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DEVELOPMENT OF ZINC-OXIDE NON-LINEAR RESISTORS AND THEIR APPLICATIONS TO GAPLESS SURGE ARRESTERS

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ABSTRACT

Compared with conventional surge arresters which consists of silicon carbide valve elements and series gaps, the new gapless arrester utilizing a zinc oxide valve element offers more excellent characteristics. Meidensha has developed a new gapless arrester series with the rated voltages of 4.2 to 280 kV. Because of its compactness and gapless feature, this series is considered to be applicable to gas insulated substation (GIS) and enclosed type switchgears. Therefore, some trial products including those for 500 kV have been produced and various verification tests have been completed. Meidensha also has much field experience. Arresters with the rated voltages of 42 to 140 kV have been installed on actual power systems of several electric power companies in Japan for about 2 years.

INTRODUCTION

The first zinc-oxide varistor(1) was released by Matsushita Electric Industrial Co., Ltd. 1968. It was a landmark invention since this type of varistor offers excellent characteristics and economy when used as a voltage stabilizer element or a surge arrester. At that time Meidensha paid special attention to its excellent characteristics and potential feasibilities for the future. Hence, Meidensha has used its own techniques on power engineering and spent abundant man-hours to develop characteristic element of surge arrester for power systems in collaboration with Matsushita Electric Industrial Co., Ltd. On the other hand, Meidensha has devoted itself to the development of surge arresters to be used on 3 to 500 kV systems. The development of characteristic elements and the improvement of the above-mentioned varistor have been focused on the following 3 essential points:

(1) Improvement of voltage-current characteristics in a wide current range of 10^{-3} to 10^5 A. (In particular the flatness in the V–I curve has been improved in a heavy-current range of 10^3 to 10^5 A.)

(2) Establishment of production techniques for large elements and improvement of discharge-current withstand capability.

(3) Establishment of characteristical stability and long life in practical usage.

As a result, it has been made possible to produce new gapless arresters for power systems. These arresters have no series gap and such a construction is the newest one in the world. The new series of general type and pollution-proof or live-washing type surge arresters covers the rated voltages of 4.2 to 280 kV.

Regarding the new gapless arrester, outline information and potential feasibilities were already released at 1973 National Convention of IEEJ(2) held in spring, 1973, at the Technical Meeting on Switching and Protective Devices of IEEJ(3) held in autumn, 1974, in the Meiden Review(4) in 1974, and the Summer Meeting of IEEE(5) held in summer, 1976. Compared with a conventional surge arrester with silicon-carbide elements and series gaps, the new gapless arrester offers the following outstanding features:

(1) Conventional arresters cannot guarantee the operating-duty capability against the attack of multiple-lightning and switching surge. The new gapless arrester eliminates this difficulty completely.

(2) The gapless arrester sufficiently withstands the artificial pollution and live-washing tests. In addition, it has an operating-duty capability under pollution. The product is of multi-section porcelain type and this achievement is the newest in the world.

(3) Characteristic elements or complete arresters may be connected in parallel. Thus super-heavy-duty arresters can be designed and manufactured easily. This achievement is impossible for conventional types.

(4) Series gaps are eliminated. This reduces overall size and elements can be used in various insulation media such as SF_6. Therefore, the gapless arrester is particularly useful for super-compact type switchgears.

In conjunction with the above-mentioned reports(2 ~4), the associated staffs of Meidensha have devoted themselves to the research and development of the zinc-oxide (ZnO) element and its application to the surge arrester for the past 7 years. Development of mass production techniques and establishment of the concerned facilities have been finished as a result of about two years of activities. In October, 1976, a new arrester was completed. It had a nominal discharge current of 10 kA and a rated voltage range of 4.2 to 280 kV. It was designed in accordance with the Japanese Electrotechnical Committee (JEC) standard. In the presence of the members from all domestic electric power companies, type tests were carried out with successful results. Regular production is scheduled to start in 1977. In addition, arresters contained in tanks filled with SF_6 gas are being developed for 77 to 500 kV systems. Arresters in insulating-oil tanks to be used on 66 to 154 kV systems have been developed also. These arresters are to be put into regular production in 1977. In all respects the new gapless arrester is superior to any conventional one. In the near future, this type of arrester will expand its applicable range further and will be used on HVDC and UHV systems. It is our belief that the ZnO element will be used in lieu of the SiC element overall. Outline descriptions of the new gapless arrester and field experience will be presented below.

FUNDAMENTAL CHARACTERISTICS OF ZINC-OXIDE NON-LINEAR RESISTORS

General characteristics of the zinc-oxide non-linear resistors have already been reported several times(3~5). The gapless arrester series to be discripted in this report covers the rated voltage range of 4.2 to 280 kV. The gapless arrester of each voltage class comes in 2 types. For one type the capacitance of special operating-duty test is 25 μF as specified in the Japanese standard, JEC-156. The other type has the capacitance of 50 μF. These duties are equivalent respectively to classes 1 and 3 of the heavy-duty arrester of the long-duration discharge class, specified by IEC Pub. 99-1 (1970). In terms of the specifications in ANSI C62.1 (1975), they are also equivalent to the transmission-line discharge capability for the rated voltage ranges of 3 to 240 kV and 258 to 312 kV. Our standard characteristic element is for the 25 μF rating. When a 50 μF rating is required, the same elements are to be connected in parallel. In this manner we have standardized the ZS-A series (for 25 μF rating) and the ZS-A2 series (for 50 μF rating). In this section the principal characteristics of the ZnO element will be presented.

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Non-Linear Voltage-Current Characteristics

1. Voltage-current curve

The ZnO element consists of zinc oxide as its major component and several additional materials. On the side surface of the element is sintered a high-insulation material which consists of inorganic substances only. Throughout the whole current range of 10^{-3} to 10^{4} A, this element offers an excellent flat characteristics that are better than those in the V–I curve of the SiC element. Figure 1 shows the V–I curves of the standard ZnO and SiC elements.

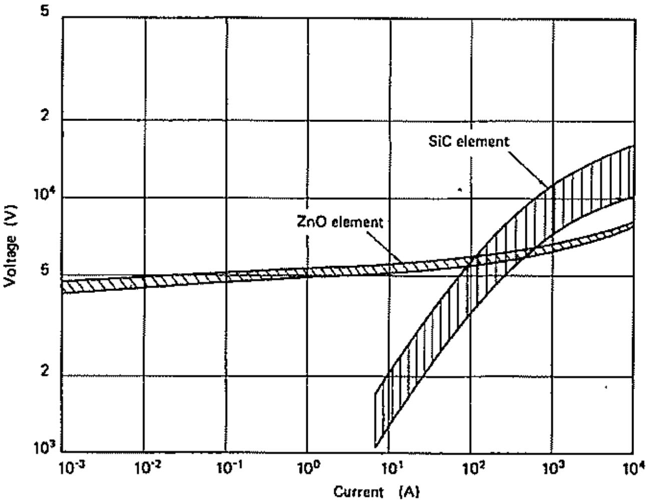

Fig. 1. V–I curves of ZnO element and SiC element (standard type).

As a result of research for mass production continuing for more than 2 years, it has been verified that the dispersion of the V–I curve of the ZnO element is very small and it is less than 1/5 that of the SiC element. The quality of products is quite stabilized.

For all completed SiC elements, measurements were carried out on their V–I curves and they were classified into 3 grades of (H), (M), and (L) according to the level of the discharge voltage at 10 kA. These grades are combined in the relationship of 2M = H + L so that the overall dispersion can be reduced as low as 1/3 approximately when plural elements are used in series. However, there is still a dispersion of about 15 % at the point of 100 A.

For ZnO elements, on the other hand, most of them offer less than 10 % (± 5 %) at 10^{-3} A and about 5 % (± 2.5 %) at 100 A without any classification and combination of elements. Obviously the ZnO element has very stabilized characteristics.

Like many other solid insulating materials, the thermal characteristic of insulation resistance of the ZnO element is negative. This thermal characteristic is more affected in a low-current region of less than 10^{-3} A. It becomes almost zero in the vicinity of 1 A, while it turns slightly positive in the region of 10 to 10^{4} A (Fig. 2). At a high temperature of 300 °C V_{1mA}* lowers remarkably, but where the temperature lowers to normal, the characteristic is restored to the original one automatically. In other words the ZnO element has the nature of self-restoration (reversibility).

Note: * V_{1mA} is defined as described below.
The ZnO element may give rise to a slight characteristic change when heavy-current discharge occurs or power-frequency voltage is applied to it for a long time. However there is almost no change in a current region over 10 mA. It is not reasonable to speak of such change for a current below 0.1 mA because of measurement error. The middle value, 1 mA dc, is considered to be most reasonable when checking a characteristic change by detecting variations in the applied voltage at 1 mA dc.
Therefore we use V_{1mA} as the representative value.

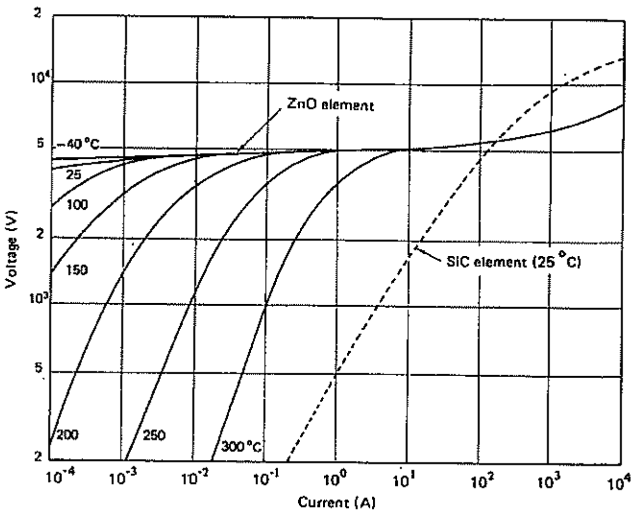

Fig. 2. Thermal characteristics of ZnO element and SiC element.

2. Discharge voltage characteristics

The first reason why the ZnO element is superior to the SiC element is that the V–I curve is flat throughout the wide current range (10^{-3} to 10^{4} A) (Fig. 2). For the second reason, the response characteristics against steep current wave forms are preferable. It is generally believed that the discharge voltage is influenced by the duration of wave front even at the same current. This tendency can be seen in both SiC and ZnO. As shown in Fig. 3, the standard duration of current wave front is 8 μs. Then, in case when the duration is 1 μs, the voltage rise rate of ZnO is lower than that of SiC. This means that the protective characteristics of ZnO are better than those of SiC against lightning surge currents with short wave front durations. Such surge currents virtually occur when attacked by direct lightning stroke near a power station or a substation or when a back flashover occurs due to the direct stroke of lightning at a steel tower.

The third reason why the ZnO element is superior to the SiC element is that the stability in the V–I curve is very good after the passage of a heavy current (100 kA). When a 4 x 10 μs 100 kA current is applied two times to a SiC element with a diameter of 90 mm and the discharge voltage is measured at 10 kA, the obtained value is more than 10 % higher than the original value. Obviously there is a characteristic change. In the case of a ZnO element, however, the change in the discharge voltage at 10 kA is less than 3 % after two shorts of 4 x 10 μs 100 kA current in spite of the cross-sectional area of ZnO is less than half that of SiC. Such a value is contained in a range that can be regarded as a measuring error. The stability of ZnO is excellent and the characteristic change can be considered to be zero in practical usage.

Discharge-Current Withstand Capability

The permissible energy absorption of the gapless arrester merely depends on the strength of ZnO element itself since there is no series gap. As compared with conventional arresters, the follow current of the gapless arrester is negligibly small. Therefore in practical usage, energy of lightning surges or switching surges only may be taken into consideration. (On the other hand, in the case of conventional arresters, permissible energy consumption around series gaps must also be taken into account.) Therefore, the discharge-current withstand capability only should be verified for each ZnO element. Then the required number of elements may be connected in parallel until they have a capability of absorbing specified energy or the required quantity of completed arresters should be installed in parallel in the same place. The number of elements or completed arresters should be determined according to the place of application (for example, protection of long-cable systems or capacitor banks). In conventional arresters, parallel arrangement of series gaps has been theoretically difficult. However, in the gapless arrester which uses ZnO elements, surge current can be distributed to the parallel elements or parallel arresters almost evenly. Thus heavy-duty arresters can be manufactured easily.

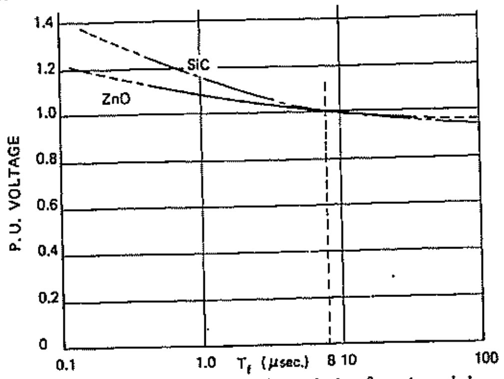

Fig. 3. Discharge voltage characteristics for virtual duration of current wave front at discharge current 10 kA.

1. High-current impulse test

According to IEC Pub. 99-1 (1970), the surge arrester with the nominal discharge current of 10 kA should offer the characteristic such that side flashover or puncture in the SiC element does not occur after exposure to two shots of 4 x 10 μs 100 kA. On the other hand, as shown in Fig. 4, the ZnO element has not so much characteristic deviation from the standard value and there is much allowance in it. Such a feature is recognized even after the ZnO element has been exposed to the wave form of 4 x 10 μs 40 kA and 100 kA repeated many times. Such excellent performance is resulting from the intrinsic characteristic of the ZnO element itself and also from contribution by good insulation characteristic of the coating material on the side surface.

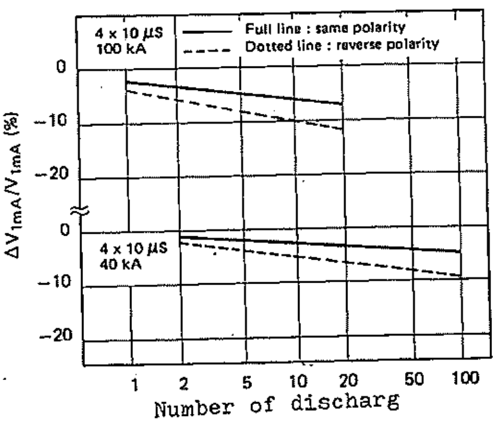

Fig. 4. Characteristics for lightning impulse currents.

2. Long-duration current withstand cpability

Both IEC Pub. 99-1 (1970) and ANSI C62.1 (1975) specify that the heavy-duty arresters with the rated voltage below 198 kV must be tested at a rectangular wave with a virtual duration of about 2 ms. (However, the current wave form for the current-limiting type arresters is not necessarily rectangular.) The amount of flowing current may differ according to the discharge voltage of the gapless arrester. However, it is generally believed that the current value will be less than 400 A (approx.) at the severest rated voltage. This ZnO element passes the tests with sufficient allowance, to be executed in accordance with, JEC standard. In these tests, the ZnO element is exposed to 20 shots of 2 ms 400 A. Actually the ZnO element is strong enough to withstand more than 20 shots of 2 ms 600 A. Figure 5 shows an example of characteristic changes occurring when such tests are repeated many times at 400 A and 600 A. As is obvious from Fig. 5, the ZnO element withstands the repeated attack of switching surges when the current is below 600 A 2 ms.

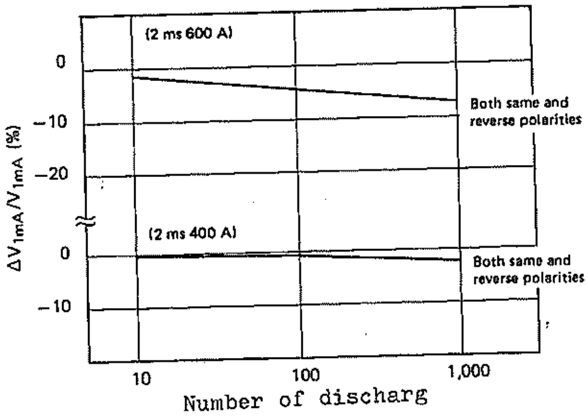

Fig. 5. Characteristics for switching impulse currents.

3. Current distribution characteristics

When plural characteristic elements with excellent non-linear voltage-current characteristics are connected in parallel, it is difficult for the current to flow evenly. This is a general belief from the past experience.

For the ZnO element, the dispersion is within ± 5 % at V_{1mA} as shown in Fig. 1. When arresters are used in parallel, the dispersion can easily be selected to be within ± 1 % (2 % in width) even though an measuring error is taken into account. In such a case, assuming that $\alpha^* \doteqdot 30$, the distribution ratio at the V_{1mA} point is 64 : 36 which is uneven. However in the current region which is close to destructive energy (500 to 1,000 A per total elements though this depends on the wave form), the value α is small and is nearly equal to 20. The width of dispersion is also about half the amount of V_{1mA}. If this dispersion is assumed to be 1 %, then the distribution characteristic is expected to be 55 : 45 (distribution efficiency approx. 90 %). Since there is a slight positive thermal characteristic in a current region of more than 10 A, the temperature rise becomes higher in the ZnO element where much more current is concentrated. For this reason the current distribution characteristic will be improved more in practical usage.

Note: * The value α is defined as follows:

$$I = \left(\frac{V}{c}\right)^{\alpha} \quad c: \text{ constant} \quad \alpha: \text{ index number of non-linearity}$$

Stability under Actual Service Voltage

As described previously, the new gapless arrester does not have any series gap and it consists of non-linear resistors made by a completely new method. Thus it is necessary to verify the characteristic stability when the gapless arrester is used on an actual power system for a long time. There are two important factors that are concerned closely with the long-term stability. One factor is a characteristic change in the ZnO element which has been exposed to continual switching or lightning surge current. The other factor is a change in the insulation characteristic (characteristic in a current region of

V_{1mA} or less) caused mainly by long-term application of power-frequency voltage. The mutual effect caused by both factors must also be investigated in terms of expected operational life (more than 30 years). Regarding the former factor, there is almost no problem in practical usage as shown in Figs. 4 and 5. Change in V_{1mA} is less than 10 % or so even when the gapless arrester is used under the operational duty that is far severer than the conditions of the number and crest values of current attacks considered to occur during the whole operation period of the arrester. Regarding the latter factor, a complete arrester or its pro-rated section designed in accordance with the Japanese stadnard, JEC-156 (1963), has been tested. This life test has been carried out under very rigorous conditions such that a voltage rise in the sound phase at time of one-line-ground fault has been applied to the specimen at all times. After this life test continuing for more than 4 years, it has been verified that there is no particular characteristic change and there is also no problem in practical usage. The accelerated deterioration test has also been carried out for many ZnO elements. This test is useful in anticipating the operational life of more than some tens of years within a very short time period.

It has been verified by many experiments that the relationship between temperature and applied-voltage life of the ZnO element well matches the Arrhenius's expression ($t = t_0 e^{Ea/RT}$) which is generally adopted. Figure 6 shows the relationship between temperature and life. To obtain this relationship, unit elements were used.

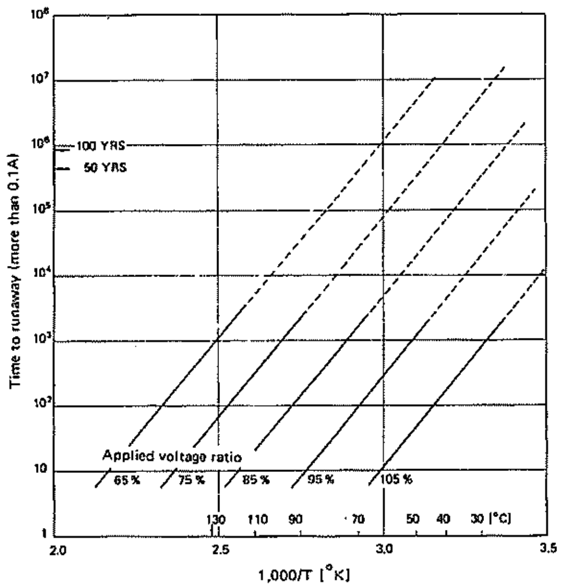

Fig. 6. Arrhenius's plotts of ZNO element life vs reciprocal temperature with power frequency voltage.

Life mentioned here is a time period in which current or power consumption attains to a constant level while temperature is changed and voltage is used as a parameter. For the arresters with the rated voltages of 196 kV or below to be used in neutral non-effectively ground systems in Japan, the applied voltage ratio* is considered to be less than 45 %. If annual average temperature is assumed to be 40 °C, the expected life will be more than 10^5 years. For the arresters with the rated voltages of 210 to 280 kV to be used in neutral effectively grounded systems, the applied voltage ratio is less than 60 % and the expected life is then more than 10^4 years. In any case, the gapless arrester has a very high safety factor. Actually in Japan, annual average temperature is 30 °C at a maximum and thus the safety factor is raised further.

The series gap of a conventional arrester is generally connected in parallel with a grading resistor which is composed mainly of silicon carbide or carbon. Consequently a resistive current of about 1 mA is always flowing. On the other hand, the amount of resistive current always flowing through the ZnO element is very small (at a level of μA) and we can understand that the safety factor of the gapless arrester is extremely high.

Note: * Applied voltage ratio = ratio of continuous power frequency voltage (peak value) to V_{1mA}.

GAPLESS ARRESTER SERIES AND ITS APPLICATIONS

Studies of Factors Affecting New Gapless Arrester Design

When developing a new gapless arrester series, the outstanding features of the gapless arrester have been carefully examined in accordance with the relevant Japanese standard, JEC-156 (1963), and its revision (under consideration). For the two types of light duty (25 μF or below) and heavy duty (50 μF or more) together with the pollution-proof and live-washing types, discussions have been repeated to study how these types should be combined for the convenience of manufacture and application. At that time IEC Pub. 99-1 (1970) and the draft of ANSI C62.1 (1975) have been taken into consideration. In the next step we have studied to reduce the number of types of porcelain housings by common usage without sacrificing the scope of rated voltages in all Japanese power-frequency systems.

1. Features of the gapless arrester

The features of the gapless arrester are as follows:

(1) The gapless arrester is essentially strong against multiple-lightning and switching surges.
(2) Economical pollution-proof and live-washing type arrester can be designed and manufactured.
(3) Heavy-duty arresters in respective grades can be designed and manufactured easily.
(4) The gapless arrester is most suitable for use in SF_6 insulated switchgears and compact substation equipment.
(5) Since the series gap is eliminated and the construction is simple, characteristics can be stable for a long time and high reliability is obtained.

2. Common usage of ZnO elements for all series

In addition to the 4 types covering the rated voltages of 4.2 to 280 kV introduced in this report, there is another arrester series projected by Meidensha for use on 3 to 500 kV systems. Size of the unit element has been carefully determined so that it can be used completely in common for all types of these arrester series. If determination of element size is successful, then only one type of element can be used in all cases when the capacitance of special operating duty is 25 μF, 50 μF, or more than 78 μF and when general type or pollution-proof type is adopted. In any case, according to the requirements, the unit elements in the required quantity are connected in parallel. Taking the above conditions into account, the standard element for 25 μF has a diameter of 56 mm.

3. Common usage of porcelain housings

When discussing the 4 types of arresters, the porcelain housing is the largest component and it has been the matter of importance that the number of housing types must be decreased as small as possible. If the rated voltage is 70 kV or above, there are already 12 arrester ratings, each having 2 duty types of 25 μF and 50 μF. If general, pollution-proof, and live-washing types are taken into consideration for the above ratings, then simple calculation indicates that only the arresters of 70 kV and above may require 72 types of porcelain housings ($12 \times 2 \times 3 = 72$). In order to meet all the above-mentioned requirements with the reduced number of porcelain housing types, the following methods have been adopted:

(1) The 70, 84, and 98 kV arresters will use the same porcelain housings.
(2) The outer housing diameter comes in A (200 ϕ), B (345 ϕ) and

C (450 ϕ) only. In addition B′ is adopted, which is somewhat shorter than B-size housing. Therefore, there are 4 housing sizes in all. The A-size housing is exclusively used for general type arresters with rated voltage below 98 kV and the duty of 25 μF. Therefore, if A-size is omitted, then the number of actual housing types is only 3.

(3) The B- and B′-size housings are used in common for general 50 μF and pollution-proof 25 μF arresters. The C-size housing is used for pollution-proof type 50 μF arresters. The C-size housing is used for pollution-proof type 50 μF and 78 μF arresters.

(4) All pollution-proof types housings are also applicable to live-washing type arresters.

(5) There is no special version for use in heavy pollution regions. According to the user's specifications and the regional conditions, the most suitable housing is chosen from the 4 types (excluding A-size).
For example, when attempting to increase leakage distance and effective length, a longer housing may be used or two short housings may be joined.

(6) All housing combinations are tested under the earthquake conditions that are considered to be most regorous in Japan.

To sum up, only one type of ZnO element is used for all arrester types, three housing types are used for 5 ratings below 42 kV, and only 4 housing types are used for 72 ratings above 70 kV. Such common usage of parts owes greatly to excellent characteristics of the ZnO element.

Outline, Construction, and Characteristics of New Gapless Arrester Series

The new gapless arresters with the rated voltage ranging from 4.2 kV to 280 kV are specified in Table 1. These arresters come in 4 types.

Table 1.

No.	Type	Rated voltage (kV_{rms})	Long-duration discharge class*	Notes
1	ZS–A	4.2 ~ 140	Ⓐ	General type
2	ZS–A2	70 ~ 280	Ⓑ	General type
3	ZS–AX	70 ~ 196	Ⓐ	Pollution-proof and live-washing type
4	ZS–A2X	70 ~ 280	Ⓑ	Pollution-proof and live-washing type

* 1. Class Ⓐ is when the capacitance of special operating-duty test is 25 μF in Japan, and is equivalent to class 1 of IEC 99-1 (1970).

2. Class Ⓑ is when the capacitance of special operating-duty test is 50 μF in Japan, and is equivalent to classes 2 and 3 of IEC 99-1 (1970).

Figure 7 shows typical photographs of respective arrester types. Outline, dimensions and weight are given in Table 2.

3. Construction

The new gapless arrester has a simplified construction. The ZnO elements are supported by the insulating rod inside the porcelain housing. All assembly work is carried out in a dust-proof room maintained at constant temperature and humidity. Finally, air within the housing is replaced by pure nitrogen. A thin pressure-relief diaphragm is devised to break when inner pressure ammounts to several atmospheric pressures. In such a case, the arc gases are led to the outside.

Table 2 shows the standard performance characteristics for typical ratings. The basic design concept for the newly developed gapless arresters is focused on a goal that the standard value of the critical operating voltage (V_{1mA}) is the rated voltage crest value x 1.1. In actual power systems, the rated voltage is applied to the surge arrester only if one-line-ground (1LG) fault occurs. The surge arrester is required to withstand such a faulty voltage in a short time period which may ammount to only several seconds at a maximum. Therefore considering above point, the protective level (corresponds to discharge voltage at 10 kA for the gapless arrester) may be reduced by more than 20 %. Thus, if the development of gapless arresters is promoted further, this will be very effective in assuring insulation co-ordination which finally results in the reduction of BIL.

Table 2. Standard characteristics of typical ratings.

Type ①	Rated voltage (kV rms) ②	Height (mm) ③	Weight (kg) ④	BIL (kV crest) ⑤	Critical operating voltage [V_{1mA}] (kV crest) ⑥	Discharge voltage at 10 kA [V_{10kA}] (kV crest) ⑦	Tolerance in ⑦ and ⑤ ((⑤ – ⑦)/⑤) (%) ⑧	Maximum system voltage (kV rms) ⑨	Notes
ZS–9A	8.4	365	18	60	13	25	58	6.9	General light-duty
ZS–28A	28	490	27	160	44	81	46	23	
ZS–84A	84	1,130	62	350	132	244	30	69	
ZS–98A	98	1,130	62	400	154	284	29	80.5	
ZS–140A	140	1,620	167	550	220	406	26	116	
ZS–196A2	196	2,370	195	750	308	530	29	161	General heavy-duty
ZS–266A2	266	3,070	350	1,050	418	716	32	287.5	
ZS–280A2	280	3,070	350	1,050	440	756	28	287.5	
ZS–84AX	84	1,620	165	350	132	244	30	69	Pollution light-duty
ZS–98AX	98	1,620	165	400	154	284	29	80.5	
ZS–196A2X	196	3,260	630	750	308	530	29	161	Pollution heavy-duty
ZS–266AX	266	4,680	890	1,050	418	710	32	287.5	

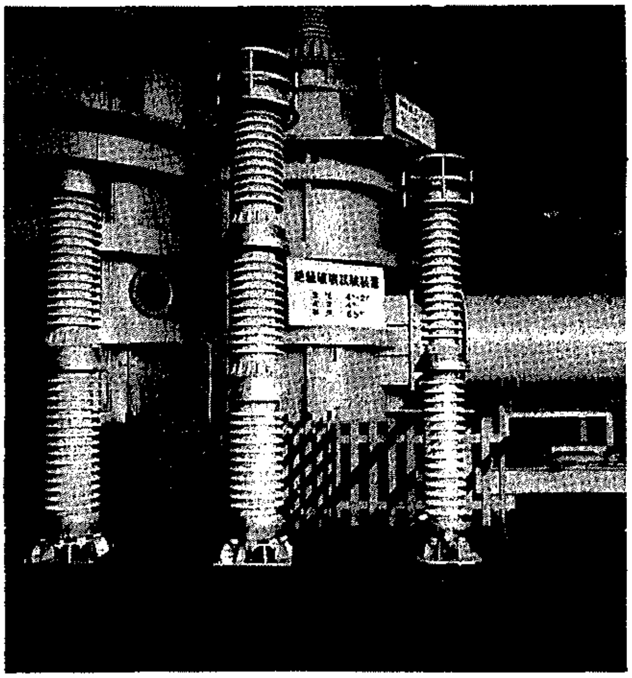

Fig. 7. Typical photographs of ZS–A2 and ZS–A2X types.
Right : ZS–266A2, 266 kV general type
Middle : ZS–266A2X, 266 kV live-washing type
Left. : ZS–196A2X, 196 kV live-washing type

Test Results for Principal Characteristics of Complete Arresters or Pro-Rated Sections

1. Critical operating voltage and power-frequency overvoltage withstand characteristics

In Japan, the rated voltage of an arrester is higher than the sound-phase voltage which occurs at the time of one-line-ground fault in the concerned system. Therefore the arrester terminals cannot be applied with power-frequency voltage which is higher than arrester's rated voltage. However, in actual power systems complex phenomena occur due to interruption of load currents, Ferranti effect, etc., or in some cases transient phenomena occur at the time of line fault. In such cases, power-frequency overvoltage above the arrester's rated voltage may be generated for several cycles to several seconds, thus surge arresters being burned and damaged. Consequently, the gapless arresters are designed to have their critical operating voltage about 10 % higher than the crest value of the rated voltage. Figure 8 shows the withstand voltage vs the ratio of overvoltage to rated voltage withstand characteristics. As is obvious from Fig. 8, 1-second is 1.4 times the rated voltage, and 0.1-second withstand voltage is about 1.55 times, always with much allowance against the rated voltage. In the case of conventional arresters, however, they are sometimes incapable of interrupting the follow current if power frequency voltage higher than the rated voltage is superposed by lightning surges or switching surges. On the other hand, the gapless arresters are free from such trouble.

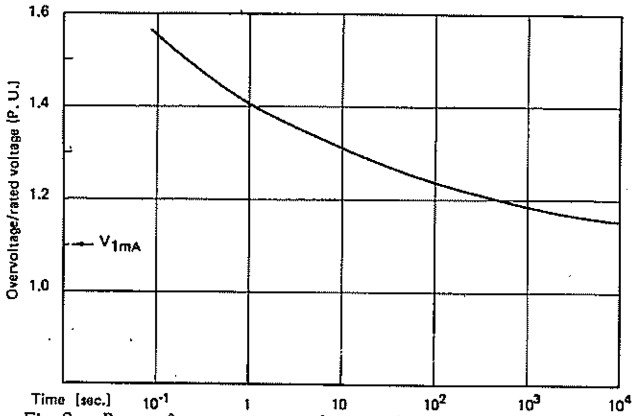

Fig. 8. Power-frequency overvoltage withstand characteristic curve.

2. Lightning impulse response characteristics

Since the gapless arrester does not have any series gap, impulse sparkover voltage test cannot be carried out and we think it unnecessary to attempt such a test. However, for reference, the standard lightning impulse voltage was applied to the ZS–266A2 type arrester to investigate its impulse response characteristic. This test used an impulse generator which was used to test conventional arresters. Figure 9 shows an example of oscillograms. As shown by these oscillograms, generated voltage 1,050 kV from the impulse generator is suppressed as low as 650 kV. This voltage is in good coincidence with the discharge voltage which is dependent on the current wave form and the crest value. The result shows that the lightning impulse sparkover voltage test can be replaced by the discharge voltage test for the gapless arrester.

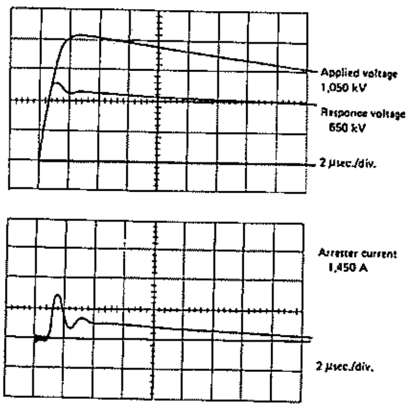

Fig. 9. Oscillograms of responce characteristics of lightning impulse. (Test specimen : ZS–266A2 type)

3. Operating-duty test for a 14 kV pro-rated section

Since the follow current is negligibly small for the gapless arrester, the operating-duty test seems to be unnecessary to be carried out. The capability of withstanding the above-mentioned short-time power-frequency overvoltage will suffice. To make sure, however, a 14 kV pro-rated section was tested in accordance with the Japanese standard, JEC-156. This test was carried out by superposing an impulse current of 8 x 20 μs 10 kA, repeated 5 times in the same polarity and 5 times in the reverse polarity. The test result shows that there is no problem.

4. Operating-duty test under line reclosure

At present the revisions for the JEC-156 standard are under consideration in Japan. The revisional panel is discussing the reclosing surge operating-duty test which seems to be most rigorous since 500 kV overhead transmission systems and 275 kV cable systems are taken into consideration. This test will be performed under the simulated condition such that a high-speed reclosure is accomplished by a circuit breaker in the reverse-phase polarity on the unloaded line which is charged at the crest value of the rated voltage. This test corresponds to the long-duration current impulse withstand test to be carried out on heavy-duty arresters specified by the IEC standard, or the transmission line discharge test specified by the ANSI standard. However, the conditions for this test are far severer than those for the above two standards.

This test was performed on the 5.6 kV pro-rated section for the rated voltage of 420 kV, using 6 ZnO elements (3 pcs. in parallel and 2 pcs. in series). Figure 10 shows the test circuit and an example of typical oscillograms. These data well coincide with the analysis result by analog computer[6] conducted by the Central Research Institute of Electric Power Industry (Japan).

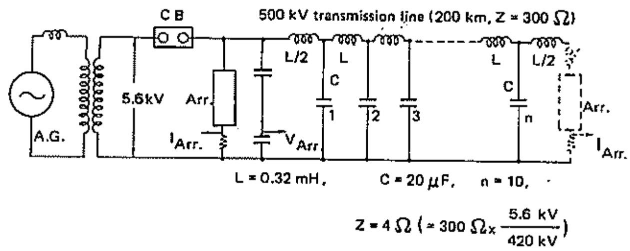

Fig. 10 (a). Test circuit of reclosing surge operating duty test for 5.6 kV prorated sections.

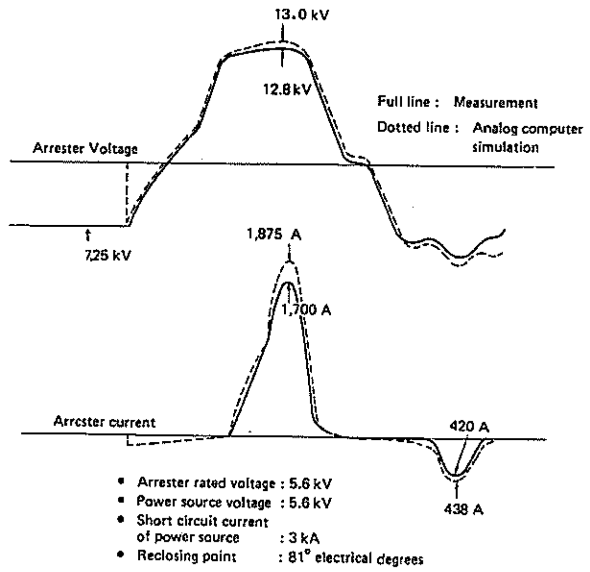

Fig. 10 (b). Comparison of test result and simulation oscillogram.

Figure 11 shows the difference between the typical results of gapless arrester obtained from calculation by analog computer and the results of the conventional arrester. As shown in Fig. 11, maximum energy absorption of the gapless arrester is about 10 % lower than that of conventional arresters even when the discharge voltage for gapless type is reduced by about 10 %. Therefore, at the same discharge voltage the amount of energy absorption reduction will amount to more than 20 %. In Japan this test is adopted since the follow current interrupting capability of the series gap is considered to be very important. Though the significance of this test is recognized also by IEC and ANSI, these two standards presently adopt the transmission line discharge test which merely absorbs of energy. When arrester's energy absorption difference caused by these two types of tests is compared with the example obtained from the conventional 500 kV arrester, then the following conditions are found. Namely, absorption energy is 8.9 kJ/rated kV in JEC method, while in long-duration class 4 of IEC it is 6.9 kJ/rated kV. The analog computer analysis indicates that the operational duty by the JEC standard is severer since absorbed energy is about 30 % higher than that specified by the IEC statndard.(6)

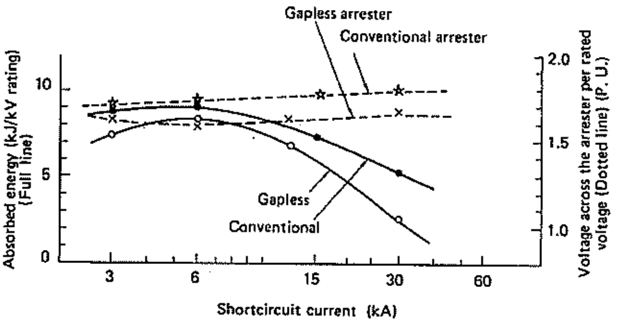

Fig. 11. Absorbed energy and arrester voltage vs short-circuit current of power source.

5. Operating-duty test under line switch operation

The arrester to be used on Japanese 500 kV power systems are required to accomplish perfect interruption of follow current even when multiple discharges occur at multiple switching surges which is generated when a line switch is switched off. This test was carried out for 30 follow current interruptions at normal line-to-ground voltage multiplied by 1.05. This test must be repeated two times. It is a very rigorous duty for a conventional arrester to permit the flow of follow current 30 times continually. This is one of the reasons for the increase in size and the rise in cost for 500 kV class arresters (in particular, those of SiC elements). The gapless arrester, on the other hand, is free from follow current and this problem need not be discussed. Though this test is unnecessary for the gapless arrester, it was carried out for reference. As a result, it has been verified that the follow current does not flow actually, while the gapless arrester operates normally.

6. Pollution test and live-washing test

The arrester types ZS–AX and ZS–A2X shown in Table 1 are designed to pass the pollution and live-washing tests performed in accordance with the revisions of JEC–156. The test method specified by the JEC revisions somewhat resembles that of ANSI. To make up the test condition, 40 g/ℓ kaolin and a proper amount of NaCl are mixed and this solution is uniformly sprayed on the surface of the arrester housing. This treatment must be adjusted so that sprayed salt concentration on the surface can be maintained at a predetermined value (0.03 to 0.06 mg/cm^2 for example). Then, voltage is applied in the order as shown in Fig. 12, E_1 and E_2 are applied for 7 cycles, and finally when the last E_2 (the 8th application) is applied the arrester is washed with water discharged from the fixed spray nozzle. Figure 13 shows an example of oscillograms obtained from the test on the ZS–266A2X type arrester. The inner current, which flows through the ZnO element, sometimes amounts to some tens mA at voltage E_2. However, when voltage returns to E_1, then tne inner current decreases below several mA. Therefore, unlike the SiC element which permits some tens to some hundreds amperes of follow current when discharge once occurs at the series gap, such a phenomenon never occurs in the gapless arrester, thus being absolutely free from such trouble.

If the sprayed salt concentration is decreased on the surface of only one out of the 3-section housings (for example, 0.06, 0.06, and 0.01 mg/cm^2 from top to bottom) to make up uneven contamintion condition artificially, the arrester still withstands application of test voltage E_1 for a long time when verification is made by the fog withstand test method. The conditions for the fog withstand test method are established in the following manner. A mixture of water, salt, and kaoline is applied to the surface of porcelain housing and then the housing surface is dried. Since then, it is put in a fog room where a constant voltage is applied to it. This method is a close simulation of an actual operating condition. In any case of the JEC standard (draft) and fog withstand test methods, the power-frequency sparkover voltage is reduced below half the ordinary level if such a method is adopted for conventional arresters in 3-section housings. This is very dangerous in actual usage. Therefore, when conventional arresters are used in a heavy-pollution region in Japan, extraordinarily large valuable one-piece housing type arresters must be used or silicone compound must be applied to the housing surface. On the other hand such considerations can be omitted for the gapless arrester with ZnO elements. Thus economical multi-sectional pollution-proof type gapless arrester can be established.

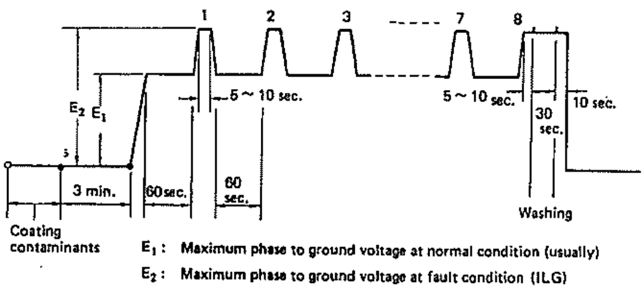

Fig. 12. Shematic diagram for pollution-proof and live-washing test by the revisional draft of JEC–156.

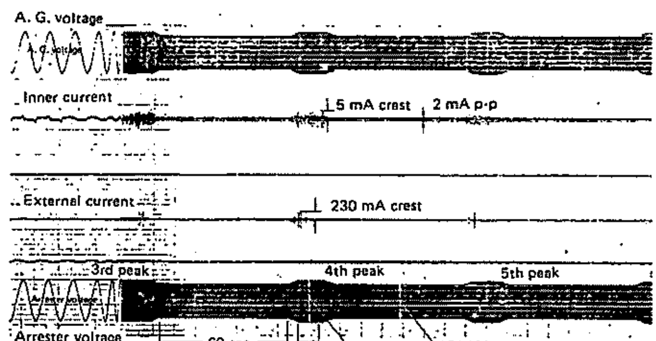

Fig. 13. Typical oscillogram of pollution test on the ZS–266A2X.

Gapless Arrester Applications to IEC and ANSI Standards

In principle, establishment of previously described arrester types and various test results are aimed at conforming to the JEC standard. However, if 2 or 3 points are revised, these arresters are basically applicable to the usage of IEC and ANSI standards without any serious problem. The following descriptions are applicable when arresters are made to conform to the IEC or ANSI standard. A construction design concept and a table for the anticipated characteristics are also given for some typical ratings.

1. Process for affecting rated voltage of unit ZnO element

The Japanese standard, JEC–156, specifys that the rated voltage is dependent on the multiple index of 14 kV and the discharge level ratio (DLR)* is smaller than 3.3. For convenience of manufacture, the rated voltage per unit ZnO element is decided to be 2.8 kV and the DLR value is fixed to 2.9 approximately. This value is 3.3 to 3.6 for IEC and less than 2.9 for ANSI. If conformity to these standards is attempted, the DLR value should be fixed to about 2.7 as a standard characteristic. Then the same ZnO element can be used for the rated voltage of 3.0 kV without any modification.

Note: * DLR = discharge voltage at 10 kA/rated voltage (effective).

2. Outline of IEC and ANSI type gapless arresters

Table 3 shows major characteristics, approximate dimensions, and weight of typical arresters with rated voltage below 198 kV, designed in accordance with the IEC and ANSI standards. A significant point which is extremely different from the JEC standard is the long-duration current impulse test of IEC (which corresponds to the transmission line discharge test of ANSI). However, in the case of the gapless arrester its discharge capacity can be obtained accurately from the circuit conditions and the V–I curves, unlike current-limiting gap type arresters.

Table 3. Representative characteristics of IEC and ANSI type gapless arrester type ZS–A.

Rated voltage (kVcrest)	Discharge voltage at 10 kA			Max. diameter of porcelain (mm)	Approxi. overall (mm) / Weight (kg)	Application
	IEC max. (kVcrest)	ANSI max. (kVcrest)	ZS–A (kVcrest)			
15	54	44	40	200	360/20	IEC, ANSI
30	108	87	81	200	500/30	IEC, ANSI
60	216	174	162	200	1,100/60	IEC, ANSI
120	400	350	324	350	1,600/160	IEC, ANSI
180	–	510	486	350	2,400/300	ANSI
198	649	–	535	350	2,400/300	IEC

Figure 14 shows the result of analysis on typical rated voltages. When an arrester with the rated voltage 180 kV is installed on the 230 kV system (this system voltage being highest for the arresters below 198 kV rating), its capability of withstanding 20 shorts of 2 ms 400 A is considered to be sufficient. In the case of 20 shorts of 2 ms 600 A which is actually covered by the ZnO element (Fig. 5), the expected allowance is still more than 30 %. This allowance will become greater for other rated voltages.

When arresters are installed on 345 kV or higher systems and higher rated voltages are required, two or three complete arresters or elements contained in a single porcelain housing adequately selected are to be connected in parallel. In this arrangement, the resultant capability is sufficient for heavy-duty usage and the protection level is low.

Application to Various Purposes and Future Prospects

The new gapless arrester makes full use of various advantages of the ZnO element. And the following products have been developed already.

(1) For SF_6 gas insulated switchgears (GIS)
- ZS–98AFT type with rated voltage 98 kV and capacitance 25 μF for 77 kV systems.
- ZS–420AFT type with rated voltage 420 kV (BIL 1,800 kV) for line protection for 500 kV substations (Fig. 15).

(2) For oil-insulated compact substations (OIS)
- ZS–84AS type with rated voltage 84 kV and capacitance 25 μF for 66 kV systems.
- ZS–196AS type with rated voltage 196 kV and capacitance 25 μF for 154 kV systems.
- ZS–112AS type with rated voltage 112 kV and capacitance 25 μF for above, neutral grounded.

For special usage such as HVDC cable protection or UHV power transmission systems (1,000 to 1,500 kV), the required energy absorbing capacity and decision of the number of required parallel elements are being investigated. Improvement of the ZnO element itself is also attempted to obtain more excellent characteristics. If the improvement is successful, then a remarkable reduction of BIL is possible and arresters with such elements may be replaced by current-limiting type arresters in the future.

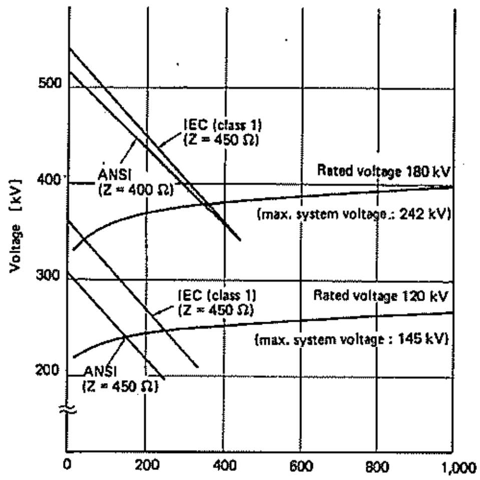

Fig. 14. Analysis of long-duration current withstand capability for typical rated voltage according to IEC, ANSI standard.

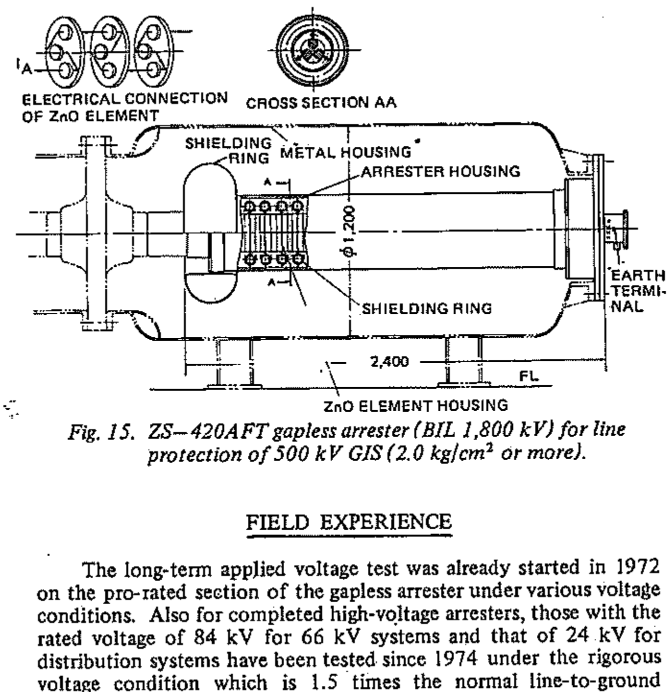

Fig. 15. ZS–420AFT gapless arrester (BIL 1,800 kV) for line protection of 500 kV GIS (2.0 kg/cm² or more).

FIELD EXPERIENCE

The long-term applied voltage test was already started in 1972 on the pro-rated section of the gapless arrester under various voltage conditions. Also for completed high-voltage arresters, those with the rated voltage of 84 kV for 66 kV systems and that of 24 kV for distribution systems have been tested since 1974 under the rigorous voltage condition which is 1.5 times the normal line-to-ground voltage. The characteristics have been checked periodically, and at present (at the time of completion of this report) it has been verified that the obtained data are almost the same as those from initial characteristics. These characteristics are actually very stable. Judging from the Arrhenius curve in Fig. 6, these data are considered to be equivalent to those which may be obtained more than 1,000 years later if the test is carried out at a normal line-to-ground voltage. In addition, voltages 1.1 to 1.9 times the normal line-to-ground voltage have been applied to 196 kV, 210 kV and 266 kV arresters for more than 6 months. Figure 16 shows the photograph of the testing site. In addition, the arresters with the rated voltage ranging from 4.2 ~ 140 kV are used on actual power systems of several electric power companies in Japan.

Summer is the severest season for the gapless arrester (because of temperature, lightning surge, and salt pollution by typhoon). The arresters under test have experienced the summertime tow times. As shown in Table 4, the data obtained on the site are found to be almost unchanged since installation. Some of these arresters have been disassembled for the detailed inspection. It has been verified that there is no abnormality within the arrester.

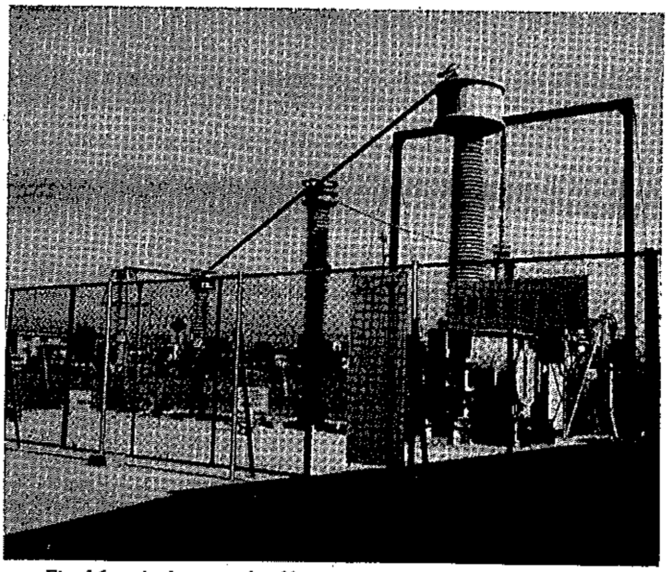

Fig. 16. A photograph of long-term applied voltage test site. from right to left
1 Testing transformer 360/180 kV
2 ZS–266A2X (266 kV live-washing type)
3 ZS–266A2 (266 kV general type)
4 ZS–210A (with housings of conventional arrester)

Table 4. Examples of field experiences.

No.	Type	Rated voltage (kVrms)	Name of substation and electric power company	Time of energizing the gapless arrester	Number	Notes
1	ZS–84AX	84	Hayato S/S Kyushu El. Power Co.	7, 1975	3	Pollution-proof (0.12 mg/cm²)*
2	ZS–98AX	98	Hayato S/S Kansai El. Power Co.	7, 1975	3	Pollution-proof (0.1 mg/cm²)
3	ZS–84AX	98	Chikko S/S Chubu El. Power Co.	7, 1975	3	Pollution-proof (0.06 mg/cm²) including semi-conducting procelain
4	ZS–84AX	84	Numazu S/S Meidensha El. Mfg. Co.	7, 1975	3	Pollution-proof (0.06 mg/cm²) (Tokyo El. Power Co.)
5	ZL–42BY	42	Tsubaki distribution line Kansai El. Power Co.	8, 1975	12	Pollution-proof (0.12 mg/cm²) semi-conducting procelain

* $0.12\ mg/cm^2$ means salt concentration on the porcelain surface.

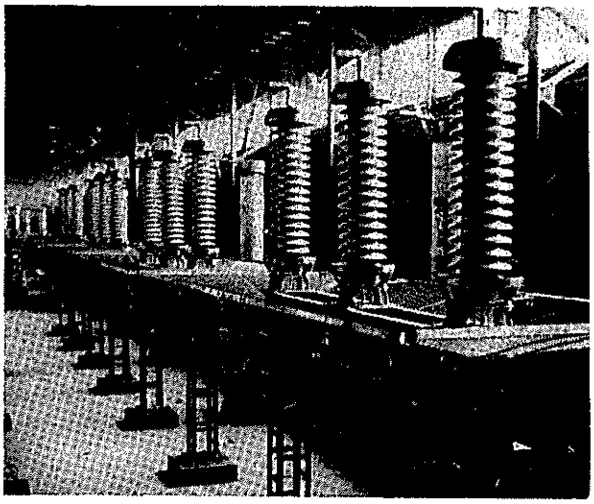

Fig. 17. 98 kV arresters in actual installation.

We have delivered so many gapless arresters to so many customers. Arresters of 84 kV and above only have already numbered about 100 by the end of 1976. Successively, more than 150 units are being manufactured. Figure 17 shows an example of the photograph arresters installed in actual power systems.

CONCLUSIONS

Meidensha has succeeded in the research of the improvement of the ZnO varistor into the arrester element for power systems. To sum up, the following points can be itemized:

(1) A ZnO element of standard dimension is decided as the arrester element for power systems and the fundamental characteristics are clearly defined. The ZnO element has been compared with the SiC element and it has been confirmed that the ZnO element is more excellent in all respects.

(2) The 4.2 to 280 kV arrester series conforming to the JEC standard include pollution-proof and live-washing types.

(3) For the gapless arrester types designed to the JEC standard, their conformity to the IEC and ANSI standards have been discussed.

(4) The new gapless arresters of pollution-proof type and those for GIS, OIS, etc., have already been completed and are in operation at present. Improvement of these arresters into those for HVDC and UHV transmission systems, as well as feasibility of the reduction of BIL, is being investigated.

(5) Field experience has attained about two years. It has been verifier that the arresters under test offer sufficient capability in practical usage.

ACKNOWLEDGMENT

For the development of arrester elements for power systems from ZnO varistors, we owe much of our success to Dr. Y. Iida, Dr. T. Masuyama, and Dr. M. Matsuoka of the Wireless Research Laboratory of Matsushita Electric Industrial Co., Ltd. In the promotion of standardization of gapless arresters, we are also deeply indebted to Prof. T. Tsurumi of Science University of Tokyo, Prof. T. Kawamura of Univerisyt of Tokyo, Dr. Y. Ozaki, Mr. M. Takanashi and Mr. T. Yokokura of Central Research Institute of Electric Power Industry for their considerable guidance and precious suggestions. We are also grateful to many people concerned of respective electric power companies for helpful discussions.

Last but not least, we wish to express our gratitude to Dr. S. Seki, President of Meidensha, Dr. Y. Murayama, Managing Director, Mr. S. Shiotani, Director, Mr. S. Hieda, Mr. N. Furuya, Mr. N. Kondo, Mr. S. Ochiai and many kind colleagues for their stimulating help.

REFERENCES

(1) M. Matsuoka, "Nonohmic properties of Zinc Oxide Cermics", *Journal of Applied Physics*, vol 10, No. 6, June, 1971.

(2) T. Nishikori, T. Masuyama, M. Matsuoka, S. Hieda, M. Kobayashi, and M. Mizuno, "Gapless Power Arrester by Zinc Oxide Non-lincar Resistor", *"1973" National Convention Records of IEEJ (Japan)*, No., 777, Page 1010, April, 1973.

(3) M. Kobayashi, M. Mizuno, M. Matsuoka, and M. Tanaka, "Gapless Arresters for Power Systems", *Technical Meeting on Switching and Protective Devices of IEEJ*, No. PD–74–12, Ocober, 1974.

(4) S. Hieda, M. Kobayashi, N. Furuya, N. Kondo, K. Mitani, and T. Aizawa, "Gapless Lightning Arresters for Power Systems", *Meiden Review*, vol. 119, No. 6, 174, page 65 ~ 72.

(5) E. C. Sakshaug, J. S. Cresge, and S. A. Miske, Jr., "A New Concept in Station Arrester Design", *IEEE Power Engineering Society 1976 Summer Meeting*, August, 1976.

(6) T. Yokokura and M. Takanashi, "Analysis and Proposal for Test Method on Switching Surge Operating Duty Test of EHV Lightning Arresters," *Central Research Institute of Electric Power Industry*, No. 176013, October, 1976, (p. 18 ~ 21, and p. 47 ~ 50).

Discussion

John E. Harder (Westinghouse Electric Corporation, Bloomington, IN): The authors are to be complemented for their description of their developments in the relatively new zinc oxide technology.

Table 3 of the paper suggests a protective level for a 120 kV arrester of 324 kV, for discharge voltage at 10 kA. A typical 120 kV station class lightning arrester in the USA might have a discharge voltage at 10 kA of 270 kV and a maximum 1.2×50 impulse sparkover of 290 kV. Will the authors please comment on any expected difficulty in building a gapless zinc oxide arrester with protective characteristics equal to or better than present USA station class arresters?

Manuscript received August 5, 1977.

S. Tominaga, N. Nagai, T. Nitta, and **Y. Shibuya** (Mitsubishi Electric Corporation, Amagasaki, Japan): The authors are complimented for their successful application of ZnO non-linear resistive elements to a station type arrester. The ZnO arrester seems to be quite promising in the field of power application, if the advantages of the material is put to use properly in the design. The discussors would like to ask the authors' opinions on the following points.

1. The authors state that "ZnO elements can be connected in parallel to design heavy duty arresters". The discussors see two types of difficulty in this approach. Even if the difference in V_{1mA} of the elements to be connected in parallel is within 2% in the beginning, the difference in high currents between these elements will be of the order of 20% as analyzed in the text. The imbalance in high current gives different ΔV_{1mA} as typically shown in Fig. 4 and 5. This means the difference in the V-I characteristics of the paralleled elements increases in the life time of the arrester. Another type of difficulty in paralleling will be produced by the difference in temperature rise due to the uneven distribution of high current impulse or switching surges. The difference in temperature gives rise to a considerable difference in the leakage current particularly after multiple surges. Since the high temperature element has more leakage current and hence more energy input as seen in Fig. 2, the imbalance will last considerably long period of time under service ac voltage. The effect will limit the high current durability of a parallel element arrester.

2. Authors estimate the life expectancy of ZnO elements by Arrhenius' plots in Fig. 6. In the figure, time to runaway is defined as the time when the leakage current exceeds 0.1 A. Does this mean the leakage current keep increasing gradually to the value? If not, can the authors give information about the way it increases to the end of the life? If the leakage current increases gradually, then the temperature of the element will very much depend on the setting condition of the specimen. Is the temperature plotted on the abscissa of the figure the temperature in the oven? If the temperature of the sample is not equalized to that of the oven, how the sample temperature increases in the course to its runaway? The overvoltage withstand characteristic shown in Fig. 8 does not agree with the life curve given in Fig. 6. They differ about two orders of magnitude in the life at room temperature. What temperature is postulated in obtaining the curve in Fig. 8 and why?

3. The authors have tested the duties of the gapless arrester on impulse and switching surges based on the present standards, in which conventional arresters with series gaps are assumed. When we consider the duty of a gapless arrester in the field, the temperature of the elements will rise to a certain level, even if it absorbes the surge energy successfully. This means the increase in the leakage current and may develop the thermal runaway of the element after a certain period of time. For this reason, the discussors consider that the duty test on a gapless arrester should be judged by watching the temporal change in leakage current under ac voltage for a specified period after the surge energy absorption.

The same sort of consideration should be taken also in the estimation of over voltage withstand in Fig. 8.

4. When a high voltage gapless arrester is set in a grounded vessel as in the GIS application, potential distribution of the series connected elements will be distorted due to the stray capacitance to the ground. This causes higher stresses on the elements at line end. The most highly stressed element will limit the life of the whole arrester.

From this point of view, the discussors assume some kind of grading means in the tank type arrester in Fig. 15. Is this guess correct? If that is the case, the requirements on the stability of the grading components will be much severer in comparison with those for a conventional arrester. This will be true since a slight distortion in the grading could be fatal for gapless arrester. Ten per cent overstress on one element corresponds to the decrease in life expectancy by about one and a half orders of magnitude as seen in Fig. 6 in the text. What kind of grading scheme is utilized in the arrester, if any, and what precautions are taken on those grading components?

Manuscript received August 18, 1977.

M. Kobayashi, M. Mizuno, M. Hayashi, T. Aizawa, and **K. Mitani:** The authors wish to extend their thanks to those who have submitted discussions on the paper.

We presume the expected difficulties pointed out by Mr. Harder are:

(1) Development of zinc oxide element having superior V-I characteristics.

(2) Stability of characteristics in the micro current region at the voltage during a long run of operation.

We are, at present, investigating the problem encountered in the above item (2) for surge arrester with better protective characteristics than shown in Table 3.

It is evident if a method of connecting by-pass gap to a part of the element is adopted, protection level can be lowered by 20 to 30% which we are prepared to supply if clients so earnestly desire.

Firstly, Messrs. Tominaga, Nagai, Nitta and Shibuya are discussing about the effect on parallel connection of ZnO element.

In case when ZnO element is used in parallel, the critical operating voltage (V_{1mA}) of the respective column can be regulated to the same value within measurable accuracy so that surge current flowing to each column can evenly be divided which has been proved logically as well as in experiments.*

Unbalance of current distribution in this case is true to exist very slightly which is however, covered by the design tolerance, therefore, "high current durability" is not limited even in "parallel element arrester".

Nextly, the discussors have raised points on Arrhenius plots in Fig. 6. We are fully aware of the thermal runaway time is largely influenced by the test conditions. Graphs shown in Fig. 6 are plotted from those which are selected from various tests and whose conditions are common to each other except for temp. and voltage.

(Note) Influential conditions affecting Fig. 6 are types and sizes of oven, whether or not air blower is incorporated, number and the method of connection of ZnO elements, dimensions and kinds of materials of electrodes, etc.

The reason why plottings of Fig. 6 and Fig. 8 for the same temperature and applied voltage do not coincide together is influential conditions as above are different. (Temp. in Fig. 6 is not for ZnO element itself but inside of the oven.)

Method to improve the estimated life time in actual usage more accurately is to measure the increase ratio of small resistive current in actual operating condition which is now being investigated apart from the method of Fig. 6.

Thirdly, argument is focused by the discussors on thermal runaway when power frequency voltage is impressed by surge current. We have the same opinion with the discussors too, but, we would like to stress the fact there will be no fear of thermal runaway in the arresters under discussion as our design of critical operating voltage (V_{1mA}) is well concerned. In other words, arresters in Table 3 as indicated in Fig. 14, are satisfactory even two shots of 2ms 400A surge current are superposed on power frequency service voltage. The temperature rise of the element with this current, even no radiation from the element is considered, is about 50°C or less than 100°C. Hence, change of V_{1mA} is almost nil which is clear from temperature characteristics of Fig. 2. Therefore, we consider there will be no fearness to get thermal runaway even after absorption of surge energy.

Fourthly, SF_6 gas insulated tank type arresters have been in discussion by the discussors. Arresters in Fig. 15 are used, for improving potential distribution, use capacitor which has been verified for having stabilized characteristics.

According to calculations and experiments, potential distribution at various parts are within ± 5% of the ideal uniform value which is the value with consideration of life time.

*(Note) T. Yokokura et al; "Application of Gapless Surge Arresters to EHV DC Cable System (part 1) - Experimental Study for Prorated Surge Arresters- "Central Research Institute of Electric Power Industry No. 176047 June, 1977 (p17-20)

Manuscript received November 11, 1977.