EVALUATION OF LIGHTNING PERFORMANCE OF A NEW 420 kV LINE AND AN EXISTING 300 kV PARALLEL CIRCUIT IN A MOUNTAINOUS AREA

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Abstract - **The Norwegian Power Grid Company is evaluating different alternative line routings for extension of the national transmission system in the southern part of the country. Two alternatives have been considered with respect to lightning performance. One of these alternatives is a parallel circuit 300 kV line where a DC line and possibly a 420 kV AC line is to be built in the same right-of-way. The other alternative is an eastern route for a new 420 kV line. The study shows that the western alternative routing is approx. 70% more exposed to lightning outages than the eastern alternative.**

The statistics of line outages due to lightning show that the existing parallel circuit in the western route has a considerable higher outage rate than other comparable 300 kV lines in Norway.

Keywords:- Outage rate, Lightning flash density, EMTP, Line routing, Grounding conditions.

I. INTRODUCTION

Part II in this paper is based on a previous work with line route studies [11]. Part III is an extension of [11] with a more detailed study of the lightning performance of a similar line.

The lightning densities in the two alternative right-of-ways have been calculated from registrations by the Norwegian lightning location system for the period 1981 - 95. These data have been used as a basis for calculation of the lightning outages. The following parameters related to line outages have been looked into:

- Evaluation of grounding conditions for the existing parallel circuit in the western right-of-way.
- Evaluation of terrain factors and exposure to lightning for the parallel circuit.
- Calculation of expected outage rate for the parallel circuit. TransiNor's own program TN-Multi is used for this purpose.
- Comparison of outages for the parallel circuit with a similar single circuit 300 kV line in a different part of Norway. The other line is in an area with higher lightning flash density. However it has better natural shielding in flat terrain and better grounding conditions than the parallel circuit.

II. LINE ROUTING

A detailed study of the lightning activities for the period 1981-94 for the two different line route alternatives is carried out. The following parameters related to lightning occurrence and mapping are important:

- The lightning activity in the areas with respect to lightning flash density and lightning flash intensity, i.e. per month, per day and per hour.
- Movement of thunderstorms in the two alternative areas.
- Correlation between the reported disturbances due to lightning in the power system and the lightning activity.

Based on this information, the two line route alternatives are compared with respect to the risk for lightning outages. This comparison has to take into account:

- Lightning flash density
- Earthing conditions
- Geographic/terrain conditions.

Figure 1 shows a map of Scandinavia where the area of the study is marked. The western alternative (1) from Kvilldal to Feda is 154 km long. The eastern alternative (2) from Holen to Kristiansand is 140 km (Fig. 2).

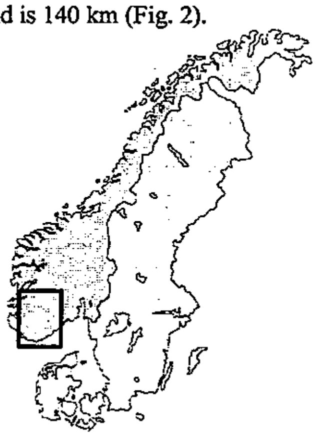

Figure 1. Map of Scandinavia. The area of study for alternative routes and double circuit is marked.

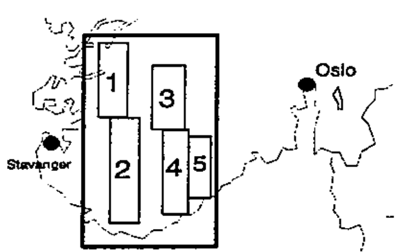

Figure 2. Map of the two alternative routes with the five lightning registration areas. The parallel circuit line is located in the southern 42 km of area 2.

II.1 Comparison of line outages and lightning activity.

In the western alternative (1 and 2) there already exist a 300 kV line, and part of the line is a parallel circuit line (from Tonstad to Feda, 42 km). For the eastern alternative there is a double circuit of 132 kV along part of the length. For both these lines statistics for outages and disturbances are available in [1].

In the period 1983 - 93 a number of 48 disturbances due to lightning are reported for the 132 kV line in the eastern route. While these disturbances occur there are registered 16 lightning strokes in the right of way and 10 strokes in the vicinity. Further it is registered with small time deviations (2 - 13 min), five strokes in the right of way and three in the vicinity. This study show that in about 70% of the registered disturbances there is lightning activity at the same time in the area.

For the western line routing only a 45 km part of the 300 kV line is part of the study. This is a double circuit line with separate towers. For this part of the line a total number of nine outages due to lightning are reported for the period 1983 - 1993. These outages are also compared with data from the lightning location system, and in seven (77%) of the disturbance cases, it has been lightning in or along the right of way. These comparisons show a good correlation between reported line disturbances due to lightning in the actual areas and detected lightning activity simultaneously.

The study also shows a high number of outages due to lightning in both areas. This is of course one main reason for conducting this study to compare the alternatives with respect to lightning activities and expected number of line outages.

II.2 Study of thunderstorm activity

The thunderstorm activity in the area is studied for a 14-year period, and line routes are split into five smaller areas. The western alternative consists of area 1 and 2, and the eastern of 3, 4 and 5. Data from the lightning location system shows that the activity increases as the observations move from west to east and from north to south in the area. This is valid for both lighting density, lightning intensity and the number of thunderstorms.

II.3 Data from the location system.

Table 1 shows the lightning flash density N_g for all the five areas. The data from the location system is corrected since it is presumed that the system detects only approx. 50% of the total numbers of strokes

Table 1 Lightning flash density, N_g, (number of strokes per year and km^2) in each of the five areas. (See also fig. 4)

Mean N_g for:	Area 1	Area 2	Area 3	Area 4	Area 5
Whole area:	0.026	0.04	0.023	0.10	0.15
Southern part	0.024	0.05	0.019	0.14	0.17
Northern part	0.028	0.03	0.027	0.06	0.13
Max value for area (10*10)	0.078	0.14	0.066	0.26	0.28

Each of the five areas in the study is split into 100 small parts and analysed separately, and the maximum value for each area is taken from the maximum of registrations in one of 100 (10* 10) part-areas. The maximum value for part areas for each of the five line route areas is given in the last row in table 1. In figure 3 the mean and the maximum lightning flash density per km^2 and year are shown as given in table 1.

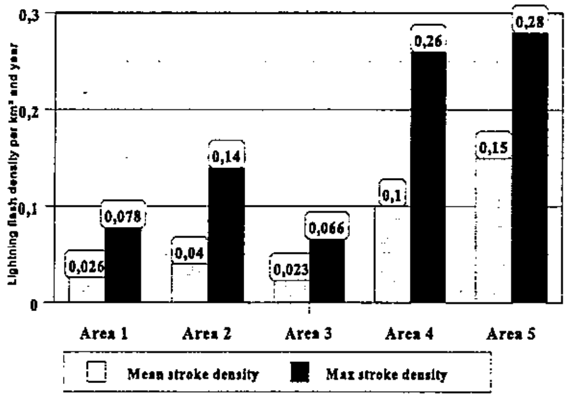

Figure 3. Maximum and mean lightning flash-density, N_g. The figures are corrected and it is presumed that the location system detects only approx. 50% of the total number of strokes.

Figure 4 shows the seasonal variations of the lightning activity. All five areas have the highest lightning activity during the summer. Seen from the data, it is not possible to decide whether one area is more exposed to lightning in one season than any of the other areas.

Figure 5 shows the total lightning activity in the five areas. From figures 3 and 5 it can be estimated that the lightning flash density is approximately two and three times higher in area 4 and 5 than in area 2. The density in area 1 and 3 is of similar size and approx. 0.5 of the density in area 2. According to figure 7, the number of days where it is registered one or more lightning strokes in area 4 and 5 is 1.3 and 2.0 times higher than for area 2.

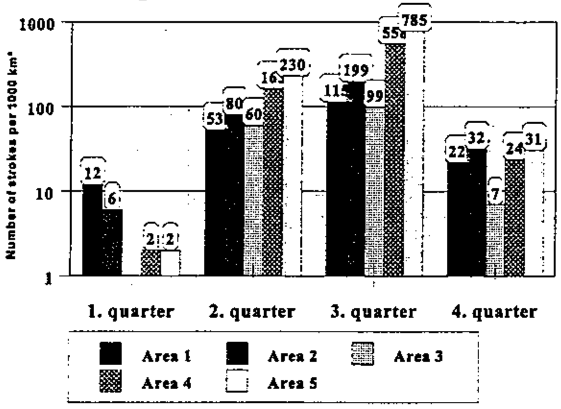

Figure 4. Seasonal variations as number of strokes per 1000 km^2 in the period 1981 - 1994. The Y - axsis is logarithmic, areas are numbered from left to right in the five columns.

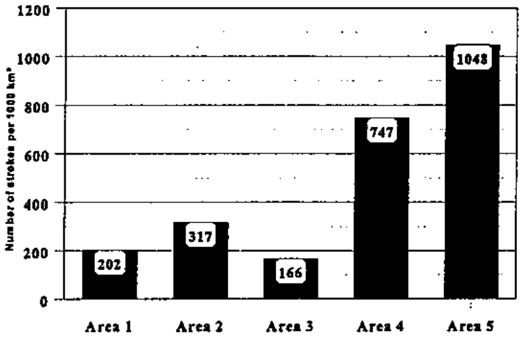

Figure 5. Total number of lightning strokes in the five areas.

II.4 Tracking of thunderstorms.

It is also of interest to know whether the same thunderstorm could cause outages for both the western and eastern alternative. This study shows that the predominant direction of the thunderstorm is from south to north, and from west and southwest to east and northeast. No storms were detected moving from north to south. Approximately 40 - 50% of the thunderstorms caused lightning strokes for both the eastern and western alternative.

The front of the thunderstorm moved at a speed of approx. 20 - 30 km per hour that gives a time difference of approx. 1.5 - 2 hours between the western and the eastern line route alternatives.

II.5 A complete evaluation of the two line route alternatives.

The lightning activity is as mentioned not the only parameter needed to make a comparison of the two alternatives. In the complete study, the two alternatives were compared with respect to the following factors:

I) Local lightning flash density and line length
II) Terrain factors, and data about the earthing conditions (surge impedance and resistance).
III) Calculation of expected outages due to lightning based on line routing in flat terrain and in the "real" terrain.

These three factors are ranked according to the required information. Factor III) requires very detailed information and good models to make a good estimate, especially when considering the exposure in the terrain.

II.5.1 Exposure based on lightning flash density and line length.

Data shown in Table 1 regarding the lightning flash density and the line lengths in each area were used to calculate a simple criterion with respect to exposure to lightning. Using this technique, it was shown that the eastern alternative was about 70% more exposed to lightning than the western alternative.

II.5.2 Exposure based on terrain and earthing conditions.

The two alternatives were also compared with respect to terrain and earthing conditions. This was based on data from a map in the ratio 1:50000 and a video from the actual right-of-ways. The terrain was split into three categories, and the result is presented in Fig.6.

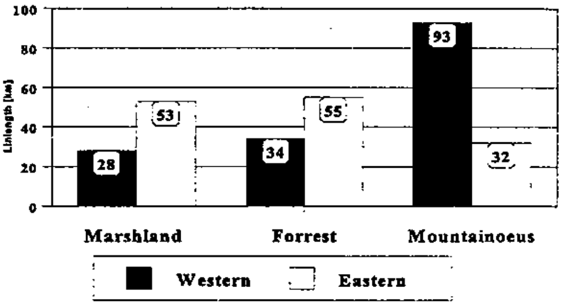

Figure 6. Terrain variations along the two route alternatives.

This part of the study led to the following assumptions:

- The new line in the eastern route will probably have remarkable better earthing conditions than the western alternative
- The western right-of-way is much more exposed to direct strokes due to routing in the terrain.

II.5.3 Calculated outages due to lightning.

The most accurate comparison for the two alternatives is to calculate the expected number of line outages due to lightning. This calculation has to take into account the local lightning flash density, tower foot grounding (surge impedance and resistance) and the line exposure to lightning in the terrain.

The calculations were done by using the program TN-Multi [2,3,4], developed at EFI and further developed by TransiNor. TN-Multi uses the well known Monte Carlo technique. The calculations were also done when taking the terrain factor into account as discussed by Dellera and Garbagnati and others [5,6,7,8,9].

$$F_{Total} = \frac{\Sigma F_N \cdot L_N}{\Sigma L_N} \qquad 1) \qquad\qquad F_N = N_{GA} \cdot F_{LN} \cdot T_{Factor} \qquad 2)$$

F_{total}	Outage rate for the whole line [outages pr. year]
F_N	Outage rate for section N [outage per 100 km line and year]
L_N	length of section N [km]
N_{GA}	relative local lightning stroke density
F_{LN}	outage rate per 100 km and year for a given section for the actual tower footing earthing for Ng = 1 stroke per km^2 and year
T_{Factor}	Terrain factor

This total study with results from **2)** in **1)** gives the following results:

1) Western alternative:	0.76 outages per year, i.e. 0.49 outages per 100 km per year
2) Eastern alternative:	0.44 outages per year, i.e. 0.31 outages per 100 km and year

This is the quite opposite conclusion compared with the case when only taking the local lightning flash density and line length in each local area into account.

These results show that for the actual case, the terrain and line exposure to direct lightning strokes are the predominant factors regarding the expected number of outages due to lightning. These factors also favourites the eastern alternative. This route seems to be less exposed to flashovers although this area has the highest lightning flash density.

The calculation of number of outages requires both accurate data and calculation models that take into account the line routing in the terrain. This matter is very important due to the large terrain influence of the results.

III. OUTAGE OF 300 kV DOUBLE CIRCUIT

The outage rate of the parallel circuit of 300 kV in the western routing shows considerably higher outage rate than the calculated outage (nine outages in ten years). To validate the calculation model a similar study was carried out for a 300 kV line in another part of the country. In addition it was also decided to carry out a line inspection of a part of the right-of-way for the parallel circuit.

III.1 Analysis of a similar 300 kV line

The line, with which the double circuit is to be compared, is the 48 km long 300 kV line from Frogner to Minne north of Oslo. The terrain in the area is flat. 35% of the route is in flat forest land and 34% in agriculture land. The measured tower footing resistances have an average value of 10.5 Ω and the values are as shown in fig. 7.

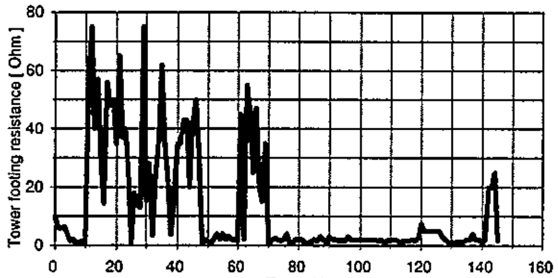

Figure 7. Tower footing resistance of compared 300 kV line.

Data from the lightning location system shows a lightning density of 0.107 strokes per km^2 and year for this line. The system also show that the area has an average of 12.2 thunderstorm days per year. This is a considerable higher lighting flash density than for the parallel circuit.

The outage rate for this line has been calculated by using the TN-Multi program. The expected outage rate is one failure once per 28 years. This give an outage rate is 0.0735 per 100 km line per year. Detailed model of the tower footing earthing and the exact geometric shape of the line was included in the calculations. This 300 kV line has been in service since 1983, and four line outages are registered. None of these are due to lightning. The four faults give an outage rate of 0.64 per100 km per year.

Compared with the observed outage rate the calculation model gives reasonable results. The conclusion of these calculations is that the line is well protected against direct lightning strokes and outages due to lightning.

III.2 Line inspection

Intention with the inspection was to find in more detail the reason for the high outage rate, and secondly to see if improvement was possible. This inspection confirmed two main reasons for the high outage rate:

III.2.1 Terrain factors

The parallel circuit is located on top of the mountainous terrain between two valleys. This line is acting as an "antenna" for lightning strokes. Fig. 8 show the line profile from north to the south end, 121 spans of a total length 42.05 km. Besides this profile, the terrain is of similar type seen across the line route. High hills with valleys on each side. From tower 19 to 20 the line has a span of 1327 metres where the line cross a valley.

III.2.2 Tower footing resistance

The grounding conditions along the line are bad. It consists for more than half the length of bare rock with very little loose material on top. The soil is mostly a thin layer that gives poor grounding conditions. These conditions make it difficult to have good grounding systems both because of the difficulty to dig the wire down, but also because of the soil conditions. It was also revealed improper design of the earthing system with respect to impulse stresses. At many of the towers just one or two buried ground wires were used. All the parallel towers along the line are connected with one wire.

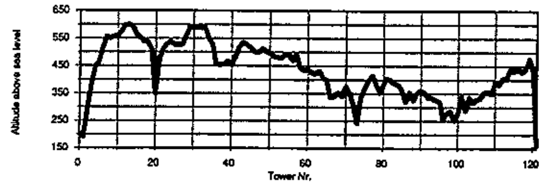

Figure 8. Line profile of 300 kV double circuit (tower footing). Height in metre above sea level.

These factors mentioned above give a very high resulting grounding resistance for the two lines as shown in figure 9a and b.

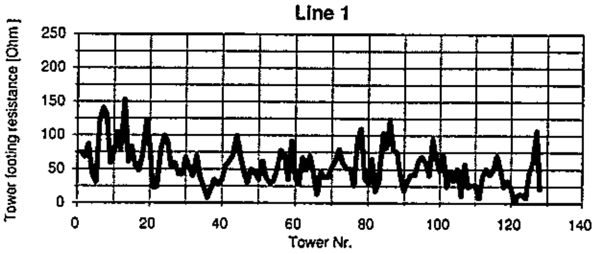

Figure 9 a) Tower footing resistance of line 1 of the 300 kV double circuit.

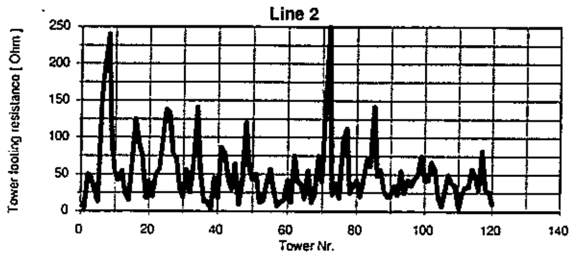

Figure 9 b) Tower footing resistance of line 2 of the 300 kV double circuit.

The inspection also identified a number of towers especially exposed to lightning. Totally a number of 35 - 40 towers were considered very exposed on top of hills and ridges of the route. These towers are highly exposed, and at the same time have bad earthing conditions. Tower 7 have only one earth wire between the parallel towers, i.e. a surge impedance of 120 Ω and tower earthing resistance of 141 Ω and 200 Ω respectively.

Methods to improve the performance some places along the line are limited. The inspection found spots of marsh and small ponds along the route, and these should be used as much as possible. The extension / size of the grounding system is however an economic question.

III.3 Grounding calculations using EMTP.

The line inspection identified that one main reason for the high outage rate was due to the design of the grounding system. Based on this fact, a study of ground systems was done with a transient model.

From the line inspection, the parallel towers at nr 7 were identified to have very high grounding resistance. This point was chosen as a point for further analysis of the grounding system. A line model for the towers 1 to 20 was set up in EMTP. The towers are assumed to have a surge impedance of 150 Ω. The grounding system is changed with respect of number of the buried ground wires (a number of counterpoise wires), length of the wires and the value of the tower footing resistance. Model of the transmission line is as eight coupled phases with a flashover criterion at each insulator set up in MODELS [10] with leader propagation as a mathematical basis. The main conclusions of this part of the study are:

- The number of buried ground wires has to be increased to a minimum of three to obtain low impulse response. This also reduces the number of double failures.
- Methods for lowering the tower footing resistance are needed for the most exposed towers. If not possible other means may be needed (line surge arresters).
- As short ground wires as possible is preferred. Short connections with high grounding resistance are of no help.
- The length of the ground wires is important, especially with lightning surges with high steepness (< 3 μs). With long front (> 4 μs) of the surge the length of the ground wires has no big influence. With high steepness the length of the wires should be as short as possible. In the studied areas, the currents usually have long front times, and a large part of the lightning strokes are during winter and these are mostly of positive polarity.

IV Conclusions

The lightning location system gives very useful information regarding the total lightning activity within a specific area, also within a right of way for transmission lines. The following conclusions are drawn from this study:

- Good correlation between observed line outages and data from the national location systems is achieved.
- A lightning location system can be used to analyse the movement of thunderstorms. Data from the areas in this study show that both right of ways are likely to be affected by the same thunderstorm.
- A lightning location system gives necessary statistical data that can be used for a complete analysis of line outages due to lightning.

However, care should be taken when doing such a study. In this specific case, evaluations of the two alternatives based only on the local lightning flash density and line length will give completely incorrect results since the terrain and earthing conditions are different.

A study of the western routing alternative, gives a much higher observed outage rate than the calculated. This is a parallel circuit, and to be able to evaluate the calculation model further, a similar 300 kV line was studied: The calculations for this line showed an outage rate of once per 28 years. The line has been in service for 13 years, and the line has not had any outages due to lightning during these years. This line has however much better grounding conditions and is routed in a flat terrain and is shielded by natura features in 35% of the line length.

The inspection of the parallel circuit showed a high exposure to lightning. Most of the routing is along the top of high mountains with lower terrain on both sides. The grounding conditions were also observed as bad, but with some possibilities for improvements. Modelling of the grounding system for one specific tower location showed that an increase of number of buried ground wires is necessary to lower the surge impedance. However, at the same time a reduction of the earthing resistance is necessary.

It is observed that the standard electro geometric models used for lightning performance studies is not valid for conditions as in the southern mountainous part of Norway. The strike mechanism for this specific parallel circuit seems to be of other characteristics than the established and well-used models. For more exact calculations strike models including terrain factors have to be used [9].

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