An Investigation of the Protection Performances for Current-Limiting Fuses Using Stainless Steel Wires

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Abstract: - Recently, owing to a high demand of and high dependence on electric power, the reliability of the distribution voltage of electric power systems has become more important. 22 kV high voltage cutout fuses have been used widely, but some melting accidents have occurred due to pollution/contamination of bushings. As the number of contaminants in bushings increases, the electric fields on the fuse element surface rise to a critical level, triggering corona discharge. A fuse element material that is more resistant to corona discharge than the Ag element is desired. A new type of current-limiting fuse made of stainless steel wires, which is low-cost and simple in design has been developed. Characteristics tests, including a blocking test with a high surge current when a voltage is applied, have been conducted. Using a model fuse, it was confirmed that this new type of fuse possesses similar performance characteristics to those with an Ag element.

Key-Words: - Large current breaking test, Stainless steel wire, 22kV high voltage cutout, Arc extinguishing tube

1 Introduction

In response to improvements in the reliability of electric supply as well as increases in short-circuit capacity, which accompany increases in electrical demand, there has been a demand for verification of improvement in the blocking capabilities of high currents in switching protection instruments used for electrical power distribution, as well as characteristics related to these blocking capabilities [1]. There has also been a gradual increase in the number of equipment with high-pressure cutout fuses installed.

In 1995, there were numerous melting accidents involving 22 kV high-voltage current-limiting cutout fuses in Japan's Kyushu coastal district [2]. Based on the authors' research results, such accidents are caused when, for example, the porcelain tube of a high-voltage cutout fuse is polluted or contaminated. In such cases, a highly electrical field is produced between the porcelain tube and fuse element, and a corona discharge is generated in the fuse element area, causing a melting accident to occur due to thermal degradation of the silver element (hereinafter referred to as “Ag”) used regularly in fuses [3,4]. As a result, improvements are necessary, and a fuse structure that prevents fuse-melting accidents caused by thermal degradation must be developed. High-voltage cutout fuses using stainless steel wires are being developed by Kakimoto [5] et al. However, since such fuses are of an emission-type structure, there is the problem of cracked gas [6] being emitted from the arc extinguishing tube, and a fusion sound being heard when the fuse melts. This in turn causes concern to the living environment.

The purpose of this research is to develop a low-cost 22 kV high-pressure cutout current-limiting fuse, by using stainless steel wires (SUS304) that are resistant to corona discharges as the element, and by comparing this to the presently used current-limiting fuse that uses Ag [7,8].

In this experiment, a 22 kV high-pressure cutout current-limiting fuse (hereinafter referred to as “model fuse”) with a newly structured element portion using stainless steel wires instead of the currently used Ag element was first experimentally created. Then, an oscillatory impulse high-current blocking characteristics test (hereinafter referred to as “blocking test”), which is one of the characteristics tests for fuses, was carried out. It was confirmed that the oscillatory impulse high-current blocking characteristics of the model fuse that is proposed here, a simulated fuse with a thin wire portion in the center, has equivalent blocking characteristics as fuses that use Ag. The results that were derived after examining the blocking characteristics of stainless steel wires, as substituted for Ag, are reported below.

2. Experimental Arrangement

For blocking tests, flashovers are prevented in the main wire area, where recovery work is difficult, and a lighting surge flashover is made to occur near the transformer. In such a state, the blocking capabilities of
the high-pressure cutout fuse to completely block the short-circuit current that starts flowing are examined [9].

Figure 1 shows the circuit for the blocking characteristic test. The power source and measuring apparatus used in this experiment are the power voltage of the arrester and a shock voltage current generator used for current characteristic tests, respectively. In the blocking test, the model fuse was substituted for the lightning protection component, and the terminal voltage and current characteristics were surveyed by measuring the terminal voltage and current waveform with an oscilloscope (Yokogawa; DL1540).

![Fig.1 Experimental circuit for large current breaking test.](image1)

Figure 2 shows the prospective current (ip) waveform when the current voltage (Vco) of the condenser is 15 kV. Two types of model fuses with different structures were used for the blocking test. Each of these is shown in Figure 3 and Figure 4. As shown in Figure 3, Type (1) represents the model fuse with a structure where one stainless steel wire is set horizontally/linearly in the atmosphere. As shown in Figure 4, the Type (2) model fuse is composed of two stainless steel wires as the fuse element, but the central part of the element is composed of one wire. Since the model fuse will definitely melt in the central part, Type (2) is structured with a gap (d). The structure of this gap has been examined by giving sufficiently taking the heat conduction equation [10] into account. The purpose of the Type (2) model fuse is to extinguish arcs generated in the fuse's central element area when melting of the fuse occurs [11]. To do so, a transparent arc extinguishing tube (Poly Tetra Fluoro Ethylene; PTFE) with an inner diameter (hereinafter referred to as "φp") of 0.5 mm was affixed, and the acrylic pipe was filled with arc-extinguishing sand.

![Fig.2 Peculiar current waveform](image2)

![Fig.3 Trial fuse (TYPE①)](image3)

![Fig.4 Trial fuse (TYPE②)](image4)
3. Experiment results

3.1 Pre-arcing process of fuse element

Figure 5 and Figure 6 are photographs of the Type (2) fuse melting as taken with the image converter camera when the applied voltage was 30kV, the element area consisted of Ag with a diameter (hereinafter referred to as "φs") of 0.1 mm and stainless steel wire with φs=0.2 mm, and an arc-extinguishing tube in the shape of φp=1.0 mm with a length (hereinafter referred to as "1p") of 100 mm was used. The value of resistance differs [12] for the material of the two different fuse elements, but characteristics tests were conducted such that the structure of the element part was the same for both model fuses.

In Figure 5, the emission of light is spread out overall, but in Figure 6, a strong emission is prominent in the center of the element part of the model fuse. This confirms that the gap in the center of the fuse element definitely contributes to the melting mechanism in the central area. It is assumed that for Ag, depending on the quality of the material, if an unexpected electric current passes through the Ag, an adiabatic increase in temperature occurs [13] and there is light emission overall.

Figure 7 shows the voltage and current waveforms measured at the same time the photographs were taken. As shown in (a), which represents the model fuse that uses Ag, melting occurs at the current waveform's peak value of approximately 4.5 kA, about 6.0 µs after power distribution begins. The arc current at approximately 40µs after the start of power distribution is about 300A. For the model fuse that uses stainless steel wires, Figure 7 (b) shows that 7.0 µs after power distribution begins, the current waveform's peak value is approximately 2.8 kA, at which fusion occurs. After a current distribution period of approximately 22 µs, the electric current subsides to nearly 0.0 A. No. 5 of Figure 6 (which corresponds to (5) of Figure 7 (b)) is a photograph taken approximately 8.0 µs after power distribution started, and is the first frame in which an emission can be clearly confirmed. This matches the peak value of the voltage and current waveform in Figure 7 (b), which confirms that melting occurred in the element portion of the fuse. The model fuse using stainless steel wires was confirmed as having the same blocking ability as the fuse using Ag.

3.2 Results of blocking test

Figure 8 shows the power voltage between fuse terminals and the temporal change during the blocking test that was performed using the Type (2) model fuse. In this case, the stainless steel wires were of φs = 0.1 mm, φp=0.5 mm, and lp=100 mm. In (a) and (b) of the same figure, the charging voltage (Vco) of the condenser is 22.5 kV and 37.5 kV, and the upper part of the waveform represents the terminal voltage, while the
lower part represents the current waveform. When $V_{co}=30kV$, the same waveform as the one for 22.5 kV was obtained. In a regular fuse melting process, after power distribution begins, the fuse element becomes heated by Joule heat, from the power distribution current [14]. The period from when power distribution starts and meltdown begins (hereinafter referred to as “$T_f$”) is the meltdown time (hereinafter referred to as “$T_m$”), and the period from when power distribution starts until the arc is generated is the fusion time (hereinafter referred to as “$T_p$”). The electric currents/voltage waveforms from the results of the blocking characteristics test are shown as the results from only one test. As shown in (b) of the same figure, an increase in applied voltage, or injected energy, results in a shortening of the fusion time. This is referred to as the “exploding wires phenomenon,” and a large amount of research is being carried out in regards to this phenomenon [15,16]. The breaking of copper wires by high currents is also reported on as a “fracture phenomenon” by Professor Arai of the Tokyo Denki University. The stainless steel wires used in this experiment, however, are composite materials and are not categorically the same as the ones discussed in reference material [17].

Figure 9 shows the power voltage and temporal change when the Type (2) model fuse is filled with arc-extinguishing sand. Compared to Figure 8, there is a prominent change in the power voltage and current waveform, depending on the applied voltage. Figure 9 (a) differs from Figure 8 in that the current value decreases to 0.0 A after surpassing $T_p$, due to the absorption of heat by the arc-extinguishing sand. A re-ascent in the current cannot be confirmed. Once the current is reduced to nearly 0.0 A, the current value rises again. In Figure 9 (b) and (c), the current is reduced to nearly 0.0 A, as an arc is generated at a point when the current waveform has passed its peak value, after starting to decrease due to a sudden increase in terminal voltage immediately after the $T_f$ value. As with the current-limiting action [18] of the current-limiting fuse and formula (1), the process of extinguishing arcs is mainly composed of the melting mechanism and the energy $P_d$ lost by the arc to the arc-extinguishing sand, resulting in the above phenomenon. The arc generated loses energy, cools down, and loses its conductive properties [19], while heating the surrounding arc-extinguishing sand. In the following equation, $K_{gas}$ represents the constant related to the gas that the arc strikes, and $R$ represents the arc resistance.

$$\frac{1}{R}\frac{dR}{dt} = K_{gas}(P_d - Ri) \quad \cdots \quad (1)$$

After fusion of the fuse element portion, the arc-extinguishing tube was visually confirmed as having slightly melted. This is because the structure of the gap between the arc-extinguishing tube and stainless steel wire is small, and fusion occurs when the central area of the stainless steel (one wire’s worth of element) is effectively heated by a high current. Generally, when a metal wire “explodes” through melting, there is (1) an increase in temperature while in the solid condition, (2) a melting process after reaching the melting point, (3) an increase in temperature while in the liquid state, and (4) vaporization at boiling point, after which an arc is generated, undergoes a four-stage change, and then the metal is fused [19]. For the model fuses that were experimentally created, after power begins in the stainless steel element, the melting point is reached after an increase in temperature by Joule heat while in the
solid state. Afterwards, the stainless steel element melts, transforms to a liquid state, and increases in temperature. It then reaches boiling point, vaporizes, undergoes a four-stage change of state, leading to the blocking of the fuse. This is based on the generalization of the authors’ past research results [20]. After the blocking of the fuse, there were also some residual substances, such as soot, inside the acrylic pipe, from after the fusion of the arc-extinguishing tube.

Figure 10 shows the relationship (hereinafter referred to as “Tm−V characteristic”) between Tm and applied voltage (hereinafter referred to as “V”) of the Type (2) fuse. Tm−V indicates that the heating characteristics inside the arc-extinguishing tube are influenced by the inner diameter of the arc-extinguishing tube. The figure indicates 3 ensemble average values; those marked with ▲ (when there is no arc-extinguishing sand in the acrylic pipe) and △ (when the acrylic pipe is filled with arc-extinguishing sand) are for when lₚ=80 mm, and those marked with ■ (when there is no arc-extinguishing sand in the acrylic pipe) and □ (when the acrylic pipe is filled with arc-extinguishing sand) are for when lₚ=100 mm. Figure 10 also shows that after the model fuse melted, the fusion time of the model fuse without arc-extinguishing sand in the acrylic pipe is shorter than for the model fuse with arc-extinguishing sand in the acrylic pipe. This is due to the heat dissipating more easily if the fuse element comes in contact with the arc-extinguishing sand.

4. Conclusion
A high-pressure cutout current-limiting fuse that is simple in structure, with superior corona discharge resistance properties than the Ag fuse element currently used, was experimentally created. Blocking characteristics of the experimentally created model fuses were examined through blocking tests. The main gathered results are as follows.

1. In blocking tests using arc-extinguishing sand, the fuse blocking time is short, and the arc current reaches nearly 0A approximately 20µs after fusion.
2. In the blocking tests, the fuse blocking time was shorter when the acrylic pipe is filled with arc-extinguishing sand.
3. The gap that was designed intentionally in the fuse element area definitely contributes to the fusing mechanism in the fuse’s central area.
4. Emissions confirm that fusion of the fuse element starts in the central area when an oscillatory impulse high-current is applied.

In the future, the application of stainless steel wires in actual 22 kV high-pressure cutout fuses will be considered after clarifying the characteristics of AC voltage superposition through experiments.
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Reference

Fig.9 Voltage and current waveforms of Type ② in 0.1 mm wire fuse with PTFE tube and arc extinguishing sand.
Fig.10 Relation between applied voltage and breaking time.


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