

# HOW TO SPECIFY THE OPTIMUM NON-GAPPED LINE ARRESTERS (NGLA)

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Bengt Johnnerfelt, Surge Arrester Senior Manager, TE Connectivity  
[bengt.johnnerfelt@te.com](mailto:bengt.johnnerfelt@te.com)

Jorge Luiz De Franco, Surge Arrester Product Manager, TE Connectivity  
[jorge.franco@te.com](mailto:jorge.franco@te.com)

First published at the INMR CONGRESS 2015

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## Abstract

What are the necessary system parameters needed to install line surge arresters successfully, not only tower and line insulator data but also other important parameters are presented. The NGLA is then selected from this data and it's coordinated with the disconnecter. The data and simulation software allows you to optimise the installation in order to reduce the line tripping.

## Introduction

Lightning is still the major cause of line tripping disturbances around the world. There are different solutions to reduce this, improving the tower footing impulse resistance, change to underground cable systems or installing line surge arresters, LSA. Installation of LSA's along a transmission line is often the most economic and easiest solution, as underground cable systems are every expensive and reducing the tower footing resistance is also expensive especially in mountainous regions.

## Gathering data

In order to be able to optimise the installation of LSA, certain data is needed:

1. Tower information:
  - height of tower and configuration of cross arms
  - location and length of phase insulators
  - maximum phase conductor movements during maximum designed wind speed
  - location of mechanical dampers
  - tower footing impulse resistance along the line
  - shield wire(s) location if used
2. Line insulator information:
  - CFO/BIL
3. System parameters:
  - reclosing times and scheme
  - short-circuit current
  - data for substation arresters
  - decisive TOV requirements
  - targeted reduction in tripping per year of the system
  - maximum switching voltage along the line for switching protection
4. Environmental data:
  - ground flash density and/or number of thunder days per year

With this data available, the selection of LSA can start with a system study to see possible solutions. There are today several programs that can be used like EMTP, Sigma, and others.

## Selecting application targets

There are basically four different applications of LSA, where the most common is to reduce tripping from lightning hitting the tower or shield wire causing back flashover or direct lightning strikes to a phase conductor causing a flashover from the line insulator to the tower [1-10]. This application will also prevent flashover due to induced over voltages from lightning strikes hitting nearby high structures like trees or wind towers. For this application both NGLA (non-gapped line arresters) and EGLA (externally gapped line arresters) can be used. It is obvious that if the target has no flashovers, you need LSA in all phases in all towers, but this is not an economical solution except in a few rare cases where the consequences are very harmful. Such a case may be double EHV circuits from a generating plant where a double circuit tripping may cause a major black-out. In most cases the number of LSA's and how many phases will depend on the target reduced outage and tower footing resistances. Charge requirements will strongly depend on if shield wires are used or not, as the risk of higher direct strike charges increases in the latter case.

The second application is to use NGLA instead of reclosing resistors to control the switching voltages along EHV

lines [11-12]. This application needs NGLA on all three phases, but only at a few towers, typically in the middle for shorter lines or at one third and two thirds of the line length for longer EHV lines. The NGLA can be used separately or together with other systems like controlled switching. The target is always non-tripping due to switching. Typically the energy/charge requirements for these NGLA is one class lower than for the substation arresters as they see only half or one third of the line length.

The third application is to build compact lines due to upgrading existing system voltage to a higher voltage and still keep towers/poles and line insulators with the help of NGLA [1], [10], [13]. For this case you will typically need NGLA in all towers and all phases, but it may still be an economical solution, as you can use the existing right of way. The NGLA will have to protect against both lightning and switching surges. This NGLA application can also be used for designing new compact lines when e.g. there is only a limited right of way possible. Depending on the design only NGLA at the top phase may in some cases be needed. The target value will be the same as for other lines with "standard insulation" in the area. Energy/charge requirements will come out of the necessary system studies.

The fourth application is to install NGLA in one to three towers closest to the entrance of a GIS substation in order to both limit incoming overvoltage amplitudes and also reduce the steepness, by preventing flashover in the selected towers. With this installation internal GIS arresters may not be required, plus GIS are sensitive to over voltages with very high steepness. GIS arresters are typically significantly more expensive than NGLA. In this case all phases must be protected in the selected towers and you may want to select NGLA with very low residual voltages in the last tower in order to increase protective distance inside the GIS. Even parallel columns may be advantageous. The other towers are just for reducing the incoming steepness so they need standard NGLA.

There is a fifth application possible, but that is not for permanent installation. During hot line work you may hang NGLA at both ends to prevent flashover of the line insulators in the towers under work. These NGLA typically do not need grading rings up to 245 kV systems and then reduced sized grading rings for 420 kV and above as they see COV for a limited time only.

## System aspects

Today the reliability of power lines are measured in total outage time including maintenance and line tripping. So if there is a flashover across a line insulator on a transmission/distribution line you want to re-energise the line back in service as quickly as possible. Hence different fast reclosing schemes are used by utilities. Installing LSA's are required not to influence the scheme even if the LSA is overloaded due to an excessive lightning discharge. It is also required that a LSA once disconnected is not allowed to leave the conductor or tower with a lower insulation withstand level because of the short-circuited arrester unit in the tower.

The mitigation against this to happen is to install disconnectors both for NGLA and EGLA. The performance must match the system's reclosing scheme, so that disconnector separation is completed before the fast reclosing occurs [14].

The available time to operate for the disconnector is the relay detection time of the earth fault plus CB opening time and then we add the reclosing time interval plus CB closing time. This total time is the window during which a successful separation shall take place.

However, disconnection time also depends on the actual short-circuit current of the system. LSA installations far distant from generation plants may have actual short-circuit currents significantly lower than close to the generation plant, even for a directly earthed system.

## Disconnector characteristics

Disconnector has a dual purpose, first to facilitate fast reclosing and also to visually show which arrester has been overloaded and need to be replaced.

A TLA disconnect device is required to operate when the arrester is overloaded and detects a current flowing for a long period of time until full system short-circuit is present. At the same time it is a simple device that is required to work in series with the arrester when dealing with lightning or switching surge events. Type Tests are carried out to prove that the disconnect device is capable of surviving the relevant temporary overvoltage, lightning and switching charges of the LSA without premature failure.

Typical disconnect characteristics showing opening time versus power frequency current, is presented in figure 1.

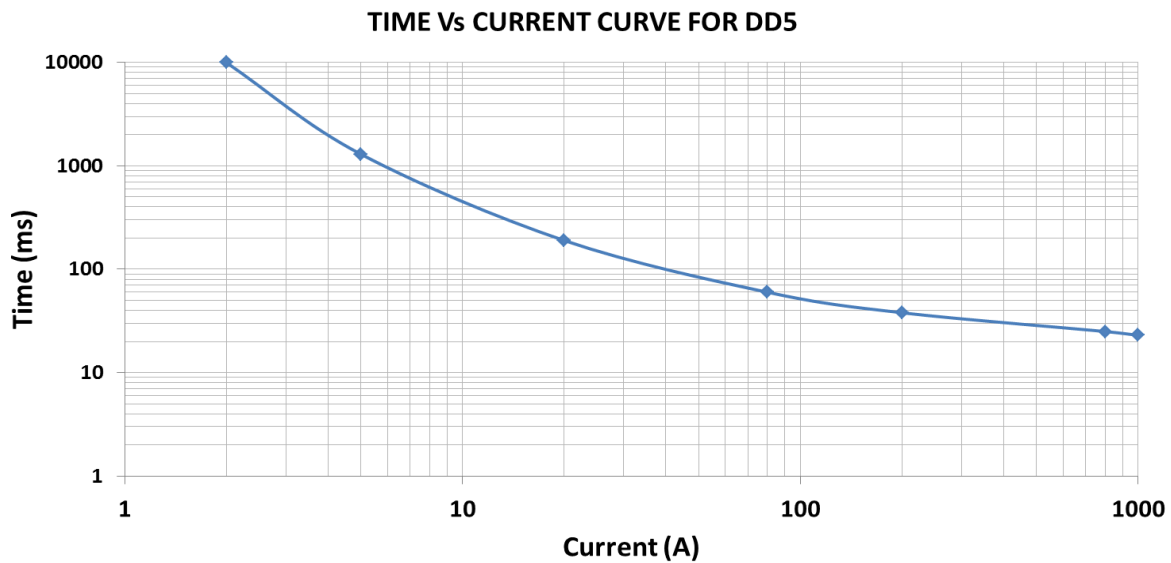


Figure 1. Typical disconnect characteristics showing opening time versus power frequency current

The lower the short-circuit current the longer opening time is needed for the disconnect. Thus it may be more critical for non-directly earthed systems to facilitate a fast reclosing than for directly earthed systems, if the disconnect is not fast enough.

Another important criterion is that once triggered to operate, it is never allowed to stop before opening is complete, even if the short-circuit current disappears. If this is not fulfilled you will have another tripping of the line when it recloses, as the short-circuited arrester is still connected to earth.

In all application the disconnect operation separates the earth wire from the arrester. Sometimes for EHV applications the length of earth lead is several meters and so typically you install some weight to make the earth connection heavier so it falls down quicker even if there are high wind gusts present.

### Arrester characteristics

Arrester and disconnect characteristics shall now be coordinated so that the optimum selection of both target goals and costs are reached [14]. For the typical application of lightning protection NGLA are only installed in a tower to prevent flashover of its line insulators. NGLA will share the lightning charges between them as a lightning stroke travels in two directions, so there is no need to have a very high charge capability of the NGLA. The exception is systems without shield wires which have a higher probability of seeing direct phase lightning strokes and therefore the NGLA need somewhat higher charge capabilities. On the other hand if you have lightning strokes with very high charges no arrester will survive such an incident.

In order to optimise the arrester charge class, all switching and TOV stresses should therefore be handled by the substation arresters especially for EHV systems. This is easily done by selecting NGLA to have higher residual voltage characteristics, so all high energy surges from switching operations and/or capacitor discharges are handled by substation arresters thereby protecting the NGLA from these stresses. There is no risk of lost protection due to that separation effects in the tower are limited and typical critical flashover voltages of line insulators are very high compared to residual voltages of NGLA.

TOV stresses are different as a disconnect cannot distinguish between short-circuit currents and arrester currents during TOV stresses. Thus a coordination of arrester and disconnect characteristics is necessary especially for non-directly earthed systems. Typical TOV curves are presented as factors of rated voltage, see figure 2.

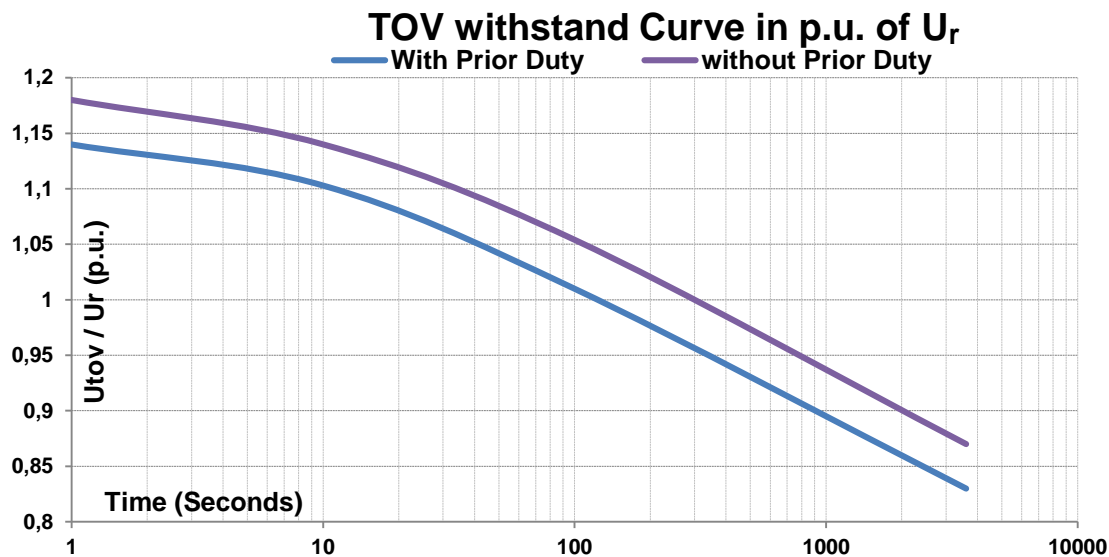


Figure 2. Typical arrester's TOV withstand curves

Figure 2 shows two curves, one with preheating due to a prior energy input before the arrester is exposed to the TOV. The other curve shows the TOV capability when the arrester is at maximum ambient temperature, (60°C). The higher the TOV, the higher is the power frequency current that passes through the arrester.

The most critical case is when there is an earth fault on one phase and the healthy phases see the increased voltage until the fault is cleared. NGLA in healthy phases will then follow the TOV withstand of no prior duty. The extreme non-linearity of the ZnO-arresters means that for shorter times we may be well into the conductive area of the characteristics. So for very short TOV durations the arrester may draw tens of ampere, which may be of the same magnitude as the short-circuit currents at the installation point of the NGLA. From the TOV testing, arrester manufacturers know what currents are decisive for different durations.

In order to ensure that TOV stresses do not interfere with short-circuit currents you need to know the TOV requirements in actual kV of the system. You then recalculate these voltages to factors of the rated voltage selected for the NGLA. The mitigation is to select a high enough rated voltage, which immediately gives you a higher TOV withstand in kV and thus lower currents.

Let us look at an example:

If we have a 145 kV non-directly earthed system with a reclosing time of 500ms. TOV conditions are 150 kV during 1s. Substation arresters have a rated voltage of 132 kV. Looking at Figure 1 we see that the disconnecter need a minimum current of 9A to operate within 500ms, which should be enough even for a far-distant location. A 132 kV rated arrester will have a TOV withstand of 150 kV (1.14 p.u.) for 1s for prior duty, see figure 2. But we need to know what current a TOV of 150 kV will draw. That current must be lower than 9A so we do not get a premature operation. The current drawn is depending on the actual rated voltage of the NGLA. So instead we look at the TOV stress that draws 9A. We see that for no prior duty a 132 kV NGLA will draw 12A from table 1. Instead we select a rated voltage of 138 kV for which 150 kV TOV is only 1.09 p.u. of rated voltage so the current is below 2A, which will not interfere with the disconnecter operation. A selection of 138kV rated voltage will be the proper solution with a maximum residual voltage at 20 kA of 387 kV, adding 30% gives us 503 kV, still with ample margin to a typical BIL of 650 kV.

TOV currents in A							
NGLA / Disconnecter	TIME/ Voltage p.u.	Voltage kV or p.u.	1 s (A)	Voltage kV or p.u.	10 s (A)	Voltage kV or p.u.	40 s (A)
NGLA	prior energy	1.14	8	1.11	6	1.05	0.4
	no energy	1.175	15	1.14	12	1.09	1.6
Ur = 132	no energy	155	15	150	12	144	1.6
<b>Ur = 138</b>	<b>no energy</b>	162	15	157	12	<b>150</b>	<b>1.6</b>
SYSTEM TOV (kV)					150		
Disconnecter Current					9A		

Table 1. Arrester currents under TOV stresses

It is advantageous for several reasons to select a higher rated voltage for the NGLA compare to the substation arresters, as you then ensure that the NGLA are only there for preventing lightning flashover in the its tower and not to handle switching, capacitor discharges or TOV stresses form the system itself. Another advantage is that for a higher rating grading rings can be smaller. The most common misunderstanding is that the NGLA for lightning protection shall be selected on the same specification as the substation arresters.

### Mechanical considerations

Installing LSA directly hanging from the power lines needs also mechanical considerations [15]. This installation method is quite common and can also be used for hot line installations. Power lines typically have dampers installed at predetermined positions around the line insulators or along the lines to prevent vibrations and swinging of the lines.

If LSA now are installed without consideration to these dampers their positive damping effects can diminish. One of the solution is to install line dampers on each side of the NGLA, but the distance between them may need to be calculated. However, today there is a CIGRE working group looking into how to install LSA without distorting mechanical properties of neither the lines nor the LSA themselves.

Another solution would be to put weights hanging under line insulators to stabilise the line. This feature can also be used with NGLA by adding weights hanging under them they can work as dampers for the lines. It is also important to allow enough free movement of the disconnector cables so that line movements do not fatigue the earth leads.

### Case study: Shielded 230 kV double circuit overhead transmission line

Computational models and methodologies have been developed to evaluate the lightning response of overhead lines. Today there are specific software and transient programs available that help the customer to select the proper energy class, position and on which phases the LSA are to be installed, in order to make the best contribution [1-6], [10]. Therefore LSA characteristics as well as the procedures to optimize the quantity and application points shall be obtained through transient studies. Basically two different studies have been performed: (1) – study to estimate the transmission line lightning performance for different line configurations; (2) studies to define the energy level absorbed by the LSA considering the lightning characteristics, the grounding system behaviour for fast transients and the probability of multiple strokes occurrence.

Starting from the results obtained in the theoretical studies and knowing the target number of outages desired for the overhead line to be evaluated, it is possible to define the methods and procedures more appropriate to improve the lightning performance of the specific overhead line considered. A technical evaluation should be usually followed by an economic analysis, allowing the user to analyse and optimize the cost – benefit balance.

LSA using NGLA concept installed along the critical sections of the overhead shielded and unshielded sub-transmission and transmission lines with poorer lightning performance have been widely used for many years to improve the reliability of transmission lines, being usually considered as the most effective among the methods for improvement the overhead lines lightning performance. However, sometimes its effectiveness and the cost – benefit balance increase with the improvement of the tower footing impedance for fast transients and/or increasing of the insulation level associated with NGLA application.

The case study below shows the effect of the NGLA installation configuration for different tower footing resistance values on the back-flashover rate for a shielded double circuit transmission lines. It is a section of a shielded double circuit 245 kV overhead transmission line with total length of 201.4 km.

The following assumptions were used in the lightning analysis for this section:

- The line insulation Critical Flashover Voltage is 1,040 kV.
- The Ground Flash Density is 6.7 strokes per km<sup>2</sup> per year.
- The evaluated section has an average soil resistivity of 1,500 Ω.m.
- The evaluated section has an average span of 320 m.
- Tower surge impedance is 198 Ω.
- NGLA rated voltage is 198 kV.

Figure 3 gives the geometrical configuration of towers for the evaluated section, with the disposals for shield wires and phase conductors.

Two different targets can be obtained during a lightning evaluation analysis for a double circuit overhead transmission line: (Case 1) – to reduce the total trip of the line for both circuits to a target outage level; (Case 2) – to reduce or eliminate the risk of simultaneous trip of both circuits (double circuit flashover).

Double circuit flashover on double circuit lines are most of the time vary detrimental to power quality [1] and for this reason most of the lightning analysis have been addressed to avoid double-circuit flashover.

The simulation was done using the sigma slp program. A total number of 1,000 statistical cases was used for each value of tower footing resistance and NGLA installation configuration. The line total flashover rate and double circuit rate for different arrester installation was evaluated.

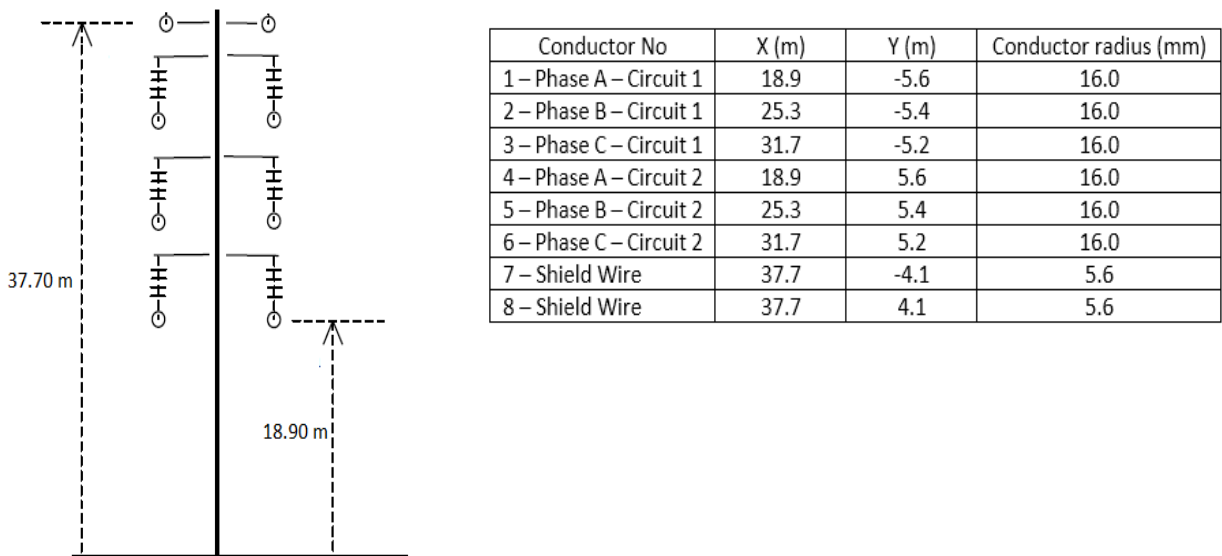


Figure 3. Geometrical configuration of the tower, shield wire and phase conductors

Results of the simulations presenting the total line flashover rate in terms of flashover per 100 km per year for different tower footing resistance values and NGLA installation configuration are shown in the Figure 4.

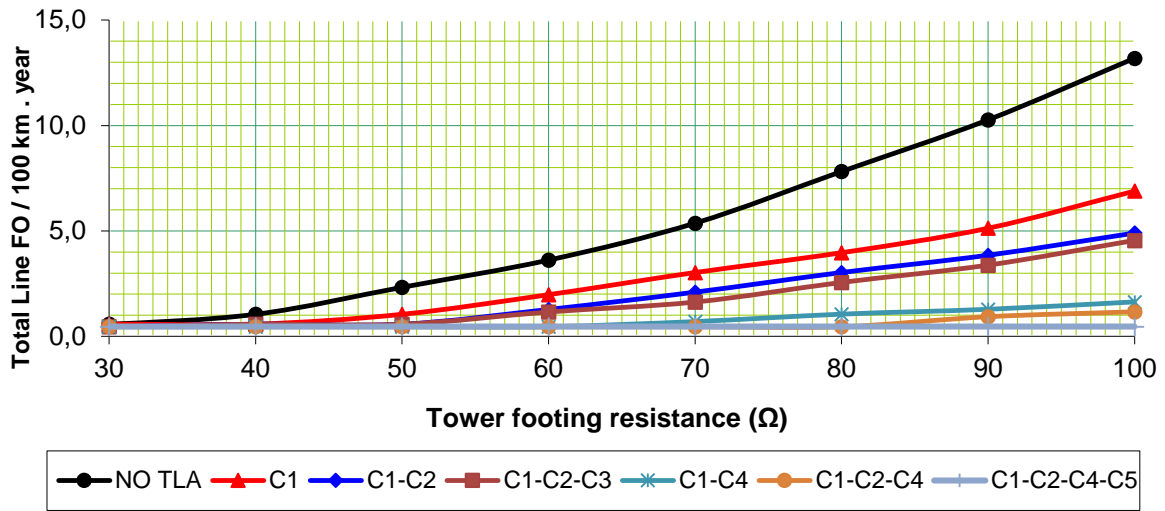


Figure 4. Effect of tower footing resistance on the total line flashover rate for different NGLA configurations

The flashover rate due to shielding failure obtained in the simulations for all configurations evaluated of 0.46 flashover per 100 km per year is considered in the total line flashover rate. To eliminate the line flashover rate due to shielding failure, NGLA shall be installed on the top phase of both circuits.

A summarized information for the line flashover rate due to the back flashover rate is shown in the Table 2.

R(Ω)							
20	0.0 0	0.00	0.00	0.00	0.00	0.00	0.00
40	0.5 8	0.11	0.00	0.00	0.00	0.00	0.00
60	3.1 5	1.51	0.81	0.70	0.00	0.00	0.00
80	7.3 5	3.50	2.56	2.10	0.58	0.00	0.00
100	12. 73	6.42	4.43	4.08	1.16	0.70	0.00

Table 2. Backflashover rate for different NGLA configurations (Flashover/100 km/year)



Figure 6 shows the double-circuit flashover rate for the same conditions. Summarized information are shown in the Table 3.

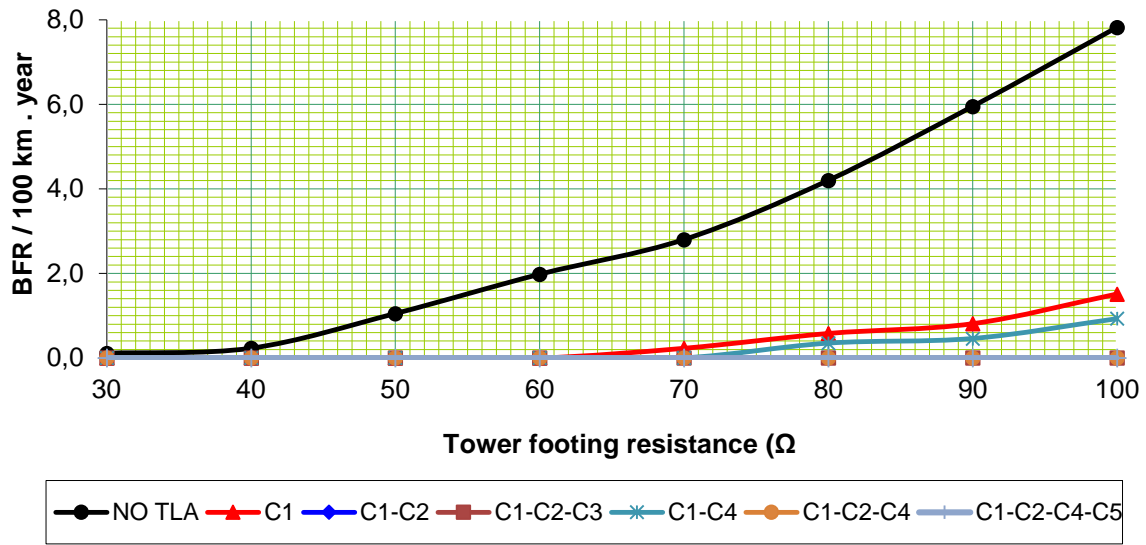


Figure 5. Effect of tower footing resistance on the double circuit flashover rate for different NGLA configurations

R(Ω)								
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
40	0.23	0.00	0.00	0.00	0.00	0.00	0.00	
60	1.98	0.00	0.00	0.00	0.00	0.00	0.00	
80	4.20	0.58	0.00	0.00	0.35	0.00	0.00	
100	7.82	1.51	0.00	0.00	0.93	0.00	0.00	

Table 3. Double circuit flashover rate for different NGLA configurations

As can be seen from the Figure 4 and Table 2, a NGLA installed on the bottom phase of the circuit 1 (C1) virtually eliminates the line back flashover rate for tower footing resistance values up to 40 Ω and reduces drastically the line back flashover risk even for higher tower footing resistance values. An expected relative improvement of approximately 50% can be seen for tower footing resistance values of 50 Ω and above. Two NGLA installed on the bottom phase of both circuits (C1-C4) virtually eliminates the backflashover rate for tower footing resistance values up to 60 Ω, with an expected relative improvement by more than 90% for tower footing resistance values of can be seen for tower footing resistance values of 70 Ω and above. Three NGLA installed on the bottom phase of both circuits and on the middle phase of one circuit (C1-C2-C4) virtually eliminates the back flashover risk for tower footing resistances up to 80 Ω, with an expected relative improvement by more than 95% for higher tower footing resistance values. No trip due to backflashover was observed during the simulations considering four NGLA installed on the bottom and on the middle phases of both circuits.

When comparing the total line flashover due to back flashover occurrence obtained in the simulations for configurations with NGLA protecting all phases of one circuit (C1-C2-C3) and with NGLA protecting just the bottom phase of both circuits (C1-C4) is possible to observe for tower footing resistance values above 80 Ω a better lightning performance for the configuration protecting both circuits in spite of lesser number of NGLA considered, justifying this configuration if the desired target is associated with the reduction of the total line flashover rate. However, as can be seen in the Figure 5 and Table 3, the protection of one circuit with three NGLA (C1-C2-C3) virtually eliminates, for this specific lightning analysis, the double-flashover rate even for tower footing resistance values of 100 Ω, being

technically the best option in terms of NGLA configuration when the desired target is eliminate or reduce the risk of simultaneous tripping of both circuits (double-circuit flashover). In this specific analysis, even the protection with two TLA installed on the bottom and on the middle phases of one circuit offers a better lightning performance against double-circuit flashover.

In case of overhead lines with rated voltages up to 145 kV, a higher line flashover rate due to backflashover occurs due to lower line insulation critical flashover voltage. In this case, sometimes a good practice to improve the transmission line reliability against lightning consists to protect one circuit with NGLA, increasing the critical flashover insulation of the no protected circuit [1]. It reduces the total line flashover rate and virtually eliminates risk of double-circuit flashover. For higher tower footing resistance values or regions with higher ground flash density, some lightning analysis have been reporting for this voltage level three NGLA protecting one circuit the other circuit with one NGLA on the bottom phase and higher critical flashover voltage for the other two phases.

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