

ENERGY STRESS ON TRANSMISSION LINE ARRESTERS CONSIDERING THE TOTAL LIGHTNING CHARGE DISTRIBUTION

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Abstract - Transmission line arresters may be subjected to high energy stresses caused by lightning. Calculations of energy stresses were carried out for a typical line arrester installation. Three line configurations with different degrees of shielding efficiency were used for the study. The primary statistical parameter was the charge of the flash, including multiple strokes. The effect of stroke current magnitude was also investigated. The calculated results were compared with energy stresses in standardized tests on surge arresters.

I. INTRODUCTION

The energy requirements for transmission line arresters with regard to lightning stresses differ from the requirements generally applied for arresters in a substation. This is because the lightning impulse is normally reduced by the lightning current paths to ground through shield wires or by flashovers across the line insulators, before entering the station.

A line arrester is more exposed to the lightning current since it is situated closer to the striking point. The current through the arrester depends heavily on the shielding efficiency of the line and on the tower grounding conditions. A well-shielded line with low tower footing resistances will cause the smallest energy stress on the line arresters. On the other hand, an ineffectively shielded line will cause a much higher stress on the arresters. At the same time, the latter case is the most relevant since the application of line arrester can be expected to significantly improve the lightning performance of the line.

In order to investigate the energy stress on line arresters, a typical application was modelled. For the study, gapless metal-oxide arresters were installed in all three phases along a 2.5 km section of a line (11 towers). At both ends, the line was terminated in a substation (with metal-oxide arresters installed) at a distance of 3 km from the protected section.

II. TRANSMISSION LINE CONFIGURATIONS

Three typical line configurations were used for the calculations of energy stresses: a horizontal 138 kV single-circuit line with two shield wires representing efficient shielding, a vertical double-circuit 230 kV line with one shield wire representing ineffective shielding, and the same 230 kV line but without any shield wire. Only one of the circuits in the double-circuit line was modelled in the study; the effects of line arresters or flashovers in the second circuit were not considered. The dimensions of the lines were taken from [1].

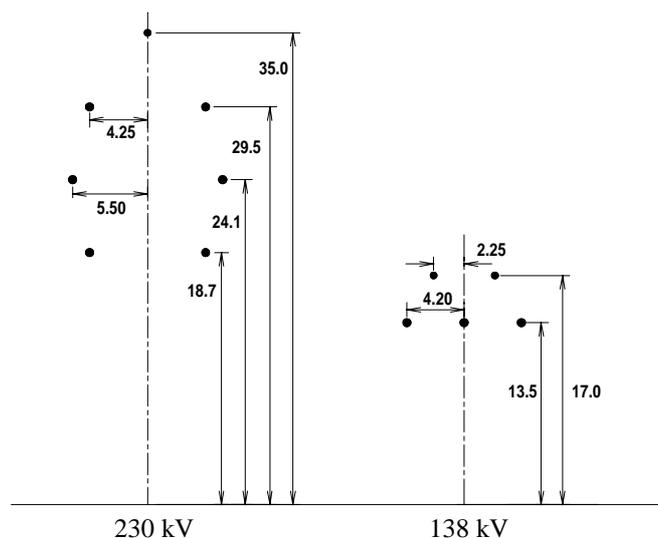


Fig. 1. Transmission line configurations.

The tower grounding resistances along the protected section were varied from 20 to 300 Ohms depending on the case studied. For shielding penetration, where a low footing

resistance will increase the current through the arrester, the resistances was 20 Ohms in the tower at the striking point, and 200 Ohms in the remaining towers. For strokes to the shield wires, where a high footing resistance will cause the highest arrester currents, the resistance was 300 Ohms in all towers. In the case of the 230 kV line without shield wires, both 20 and 300 Ohms were used in all towers to reflect different grounding conditions. In the substations, the arrester grounding resistance was set to 1 Ohm.

III. LIGHTNING PARAMETERS AND SURGE ARRESTER DATA

The total lightning charge, including multiple strokes, is the primary parameter for the absorbed arrester energy. However, due to the non-linear voltage-current characteristic of the arrester, the amplitude of the lightning current is also essential for the results. Therefore, the influence of the current amplitude was also investigated by varying the stroke current for a given total charge.

The statistical lightning parameters in terms of total flash charge and first stroke current amplitudes were taken from [2]. Only negative flashes were considered in the study. Since the published statistical data for the total flash charge is more complete, it was chosen instead of the sum of individual stroke charges. This means that the calculated arrester energies are somewhat higher than actual, since the charge of the low intermediate and residual currents of the flash do not contribute significantly to the absorbed arrester energy.

The arrester type chosen for the study is a metal-oxide IEC line discharge class 3, or ANSI/IEEE 362 kV station-class arrester. The single impulse energy capability is 4.5 kJ/kV rated voltage. The rated voltages (U_T) are shown in Table I. The residual voltages are $2.40 \cdot U_T$ at 10 kA, $8/20\mu\text{s}$.

IV. STATISTICAL PROCEDURE

The energy requirements on transmission line arresters may be expressed in different ways depending on how the acceptable failure rate is formulated. In this study, the requirement was expressed in terms of a statistical energy stress level with a return period (MTBF) of 25 years for the arresters on the protected line section. By this, the calculated results for the various line configurations can be readily compared on the basis of a reasonable arrester failure rate of 0.04 per year. For the complete set of 33 arresters, this is equivalent to 0.0012 per arrester and year.

To enable the use of published data on lightning parameters, the given probability is recalculated into a "design probability" for each flash to the line section. Since the total flash charge was chosen as the main parameter for the arrester energy stress, the "design charge probability" was used for the statistical calculations.

The resulting number of flashes per year to the shield wires (N_{sw}) and phase conductors (N_{ph}) along the protected section (2.5 km) of the line was calculated according to [1] for the three different line types. The ground flash density (N_g)

was assumed to be 10 per km^2 and year. This comparatively high value was chosen to reflect the conditions in regions where the application of line arresters is expected to significantly improve the lightning performance of transmission lines.

TABLE I
SURGE ARRESTER DATA

System voltage	Rated voltage	
	Line arresters	Station arresters
138 kV	120 kV	108 kV
230 kV	210 kV	192 kV

The design probability for each flash to the shield wire(s) is then $0.04/N_{\text{sw}}$ and to the phase conductors $0.04/N_{\text{ph}}$. The corresponding design charge values were found in Fig. 3 of [2]. The complete distribution of charges was used despite the fact that for shielding penetration, the distribution of stroke current amplitudes is limited to values below the critical current. Since there is a certain correlation between the stroke current amplitude and the flash charge, this may also influence the charge distribution. However, for the cases under study, the complete distribution is still justified since the 230 kV line has a critical current as high as 111 kA, and the 138 kV line is so well shielded that the number of strokes to the phase conductors is below the design probability and need not be considered. The resulting design charge data for the three line configurations are summarized in Table II.

TABLE II
DESIGN CHARGE DATA

Line configuration	Striking point	Strokes per year	Design probability	Design charge - As
138 kV horizontal with two s.w.	s.w.	4	0.01	80
	ph.	0.015	n.a.*	n.a.*
230 kV vertical with one s.w.	s.w.	6	0.007	90
	ph.	0.235	0.17	20
230 kV vertical without s.w.	-	-	-	-
	ph.	6	0.007	90

* no. of strokes per year is below 1 / MTBF
s.w. = shield wire, ph. = phase conductor

V. CALCULATION PROCEDURE

The calculations were carried out using the DCG version of the EMTP. The lightning flash, including multiple strokes, was represented by a single current impulse in order to reduce the computation time. The duration of the impulse was varied to obtain the desired value of the total flash charge for each given stroke current amplitude.

The current front parameters were chosen as the median values of steepness and front time for a concave front as given in [1], yielding a maximum front steepness of:

$$6.50 \cdot I^{0.376} \text{ kA}/\mu\text{s}$$

and a 30/90% front time of:

$$0.906 \cdot I^{0.411} \mu\text{s}$$

where I represents the stroke current amplitude.

The flash to the line was assumed to hit the centre tower on the protected line section. To study the effect of the current amplitude, the stroke current was varied to represent probabilities of 0.1, 0.05 and 0.01, equal to 72, 90 and 136 kA as obtained from the complete distribution of stroke currents [2]. For the case of shielding penetration on the 230 kV line, where the distribution is limited to levels below the critical current, the corresponding currents were 57, 66 and 84 kA for probabilities of 0.1, 0.05 and 0.01.

VI. RESULTS AND DISCUSSIONS

The results of the calculations are presented in Table III. The arrester energy is given in kJ/kV of rated voltage for the most exposed arrester on the protected section of the line.

The distribution of arrester energies is exemplified in Fig. 2 for strokes to the shield wire of the 230 kV line with a stroke current probability of 0.01, and for shielding penetration with a stroke current probability of 0.1.

Typical energy capabilities of arresters used for transmission line applications are in the range 1 to 5 kJ/kV rated voltage. A comparison with the results of Table III show that the energy requirements on the line arresters are quite modest for the well-shielded 138 kV line. High values are obtained only if the design charge occurs together with a very high current amplitude.

The ineffectively shielded 230 kV line puts a considerably higher energy requirement on the arresters, especially for shielding penetration.

The arresters on the unshielded 230 kV line is heavily exposed to the lightning current, and very high energy requirements must be put on the line arresters to reach the originally assumed failure rate. Furthermore, the tower grounding resistance is very important to the energy stress of the arrester. It should be noted that in this study, all strokes were assumed to hit the phase conductors, while in a real situation some of the strokes will hit the tower tops.

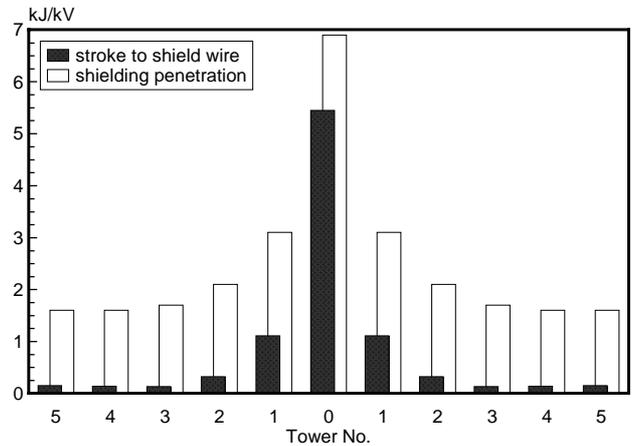


Fig. 2. Distribution of line arrester energy.

Since only one circuit of the double-circuit line was modelled, the influence of possible flashovers in the second circuit was not included. However, in general it can be stated that the additional current path to ground created by such a flashover will reduce the energy stress on the line arresters if the lightning stroke hits the shield wire or tower top. For strokes to the phase conductor, on the other hand, the energy stress will generally increase.

TABLE III
CALCULATED SURGE ARRESTER ENERGY
FOR DIFFERENT LINE CONFIGURATIONS

Line configuration	Striking point	Design probability	Design charge - As	Tower ground resistance - Ohms	Line arrester energy - kJ/kV		
					Stroke current probability		
					0.1	0.05	0.01
138 kV horizontal with two shield wires	s.w.	0.01	80	300	1.1	2.0	4.7
	ph.	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*
230 kV vertical with one shield wire	s.w.	0.007	90	300	1.4	2.4	5.5
	ph.	0.17	20	20 / 200	6.9	7.9	9.9
230 kV vertical without shield wire	ph.	0.007	90	20	19.2	20.4	23.2
	ph.	0.007	90	300	5.9	7.0	10.7

* no. of strokes per year is below 1 / MTBF

s.w. = shield wire, ph. = phase conductor

The simplified modelling of the unprotected section of the line may have slightly influenced the calculated results in comparison with real conditions. For example, if flashovers occur on the unprotected sections, the energy absorbed by the line arresters will be somewhat different.

Although not discussed in detail here, the station arresters need special consideration in conjunction with line arresters. When lightning strikes a phase conductor, and no flashovers occur due to the presence of the line arresters, current may pass through the station arresters for the major part of the duration of the flash. This is due to the lower grounding resistance, and possibly lower rated voltage, of these arresters. More energy will then be absorbed by the station arresters compared with a situation without line arresters, when flashovers along the line will prevent the major part of the flash current from reaching the station arresters.

VII. ENERGY STRESS ON ARRESTERS IN STANDARDIZED TEST PROCEDURES

In the following, the calculated energies are compared with the energy stresses in standardized tests. Only the test procedures related to different varistor failures from the excessive energy absorption are discussed, e.g. cracking, puncture or flashover. The thermal aspects of the different arrester designs, verified in the operating duty test, are not considered here.

According to the IEC standard for metal-oxide arresters, IEC 99-4, arresters with a nominal current of 5 kA shall be subjected to a conditioning test comprising twenty 8/20 μ s impulses of nominal current and two 4/10 μ s high-current impulses of 65 kA. The same requirements apply for arresters with a nominal current of 10 kA and line discharge class 1, but the high-current amplitude is 100 kA.

The nominal current impulses give a negligible energy, while the high current impulses represent a considerable energy stress of 1.7 to 2.7 kJ/kV of rated voltage assuming a relative protection level of 4 times

the rated voltage [3]. However, neither the amplitude, nor the duration of the current, represents stresses found in practice.

In addition, the number of impulses is only two, and it could be questioned if

the arrester would survive a larger number of impulses. It should be noted that the high-current impulse test, in addition to being a

conditioning test, is primarily intended to verify the insulation withstand of the arrester design. The information obtained from

the test can therefore be misleading with regard to energy capability.

For arresters with higher line discharge classes and nominal currents of 10 and 20 kA, the long duration current impulse test is the most relevant test to give a measure of the energy capability. All other tests, such as the high-current or nominal current impulse test, generally subject the

arresters to considerably less energy. Only for line discharge class 1 and class 2 arresters with relatively high protective levels, the high-current impulse test gives an energy stress comparable with the long duration current impulse.

Approximate values for the energy absorbed in each impulse of the long duration current impulse test are shown in Table IV, assuming a relative protection level of 2 times the rated voltage [3].

TABLE IV
SURGE ARRESTER ENERGY
IN LONG DURATION CURRENT IMPULSE TEST

IEC line discharge class	Energy per impulse - kJ/kV
1	1.0
2	2.0
3	3.0
4	4.2
5	5.0

In the corresponding ANSI/IEEE standard, the high-current tests are comparable with the IEC tests and give similar energy stresses. The transmission line discharge test give stresses comparable with the IEC line discharge test, except for the higher transmission line classes, where the ANSI/IEEE tests generally give lower energy stresses.

Although the energies shown in Table IV are comparable with the calculated results of Table III, it should be noted that the amplitude and duration of the current pulses are quite different. The long duration current impulse has an amplitude less than 1 kA and a duration in the millisecond range, while the current through the line arrester is typically 10-20 kA with a duration of only a few hundred microseconds. Depending on the design and manufacturing of the varistor elements, either one of these stresses will be the most critical.

VIII. CONCLUSIONS

It is clear from this limited study that many parameters affect the energy stress on line arresters. As expected, the shielding properties of the line is especially important along with the tower grounding conditions.

The risk of arrester failure must be based on statistical data for the total flash charge. However, also the magnitude of the stroke current influences the results, as seen in Table III. Therefore, the statistical correlation between the flash charge and first stroke current magnitude will be the subject for future studies on line arrester energy stress.

From the results presented in Table III and Table IV, it is obvious that new applications like transmission line arresters could subject the

arresters to energy stresses which are not covered by existing standards. This is especially true for lines with ineffective shielding or no shielding at all. Considering also that the amplitude and duration of the line arrester current may differ

significantly from the standardized values, additional test procedures are needed for suitable dimensioning of transmission line arresters.

IX. REFERENCES

- [1] CIGRÈ SC 33/WG 01, "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines," 1990.
- [2] K. Berger, R.B. Anderson, H. Kröniger, "Parameters of Lightning Flashes," *Electra*, no. 41, July 1975.

- [3] CIGRÈ SC 33/WG 06, "Metal Oxide Surge Arresters in AC Systems," 1991.

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