Thermal Resistance of Optical Ground Wire to Direct Lightning Strike

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Abstract— **The need to speed up the construction of trunk digital communications cause the existing infrastructure to be used for communication lines. Often optical fibers are incorporated into a ground wire. From experience to date the necessity follows to perform a detailed analysis of thermal resistance of optical ground wire to a direct lightning strike.**

The paper describes the method and exhibits the results of simulation of transient electromagnetic and temperature field in optical ground wire. The method makes possible to take into account actual cable geometry, physical properties of materials, skin and proximity effects. The selection of idealized lightning current pulse has been justified for thermal simulation.

I. PROBLEM OF THERMAL CAPABILITY OF OPTICAL GROUND WIRE

When using the optical ground wire with incorporated fibre optical unit the problem of thermal capability arises in a new way. The primary function of a ground wire is to transmit the short-circuit current and currents induced by lightning overvoltage. The thermal capability of OPGW shall be calculated in a way to ensure not only the residual mechanical strength of a wire as a whole and of its separate conductors but to effectively remove heat from an optical unit.

The design rules of fiber-optic installation on overhead power lines [1] require that the analysis of thermal capability of optical ground wire has been done for the following conditions:

- short-circuit current effect;
- induced over-voltage effect;
- direct lightning strike effect.

This paper deals with the analysis of optical ground wire thermal capability at direct lightning strike, though the proposed procedure may also be applied to other conditions.

The problem of OPGW thermal resistance calculation contains the following stages:

- Selection of the shape and parameters of modelling current pulse which simulates a direct lightning strike onto a ground wire;
- Simulation of transient magnetic field induced by current pulse. The simulation gives distribution of current density in each individual wire as a function of time. The analysis should take into consideration the magnetic saturation of steel wires, skin and proximity effects.
- Simulation of transient temperature field using as a heat source Joule's losses generated by transient current density found at previous stage.

A. *Problem complexity and calculation method*

A physical pattern of studied phenomenon is relatively complicated for simulation for the following reasons:

- There is a need to solve a multiphysics problem dealing with data exchange between electromagnetic and thermal problems. At least, it shall be necessary to use an estimated Joule's loss density as a thermal source. For a more advanced study it should be advisable to transmit the data on temperature field back to electromagnetic problem so as to take account of temperature dependency of material properties.
- The skin effect and proximity effect under impulse loading should be considered.
- A magnetic saturation of steel conductors makes its contribution to the solution of a problem;
- As it will be shown below, to simulate a stranded ground wire structure, it shall be necessary to simulate electromagnetic field together with connected electric circuit equations for correct definition of currents in separate conductors;
- Because the analysis contains multiple stages it shall be useful to script repetitive operation sequence with the possibility to store and retrieve the input data and results.

The authors know only one paper [2] where current distribution is analytically calculated using simplified problem geometry and linear magnetic materials. A numerical simulation of lightning strike current distribution using finite-difference method has been shown in paper [3] where a simplified one-dimensional geometry of three coaxial cylinders was used. The papers of the same authors where a more realistic geometry of a wire has been considered required the application of finite element method [4], [5]]. Here, the electromagnetic field was calculated in frequency domain which is justified for short-circuit current analysis but is not applicable for calculation of a pulse at lightning strike. Besides, the analysis of AC current magnetic field did not allow considering steel saturation.

The task complexity requires using advance FEA software. We use the QuickField by Tera Analysis [9]. The current density distribution computed with skin and proximity effects taken into consideration shall be transmitted to a coupled problem of transient temperature field analysis. The 2D transient magnetic analysis is performed taking into account of a coupled electric circuit with lumped elements.

B. Current pulse waveform at lightning strike

The physics of lightning strike is not completely studied; its parameters are of stochastic nature. Nevertheless, for the goals of testing and computer simulation it shall be necessary to know the pulse waveform. This matter is investigated in multiple papers. The simulation goals determine the selection of convenient mathematic formulation.

Most often the standard lightning pulse of 1.2/50 µs is considered, that is the sum of two exponentials functions with different time constants.

$$I = I_0\left(e^{-t/\tau_1} - e^{t/\tau_2}\right) \quad (1)$$

This pulse is universally used for testing electric strength and electromagnetic compatibility. However, for current test pulse corresponding to the worst case there are other well-grounded alternatives.

The detailed studies of current pulse parameters under worst-case lightning strike have been performed in aerospace industry in the context of several accidents with civil and military aircrafts and space missiles. As a result, the Technical NASA Memorandum [6] was issued, the main clauses of which were introduced into SEA International Recommendations [7].

According to these Recommendations it is suggested to use for tests and calculations of thermal strength at lightning strike the pattern of idealized lightning pulse (Fig. 1) containing 4 elements: A, B, C and D (SAE ARP5412)

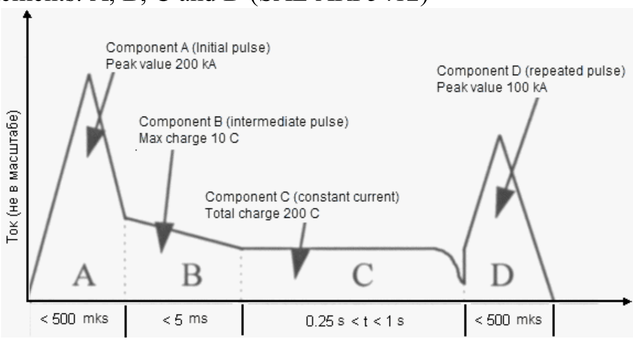

Fig.1 Idealized lightning pulse cited from [7]
Elements A, B, and D are described by double exponent, while the current of C element is considered as approximate constant.

For worst-case direct lightning strike it is recommended to take the following parameters of current pulse:

In [8] the advisability of using 4-element model pulse for calculation and test of optical ground wire has been justified. In the same place an insufficient applicability of optical ground wire test methods designed for standard ground wires has been pointed out.

C. Electromagnetic field simulation

The goal of simulation is obtaining the current density distribution over the cable cross-section as a function of time. Design data are: cable geometry, material properties (conductance and magnetic conductivity as a function of magnetic field) and prescribed current pulse waveform.

A simplified cable cross-section is one of calculation conditions. At this stage it is supposed that the magnetic field does not change along the cable length, i.e. two-dimensional approach (plane-parallel) has been applied.

As the process of lightning strike to a wire is not sufficiently studied and its parameters are known only in the most general terms it shall be necessary to make model assumptions about the current distribution. To begin with we shall suppose that all current of lightning channel passed into a ground wire and was distributed in some way over its cross-section. At that the following cases are to be identified for analysis:

1. The current is distributed over the whole cable cross-section (the exact current density distribution, essentially non-uniform, is subject of calculation);
2. A given current is distributed only over cross-section of one wire while other wires connected in parallel with the first one perform the role of a damper;
3. The current was distributed over several (two, three) adjacent wires, while other wires carry a back current performing the role of a damper.

It seems that an actual state of things is somewhere between the indicated limit cases.

The simplest optical ground wire cross-section with one central optical unit and six steel conductors wrapped in one layer has been selected for calculations. It must be noted that the above method may be applied for more complicated cross-sections, including aluminum clad steel wires, wires with shaped cores etc.

1) Lightning current is distributed over the whole cross section of a wire

Let us suppose that the current pulse described above is distributed over the whole cross-section of a wire.

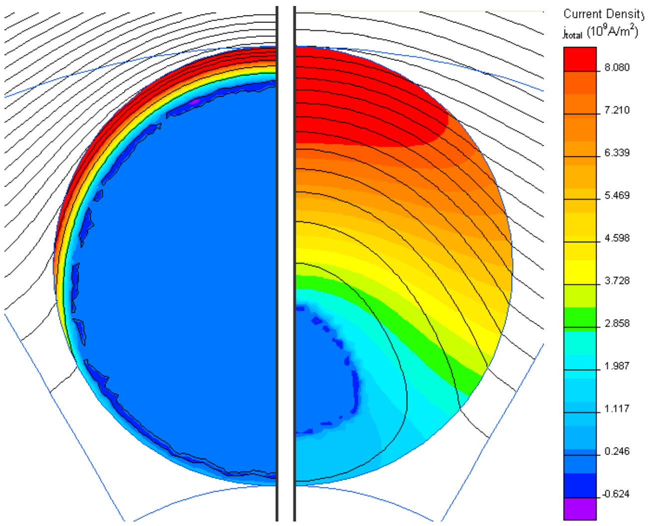

Fig. 2 Pattern of magnetic field and current density at the initial stage of a pulse (at the top) and in the region of maximum current (at the bottom)

The field source is a given in form of known total current as a function of time. The matter of simulation is a detailed distribution of current density at each moment of time. Conductors are made of steel, the relationship B (H) is given by B-H curve.

The pattern of magnetic field and the current density distribution over the cross-section is shown on Fig. 2.One may see that the process of gradual field penetration into a conductor is definitely seen starting with its outer edge. A non-uniform field distribution is conditioned by the proximity effect of neighbor conductors which are not included into the model itself but are present therein due to boundary conditions of the symmetry.

2) Lightning current is concentrated in one conductor

Now let us consider another extreme assumption: during first moments after lightning strike the current is distributed exclusively in one of wire conductors marked by red color.

On Fig. 3 a geometric model and a finite element mesh are shown for this case (on the right side).

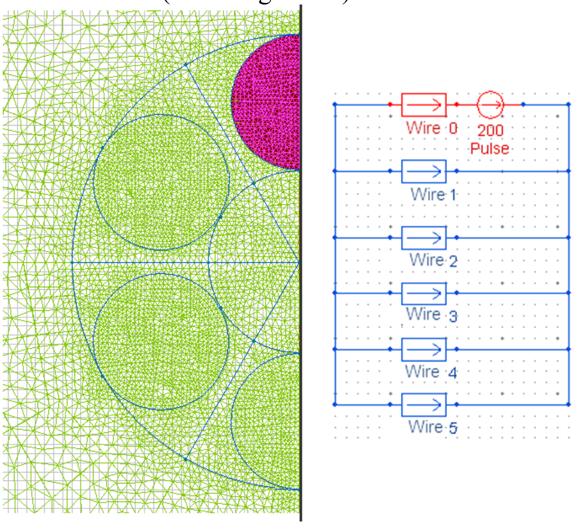

Fig. 3 Left side:the FEM model assuming lightning current is concentrated in one conductor.
Right side: The electric circuit coupled to the FEM model: one conductor carries current, other conductors form a damping circuit.

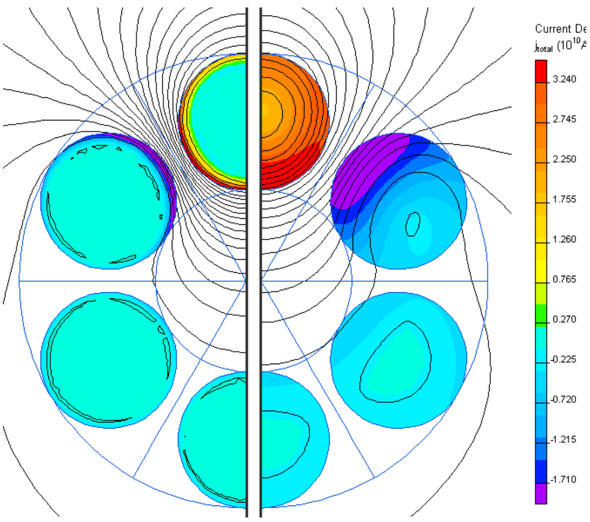

Fig. 5 Current density distribution concentrated in two and three neighbour conductors

Other wire conductors are connected in parallel with a conductor at which the lightning strike fell. All other perform the role of back wires. To consider the action of other wire conductors it is necessary to interconnect conductors of a model into electric circuit, as it is shown on Fig. 3 (left side).

The field pattern (Fig. 4) for this case as on Fig. 3 is given for two distinctive moments: at the initial stage of a pulse (at the left side) and at the moment close to the maximum current (at the right side):

3) Lightning current is concentrated in a part of conductors

Few intermediate cases remain to be considered when the lightning current at initial moment is concentrated in some but not in all wires. In this case the connection diagram is almost the same as presented on Fig. 3 while the current source "Pulse" in connected in series with some (two, three) conductors connected in parallel.

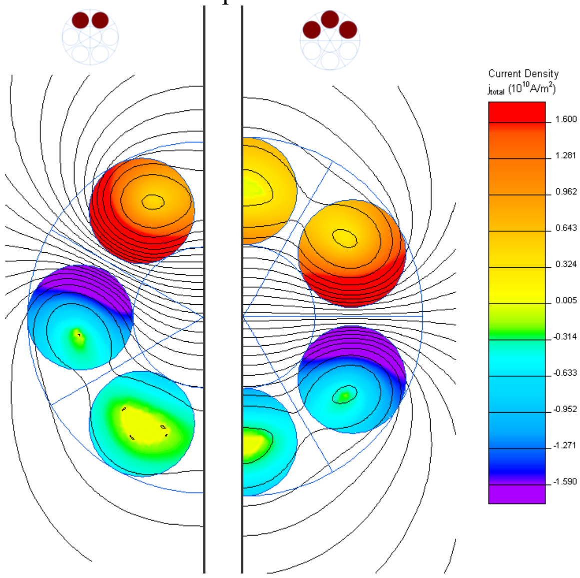

Fig. 5 Current density distribution concentrated in two and three neighbour conductors

D. Temperature field calculation

To simulate the temperature field induced by current passing through ground wire conductors the transient heat transfer formulation of QuickField is to be used, coupled to respective electromagnetic problem. The coupled transient electromagnetic and heat transfer problems share the same finite-element mesh. The distribution of Joule's losses calculated for each stage of electromagnetic process serves as the source of heat transfer problem at a given moment of time.

Because the time constant of electromagnetic process is considerably less than that one of thermal process, it shall be necessary after electromagnetic attenuation to continue simulation of temperature field once upon current pulse (thermal source) termination so as to simulate the process of temperature equalization and subsequent cooling. At this stage of calculation the greater time step may be taken.

On Fig. 6 there are shown temperature-time dependence plots for two typical points: at the proximity of wire periphery (red curve), on the surface of optical unit (green curve) and an average temperature of the most heated wire (blue curve). The calculations have been made for a standard lightning pulse

(1.2/50 µs) and phase A of SAE pulse (3.5/70 µs). Pulse peaks are taken equal to 200 kA according to SAE recommendations.

Legend to the figure 6:

Maximal Temperature
Temperature on the optical module surface
Average wire temperature

Continuous line: pulse SAE 3.5/70 µs
Dotted line: standard pulse 1.2/50 µs

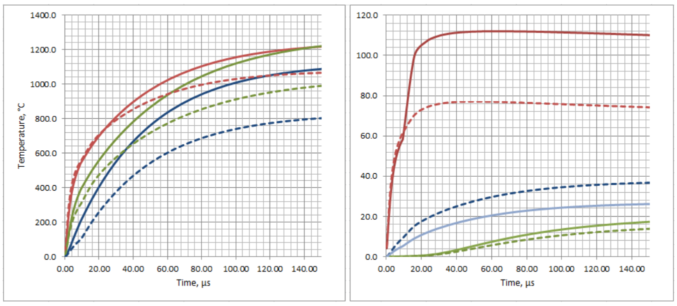

Fig. 6a Thermal state of the most heated wire:
Lightning current concentrated in one single conductor (left side), lightning current in all six wires (right side)

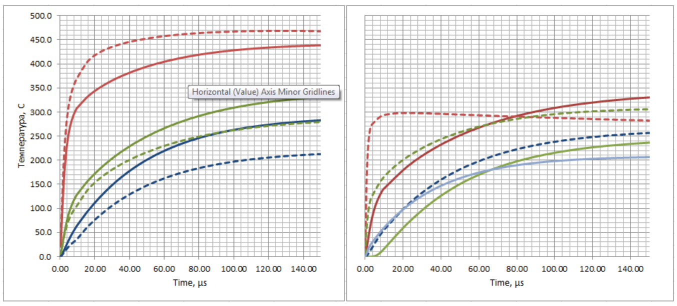

Fig. 6b Thermal state of the most heated wire:
lightning current in two neighbour wires (left side), and lightning current in three neighbour wires (right side)

Studying the plots one may say that the difference between current pulses does not significantly modify the pattern of thermal state. SAE pulse has a longer leading edge that contributes to reduce eddy currents and heating at the initial stage of a pulse but the latter has a longer droop that increases the final temperature.

The adopted hypothesis on lightning current distribution over wire conductors has a decisive influence on thermal state of a wire. Nevertheless, one may conclude that for the most probable cases (lightning strike affecting 1-2 conductors), the thermal resistance of a cable of given construction is not sufficient.

CONCLUSIONS

1. The proposed field method of studying electromagnetic and temperature states of a wire at direct lightning strike allows us to consider essential peculiarities of physical process: real current pulse shape, proximity effect, skin effect, steel wire saturation, real geometry and physical properties of conductors.
2. The design data for calculations is the current pulse shape at direct lightning strike. It is probable that the selection of convenient shape of a pulse may be done on the basis of static analysis of experimental information. The comparison of standard pulse of 1.2/50 µs and of 3.5/70 µs pulse recommended by SAE has been made in this paper. It was shown that the thermal state of conductors is affected both by pulse rate of rise and pulse length, while this influence is different for various hypotheses on current distribution over conductors. In total the both pulse waveforms are acceptable for analysis.
3. A numerical simulation shows that the studied cable of simple construction with one optical unit and six wires does not withstand a direct lightning strike of maximum strength.

DISCUSSION

In order to properly set up a problem it shall be necessary to make assumptions about the nature of current distribution over different conductors of a wire at the initial pulse stage due to a direct lightning strike on a wire. These assumptions are arbitrary. It is quite difficult to find essential grounds so as to prefer one or another assumption because of atmospheric events being of random nature.

So, the real value of a proposed procedure consists, to our opinion, in giving an objective comparative assessment of thermal resistance of different constructions of optical ground wire. This problem may be exhaustingly resolved. At the same time, to predict a real thermal process for a given wire proves not to be a simple task.

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