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Rocket-Triggered Lightning Experiments on Zinc Oxide Arresters and Their Applications to Power Transmission Lines

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SUMMARY

In measurements of rocket-triggered lightning current and voltage performed between 1986 and 1995 on the mountain top of Okushishiku in the Kanazawa area, the authors succeeded in artificially inducing winter lightning to arresters. Using the data obtained from those measurements, we analyzed the energy absorption characteristics of surge arresters, such as are installed on every transmission line tower for three phrases, by EMTP.

The energy withstand capability of an individual arrester was verified to be approximately the same as the expected value. The analysis results for the energy share of each arrester connected in parallel showed that the usual light duty arresters installed on every tower have the possibility to be able to absorb extreme winter lightning energy even if the lightning hits the power line directly. ©1998 Scripta Technica. Electr Eng Jpn, 122(4): 25–33, 1998

Key words: Rocket-triggered lightning experiment; winter lightning; transmission line arresters.

1. Introduction

The majority of accidents on overhead power transmission lines are caused by lightning strikes. Installation of zinc oxide lightning surge arresters on transmission towers is actively promoted as a measure to protect against such accidents, especially on double-circuit lines [1]. At present, external gaps are used to protect arresters from such accidental damage as direct lightning strikes (shield failure), but we believe that in the future they will be replaced with gapless arresters which make it possible to distribute the energy. An important feature of gapless arresters is that the current generated by a direct strike from strong winter lightning on a power line will be branched to arresters installed on all towers, thus dissipating the energy.

The authors were members of a team involved in rocket-triggered lightning experiments conducted initially (from 1977) at Kakokengata (Ishikawa Prefecture) and from 1996 at the top of Okushishiku Mountain. Over a period of eight years, from 1988 to 1995, we managed to induce ten direct lightning strikes on ground-based arresters. In the course of these experiments, we obtained valuable information concerning surge protection equipment, including actual measurements of the current and voltage applied to the arrester, examination and analysis of damaged arresters, studies of conditions of damaged ZnO elements, and estimates of the breakdown energy.

Based on data obtained from 152 successful cases of lightning induction over the period of 1977–1995 [2] and results of experiments on surge arresters, we formulated assumptions concerning the typical waveform of winter lightning current. Using an EMTP, we analyzed the energy absorbed by all arresters when gapless arresters are installed on all transmission towers.

Below, we provide explanations concerning the set up used in the experimental induction of lightning and the results of our analysis of the energy distribution characteristics of arresters for power transmission lines, as well as specifications for arresters used in power transmission lines.

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2. Summary of Rocket-Triggered Lightning Experiments

2.1 Experimental methods

Figure 1 depicts the measurement circuit used in the experiments. Lightning strikes were induced directly to a gapless arrester by launching a rocket with an attached wire. The measurements were carried out by converting electrical output signals from a coaxial shunt and a resistance-type potential divider, to optical signals (E/O conversion) which were transmitted by optical fiber cables to an O/E converter. The converted electrical signals were fed to a data recorder having response characteristics from 0 to 40 kHz (in some cases, to 125 kHz).

The surge arresters used in the experiments were polymer housed devices designed for 22 kV transmission line arresters (some for 66 kV lines). Usually, we used one arrester; however, in 1994–95, experiments for measuring the shape of absorbed energy were conducted on two arresters connected in parallel, and each arrester was connected to the memory via a Rogowsky coil.

2.2 Results of measurements

The results of ten successful cases of triggered lightning in the course of experiments conducted over the 8-year period from 1988 to 1995 are shown in Table 1.

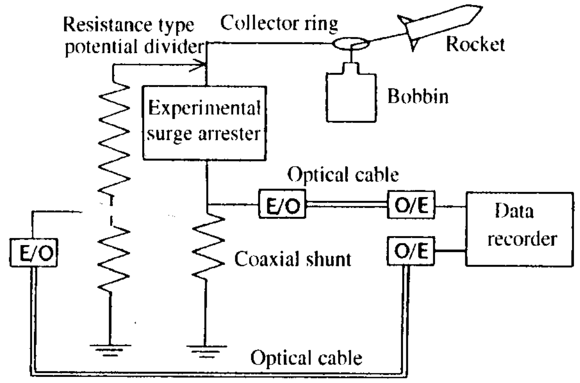

Fig. 1. Measurement circuit used in experiments.

(1) Magnitude of the lightning current

As one can see from Table 1, the magnitude of the lightning current was within the range ±1–50 kA; the current polarity was positive in seven out of ten cases, negative in two cases, and in one case it was both positive and negative. The duration time was 15 to 200 ms.

Charge was measured only in seven cases. Its magnitude varied from 12 to 460 C, which is 10 to 100 times greater than charges observed in summer lightning, usually not exceeding several coulombs. These extremely large charges have a tendency to self discharge (over a long period of time).

Table 1. Results of measurements

Experiment No.	Date	Max. current value (kA)	Interruption time (ms)	Charge (C)
88-07	11/16/88	+11.4	—	—
89-08	11/18/89	+32.25	approx. 30	approx. 460
89-14	11/28/89	+9.9	approx. 20	approx. 60
90-11	12/2/90	+1.0	approx. 25	12.0
90-17	12/2/90	−1.0	impulse	< −1
91-02	11/11/91	+15.1	35.1	89.6
91-05	11/14/91	+50.0	14.5	97.1
93-11	11/23/93	−3.4	184.0	−76.1
94-15	11/26/94	+14.0	54.0	166.0
95-06	11/11/95	−3.8/+4.6	225.0	−98/23.7

(Note: All elements of arresters, except for the arresters used in experiment No. 90-17, were damaged.)

In the course of rocket-triggered lightning experiments conducted over a period of 19 years (1977–1995), we had 152 successful cases of lightning inducement in which the largest observed magnitude of the lightning current was approximately 60 kA (150 kA in pulse) and the largest magnitude of the charge observed was about 500 C [2].

(2) Damage to arresters

Damage to arresters was manifested in the fact that, except for the case of pulse currents of the order of 1 kA (less than 1 C), all ZnO elements were damaged. However, the pressure relief device operating as safety equipment at the time when the ZnO elements were damaged worked properly at current values over 10 kA (60 C and higher); it operated properly even at combined positive and negative charges of over 100 C when the current magnitude was 3 to 4 kA. However, at intermediate current (–3.4 kA) and charge (76.1 C) values, all ZnO elements were damaged and arc discharges inside the housing resulted in gas generation, which caused swelling of the housing, thus rendering the pressure relief device inoperable.

It is reasonable that ZnO elements were damaged, because the large charge from winter lightning completely passed through the ZnO elements. It was verified, however, that the pressure relief device could operate properly when large internal arc energy was generated, even if without power frequency fault current. We believe this to be the first time this phenomenon has been established in Japan, perhaps also in the world.

(3) Energy withstand capability of elements

The capability of elements to withstand energy before being damaged can be expressed as $\int i \cdot v dt$ (where i is the current through the arrester and v is the voltage across the arrester). In many cases it was impossible to determine the moment when the element was damaged because of unstable operation of the voltage measuring system. In cases when it was possible to determine the moment of damage, we were able to find the breakdown energy of elements (in J/cm^3) based on the known V-I characteristics of the element and the value of $\int i \cdot v(i) dt$. An example with these characteristics is shown in Fig. 2 [3]. Breakdown energy was calculated for two cases (among 10 experiments) for which the current waveform and the time of the element damage could be determined. The calculated values, 840 J/cm^3 (Experiment 91-02) and 850 J/cm^3 (Experiment 94-05), were substantially higher than previously published data, 125 J/cm^3 [4], 250 J/cm^3 [4], and 400 J/cm^3 [5].

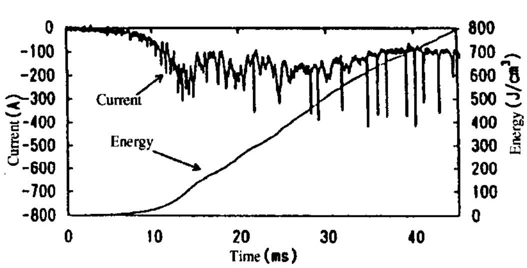

Fig. 2. Energy calculated as a function of lightning current.

3. Characteristics of Energy Distribution in Gapless Arresters Mounted on Power Transmission Lines

3.1 Background

In Japan, the approved system for protecting power transmission lines from lightning strikes is based primarily on shielding by means of overhead ground wires. In the event of a current surge generated by lightning in a supporting tower or in an overhead transmission line, the protection system briefly interrupts current through both circuits of a double circuit line and then immediately restores the power supply. However, due to the ever increasing need for reliable power supply presented by the demands of an information intensive society, the studies are being concentrated on eliminating occurrences of double circuit line tripping by mounting compact but highly reliable zinc oxide arresters on transmission towers. Field tests of 66/77 kV class gapless arresters began in 1978, polymer housed arresters with external gap were implemented in 1986, and recently, units for 500 kV transmission lines have been developed [1, 6]. Studies have also been undertaken on gapless ZnO arresters incorporated in suspension insulators. Field tests on such insulators began in 1992 and it is expected that they soon will be placed in operation [7]. In the United States, starting in 1985, polymer housed gapped arresters for 138 kV systems were field tested [8, 9], and later they were installed on lines of under 66 kV rating [10].

At present, polymer housed arresters with an external gap are the mainstream of this technology. However, the authors believe that the future configuration of surge protection systems will be centered around small-size, lightweight, economical, polymer housed, gapless arresters able to withstand high energy winter lightning strikes, that will be installed on all transmission circuits and towers, thus providing more reliable and economical power supply. In order to investigate the feasibility of such a system, we conceived a series of experiments for the purpose of determining the energy withstand capability of individual ZnO arrester elements by means of EMTP, based on the assumption that lightning strikes the power transmission line directly (shield failure) and a determination of the minimum possible size of the arresters.

3.2 EMTP analysis

We used the values obtained from experiment No. 91-02 (out of a total of 152 experiments on lightning strike inducement) as representative data for the current and charge (15.1 kA, 90 C) that describe the current waveform generated by a winter lightning strike [2]. These were considered maximum energy levels to be dealt with by an arrester in the event of a direct lightning strike to a transmission line as a result of shield failure.

1. Assumptions for the analysis

(1) The object of study is a 77 kV power transmission line.

(2) A direct strike to the power transmission line occurs as a result of shield failure at the middle point of the line.

(3) From the waveform of experiment No. 91-02 (see Fig. 4 (a)), we analyzed the TOV (temporary overvoltage) area. Therefore, it is possible to disregard the resistance of the tower and the footing resistance for the TOV area.

(4) In order to simplify analysis of arresters for transmission lines, we considered only gapless arresters contemplated for future applications.

(5) The analysis was made for three-phase systems.

2. Model and parameters assumed for the analysis

(1) 77 kV power transmission line (with 30-m towers):

A three-phase distributed constant circuit with allowance made for mutual induction (fixed line length of 40 km).

- positive phase circuit: $r = 0.01$ Ohm/km; $L = 1.75$ mH/km; $C = 0.0067$ μF/km
- zero phase circuit: $r = 0.1$ Ohm/km; $L = 6.33$ mH/km; $C = 0.0034$ μF/km

(2) Substation transformer:

- 20 MVA, 77/6.6 kV, Y-Δ connection
- leakage inductance = 100 mH (corresponds to 12% of the impedance)
- saturation is disregarded for the excitation characteristics

(3) Impedance of the power generating source:

- capacity: 20 MVA; 6.6 kV
  $X'd = 1.7$ mH (corresponds to 30%)

(4) Neutral point grounding:

- resistance grounding (111 Ohm: 400A grounding) and direct grounding

Table 2. Characteristics of arresters for 77 kV lines

Current (kA)	2.5	10	50
Voltage (kV)	167	191	261

(5) Characteristics of arresters for the transmission line:

- modeled after Type 92 non-linear resistance having the characteristics shown in Table 2
- characteristics of an individual arrester for transmission lines are as shown in Table 2, but since it would be practically impossible to execute computations based on a model calling for the installation of arresters on all towers over the entire length of the transmission line (40 km), 20 units were considered as one arrester, and therefore the characteristics were determined for 20 arresters connected in parallel at a rate of 1 unit per 4 km

The equivalent circuit used for the analysis is shown in Fig. 3.

(6) Waveform of the input lightning current:

- Fig. 4(a) depicts an actual waveform obtained in experiment No. 91-02; the line shown in (b) is a simulated input lightning current waveform Type 13 of EMTP similar to that shown in (a), applied to an arrester. The lightning path impedance is 400 ohms (resistance component only).

(7) Analysis parameters:

- the grounding system, the saturation excitation characteristics of the transformer, the superimposed high-frequency components, the magnitude of the lightning current, and the time axis and input waveform of an intensive lightning strike are the analysis parameters.

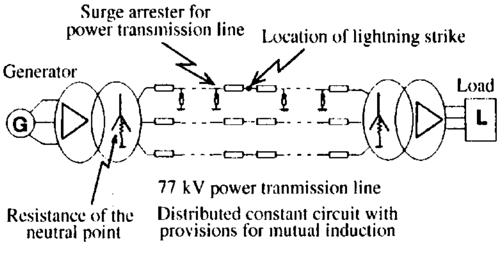

Fig. 3. Equivalent circuit.

Table 3. Analyzed cases and maximum absorbed energies

Case	Parameters		Resistance grounding system (kJ)	Direct grounding system (kJ)
0	Base case	—	66 (1.00)	66 (1.00)
1	Lightning current magnitude	×2	188 (2.84)	183 (2.77)
2	"	×4	492 (7.45)	510 (7.73)
3	Time axis	×2	91 (1.38)	93 (1.41)
4	"	×4	123 (1.88)	91 (1.38)
5	10 kHz current superimposed	8 kA*1	88 (1.33)	84 (1.27)
6	"	4 kA*1	69 (1.05)	69 (1.05)
7	3.3 kHz current superimposed	4 kA*1	70 (1.06)	69 (1.05)
8	"	4 kA*2	91 (1.38)	85 (1.29)
9	Saturation char. of transformer	(I)	66 (1.00)	62 (0.94)
10	"	(II)	66 (1.00)	64 (0.98)
11	Waveform of large lightning	91-05	207 (3.14)	210 (3.18)
12	154 kV system	—	87 (1.32)	88 (1.33)
13	275 kV system	—	100 (1.52)	99 (1.50)
14	Single phase analysis	—	40 (0.61)	29 (0.44)

Note: *1 and *2 indicate conditions when a high frequency current was superimposed on the lightning current waveform of experiment 91-02 over the section where the current magnitude is larger than 8 kA and 4 kA, respectively.

Cases 12 and 13 are similar to the base case with respect to the system conditions, but the characteristics of the line arresters are different. (Arresters for 154 kV are rated 2 times higher, and arresters for 275 kV are rated 2.5 times higher.)

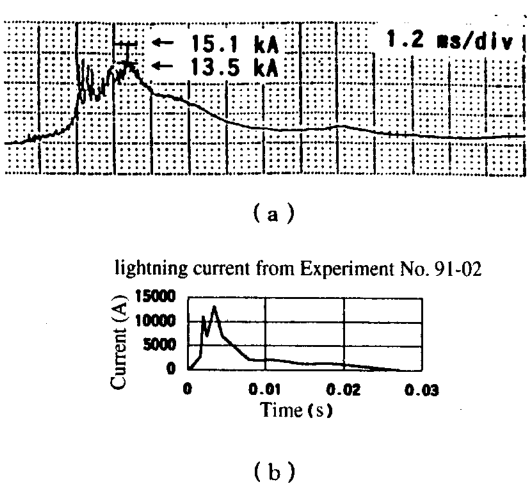

Fig. 4. Input lightning current waveform.

3.3 Analyzed cases

The cases analyzed according to our parameters are summarized in Table 3; 154-kV and 275-kV systems and a single-phase circuit were also analyzed for reference purposes.

Figure 5 shows waveforms of the input lightning current for the cases when: (a) the lightning current magnitude is doubled; (b) the time axis of the lightning current is enlarged twofold; (c) a 10 kHz high frequency 8 kA current is superimposed on the main curve; and (d) a 33 kHz high frequency 4 kA current is superimposed on the main curve. Figure 5(e) shows the saturation characteristics (two types) of the transformer and Fig. 5(f) is a simulated waveform of the input lightning current of experiment No. 91-05.

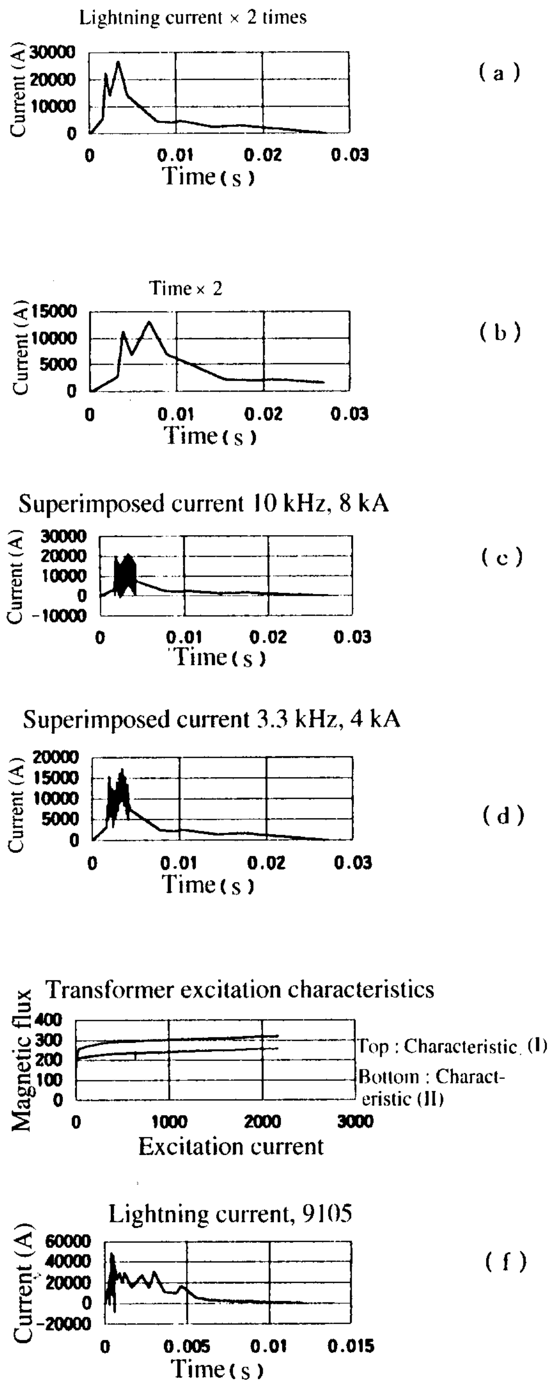

Fig. 5. Parameters of input waveforms.

3.4 Results of analysis

The results of the analysis are summarized in Table 3. The values in the table reflect the maximum energy absorbed by arresters for power transmission lines. Values in parentheses are factors for individual cases relative to the base case.

3.5 Considerations

Our considerations are based on the fact that the arrester closest to the location of the lightning strike must absorb the greatest energy.

(1) The ratio of the absorbed energy values for three-phase analysis (Case 0) and single-phase analysis (Case 14) [11] is 66/40 = 1.65. This difference is produced by the differences between the models of the transmission lines and transformers. In the transmission line model for the single-phase analysis, a distributed constant circuit is used, but for the three-phase analysis we used a distributed constant circuit including a contribution due to mutual induction (the single-phase circuit and the positive phase circuits of the three-phase circuit are equivalent); therefore a difference caused by mutual induction and the zero-phase circuit appears. (Circuit impedance plays a major role in the current generated by a lightning strike; therefore the voltage at the strike location is increased, without substantial effect on the substation voltage.) The transformer model used in a single-phase circuit analysis takes into account only the leakage impedance, but the model for a three-phase circuit analysis includes both the excitation impedance and the leakage impedance; therefore the results of the three-phase analysis are affected by the excitation impedance. We believe that these factors do not substantially affect the voltage at the lightning strike location in the single-phase analysis compared with the three phase analysis. However, the effect of these factors is more noticeable in directly grounded systems.

(2) In Cases 1–4, the increase in the lightning current value and the enlargement of the time axis resulted in the maximum absorbed energy. In Cases 1–2, the absorbed energy is increased due to an increase in the lightning current value. In Cases 3–4, the absorbed energy is increased due to an increase in the voltage at the absorption point owing to an increase in the direct current passing through the resistance grounding system. On the other hand, with the direct grounding system, the absorbed energy changes only slightly due to voltage oscillations arising at the lightning strike point as a result of the substation reaction.

(3) In Cases 5–8, we investigated the effect from oscillating components superimposed on the current. The contributions from oscillating components depends on their duration and current value, but their overall effect on the energy is not significant. Taking into account the tower surge impedance, we believe that it is safe to assume that

the energy to be absorbed by the arrester at the point of the lightning strike will be even lower.

(4) In Cases 9–10, we investigated the effect produced by differences in the excitation characteristics of the transformer and found that the effect was only minor.

(5) In Case 11, we investigated the worst case scenario in which the power transmission line received a direct (shield fault) strike from rocket-triggered winter lightning, resulting in a 50 kA current impulse having a long waveform. The shielding conditions usually depend on the position of the overhead ground wire, height of the tower, and the distance from the lightning strike location. As for the distance from the lightning strike location, the expression $R_{ss} = 6.72 I_L^{0.8}$, based on the A-W theory; is not necessarily correct. Berger/Anderson, Golde, Wagner, and other researchers have advanced a number of other options. In this paper, we assume that the shielding failed on the tower shown in Fig. 6 due to a current surge lower than 23 kA and due to a current surge of 15 kA as specified in experiment 91-02 [12]. The waveform in Case 11 is based on the waveform of experiment 91-05 with oscillation peaks superimposed. Despite the fact that these peaks are of a rather large magnitude, their combined contribution to the energy is insignificant (see Cases 5–8). Therefore, the increase in the absorbed energy from Fig. 5(f) consists of additional oscillation components. Since the current magnitude of these components is large (approximately 20 kA), the absorbed energy is higher than in the base case (about 10 kA).

(6) In Cases 12 and 13, which apply to 154 kV and 275 kV systems, we think that the absorbed energy is increased by an amount corresponding to an increase in the limiting voltage of the transmission line arrester, but since the arresters for 154 kV and 275 kV systems are large, the absorbed energy per volume of the arrester element (J/cm^3) is even lower than that for the arresters of the 77 kV system, and should not represent any problem.

(7) For the purposes of analysis covering the subject of this paper, and based on consideration of the tool and the time required for the analysis, we have proposed to treat 20 arresters as a single unit formed by 20 arresters connected in parallel (see section 3.2 (2) and (5)). However, in order to study the performance of 20 units, we have compared several cases for a 20 km long transmission line with the arresters mounted at 200 m intervals. From the results of these studies, it became clear that the calculated maximum absorbed energy of a group of 20 arresters arrayed at 200 m intervals is 3 to 4 times higher than the maximum absorbed energy of a single arrester. (The energy distribution ratio changes depending on the width along the time axis, and the ratio tends to be low when the width of current is low. In experiment 91-02 described in this paper, the interruption time is 3 to 4 times longer.)

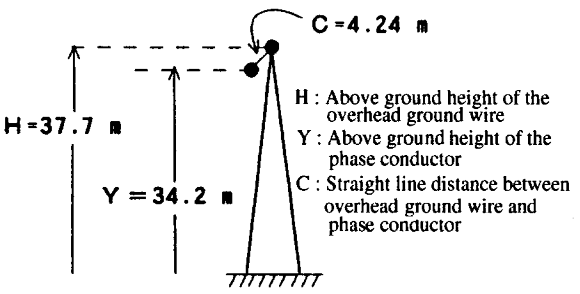

Fig. 6. Support tower for 77 kV system.

4. Considerations Concerning the Specifications for Arresters Used in Transmission Lines

Below, we analyze the results of our experiments and cases in which arresters were installed on all towers of a 77 kV (154 kV, 275 kV) power transmission line.

4.1 Specifications for ZnO elements

The advantages of ZnO arresters, from the standpoint of installing multiple arresters on transmission line towers, include their compactness, light weight, and economic efficiency. Another important feature of ZnO elements is that they can be made with small diameters.

However, according to current specifications [1], arresters have external series gaps, and in the event of a rare strong winter lightning strike directly on the power line (shield failure) the lightning current will not be branched (or will be branched to only few channels). This will result in damage to the arrester. In contrast, installation of a large number of arresters in parallel reduces the energy share to each individual arrester.

On the other hand, according to the analysis given in the preceding sections, even if the transmission line is directly struck by lightning of the same category as in experiment No. 91-02 (about 15 kA, 100 C), the energy withstand capability of the arrester (> 500 J/cm^3) is greater than the energy actually applied to the arrester (70 J/cm^3). Even arresters located near the lightning strike location, where the energy applied to an arrester may be as high as 200–300 J/cm^3, have a sufficient margin of safety (for a group of 20 units, it is 3 to 4 times higher). However, if the lightning current is 2 to 4 times higher (Cases 1, 2), the energy density can be as high as 400 to 1,200 J/cm^3, and at these magnitudes one can expect that ZnO elements will break down. Considering that such large winter lightning strikes do not happen very often and that the shield performance is sufficiently high, we plan to investigate these issues in the future.

It is reasonable to expect that the installation of surge arresters on all towers and on all phase lines as described above will considerably reduce the possibility of tripping of not only two circuits, but also one circuit in double circuit power transmission lines, thus improving the overall reliability of power transmission lines.

4.2 Topics for future studies

The full-scale implementation of compact and economical surge arresters for power transmission lines requires additional study, covering the following topics:

1. Subjects for examination

(1) Effect of ground resistance
- Dispersion and absolute values.
- Frequency characteristics and current characteristics.

(2) Interaction with substation surge arresters
- General characteristics (JEC-217).
- High performance type (JEC × 0,7).

2. Subjects for investigation and decision making

(1) Treatment of summer lightning
- At the present time, it is assumed that the wave pattern of summer lightning strikes is (1-2)/70 μs. In the usual measurement of lightning current, a magnitude less than several kA is not detected, thus there is no evidence as to whether the measurements include such a range of current in its tail part.
- At the present time, the lightning current value for 66/77 kV lines is assumed at 30 to 40 kA; it is necessary to increase this value to above 60 kA.

(2) Shield failure
- We think that it is necessary to reconcile the approaches to shield failures that are adopted in Japan [12], in the United States [13], and by CIGRE [14].

(3) Long-term reliability of polymer housing
- Establishment of methods for accelerated aging tests (effects of electric loads, weather and composition).
- Economic considerations regarding polymer materials and manufacturing processes.

(4) Specifications for disconnectors
- Operational characteristics (I-t).
- Design (configuration after tripping).

5. Conclusions

In this paper, we have provided a review of experiments on rocket-triggered lightning strikes, an analysis of the maximum absorbed energy based on the EMTP modeled current waveform generated by typical winter lightning, and an examination of specifications for compact economical surge arresters used in power transmission lines. We have suggested several subjects for future investigation. We think that further investigations are needed in such important areas as the specifications for surge arresters for transmission lines and the methods of their installation accepted in other countries, as well as methods of field testing. We would be happy to receive any suggestions, critiques, and proposals in this respect.

Acknowledgments

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