front time of the lighting increases the maximum limit of the lightning current.

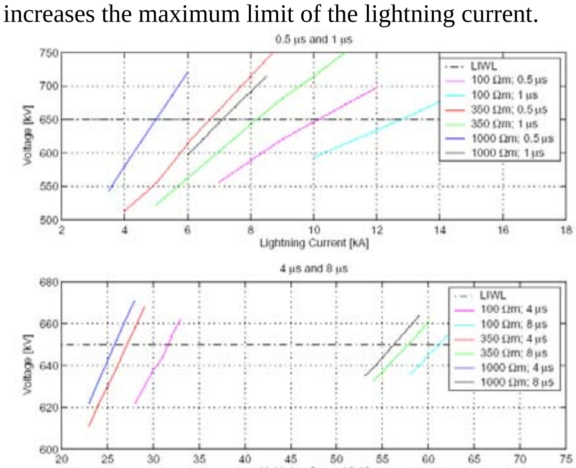

Fig. 6. The plots show the amplitude of the lightning current $I_{lightning}$ which will cause the voltage U_{trafo} to exceed its LIWL, when different values of the soil resistivity and front times were used.

Figure 6 illustrates graphically the results of table 1-4. LIWL=650 kV for the LV side of the power transformer is shown and it is seen that for a certain specific soil resistivity and front time one could expect an exceeding of the LIWL if lightning current is above a certain value.

3.2 Reduced mesh size, proposal no. 1.

A current impulse that propagates through a surge arrester to the earth grid will generate strong electromagnetic fields under the surge arrester and in it's nearest vicinity which will result in GPR under the surge arrester and the nearest surroundings. The strongest field density will always be around the surge arrester as the current density is largest at the injection point and the wire structure in the nearest vicinity. As the wire structure is a meshed grid with the current distributed according Kirchoff's current low, this means that the current density becomes smaller the further away it comes from the injection point, resulting in a lower amplitude of the field density. A small mesh size has a positive influence on the reduction of GPR and an uneven grid with smaller mesh size at the feed point is recommended. It is therefore interesting to simulate the earth grid with a decreased mesh size in the nearest vicinity of the feed point (between surge arrester and periphery). The present mesh size between the surge arrester and the periphery is approximately 4 x 10 m. The mesh is reduced by means four new wire segments (shown in red in figure 6) placed between surge arrester downconductor connection and earth grid periphery.

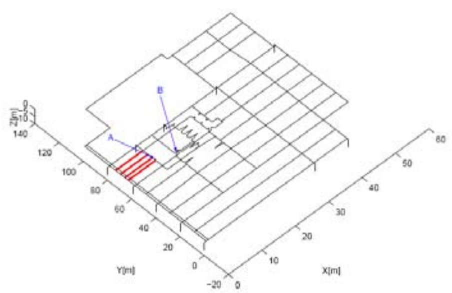

Figure 6. The new grid configuration (proposal no.1) plotted from TEMP. The bold red lines are the added segments. A is the surge arrester ground terminal and B is the transformer neutral point.

The comparison of the results from the simulation of the original grid layout with proposal no. 1 layout may be seen in table 5 for soil resistivity ρ=350 Ωm

$\rho = 350\,\Omega$m						
		Present configuration		New configuration		
t_f [μs]	$I_{lightning}$ [kA]	R_{st} [Ω]	U_{trafo} [kV]	R_{st} [Ω]	U_{trafo} [kV]	Decrease in Voltage, [%]
0.5	7	49.0	664	40.3	617	7.08
1	8.5	35.1	662	26.1	609	8.01
4	27.5	11.4	653	8.8	616	5.66
8	58.0	6.0	651	4.9	622	4.45

Table 5. Comparison of results from the present earth grid configuration and the new configuration proposal no. 1 with a smaller mesh size from surge arrester to the periphery.

The comparison showed that by decreasing the mesh size configuration the voltage from phase to neutral on the transformer decreased a few percent. For the fast front surges and ρ=100 Ωm in soil resistivity the decreases were minimal or about 3 percent. For higher resistivity and for the faster front times the voltage decreased up to 10 percent.

3.3 Further reduced mesh size, proposal no. 2.

A configuration with reduced mesh size from the surge arrester to the periphery was presented, in section 3.2. Using this configuration and additional adding wire segments between the surge arrester and the transformer will decrease the current density and the electrical field in the nearest vicinity to the injection point will therefore decrease resulting in a decrease in voltage, U_{trafo}. The configuration is plotted by TEMP and may be seen in Fig. 7. The mesh size of the new configuration was approximatly. 2 x 4 m.

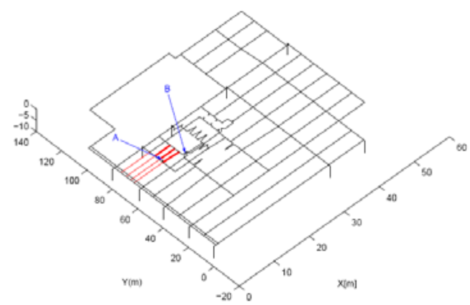

Figure 7. The new grid configuration (proposal no.2) plotted from TEMP. The bold red lines are the added segments and the non-bold redlines the already added segments from proposal 1. A is the surge arrester ground terminal and B is the transformer neutral point.

The comparison of the results from the simulation of the original grid layout with proposal no. 2 layout may be seen in table 6 for soil resistivity ρ=350 Ωm

$\rho = 350\,\Omega$m						
		Present configuration		New configuration		
t_f [μs]	$I_{lightning}$ [kA]	R_{st} [Ω]	U_{trafo} [kV]	R_{st} [Ω]	U_{trafo} [kV]	Decrease in Voltage, [%]
0.5	7.0	49.0	664	25.7	560	15.66
1	8.5	35.1	662	14.8	540	18.43
4	27.5	11.4	653	4.6	553	15.31
8	58.0	6.0	651	2.6	562	13.67

Table 6. Comparison of results from the present earth grid configuration and the new configuration proposal no. 2 with a smaller mesh size from surge arrester to both transformer and the periphery.

The comparisons showed a considerable decrease in the overvoltage when the mesh size around the surge arrester was decreased. The changes gave a reduction in the voltage for fast front surges from 7 % with ρ=100 Ωm up to 21 % for ρ=1000 Ωm

3.4 Extension of the earth grid, proposal no. 3.

Experiments from [16] and [17] showed that by locating the feed point at the center instead of at the corner of the grid has a profound decreasing effect on the GPR at the feed point. It was also shown in [16] that GPR was decreased by increasing the length of the electrode up to a certain effective length, after which the length had no influence. It is therefore interesting to simulate an enlargement of the earth grid in order to locate the feed point (surge arrester ground terminal) more central than it is in the present configuration. The earth grid near the surge arresters was therefore extended. The new configuration may be seen in Fig. 8.

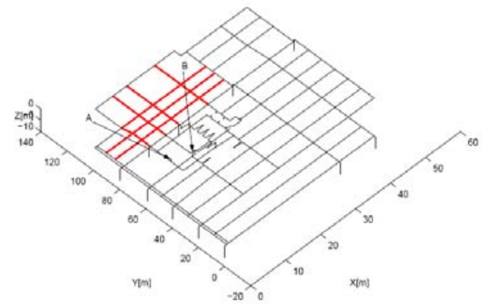

Figure 8. The new grid configuration (proposal no.3) plotted from TEMP. The bold red lines are the added segments A is the surge arrester ground terminal and B is the transformer neutral point.

The comparison of the results from the simulation of the original grid layout with proposal no. 3 layout may be seen in table 7 for soil resistivity ρ=350 Ωm

$\rho = 350\,\Omega m$						
		Present configuration		New configuration		
t_f [μs]	$I_{lightning}$ [kA]	R_{st} [Ω]	U_{trafo} [kV]	R_{st} [Ω]	U_{trafo} [kV]	Decrease in Voltage, [%]
0.5	7	49.0	664	49	664	0.0
1	8.5	35.1	662	35.1	662	0.0
4	27.5	11.4	653	11.4	653	0.0
8	58.0	6.0	651	6.0	651	0.0

Table 7. Comparison of results from the present earth grid configuration and the new configuration proposal no. 3 with enlargement of the earth grid.

The extension of the earth grid has no effect on the voltage compared to the present configuration. The earth grid was also simulated with an extended grid outside the grid periphery which yielded the same results. This is in good agreement with the concepts of effective electrode length. Extending the earth grid is therefore not advised as a solution.

3.5 Greatly reduced mesh size around the surge arrester and the transformer, proposal no. 4.

Solution propositions in section 3.2 and especially in section 3.3 showed that the voltage was reasonably decreased, although the resistance, *Rst* was relatively high for fast front surges, (0,5 μs and 1,0 μs) compared to more standard surges (4 μs and 8 μs). It is therefore interesting to simulate the earth grid with a very small mesh size all around the transformer and the surge arrester. The new configuration may be seen in Fig. 9 where the mesh size was approximately 1.5 x 1.5 m.

The comparison of the results from the simulation of the original grid layout with proposal no. 4 (greatly reduced mesh size) layout may be seen in table 8 for soil resistivity ρ=350 Ωm

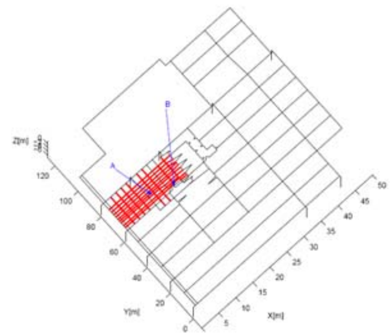

Figure 9. The new grid configuration (proposal no.4) plotted from TEMP. The bold red lines are the added segments giving the greatly reduced mesh size. A is the surge arrester ground terminal and B is the transformer neutral point.

$\rho = 350\,\Omega m$						
		Present configuration		New configuration		
t_f [μs]	$I_{lightning}$ [kA]	R_{st} [Ω]	U_{trafo} [kV]	R_{st} [Ω]	U_{trafo} [kV]	Decrease in Voltage, [%]
0.5	7.0	49.0	664	19.7	530	20.18
1	8.5	35.1	662	10.3	510	22.96
4	27.5	11.4	653	2.8	523	19.91
8	58.0	6.0	651	1.5	534	17.97

Table 8. Comparison of results from the present earth grid configuration and the new configuration proposal no. 4 with greatly reduced mesh size around transformer and surge arrester.

Reducing the mesh size to almost 1.5 x 1.5 m showed a great reduction in the voltage from phase to neutral on the transformer for fast front surges from 9 % with ρ=100 Ωm up to 27 % for ρ=1000 Ωm

3.6 Exchanging the soil around the ground wires with backfill, proposal no. 5.

This solution proposition is made to show the effect it would make on *Rst* if the soil in the wire trenches around the ground wires close to the surge arresters would be exchanged with Clay Based Backfill Mixture. This type of backfill is suggested as it has a low resistivity of 0.2-0.8 Ωm and combines the necessity of retention of moisture and reduced variation of resistivity due to moisture variations. A mean value of ρ=0,5 Ωm is chosen as the value for the fixed soil resistivity in the simulations. Exchanging the soil in the trenches in the nearest vicinity of the surge arresters is expected to give approximately the same results as exchanging the trench soil for the whole earth grid, based on the results from TEMP of the fast decaying electric field around the surge arrester, see figure 4, indicating that the current is dissipated in the soil in a small radius of few meters from the feed point. Simulations were made for both the present configuration of the earth grid and for the new configuration presented in section 3.5. The results for a front time of t_f = 1 μs is listed in Table 9. Exchanging the soil in the trenches gave, like the greatly reduced mesh size, a profound reduction of the voltage from phase to neutral on the transformer from 20-37 %. Simulation showed additionally that when a soil resistivity of ρ=0,5 Ωm was used, no additional reduction was observed when the mesh size of the present grid was greatly reduced as in solution 4.

$t_f = 1\,\mu s$						
		Present configuration		Configuration of sol. no.4		
ρ [Ωm]	$I_{lightning}$ [kA]	R_{st} [Ω]	U_{trafo} [kV]	R_{st} [Ω]	U_{trafo} [kV]	Decrease in Voltage, [%]
0.5	48.0	0.9	653	0.9	653	0.00
100	13.0	18.1	655	9.3	561	14.35
350	8.5	35.1	662	10.3	510	22.96
1000	7.5	45.2	668	10.8	483	27.69

Table 8. Comparison of results from the present earth grid configuration and the configuration with greatly reduced mesh size using soil resistivity for the backfill 0,5 Ωm as well as the soil resistivity for 100 to 1000 Ωm and a front time of $t_f = 1$ µs

The effect it has on the voltage from phase to neutral on the transformer, *Utrafo*, to reduce the soil resistivity to ρ=0,5 Ωm by exchanging the soil in trenches around the wires in the present earth grid, is shown in Table 9. The voltage decrease is shown in percent.

U_{trafo} difference in percent, using different values of soil resistivity				
Reduction of soil resistivity, ρ [Ω m]	0.5 μs	1 μs	4 μs	8 μs
from 100 to 0.5	30.50%	28.54%	22.92%	20.89%
from 350 to 0.5	35.24%	32.63%	25.27%	22.43%
from 1000 to 0.5	36.70%	35.03%	25.92%	23.55%

Table 9. Comparison of the difference in voltage from phase to neutral on the transformer in percent reducing the soil resistivity to 0.5 Ωm in the present grid configuration. The voltages used in the comparison were calculated using the lightning current which caused the voltage, Utrafo, to exceed the LIWL when a soil resistivity of 100, 350 and 1000 Ωm was used.

3.7 Variation of the grid wire radius, proposal no. 6.

A variation of the wire radius from the original 5,50 mm(95 mm^2) up to 8,75mm (185mm^2) showed no decrease in R_{St} . This means that the difference in GPR, under the surge arrester and under the transformer is unaffected by the wire radius and does therefore not affect the voltage from phase to neutral.

4 CONCLUSIONS

A complete model of a power transformer overvoltage protection system has been modelled and simulated. Overvoltage magnitude at the transformer LV bushing has been calculated for varying soil resistivities, lightning current magnitudes and front steepness for different real life earth grid layouts. It has been shown clearly that the engineering design of the earth grid in the vicinity of the surge arrester downconductor connection to the earth grid plays an important role for the effectiveness of the overvoltage protection of the transformer. A "bad" (to large mesh and/or gravel with bad specific resistivity) earth grid design may give rise to a considerable additional voltage to the surge arrester residual voltage. It is necessary to use models based on the dynamic electromagnetic behavior of the earth grid to reveal this phenomena as static grounding resistance values are meaningless for the discussion and describtion of the injection of fast-varying lightning currents into an extensive earth grid. Simple guidelines for the layout includes using a dense mesh (few meters x few meters) around surge arrester injection points combined with a soil with a low specific resistivity. Never use normal construction gravel around ground wires !

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