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SELECTION, DIMENSIONING AND TESTING OF LINE SURGE ARRESTERS

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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 138 kV line arrester installation. 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. An additional type test procedure is proposed to account for energy stresses typical for line arresters with regard to lightning conditions .**

1. INTRODUCTION

The energy requirements for transmission line arresters with regard to lightning stresses differ from requirements generally applied for arresters in a substation. For station arresters, 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.

In order to investigate the energy stress on line arresters in a typical application, a 138 kV line with one shield wire was modelled for EMTP studies. The main parameters of the line were taken from the line Rio Verde - Couto Magalhães, belonging to the FURNAS 138 kV system in Brazil.

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For the investigation, a section in the middle of the line was protected by surge arresters, while the remaining part was unprotected. The grounding conditions were chosen to reflect typical values for the different line sections and for different towers within the protected section. The number of line arresters in each tower was varied from one to three in order to simulate different degrees of protection.

2. ENERGY STRESSES ON LINE ARRESTERS BY LIGHTNING STROKES

Line arresters are typically applied to line sections where the tower grounding conditions are insufficient to provide acceptable lightning trip-out rates. By installing line arresters, the risk of flashovers due to lightning can be reduced to practically any desired level, regardless whether the lightning strikes the shield wire, the tower top or the phase conductor.

If all phases in a tower is protected by line arresters, the risk of flashover in that tower is virtually eliminated. Reducing the number of phases protected by arresters in each tower will increase the risk of flashover. It is therefore possible to optimize the application of line arresters with regard to the installation cost and the acceptable trip-out rate. In the same manner, the selection of line arrester energy capability should be optimized with regard to the installation cost and the acceptable rate of arrester failure.

The energy stress on the arresters is influenced by the striking point, the stroke current amplitude, the total flash charge and the tower grounding resistances. Apart from the grounding resistances, these parameters can only be expressed in statistical terms. The selection of a suitable arrester energy capability must therefore be made on statistical basis. The statistical procedure used in this study is described in the following.

3. STATISTICAL PROCEDURE FOR ENERGY STRESSES ON LINE ARRESTERS

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 is expressed as a statistical energy stress level with a given return period (MTBF) for the total number of arresters within the protected line section.

The total lightning charge, including multiple strokes, is the primary parameter for the absorbed arrester energy. To enable the use of published data on lightning parameters, the given return period is recalculated to a "design probability" of the total charge for each flash to the line section. The design probability is used to find the corresponding "design charge" based on the statistical distribution of the total flash charge. For the EMTP studies, the design charge is represented by an impulse current having an amplitude and duration corresponding to the given charge.

The result of the EMTP calculations is the arrester energy stress that appears with the given return period. The originally assumed MTBF is obtained by choosing an arrester with an energy capability equal to or higher than the calculated energy stress.

For shielded lines, the calculated results depend heavily on the striking point (phase conductor versus shield wire or tower top). It is therefore necessary to perform the statistical calculations with both cases in mind.

The proposed statistical procedure can be summarized in the following steps:

1. Determine the acceptable return period, MTBF, for arrester failure along the protected section, e.g. 10 years.

2. Calculate the number of flashes per year to the shield wire(s), N_{sw}, and to the phase conductors, N_{ph}, for the protected section based on information about line geometry and ground flash density.

3. Calculate the design probability for each flash to the shield wire(s), p_{sw}, and to the phase conductors, p_{ph}, as:

$$p_{sw} = 1 / (MTBF \cdot N_{sw}) \qquad p_{ph} = 1/ (MTBF \cdot N_{ph})$$

4. Calculate the design charge for each flash to the shield wire(s), Q_{sw}, and phase conductors, Q_{ph}, from the statistical distribution of the total flash charge.

It should be noted that the amplitude of the lightning current influences the distribution of the energy stress due to the non-linear characteristic of the arresters. This can be considered in the calculations by varying the combination of stroke current amplitude and duration. As an example, the current amplitude may be chosen from the statistical distribution of first stroke currents with exceedence probabilities of 1, 5 and 10%.

4. EXAMPLE CALCULATION

The proposed statistical procedure for estimation of the required arrester energy withstand capability was applied to the 138 kV line described in Section 1.

4.1 Line Configuration

The line configuration chosen for the study is a triangular 138 kV single-circuit line with one shield wire. The dimensions of the line are shown in Figure 1.

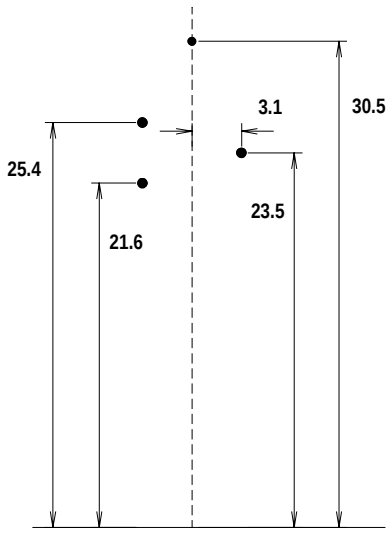

Fig. 1. 138 kV line configuration.

4.2 Tower Grounding Conditions

The tower grounding resistances along the line were selected to represent typical values for protected and unprotected sections. For the protected section, the resistances were chosen as 50 and 300 Ohms. The lower value is considered typical for the majority of towers with normal grounding resistance, while the higher value represents towers with exceptionally high resistance.

The towers at each end of the protected section were assumed to have a grounding resistance of 20 Ohms. It is necessary that the end-towers have a comparatively low resistance, since lightning strikes to the protected section will otherwise cause flashovers on the unprotected section of the line.

The towers on the unprotected section were assumed to have a grounding resistance of 20 Ohms, and the grounding resistance of the substations was chosen as 1 Ohm.

The tower grounding resistance values are summarized in Table I.

TABLE I
TOWER GROUNDING CONDITIONS

Line section	Grounding resistance Ohms
Protected section - High-resistance tower - Normal-resistance tower - End-tower	 300 50 20
Unprotected section	20
Substation	1

4.3 Surge Arrester Data

For this study, gapless metal-oxide arresters were installed in 11 towers along a 3.5 km section of the line. At both ends, the line was terminated in a substation at a distance of 3 km from the protected section. The distance to the substation was reduced in comparison to the real line in order to minimize the computation time.

The arrester type chosen is an IEC line discharge class 3, ANSI/IEEE station-class arrester. The rated voltage (U_r) for the lines arresters is 144 kV and for the station arresters 120 kV. The residual voltages are $2.40 \cdot U_r$ at 10 kA, 8/20µs.

4.4 Calculation of Design Charge Values

On the basis of the number of thunderstorm days in the region, the ground flash density (N_g) was calculated to be 12.5 per km^2 and year [1]. Based on the line geometry, the number of lightning strokes per year to the shield wire and to the phase conductors along the 3.5 km protected section was calculated to [1]:

$$N_{sw} = 9.8 \qquad N_{ph} = 0.12$$

The acceptable return period (MTBF) of an arrester failure on the protected section was chosen to be 10 years. The design probabilities can then be calculated as:

$$p_{sw} = 1 / (MTBF \cdot N_{sw}) = 0.01$$

$$p_{ph} = 1 / (MTBF \cdot N_{ph}) = 0.85$$

The design charge values corresponding to these probabilities are derived from the distribution of total flash charges found in Figure 3 of [2]:

$$Q_{sw} = 80 \text{ As} \qquad Q_{ph} = 2.6 \text{ As}$$

Only negative flashes were considered in the study. Since the available statistical data for the total flash charge is more complete, it was chosen instead of the sum of the individual impulse charges. The complete distribution of charges was used also for strokes to the phase conductors. This is a conservative approach since the distribution of stroke current amplitude is limited to values below the critical current, and the charge distribution is naturally affected by this limitation.

4.5 Studied Cases

The arrester energy stresses were calculated for a number of cases representing different striking points, tower grounding resistances, impulse current amplitudes and number of arresters in each tower on the protected section. The results are summarized in Table II.

For strokes to the shield wire, the striking point was at the centre tower and at the second tower from the end of the protected section.

The number of arresters in each tower was varied from three to one in order to reflect different degrees of arrester protection.

The grounding resistances were 50 and 300 Ohms along the complete protected section apart from the end-towers where the grounding resistance was 20 Ohms.

The design charge levels were chosen in accordance with the statistical procedure described previously.

For strokes to the shield wire, the impulse current amplitude was varied to represent exceedence probabilities of 10, 5 and 1%, equal to 72, 90 and 136 kA as obtained from the complete distribution of negative first stroke currents [2]. For strokes to the phase conductors, the current amplitude was chosen equal to the critical current, 48 kA.

The arrester energy is given in kJ/kV of the rated voltage for the most exposed arrester on the protected section of the line.

The occurrences of flashovers outside the protected section were investigated in some of the cases by modelling the line insulators in three towers on the unprotected section.

5. DISCUSSION OF RESULTS FROM CALCULATIONS

5.1 General observations

Comparing cases 1 and 2 shows that the tower grounding resistance is very important to the arrester energy stress when the lightning strikes the shield wire or tower top, since high grounding resistances tend to force the current to the phase conductors via the arresters.

If a flashover occurs outside the protected section as in case 2c, the energy stress is further increased in relation to case 3c where flashovers were suppressed in the calculation.

When the lightning stroke hits a tower at the end of the protected section, the stress is lower, as seen in case 4b when compared with 2b. However, if the stroke results in a flashover on the unprotected section, the energy stress goes up, as in case 5b.

Reducing the number of arresters in each tower will increase the arrester energy stress considerably. This can be seen from cases 6b through 9b when compared with the

TABLE II
CALCULATED ENERGY STRESSES

Case No.	Striking point	Tower position	No. of arresters	Grounding resistance	Design charge	Impulse current	Line arrester energy	Flashover occurrence
				Ohms	As	kA	kJ/kV	
1a	shield wire	centre	3	50	80	73	0.6	n.a.*
1b	shield wire	centre	3	50	80	90	1.0	n.a.*
1c	shield wire	centre	3	50	80	136	2.9	n.a.*
2a	shield wire	centre	3	300	80	73	2.3	no
2b	shield wire	centre	3	300	80	90	3.6	no
2c	shield wire	centre	3	300	80	136	12.6	yes
3c	shield wire	centre	3	300	80	136	7.7	n.a.*
4b	shield wire	second	3	300	80	90	1.6	n.a.*
5b	shield wire	second	3	300	80	90	2.7	yes
6b	shield wire	centre	2	50	80	90	1.3	n.a.*
7b	shield wire	centre	2	300	80	90	4.8	n.a.*
8b	shield wire	centre	1	50	80	90	1.9	n.a.*
9b	shield wire	centre	1	300	80	90	7.2	n.a.*
10	phase cond.	centre	3	50	2.6	48	2.1	n.a.*

*flashovers not included in the model

original cases 1b and 2b for the different ground resistance values.

Case 10 shows the energy stress for a lightning stroke to a phase conductor. Here, low grounding resistances result in high currents through the arresters, therefore, only the low-resistance energy stress is shown. Furthermore, the number of arresters installed in each tower is not critical in this case.

Although not covered by this study, it is obvious from case 10 that a stroke to a phase conductor in the vicinity of an end-tower may cause a high energy stress on the arresters in that tower. This is due to the fact that the end-towers must have a comparatively low grounding resistance to prevent flashovers on the unprotected section of the line.

It was also shown by the calculations that the energy stress on the station arresters was only about 20% of the line arrester stress.

5.2 Modelling of the Impulse Current

The calculations were carried out using the DCG version of EMTP. In order to reduce the computation time, the lightning impulse was represented by a single impulse with front and tail shape parameters chosen in accordance with [1]. The duration was adjusted to obtain the desired design charge value.

The representation of multiple strokes by a single impulse current was justified by performing additional calculations for cases 1b and 2b. The stroke sequence was modelled by a first stroke with the original amplitude 90 kA and two subsequent strokes with amplitudes of 35.6 kA. The total charge was divided into stroke charges of 57 As and 11.5 As, respectively. The ratios of current amplitudes and charge values between the first and subsequent strokes were based on the median values found in [1].

The calculations show that dividing the single impulse into three impulses give arrester energy stresses of 1.1 As compared to 1.0 As for case 1b (50 Ohms) and 4.2 As compared to 3.6 As for case 2b (300 Ohms). Considering that the ratio of current amplitudes between the first and subsequent strokes is also a statistical parameter, the representation of multiple strokes by a single impulse can be considered a reasonable approximation for calculations with EMTP.

6. ENERGY STRESSES ON ARRESTERS IN STANDARDIZED TEST PROCEDURES

6.1 Existing test methods

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 µs impulses of nominal current and two 4/10 µs 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 III, assuming a relative protection level of 2 times the rated voltage [3].

TABLE III
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.

6.2 Proposed Test Method for Lightning Energy Stresses

As can be seen from the calculated results in Table II, several cases will cause energy stresses that are comparable to the energy stress in existing standardized tests. However, the duration of the current impulse is generally quite different.

As an example, typical calculated arrester current wave shapes are shown in Figure 2 for case 1c, with a stroke current of 136 kA to the shield wire, a total charge of 80 As and a resulting arrester energy stress of 2.9 kJ/kV. Figure 2 shows the currents in the three arresters in the struck tower. As discussed previously, the current impulse used in the model represents the combined effect of multiple strokes, therefore, the actual duration of the individual stroke currents will be shorter. However, it can be concluded that for a stroke to the tower top or shield wire, the arrester current is typically triangular with a duration in the range of one hundred to several hundred µs. In existing standards, there is no test procedure covering this type of arrester duty.

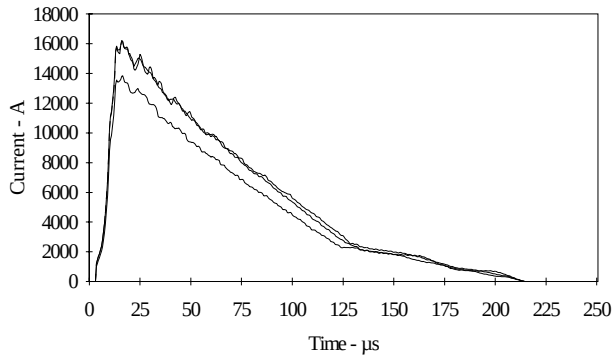

Fig. 2. Calculated arrester currents.

A suitable choice of test current to verify the energy capability of arresters in this application would be a sinusoidal impulse with a duration of 200 µs. The front of such an impulse is not as steep as in the real case, however, the effect of very steep fronts is already covered by the standardized high-current impulse test having a wave shape of 4/10 µs and an amplitude of 100 kA.

For shielding penetration, on the other hand, the duration of the arrester current is considerably longer since current will flow through the arresters during the major part of the stroke current duration. For the same amount of energy, strokes to the phase conductors are therefore better covered by the existing standards, i.e. the line discharge test.

6.3 Tests Performed with the Proposed Method

For the type of arrester used in the study, with a nominal discharge current of 10 kA and line discharge class 3 as per IEC, the expected energy capability for single impulses is at least 3 kJ/kV in the line discharge test, as seen in Table III.

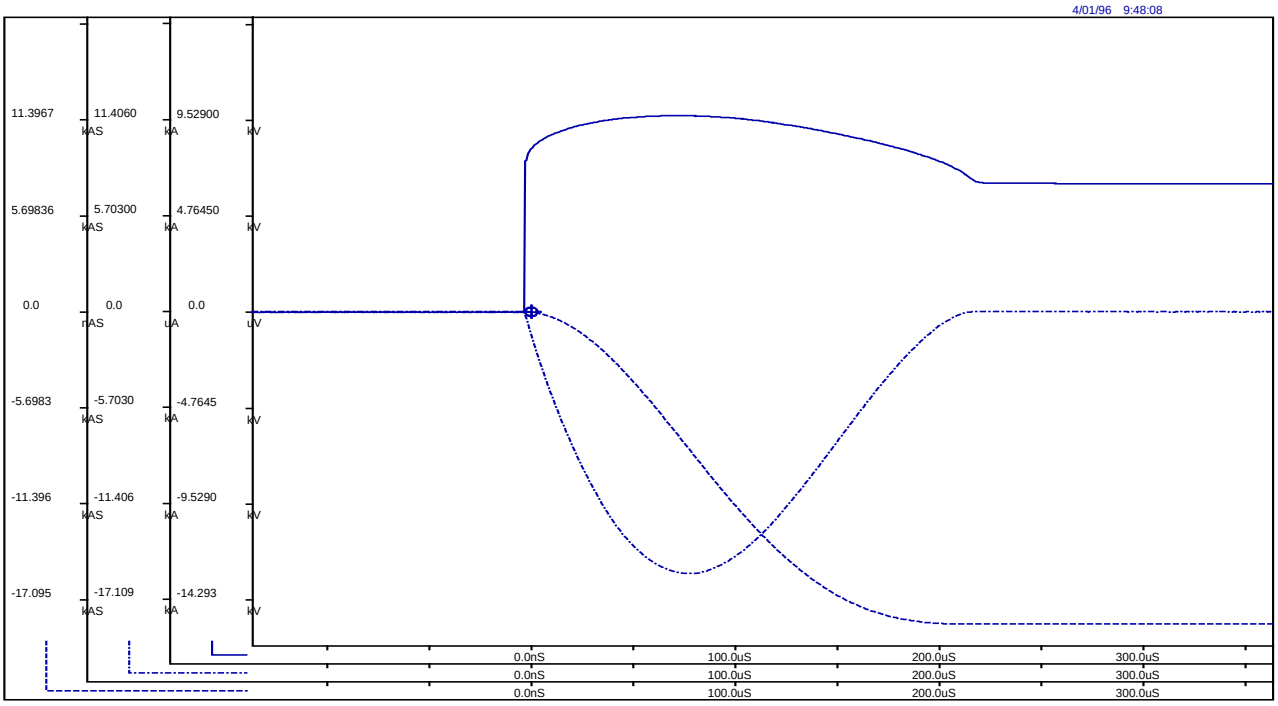

Fig. 4. Oscillogram from test with 200 µs current impulse.

Furthermore, for the particular arrester the rated energy is 4.5 kJ/kV, defined as the maximum energy the arrester can withstand for a 4 ms current impulse. However, it could not be taken for granted that the arrester is able to withstand the same amount of energy with a much shorter duration and much higher current amplitude.

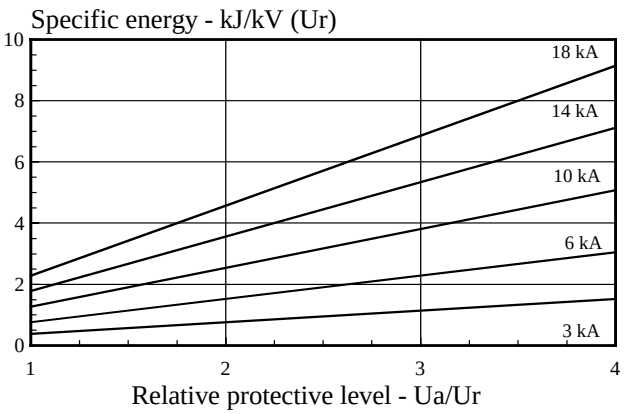

Fig. 3. Energy for a 200 µs sinusoidal current impulse.

To obtain the same arrester energy as for line discharge tests, but with a 200 µs sinusoidal impulse, the current amplitude can be found in Figure 3. As can be seen in the figure, the required current amplitude is about 15 kA to obtain 4.5 kJ/kV assuming a relative protective level of 2.5 p.u.

An oscillogram from application of such an impulse to a test sample with a rated voltage of 4 kV is shown in Figure 4. The actual current impulse had an amplitude of 15.6 kA and the total energy was 18.5 kJ corresponding to 4.6 kJ/kV. To verify a sufficient energy capability, a total of six discharges was applied to each of the ten test samples.

Since the specified test energy accounts for the combined effect of multiple strokes, there should be no need to apply the impulses with short time intervals. Therefore, the time between discharges was chosen long enough to let the samples cool to ambient temperature.

All test samples successfully withstood the test. Thus, a design lightning energy capability of at least 4.5 kJ/kV is considered appropriate for this type of arrester.

7. CONCLUSIONS

A statistical procedure for estimating the requirements on energy withstand of line arresters has been applied to a 138 kV line equipped with shield wire. The statistical approach provides a possibility to study the influence of various parameters on the arrester energy stress based on a given MTBF for the complete line arrester installation.

The study shows that tower grounding conditions are especially important to the arrester energy stress. It is essential to have a good knowledge about the actual grounding conditions when selecting the required energy capability of the arresters.

The towers at both ends of the protected section must have low grounding resistances to prevent flashovers on the unprotected sections This fact may lead to special

requirements on the energy capability of the arresters installed in those towers.

The highest stress will occur on arresters in the middle of the protected section, while the stress is reduced toward the ends. This is due to the differences in grounding conditions between the protected and unprotected line sections. The exception is the end-towers of the protected section, as discussed above.

The number of arresters installed in each tower is also important to the energy stress. A reduction in the number of arresters installed in each tower increases the energy stress. This should be taken into account when optimizing the number of arresters with regard to the trip-out rate of the line.

The amplitude of the stroke current also greatly influences the calculated results. In this study, different probabilities for the current amplitude were used to account for this effect, in lack of statistical data on the combined distribution of stroke current and total charge.

Flashovers on the unprotected section of the line tend to increase the energy stress on the arresters due to the additional current paths to ground that are established.

From the results presented in Table II, it is obvious that new applications like transmission line arresters could subject the arresters to energy stresses which are not covered by existing standards.

The amplitude and duration of the line arrester currents may differ significantly from the values used in standardized tests. An additional test procedure with a current impulse duration of approximately 200 µs is therefore suggested. The aim of the test is to verify the capability of the arrester when subjected to energy stresses from lightning including the effect of multiple strokes.

8. REFERENCES

[1] CIGRÉ SC 33/WG 01, "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines," 1990.

[2] K. Berger, R.B. Anderson, H. Kröninger, "Parameters of Lightning Flashes," *Electra*, no. 41, July 1975.

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