MTBF DUE TO LIGHTNING IN 400 kV SUBSTATIONS WITHOUT ARRESTERS

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Abstract.- In High Voltage Transmission Networks sometimes there are lines with insulation level substantially higher than the insulation level of the substations in both ends of the line.

There are two main reasons for this:

- **Usage of composite insulators because a section of the line is placed in a contaminated area.**
- **Line built to work at a certain voltage (p. e. 400 kV) but temporarily working at a lower voltage (p. e. 220 kV).**

The difference of insulation level between the line and the substation endangers the equipment in the substation, specially those located in the entrance of the line, in those cases where no surge arresters are installed.

It has been elaborated a procedure to determine the need of installing protective devices (old and new lines) or of changing any design parameter of the installations, (new lines) in order to achieve an acceptable Mean Time Between Failures (MTBF). In this procedure variables like: lightning density, tower configuration, insulation levels, ... are taken into account to calculate the critical distance (in the line) and the rate of failures.

To illustrate this procedure, it is shown an example based on a real case

Keywords: Insulation Coordination, Lightning, EMTP

1. INTRODUCTION

Polution has been and still is a main cause of tripout in lines placed in some specific areas of Spain, due to industrial as well as marine contamination. In order to lower down the tripout rate of these lines, special insulators (composite) and longer insulating chains have been used, obtaining also higher insulating levels.

In special cases where 400 kV is needed in the future, but at the moment only 220 kV substations are available, it can be a good choice to build up the line with 400 kV characteristics but working at 220 kV for the moment.

The cases explained above justify a line having higher insulation level than the substations in both-ends of the line. This means that lightning overvoltages generated in the line with values exceeding the substation's insulating level and under the line's insulating level can reach the substation (if they are close enough), and could damage the equipment in it.

To study in detail these situations, a procedure has been elaborated. This procedure calculates the number of lightning surges that reach the substation coming from the line, and the number of failures that these surges produce in the substation.

It has been considered that there are not surge arresters in the substation entrance as this is the case in most of the 400 kV substations in Spain.

2. STUDY METHODOLOGY

The aim of the study is to calculate the number of dangerous surges that arrive to a substation coming from a certain line. For this calculation three different aspects have to be considered:

- The number and magnitude of overvoltages originated in the line due to lightning.
- The attenuation of the overvoltages in the line before they reach the substation.
- The reduction of the surge with reflections from other lines, once it reaches the substation.

Overvoltages arriving to a substation due to lightning strokes may be originated by direct strokes or back flashovers.

Overvoltages originated in the line due to direct stroke (shielding failure) are calculated using the electrogeometrical model [1].

Overvoltages originated in the line due to back-flashover are calculated using two different methods:

- RAYO program.- Calculations have been made following the algorithm explained in [1], [6].
- Simulation.- The simulation program EMTP/ATP has been used for the calculations [4].

Before the overvoltage reaches the substation, its amplitude and front of wave are reduced by corona effect. This effect limits dangerous overvoltages to the substation to those originated in the closest part of the line, called influence zone.

Once the surge reaches the substation, reflections from other lines reduce the surge's amplitude.

2.1 Overvoltages rate and amplitude

Lightning overvoltages in the phase conductors are due to direct strokes or back flashover after a stroke to the shielding wires or line tower has occurred.

2.1.1 Direct stroke

The rate of failures due to direct stroke is calculated using the electrogeometric model.

In figure 1, it can be seen that for a certain lightning current there is a certain strike distance (s) that defines the uncovered area..

In this study there is not interest in the number of failures in the line but in the substation. Therefore it is necessary to take into account those strokes that generate overvoltages greater than the substation insulation level (I_1) and smaller than the line insulation level (I_2). So we use:

$$\text{Strokes} = N_R \cdot L \cdot \int_{I_1}^{I_2} X_s(I) \cdot p(I)\, dI$$

I_1 = Substation breakdown current
I_2 = Line breakdown current
N_R = Number of strokes per km^2 in the area
L = Length of considered line
$p(I)$ = Probability of a stroke of I amps
$X_s(I)$ = Wideness of the uncovered area for a stroke of current I

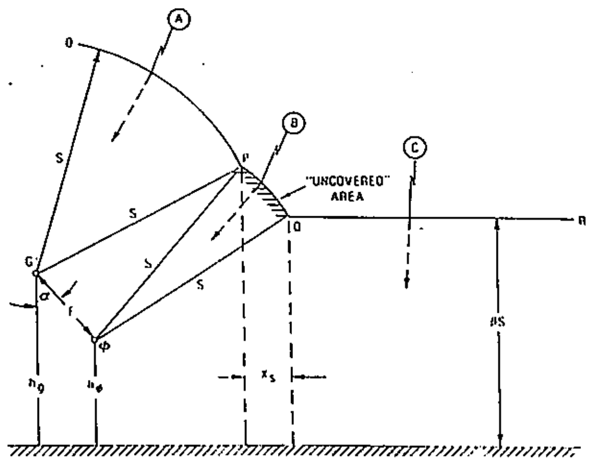

Figure 1

2.1.2 Back flashover

When a back flashover, in the lines insulators, takes place due to a high overvoltage in the shield wires, this surge enters the conductor and travels towards the substation. It is therefore necessary to calculate the number of back flashovers in the length of interest and the magnitude of the overvoltages.

The calculation of the number of back flashovers is done using two different methods: RAYO program [1] [6] and EMTP/ATP simulations. The magnitude of the overvoltages is either calculated with the EMTP/ATP simulation program or estimated from the line's BIL.

2.1.2.1 RAYO program

RAYO program [6] implements the algorithm explained in [1]. This algorithm is based on the reflection of the surges in the studied circuit. Using reflection and refraction rules, expressions can be obtained to calculate the overvoltage in each prominent point. In order to make it feasible several simplifications are done, being justify these simplifications with the sparsity of the data used (lightning data, flashover data, ...).

The method explained in [1] for calculating the number of back flashovers can be summarized in the following steps:

- Calculation of the voltage in each important point of the tower in the moment the highest amplitude of the stroke is reached (supposing a 1 kA stroke).

- Calculation of the voltage in the insulators, including the industrial power and the couplings, for each moment of the power cycle.
- Calculation, for each point of the power cycle, of the minimal current needed for flashover (critical stroke current).
- Add the probability that the critical stroke current is reached for each point of the power cycle.
- Multiply the result by the number of strikes per year in the area of study.

Finally, the number of back flashovers in the length of interest is obtained.

2.1.2.2 ATP/EMTP Simulations

The methodology of this part is to build an equivalent circuit of the physical arrangement of the substation and overhead line to simulate the lightning stroke and calculate the rate and amplitude of the overvoltages in the substation.

The equivalent circuit of the studied case is made taking into account the following elements:

- Tower: The tower is represented as a ground resistance and a constant impedance transmission line of 144 Ω, as result of calculation from its physical dimension. Two values of the ground resistance (5 and 10 Ω) have been choosen to be included in the equivalent circuit.
- Transmission Line: Each span of line has been represented by, JMARTI model in ATP, including frequency response of the line. Shield conductors are grounded in every tower.
- Substation: Every equipment inside substation has been modelled by its stray capacitance except surge arresters which are modelled as variable resistance with data from manufacturer.
- Network: The rest of the network is represented by a Thevenin equivalent with an ideal sinusoidal voltage source and an impedance calculated from the short circuit studies in the substation.
- Stroke: A ramp current source with 2/80μs characteristic and different amplitude values is used to model lightning stroke.
- Back flashover: A simple circuit breaker initially opened and closing by voltage level is considered to model flashover.

In the complete model, a lightning stroke affect a tower at the limit of the influence zone to substation. Different values are obtained as result of different instants of strike (over the source wave) and different phase flashover.

Every value of the stroke current has a probability to be produced, so with this value and the "influence zone" is possible to get the expected failure rate in the substation insulation.

2.2 Corona attenuation

Using the tower represented in figure 2 and the calculations developed in [3], the values shown in table 1 have been obtained [7]. With these values we can calculate the length of the influence zone, depending on the maximum overvoltage that can reach the substation and does not produce a flashover, and the expected overvoltage originated by the stroke in the line.

	Attenuated overvoltage			
Surge (kV)	1 km	3 km	5 km	7 km
1500	1418	1277	1172	1105
1800	1709	1577	1410	1279
2000	1900	1750	1581	1431
2300	2181	1974	1816	1510
2500	2375	2180	1979	1690

Table 1

2.3 Amplitude reduction due to reflections

When the lightning surge arrives to the point where other lines join, there is a reflection of a wave with an amplitude that depends on the number of lines, the characteristic impedances of the lines and the magnitude of the incident wave.

If the number of lines is **n**, and all the lines have the same characteristic impedance, the overvoltage coming into the substation can be calculated as:

$$U' = \frac{2}{n} U$$

2.4 Final procedure

To calculate the MTBF in the substation equipment we have to combine the three calculations explained above following these steps:

- Calculate the overvoltage that will produce an acceptable overvoltage in the substation after taking into account reflections. This acceptable value is the equipment's BIL divided by a security coefficient (1,1 can be a good value). So the overvoltage accepted in the substation is:

$$U = \frac{n}{2} \cdot \frac{BIL}{Cseg.}$$

- Calculate the length of line necessary for achieving enough attenuation due to corona that will reduce the overvoltage from the value in the line to the accepted value calculated in the previous step. Table 1 is used in this step. The value of the overvoltage in the line can be calculated with ATP/EMTP simulations or can be estimated from the line's BIL (using $U_{50\%}$ [5]). This value, calculated or estimated, is a conservative value.

- Finally using one the two proposed methods, the rate of faults in the influence zone is calculated. This rate is the rate of failures in the substations due to "one" line. All the lines must be taken into account.

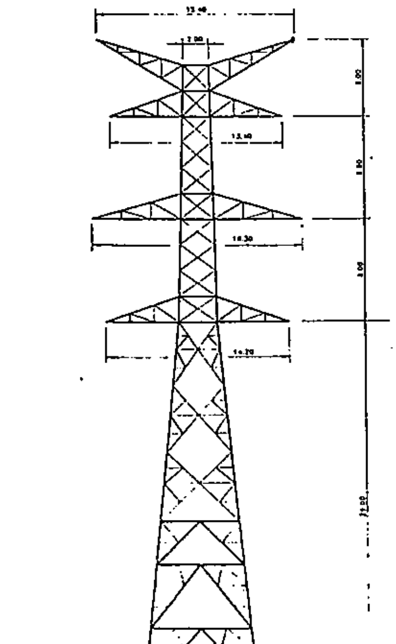

Figure 2

3. STUDY CASE

The methodology explained above is applied to a planned line in the South of Spain.

This case is made up of a 400 kV line and a 400 kV substation. The substation's BIL is 1550 kV and the line's $U_{50\%}$ is 2040 kV. The line is a double circuit line with only one circuit installed and two shielding wires on 51 meters high towers (figure 2). The substation follows a 1 1/2 circuit breaker arrangement, and has 2 overhead lines connected.

The study has been carried out for two different values of tower ground resistance: 5 and 10 Ω (lightning frequency value).

Using table 1 and for the case of study, a distance of 7 km has been considered as "influence zone" in the line. For this reason the failures in these 7 km are of interest.

Back flashover or direct strokes further than 7 km are not considered dangerous for substation equipment, because their amplitudes attenuate due to corona and reflections, and therefore they are withstand by the equipment.

3.1 Direct stroke

In the case of study, the two shielding wires reduce the number of direct strokes to a very small number compared to back-flashover failures rate.

For this reason these failures are neglected.

3.2 Back-flashover

Back-flashover failures in the 7 km of the line closer to the substation are the uniques that produce failures in the substation. Using the two methods explained above and for 5 Ω and 10 Ω of grounding resistance in the tower, the following results have been obtained:

R = 10 Ω

RAYO program	Icritical =119 ÷ 138 kV failures = 0,0320 failures/year MTBF= 31 years
EMTP/ATP	Icritical = 121 ÷ 135 kA failures = 0,0308 failures/year MTBF = 33 years

R = 5 Ω

RAYO program	Icritical = 159 ÷ 184 kA failures = 0,0152 failures/year MTBF = 66 years
EMTP/ATP	Icritical = 138 ÷ 170 kV failures = 0,0191 failures/year MTBF = 52 years

The two different values of the critical current correspond to the minimum and maximum value of lightning current that cause flashover.

International committees, CEI[5] and CIGRE SC33[2] recommend MTBF values between 250 and 1000 years.

Results indicate that MTBF is very sensible to tower ground resistance, a reduction to 5 Ω allows 50% reduction on failure rates. Due to the difficulties (and sometimes impossibility) of reducing the grounding value, other solutions can be used, as installing surges arresters.

4. CONCLUSIONS

Influence zone, lightning density, tower configuration, grounding resistance value and insulation levels are the main parameters that should be taken into account when calculating the MTBF.

For calculating the tripout rate of the line, two methods have been applied. Both methods show similar results, being easier and faster to use the RAYO program method, following [1].

A procedure has been developed and showed for calculating failures in a substation due to lightning in the incoming lines, and to evaluate the necessity of using further protection (surge arresters, better grounding, ...), achieving an adequated insulation coordination between the lines and the substation.

This procedure considers corona and wave reflections as the main attenuating effects.

5. REFERENCES

[1] "Lightning Performance of Transmission Lines", chapter 12 of "Transmission Line Reference Book, 345 kV Above". EPRI 1982.

[2] "Risk of Failures Analysis". P. Jostein Huse. Technical Sessions. UNESA.

[3] "Distortion and Attenuation of Travelling Waves causes by Transient Corona". Study Committee 33. CIGRE 1989.

[4] "Alternative Transients Program Rule Book". Leuven EMTP Center. Belgium.

[5] "Insulation Coordination, Application Guide", IEC-71-2, 1996. Final draft.

[6] "Evaluation of the risk of failures due to lightning in HV overhead lines". D. Alvira, F. Soto, J. L. Sancha, (in Spanish), V International Electrical Insulation Sessions, Bilbao (Spain), October 1995.

[7] "Corona Modelling for Attenuation and Distortion of Lightning Surges in Overhead Transmission Lines". J. Ciudad, D. Alvira, F. Soto. EEUG Meeting. Budapest. November 1996.