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Evaluation and Application of Oil-Immersed Zinc Oxide Elements Enclosed in Pole-Mounted Distribution Transformers

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SUMMARY

Voltage due to lightning surge is now a major problem to be overcome to ensure full reliability of any power supply. Hence, gapless oil-immersed surge arresters using zinc oxide elements have been applied to pole transformers. These surge arresters are used as a means of insulation coordination for pole transformers. These arresters contribute to the reduction of the number of failure of pole transforms. This paper describes applications and effects of specially developed oil-immersed surge arresters in pole transformers on 6.6-kV distribution lines. © 1997 Scripta Technica, Inc. Electr Eng Jpn, **121**(2): 37–46, 1997

Key words: Lightning; distribution line; arrester; zinc oxide element; oil-immersed; transformer.

I. Introduction

Failures of power equipment have been recently reduced in number due to active development and implementation of new techniques. Among the reasons for failures are overvoltages related to both direct and induced lightning strokes because of the relatively low level of insulation of insulators and various equipment as compared to that of transmission lines and power substations. In the context of lightning-protection measures in distribution networks, such techniques have been proposed as overhead ground wires and lightning arresters [1]. Figure 1 shows distribution of power supply faults for 6.6-kV distribution lines; as seen from the diagram, 43.2% is related to pole transformers [2]. On the other hand, the fault rate of pole transformers for nine power suppliers changed from 24 per million units per year in 1985 to 17 per million units per year in 1991 [3]. As to lightning protection of pole transformers by means of lightning arresters, a variety of techniques have been used such as installation of surge arrester elements, mounting of arresters in high-voltage cutout fuses [1, 4], and application of surge-arresting elements enclosed in pole transformers [5–8]. This paper is dedicated to evaluation of surge-arresting elements made of zinc oxide elements placed into

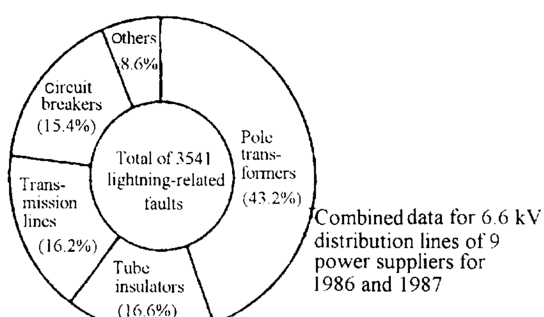

Fig. 1. Classification of lightning-related faults in power distribution equipment.

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ceramic containers [9], and their application to pole transformers in 6.6-kV distribution lines.

2. Design Concept of Oil-Immersed Surge Arresters

The basic design concept of lightning surge arresters is to improve lightning protection of pole transformers by enhancing the overvoltage-suppression effect through the use of surge arresters immersed in the transformer oil, and therefore shortening the lead wires from the surge-arrester elements to the transformer windings. Figure 2 shows comparative configurations in open-air lightning arresters, and in a surge arrester enclosed in pole transformer. Explained below are key questions to be investigated in the application of surge arresters to pole transformers in distribution lines.

(1) Should series-gap devices be employed, or gapless elements with zinc oxide?

(2) Should surge arresters be built into pole transformers, or installed externally?

(3) What temperature specifications should be designed with regard to operating conditions inside pole transformers?

(4) What kind of relationship exists between overvoltages in distribution lines, test voltage in site testing, and reference voltage?

(5) What kind of container should be employed, open-type or closed-type?

(6) Can degradation of service life due to the adsorption of oil immersed arresters be avoided?

(7) What kind of maintenance and inspection should be used?

The authors have implemented the concept by solving the above problems.

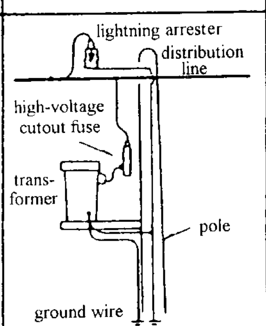
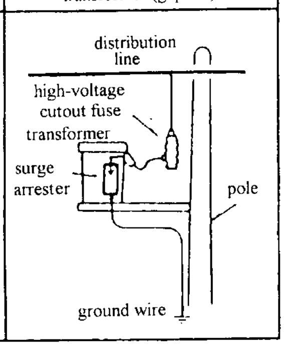
Type	Surge arrester with series gap	Surge arrester built in pole transformer (gapless)
Layout		

Fig. 2. Comparison between installation of open-air surge arresters, and incorporation of oil-immersed surge arresters in pole transformers.

2.1 Overvoltage suppression by surge arresters

The basic approach to protection of equipment by means of lightning surge suppression using surge arrester elements is to make the terminal voltage V of the equipment closer to the terminal voltage E_a of the arresters, which implies more effective coordination of overvoltage protection. In other words, the potential rise ($L \cdot di/dt$) caused by the inductance L (of lead wires, ground wires, and so on) should be reduced as much as possible.

$$V = E_a + L \cdot di/dt$$

In case of gapless surge arrester elements built into pole transformers, the limiting voltage is 36 kV/2.5 kA, which is higher than the rated limiting voltage of 33 kV/2.5 kA offered by series-gap arresters [10]. On the other hand, gapless arrester elements offer better response for steep waveforms of lightning voltage [11], which means good coordination with pole transformer insulation. Besides, building of oil-immersed arrested elements into pole transformers would automatically solve the problem of immersion into porcelain containers.

2.2 Setting of ambient temperature for surge arresters

Ambient temperature is an important factor for zinc oxide elements. With pole transformers, the normal year-average temperature of oil in operational state is about 85°C, but the temperature may exceed 100°C for short overload periods due to load fluctuation. Thus, continuous service temperature for surge arresters was set as an ambient air temperature of 40°C plus a temperature rise of 70°C, corresponding to 130% overload operation, and a temperature rise of 10°C due to direct sunlight, totaling 120°C.

2.3 Setting of reference voltage for surge arresters

Since 6.6-kV distribution lines belong to a noneffectively earthed system, temporary overvoltage in sound phases in case of one-phase ground fault should be taken into account when using zinc oxide elements. While quite uncommon in isolated-neural systems, overvoltages caused by the intermittent arc phenomenon have a theoretical value of about 3.5 pu with duration of several seconds (see Fig. 3). The standard JEC-217-1984 "metal oxide surge arresters" specifies a temporary overvoltage of 3.2 pu × 10 s. As shown in Fig. 4, surge-arresting elements can be made to withstand a voltage of 3.5 pu × 10 s by setting higher reference voltage. On the other hand, zinc oxide elements are temperature-dependent, a fact which should be taken into consideration when setting reference voltage. Figure 5

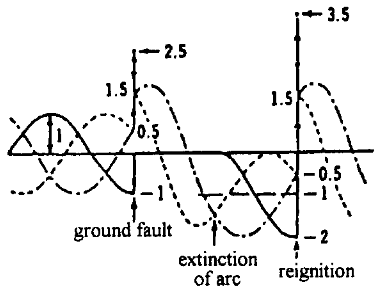


Fig. 3. Intermittent arc phenomenon in isolated-normal system [12].

shows examples of voltage-current characteristics at the normal temperature and at 120°C. Figure 6 shows the relation between ambient temperature and reference voltage. As evident from the figures, the reference voltage drops by about 10% at 120°C as compared to the normal temperature. Thus, the reference voltage of the surge arrester elements was set to over 17 kV at 120°C, and to 18.5–21 kV at the normal temperature. These values are higher than the lower limit of 14.3 kV for 8.4 kV surge lightning arresters specified in JEC-217-1984. An example of discharge voltage-current characteristics of surge arrester elements is shown in Fig. 7, while typical specifications are listed in Table 1.

In addition, such factors have been also regarded as complying with on-site withstand voltage tests at 6.6 kV distribution lines (testing voltage of 10.35 V_{rms} = 6.9 kV rms × 1.5 pu = 14.7 kV_p), resistance to probing pulses of fault detector (peak value of 15 kV, pulse width of 10 ms), and others.

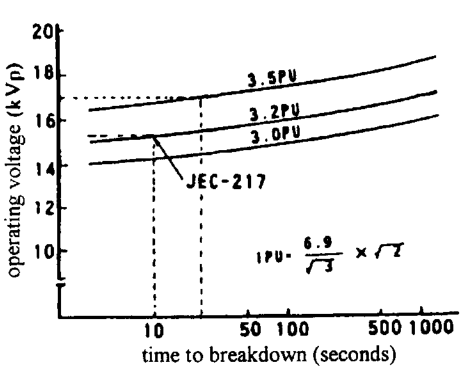


Fig. 4. Temporary overvoltage vs. time-to-breakdown (commercial frequency).

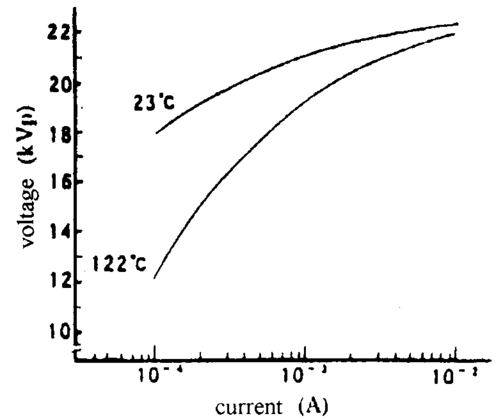


Fig. 5. V-I characteristics of surge arresters in low current area.

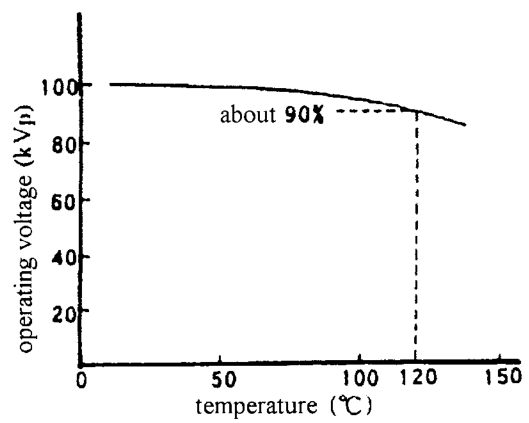


Fig. 6. Temperature vs. reference voltage.

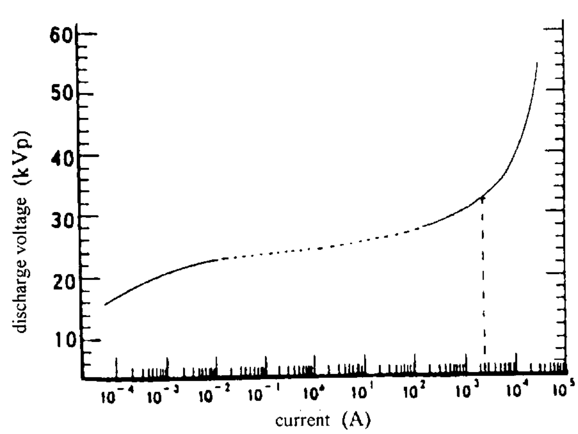


Fig. 7. Discharge voltage-current characteristics of surge arrester elements.

Table 1. Specifications of surge arrester elements

Characteristic	Base value
Ambient temperature	120°C in oil (continuous)
Continuous operating voltage	$6.9/\sqrt{3}$ kV_{rms}
Rated voltage	8.4 kV_{rms}
Nominal discharge current (8/20 μs)	2.5 kA
Reference voltage (V_{1mA})	above 17 kV at 120°C
Discharge voltage (8/20 μs, 2.5 kA)	above 36 kV
Stability test (JEC-217)	Aging test 150 hours in oil at 120°C, applied voltage ratio of 75%
Lightning impulse current (4/10 μs)	10 kA
Rectangular wave current (2 ms)	75 A
Temporary overvoltage	3.2 pu × 10 s

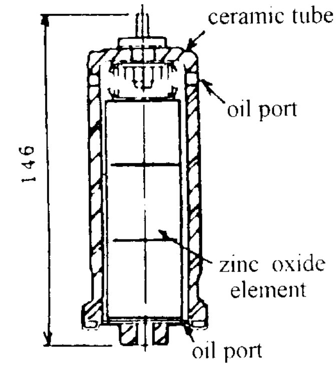


Fig. 9. Construction of surge arrester.

2.4 Construction of surge arresters

When building surge arresters in pole transformers, it is important to simplify the structure of elements themselves, and to optimize their mounting position (distance from oil surface in transformer). An example of a lightning-proof transformer with surge-arresting elements is given in Fig. 8.

The main structural elements follow: (1) Insulating pipe (FRP pipe), epoxy container, ceramic container and some other solutions were considered as containers for arresting elements, and finally, ceramic tubes were chosen in terms of operating conditions and cost. (2) As for the type of insulation inside the container, the design was chosen as shown in Fig. 9; that is, through holes provided in the ceramic tubes, and the arresting elements were immersed in transformer oil to insulate and to cool the zinc oxide elements by means of natural convection. (3) As for the mounting position of arresters, the oil level was set so that arresting elements protruded from the oil surface, thus preventing involvement of air bubbles. An outside view of surge arresters built into a pole transformer is shown in Fig. 10.

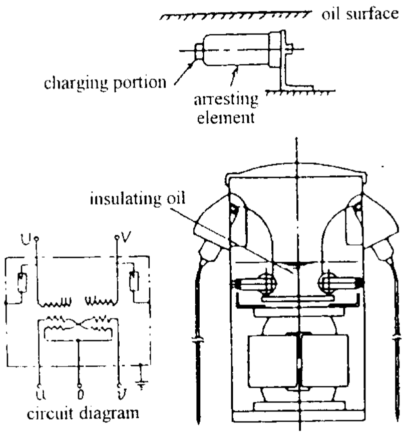


Fig. 8. Construction of pole transformer for distribution lines (with built-in surge arresters).

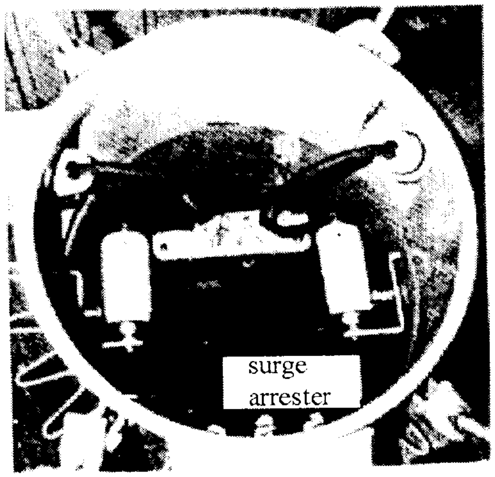


Fig. 10. Outside view of surge arresters built in pole transformer.

3. Evaluation of Surge Arresters

3.1 Service life

Since surge arresters are immersed in hot oil in pole transformers, the most important point of evaluation is the service life of zinc oxide elements when energized in oil. An example of temperature dependence for leakage current and watt loss of zinc oxide elements at normal operation in oil is shown in Fig. 11. Zinc oxide elements offer a negative temperature coefficient in the area of normal-voltage operation, while leakage current increases with ambient temperature. Since the leakage current grows with time, in the initial stage of development of zinc oxide elements for power applications, the service time was evaluated at actual operating temperature from the Arrhenius empirical formula $L = \exp(-E/kT)$, where L is the service time, E is the activation energy, T is the is absolute temperature, and k is the Boltzmann constant. Using the fact that the degradation factor grows by a factor of 2.5 with a temperature rise of 10°C, temperature-accelerated tests were developed. The standard JEC-217-1984 "Zinc oxide lightning arresters" prescribes tests at 105°C for 180 h, or at 115°C for 70 h, which corresponds to 30-year operation at 25°C. Besides, experiments suggest that the degradation factor for zinc oxide elements increases by a factor of about 8 with the voltage application ratio increasing by 10%. Figure 12 shows the baseline of service life of zinc oxide elements as estimated by means of accelerated tests. In our experiments to evaluate the service life of zinc oxide elements, the conditions were set as follows: voltage application ratio 75%, ambient temperature 120°C, energizing time over 150 h. From the example of test results shown in Fig. 13, the leakage current and watt loss of zinc oxide elements are sufficiently stable. In addition, to investigate environmental influence, the authors investigated the following three cases: (1) 50 cc of transformer oil + 1 cc of water (transformer oil with water content of 2%), (2) pure transformer oil, and (3) atmosphere (air). In the tests, the voltage was set 1.5 times higher than the normal operating voltage to be applied during 2.5 h (which corresponds to applying the normal voltage for about 10 years) at the ambient temperature of 120°C. As may be seen from the results shown in Fig. 14, the leakage current does not show any major change; besides, no differences in voltage-current characteristics were observed before and after the tests. On the other hand, some types of zinc oxide elements may show considerable degradation in a non-oxygen atmosphere (transformer oil), even though stable in air [13]. Therefore,

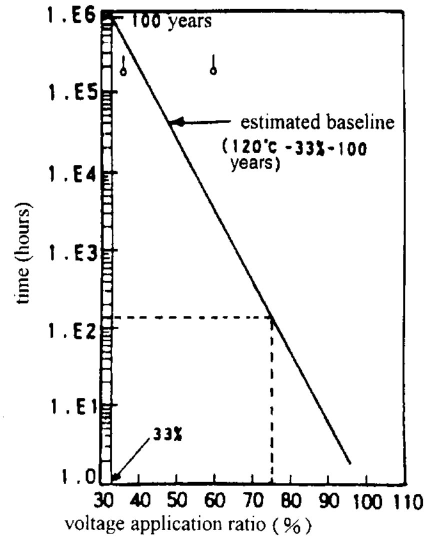


Fig. 12. Voltage endurance curve.

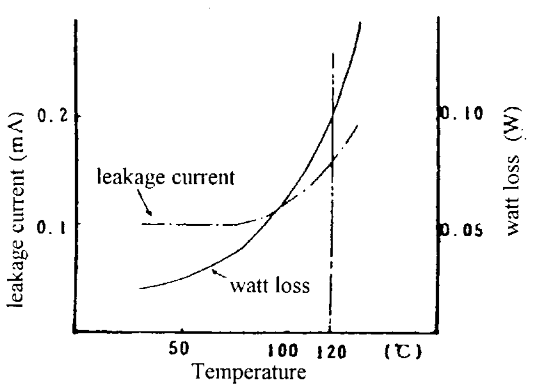


Fig. 11. Relation between leakage current, watt loss, and temperature of oil-immersed zinc oxide elements.

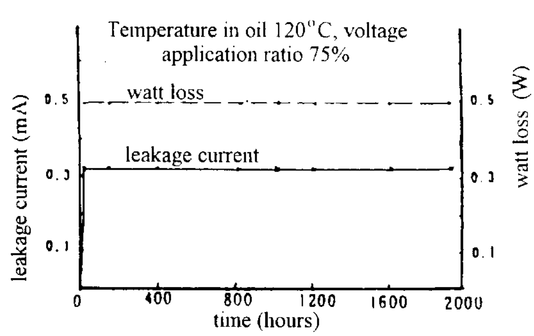


Fig. 13. Leakage current and watt loss in accelerated test (in oil) of zinc oxide elements.

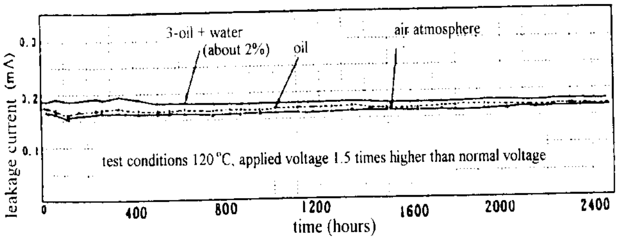


Fig. 14. Leakage current in different environments.

zinc oxide elements that offer acceptable service life in oil were chosen. As to the surface voltage endurance of zinc oxide elements, oil gives better results than air or nitrogen gas.

3.2 Relation between lightning impulse current and number of discharges

With zinc oxide elements, it is important that the reference voltage (V_{1mA}) does not drop substantially due to lightning impulses. In this context, the change rate of the reference voltage (V_{1mA}) was found while applying repetitive lightning impulse currents (4/10 μs). The results are shown in Fig. 15. The zinc oxide elements had an acceptable characteristic for two-time lightning impulse currents of 10 kA as specified for surge arresters.

3.3 Critical discharge tests

Previously, characteristics of lightning arresters were evaluated using two applications of lightning impulse current 10 kA (4/10 μs) and 20 applications of rectangular watt current of 75 A (2 ms) [10]. In this study, performance improvement of the arresting elements was pursued, and the elements were proved, by means of critical discharge tests [9], to withstand a lightning impulse current of 4/10 μs, 30 kA, 30 times in 5 min, and a rectangular watt current of 2 ms, 150 A, 30 times in 2 min.

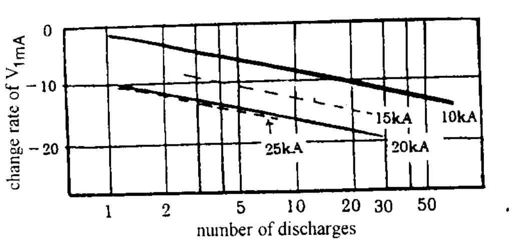


Fig. 15. Number of lightning impulse currents vs. V_{1mA}.

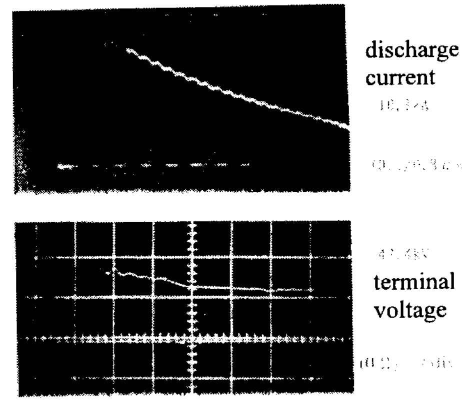


Fig. 16. Steep-impulse current-voltage waveforms (10 kA).

3.4 Stability tests

In the basic evaluation of surge arresters, procedures were employed that were similar to stability tests of station type surge arresters [14], in severe conditions at an oil temperature of 120°C. The basic specification for surge arresters calls for a lightning impulse current of 10 kA, and a rectangular current wave of 75 A, 2 ms, but in this stability test, a lightning impulse current of 20 kA and a rectangular wave current of 150 A, 2 ms were used. The tests confirmed that the critical reference voltage at which arresters show degradation caused by heavy surges and thermal run-away, is about 12 kV.

3.5 Steep-current impulse residual voltage test

Since gapless arresters offer good response, the steep-impulse residual voltage-current characteristic was investigated. Shown in Fig. 16 are test waveforms for a steep-impulse current of 10 kA. Since the withstand voltage of pole transformers is specified as LIWV 60 kV, coordination of insulation can be achieved by installing arrester elements in transformers even at steep impulses. Besides, the problem of steep impulses that is inherent in series gap surge arresters [15] was confirmed to be improved by using gapless design.

4. Degradation of Surge Arrester Elements and Criteria of Reusability

The main factors of degradation of surge arresters include both the normal continuous operating voltage and

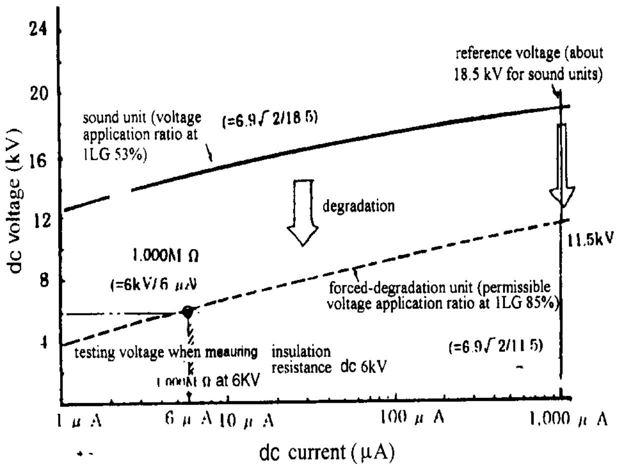


Fig. 17. Evaluation of arresters using measurement of insulation resistance.

voltage surges. The degradation manifests itself in a change of the voltage (V)-current (I) characteristics. Methods of on-site diagnostics of surge arresters that have been proposed include: (1) measurement of insulation resistance, (2) measurement of reference voltage, and (3) monitoring of leakage current. The authors have developed an on-site inspection method (measuring of insulation resistance using 10 kV megger).

Figure 17 shows the relation of the V–I characteristic and insulation resistance of arresters for sound units and forced-degradation units. For example, if the insulation resistance measured at the test voltage of 6 kV dc ($\approx 6.9\sqrt{2}/\sqrt{3}$) is 1,000 MΩ or more, the reference voltage can be estimated as 11.5 kV. By measuring the insulation resistance at high voltages (6 kV, 10 kV), degradation of surge arresters can be evaluated. Figure 18 shows measurements of oil-immersed arrester units using a 10 kV megger.

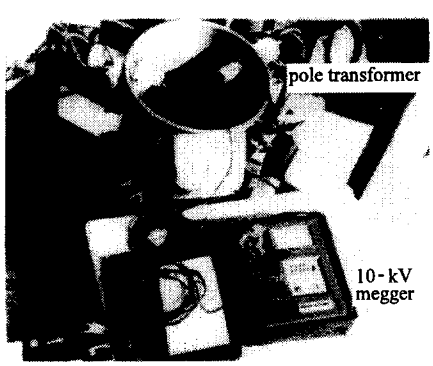


Fig. 18. Measurement of insulation resistance of arresters using 10 kV megger.

5. Applications of Oil-Immersed Surge Arrester Elements

5.1 Installation of surge arresters

After field tests in 1983–1984, surge arrester elements were put into use in 1985 in urban areas and high lightning areas. During the following ten years, about 70% of all pole transformers used by Tokyo Electric Power Co. operated successfully. An outside view of installation is shown in Fig. 19. Figure 20 shows how the transition of IKL and the number of lightning faults of pole transformers have changed. It is obvious that the number of faults has been considerably reduced by installing surge arrester elements in pole transformers.

5.2 Discharge current of surge arresters

Measurements of operating currents in surge arresters were made from 1984–1988 using magnetic tape. In 95% of cases, the discharge current in surge arresters was under 2500 A while the maximum current recorded was 5,920 A. Only one case of damage of surge arresters was recognized to be due to high duty.

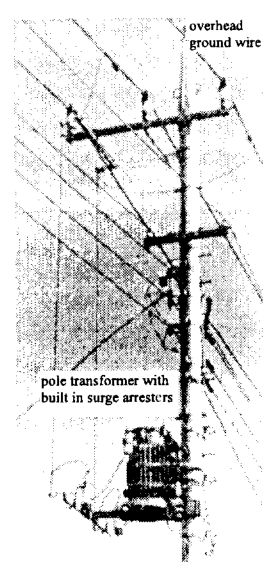


Fig. 19. Outside view of pole transformer with built-in surge arresters.

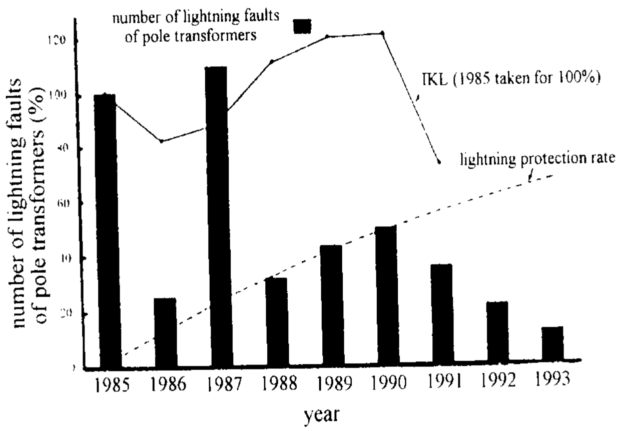


Fig. 20. Number of lightning faults of pole transformers (data from TEPCO, 1985 taken for 100%).

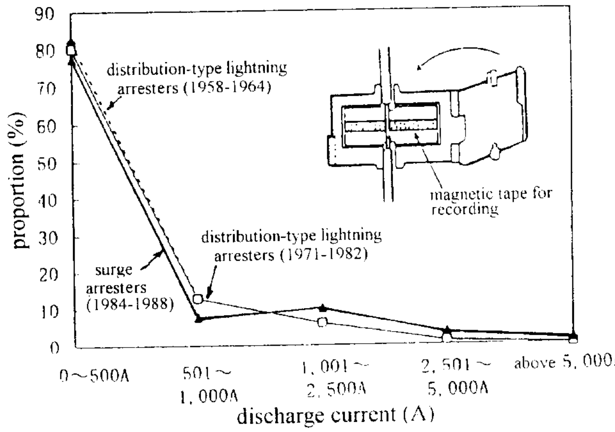


Fig. 21. Discharge current (lightning arresters, surge arresters) and its distribution.

5.3 Discharge current of lightning arresters and surge arresters

It is important to establish the discharge current in surge arresters. For lightning arresters, there are data collected in 1958–1964 with the discharge current being mostly under 1000 A [1]. Besides, there are data for lightning arresters used in distribution networks collected in 1971–1982 with the maximum current registered as 9200 A. The measured data related to discharge current in surge arresters can be summarized as in Table 2. Distributions of discharge current are given in Fig. 21 and Fig. 22. Proceeding from these data, the cumulative probability of discharge current can be estimated as in Fig. 23.

The fact that many measured data lie near 1000 A is consistent with the value of 1200 A [16] for discharge current in lightning arresters that was calculated in terms of voltage suppression effect for induced strokes (induced strokes were analyzed for 6.6 kV distribution network with

Table 2. Probability of discharge current

Discharge current	Distribution-type lightning arresters (1958–1964)	Distribution-type lightning arresters (1971–1982)	Surge arresters (1984–1988)
0–500 A	82%	80%	77.5%
501–1000 A	13%	12.7%	7.6%
1,001–2,500 A	—	5.9%	9.9%
2,501–5,000 A	—	1.1%	3.4%
over 5000 A	—	0.24%	1.08%
5,850 A	—	—	0.26%
5,920 A	—	—	0.26%
9,200 A	—	06%	0
Number of measurements		1650	382

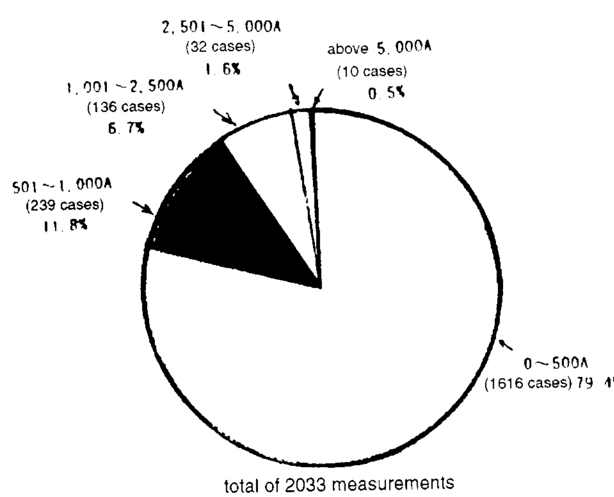


Fig. 22. Discharge charge of discharge current (lightning arresters, surge arresters).

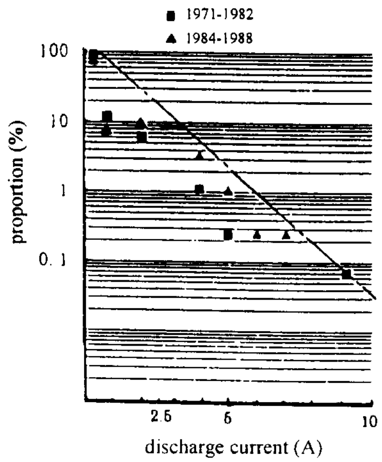


Fig. 23. Cumulative probability of discharge current (lightning arresters, surge arresters).

lightning current of 100 kA, which corresponds to a distance of 50 m from the lightning stroke).

6. Conclusions

The following results were obtained in this study.

(1) Surge arrester elements contained in transformers were evaluated by service life tests using voltage acceleration, and were proved practicable.

(2) As to degradation of the V–I characteristic of surge arresters, measurements of insulation resistance were held using a 10 kV megger, and criteria to estimate degradation and reusability were established.

(3) Built-in surge arresters offer excellent protective capabilities since they are coupled directly to the windings of pole transformers, which contributes to reduction of lightning faults in distribution lines. Among 382 measurements of discharge current in surge arresters, 95% were below 2500 A.

(4) The rated discharge current of 2500 A for surge arresters contained in pole transformers of distribution lines was proved adequate, though requiring further investigation.

Furthermore, the built-in surge arresters can resolve problems of lightning arresters such as breakdown of lead wires due to poor installation, ground faults caused by birds, and degradation of air-tightness. In the future, surge arresters may become basic elements for overvoltage protection of transformer windings.

REFERENCES

1. Guidebook of Lightning-Proof Design in Distribution Networks. Report of Central Research Labs No. 175030 (1976).
2. Yokoyama. Lightning protection in distribution networks. Journal of I.E.E., Vol. 110, No. 1 (1990).
3. Diagnostics of degradation of equipment in distribution networks. IEEJ Technical Reports, No. 555 (1995).
4. Mizuno et al. Zinc oxide lightning arresters for distribution networks. 1992 Nat. Conf IEE Japan, S13-4.
5. New technologies of power distribution equipment. Cooperative Electrical Research, Vol. 42, No. 1 (1986).
6. Kawano. Lightning protection in distribution lines. Production and Electricity (1991).
7. Uchida. Lightning protection of distribution equipment in TEPCO. Railroads and Electrical Technology, Vol. 4, No. 8 (1993).
8. Shirakawa. Recent trends in zinc oxide lightning arresters. EEJ, Vol. 114-B, No. 5 (1994).
9. Uchida et al. Application and evaluation of surge arresters built in pole transformers of distribution networks. Reports of IEE Japan on Switches and Protective Devices, SP-95-26 (1995).
10. JEC-203-1978, Lightning Arresters (1978).
11. Kaku et al. New technology of lightning arresters for distribution networks. Mitsubishi Electrical Co. Technical Reports, Vol. 62, No. 3 (1988).
12. New applications of zinc oxide elements. Technical Reports on Electricity No. 579 (1996).
13. Hayashi et al. Long-term reliability of zinc oxide elements. Meiden Journal, Vol. 226, No. 5 (1992).
14. Characteristics and evaluation tests zinc oxide lightning arresters. Technical Reports on Electricity No. 474 (1993).
15. Takagi et al. Discharge characteristics of steep-impulse voltage in lightning arresters for 8.4 kV distribution networks. IEE Journal, Vol. 91. No. 8 (1971).
16. Yokoyama et al. Dynamic analysis of induced lightnings. 1988 Nat. Conf. IEE Japan, No. 1260.
17. Degradation analysis of power distribution equipment. Cooperative Electrical Research, Vol. 43, No. 2 (1987).

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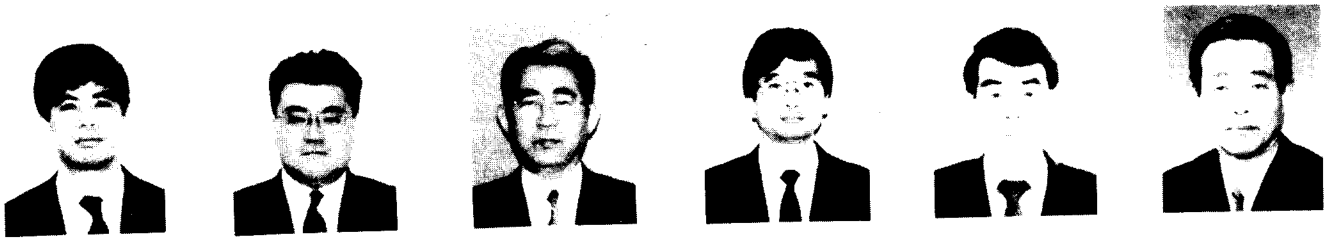

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