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Reduction of the visual impact of overhead transmission line systems through utilisation of line surge arresters as lightning protection

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SUMMARY

The main reason for the increasing public resistance to overhead transmission line systems in Denmark is the impact on the environment with emphasis on the visual aspect. Therefore the Danish Transmission System Operator Energinet.dk is currently carrying out a research project, in cooperation with the Technical University of Denmark, on how to lessen the visual impact of 400 kV overhead line transmission systems. In this paper omission of shield wires combined with installation of a suitable number of line surge arresters is investigated as a possible alternative to transmission lines equipped with shielding wires thereby reducing tower height, allowing more compact designs of towers thus minimizing the visual environment impact of the lines.

Omission of shield wires in the system and instead utilizing a larger number of surge arresters in the (upper) phases of an overhead line without reduction in line performance and lightning protection of the nearest substations requires thorough modelling of the new line including all electrical parameters necessary for performance evaluation under all conditions.

In this paper, explicit use of line surge arresters as lightning protection on the line will be investigated by transient simulations on a 400 kV line with either shield wires or line surge arresters. These simulations will also be used to estimate number and location of the line surge arresters in the line to ensure a satisfactory performance of the line when omitting shield wires in the tower top. The simulation model will consist of a line section modelled in PSCAD/EMTDC as a distributed frequency dependent parameter line.

Based on results from numerical simulations it is shown that line surge arresters can be used instead of shield wires however this has consequences with respect to the performance of the line and the required protection level in substations. The use of line surge arresters gives the possibility to decrease the height of towers thereby improving the visual impression of the overhead line transmission systems. However the usage of line surge arresters will, dependent upon line surge arrester placement, result in a denser visual impression of the tower top.

The results will be discussed in particular with respect to possible future tower top geometries.

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KEYWORDS

Overhead Line Systems, Line Surge Arresters, Aesthetics, Fast Front Transients, Unshielded, Transmission Line, 400 kV.

INTRODUCTION

The Danish Transmission System Operator Energinet.dk is currently carrying out a research project in cooperation with the Technical University of Denmark on future composite based overhead lines. One purpose of the project is to investigate how to lessen the visual impact of 400 kV transmission lines.

In this paper the usage of line surge arresters instead of shield wires for lightning protection is investigated on a 400 kV transmission line segment. Only transient overvoltages caused by direct lightning strokes to the lines with either shield wires or with line surge arresters are compared. This is to determine if it is technically possible to use a system solely with line surge arresters as lightning protection without considerable reduction in lightning protection performance.

It is considered if there is an aesthetic improvement of the system by using line surge arresters. This is done after the evaluation of the technical possibilities. Evaluation of whether or not something is an aesthetics improvement is very much an individual question.

Several different models for representing the system have been considered and the final representation of the line segment is presented in the Modelling section. Transmission lines are represented by frequency dependent distributed parameters lines [1], [2], [3], towers by multiconductor equivalents [4] and line surge arresters by the IEEE arrester model [5].

In principle it should be possible to protect a transmission line system with line surge arresters. However the performance and continued operation of the system is very much dependent upon the placement, number of arresters and the arrester characteristics [6], [7]. These are the parameters varied in the paper, however without given a complete picture of all possible solutions. Flashover along insulators is included in the model, all other clearances in the system are assumed to be of sufficient length to avoid flashover.

The results are shown as line voltage for selected phases as a function of the mentioned parameters.

MODELLING

A model of a three phase 400 kV transmission line equipped with line surge arresters have been made in the simulation program PSCAD/EMTDC 4.2.1 [3]. The transmission line is represented by 300 m line sections modelled as multiconductor frequency dependent transmission lines [1], [2], [3].

The transmission line is based on Energinet.dk's "*Design Tower*" - a delta tower with two shield wires. The tower is modelled based on a paper by Hara and Yamamoto [4]. The tower is thus represented by a multiconductor model (Figure 1.b) where the surge impedances are determined based on the real tower structure geometry (Figure 1.a).
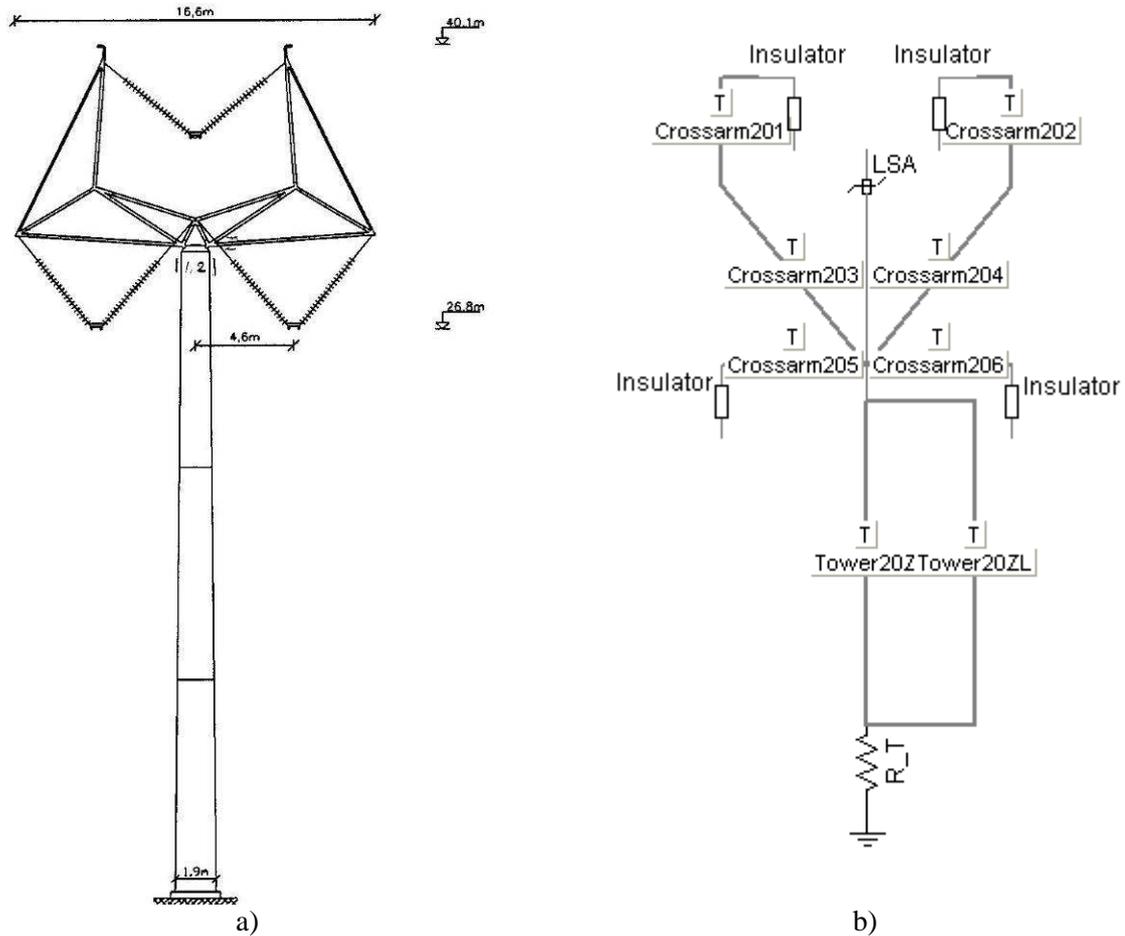
Figure 1 a) The *Design Tower* b) The *Design Tower* multiconductor model.

The footing impedance of the tower is presented by a nonlinear resistance R_T. The footing impedance model is given by the IEEE guideline for fast front transients [1] and Cigré guidelines [2], see equation (1).

$$R_T = \frac{R_0}{\sqrt{1 + \dfrac{I}{I_g}}}$$

(1)

Where R_0 is the tower footing impedance at low current and low frequency (Ω), I is the lightning current through the footing impedance (A) and I_g the limiting current to initiate sufficient soil ionization (A). I_g is determined from the soil resistivity ρ (Ωm), the soil ionization gradient E_0 (kV/m) and R_0 by equation (2).

$$I_g = \frac{E_0 \rho}{2\pi \cdot R_0{}^2}$$

(2)

3

Insulators are represented with the Leader Progression Model [1], [2] which divides the breakdown along the insulator into three stages. The three stages are corona inception, streamer propagation and leader propagation, so that the total time to breakdown t_c can be expressed as:

$$t_c = t_i + t_s + t_l \qquad (3)$$

The corona inception t_i is neglected in the equation above since corona inception is reached relatively fast. The streamer propagation time, t_s, is evaluated based on equation (4) and the streamer propagation time t_l is found from equation (5).

$$\frac{1}{t_s} = 1.25 \frac{E}{E_{50}} - 0.95 \; \left(\mu s^{-1} \right) \qquad (4)$$

Where E (kV/m) is the maximum gradient in the gap before breakdown and E_{50} (kV/m) the average gradient at critical flashover voltage.

$$\frac{dL}{dt} = K \cdot V(t) \left(\frac{V(t)}{g - L} - E_0 \right) \qquad (5)$$

Where $V(t)$ is the voltage across the air gap (kV), L is the leader length (m), g the gap length (m) and K and E_0 are insulator and voltage polarity dependent constants (see [1] for values). Breakdown will only take place if the leader crosses the gap across the insulator ($L \geq g$). The insulator model can be found in IEEE guidelines [1] and Cigré guidelines [2].

For towers where insulators are not represented by the leader progression model, a capacitance between the phase and tower of 4.75 pF will be used in accordance to [1] to represent the coupling between towers and phases.

Line surge arresters are modelled according to the IEEE Arrester Model [5]. The arrester is in this model represented by two nonlinear volt-current characteristics, A_0 and A_1, two L,R-filters and a capacitance C in parallel with A_0. The arrester model is depicted in Figure 2.
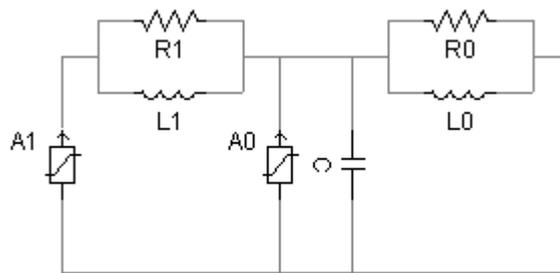

Figure 2 IEEE Arrester model [5].

The parameters of the model are determined based on information given in the arrester data sheet. These data are arrester height d in meters and number of parallel metal oxide columns n. Thus the following equations should be applied to determine L_0, L_1, R_0, R_1 and C.

$$L_0 = 0.2d/n\,[\mu H] \qquad\qquad L_1 = 15d/n\,[\mu H] \qquad\qquad (6)$$

$$R_0 = 100d/n\,[\Omega] \qquad\qquad R_1 = 65d/n\,[\Omega] \qquad\qquad (7)$$

$$C = 100n/d\,[pF] \qquad\qquad (8)$$

Some parameter adjustment was made to L_1 to get a good correspondence between the model and data from the arrester data sheet.

The phase voltage of the system should also be represented in model since the system voltage will give an offset of the lightning voltage surge in the system and thus in some case give higher voltages across arresters and insulators than else expected. The phase voltages are modelled with a three phase 400 kV voltage source of 50 Hz. In order to simulate a worst case situation, the phase angle is chosen so that the upper phase of the system is at maximum system potential when the lightning strikes. Only lightning strikes to the shield wires (where present) or the upper phase are considered.

The lightning stroke is represented by a current source connected to the strike point, e.g. a phase wire or a shield wire at the tower. The standard lightning waveform is described by a double exponential function with a 1.2 μs front time and a half time of 50 μs [7].

Line ends are in the model represented by two ways. One end of the model is terminated with a reflectionsless line thus ensuring that the reflections from the line ends will not distort the simulation. The other end of the line, where the system voltage is applied, is represented by a line of 75 km length. The length of 75 km ensures that the reflections from the end of this line will arrive much later than the lightning impulse as it crosses the line system.

RESULTS

The system is modelled in PSCAD 4.2. For the full model with shield wires represented, a lightning impulse of approximately 100 kA 1.2/50 μs can be applied to the shield wires of the system without flashover of the insulators on the tower subjected to the impulse. This is a reasonable representation of the expected behaviour. Lightning hitting other phases are not considered in this paper.

Figure 3 shows the maximum absolute surge voltage (line to ground) in the upper phase of the tower when the upper phase (or shield wire) is subjected to 100 kA lightning impulse. This is done in relation to the tower struck. The struck tower is marked 0.

The original system with shield wires and no arrester is denoted "2 Shield Wires - $n = 0$". The letter n is here used to give the ration between arresters and the number of towers.

$$n = \frac{\text{number of arrester}}{\text{number of towers}} \qquad\qquad (9)$$

The system is then simulated without shield wires and equipped with arrester. Only lightning hits to the top phase are considered. The arrester is modelled as mounted between the top of the tower and upper phase. The system is simulated without any protection ($n = 0$), with an arrester in every third

tower ($n = 1/3$), an arrester in every second tower ($n = 1/2$) and with an arrester in every tower ($n = 1$) connected to the upper phase.
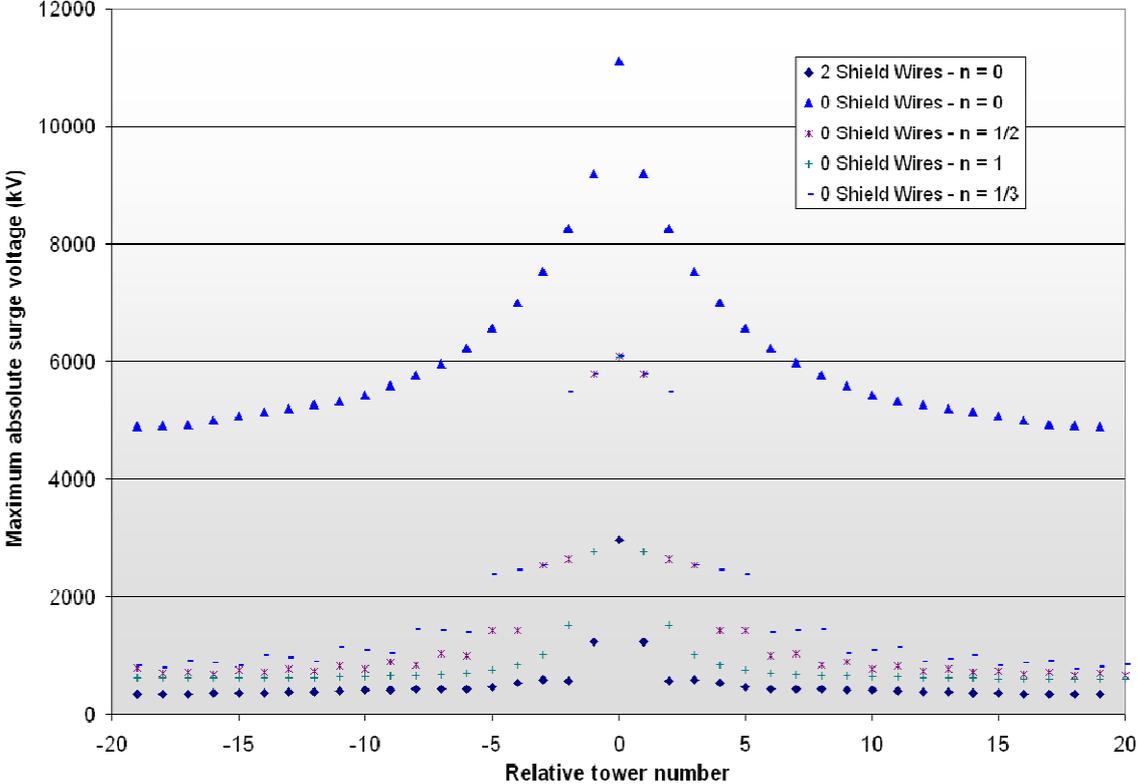

Figure 3 Maximum absolute surge voltage (line to ground) under 100 kA lightning impulse with different arrester configurations - Upper phase voltage.

When the line is unprotected the phase voltage is raised considerably along all towers. This also applies for the lower hanging phases. The result is that several phases of the system flash over.

Arresters are then inserted in the system - for every third, second and finally every tower. The results are given with the protected and unprotected line in Figure 3. From this it can be seen that equipping the line with arresters lowers the phase voltage - as expected.

It can also been seen from Figure 3 that as the number of arresters are increased along the line, the phase voltage decreased faster as lightning surge travels along the conductor. However the maximum absolute surge voltage of the system cannot be lowered more than to 6 MV independent upon the number of arrester mounted on the line. This however does not mean that the insulators at the struck tower flash over since the voltage given in Figure 3 in the line to ground voltage of the phases and not across the insulator.

Even though the struck tower does not flash over if equipped with an arrester, the rest of towers can still have flashovers along the insulators. If the neighbouring towers are not protected with surge arrester the voltage across the insulator can developed to such an extent that flashover will take place. In Table 1 it is given if flashover takes place along any insulator in the system in the different cases.

Case			
n	No. of shield wires	Flashover	Maximum dissipated energy
0	2	No	N/A
0	0	Yes	N/A
1/3	0	Yes	728 kJ
1/2	0	Yes	1824.1 kJ
1	0	No	1295.9 kJ

Table 1 Flasover and maximum dissipated energy in an arrester.

From the table it can be observed that only the system with arresters at every tower connected to the upper phases prevents flashover along the line. It can further be seen from Figure 3 that the $n = 1$ case has a close resemblance to the shield wire protected line about four towers away from the strike point. Thus a good protection of the line can be achieved when only considering lightning strikes to the upper phase.

The energy capability of the arrester used is 12 kJ/kV rated voltage. This corresponds to approximately 4000 kJ. Compared to the values in Table 1 there should not be a problem with overheating and thermal runaway of the arrester.

The line with $n = 1$ - arresters connected to the phase in every tower - can take up to a 125 kA 1.2/50 µs impulse without flashover. At this level the arrester at the struck tower dissipates approximately 1800 kJ with a maximum current of 2.0 kA through the arrester. However when the line is not equipped with shields wires lightning of higher impulses can also hit the line. The correct approach to determine the performance of the line would be a flashover rate study.

DISCUSSION

Using line surge arresters for lightning protection instead of shield wires must be considered carefully. As have been shown in the results section the maximum phase voltage in an arrester protected system can be reduced to the level close to that of a shield wire protected transmission systems. This consideration is though based upon that only the upper phase will get hit by lightning. In reality, as observations and the geometric line model will confirm [2], the outer phases of the delta configuration are also exposed to lightning hits.

Thus to fully consider the implications of implementing line surge arresters as the only mean of lightning protection a flashover rate study should be carried out. Thus hits to the lower phases would also be included in the study. Other measures of improving the reliability of an arrester protected system could also be considered. One of these measures could be increasing the clearances in the tower top geometry and thus increasing the insulation of the lines. Again this will result in a relatively larger tower top geometry which must be weighed against the reduction in number of conductors.

Removing shield wires from a 400 kV overhead lines system will result in a lessened visual impact of the lines. The line number in case of a single system 400 kV line is reduced from 5 to 3. This reduces the perceive space created between the phases. However the insertion of LSAs in tower tops will result in a denser impression of the towers. Making the tower top more "heavy" to look upon. The weight of the different measures must be considered against one another to find which solution is the least disturbing to the eye. Thus no clear indication on which solution is the better can be given here,

however it is the authors' opinion that reduction of the conductor number by removing the shield wires would be more aesthetically correct.

To fully evaluate the performance of line surge arrester protected system it is necessary to carry out a flashover rate study. Also multiple strokes to the line and the resulting thermal stress of the arresters due to the energy build up in the arrester should be further examined.

CONCLUSION

Lightning protection of 400 kV transmission lines without shield wires requires equipment of each tower with line surge arrester of the upper phases in order not to reduce the lightning protection performance of the system under direct stroke to the protected phase.

Lines equipped solely with arrester at every other (n = 1/2) or every third (n = 1/3) tower will experience flashover independent upon whether or not lightning hits at an arrester equipped tower or not. However the number of flashovers will not be the same along the line since the different arrester configuration will give different phase voltages along the line.

The use of line surge arrester does though present a way of reducing the visual disturbance caused by overhead transmissions lines. This is through reduction of the total number of conductors needed between towers.

Equipping a 400 kV transmission line with line surge arrester still needs to be further investigated through flashover studies and evaluation of the need maintenance of arresters.

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