A High-voltage High-current Relay with a Radial Component Magnetic Field

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Abstract

In recent years, battery-electric vehicles, hybrid-electric vehicles, fuel-cell vehicles or industrial inverters are being mass-produced which use DC high-voltage high-current. Because of this, a highly reliable electric relay, which assures the shutdown of circuits in a situation where the electric current exceeds 500A, has required development as a safety measure. A new type of electric relay for DC high-voltage high-current power is developed by applying a radial component magnetic field to the relay's contact point. Evaluation tests are conducted and the results indicate that the performance of the new relay is significantly higher in comparison to conventional products.

Keywords

electric relay, arc, jxb force, plasma, contactor

1. INTRODUCTION

The development of electric-, hybrid-electric- and fuel-cell vehicles has been promoted for such reasons as good mileage and prevention of air pollution caused by carbon dioxide, the efficient use of energy and other global environmentally-related issues, efficient fuel consumption and low air pollution. One of the development integrants shared in electric vehicles and DC high-current devices is a high-voltage high-current DC electric relay with high reliability and capable of high mass-production.

A high-voltage DC relay, which is equipped to a path line in order to connect high-voltage batteries or a fuel-battery power source and a high-voltage component, is required to perform two functions simultaneously. One of these capabilities is that a switch of DC high-voltage, of which the level is several 10A, can perform more than several tens of thousands of opening and closing motions without any problems under conditions whereby the applied voltage is several 100V. The other capability is to shut down over several 100A of fault-current without fail, when troubles occur to vehicles or accidents happen to the load side. The biggest problem to be solved in relation to these breaker functions is the issue of arc phenomena. With the circuit to which a high-voltage is applied, when the relay contact is opened by over several 10A of current region, the electrode neighborhood is heated up to several 1000°C locally and an arc, an electric current continuously flowing through plasma with a high conductivity, is generated. A mechanism to shut down the arc is an essential element for improving the performance of the breaker's function, and this is the biggest issue to be solved in order to develop and mass-produce a high-voltage DC relay. But no relay has been completely reliable yet. One way to solve this problem is the challenge of taking out the arc in the hydrogen ambience [Panasonic, 2005]. Another is the method of trying to conduct a safe and complete high-speed shutdown of the arc by applying a magnetic field to the electrodes neighborhood so that the arc length will be extended. We have demonstrated that an occluded hydrogen fuse can shut down a DC high-current arc quickly. [Minami et al., 2004, Kitajima et al., 2005, Kitajima et al., 2006a, b] Using hydrogen is surely an effective method. However, this paper shows the results of a study in which a method to shut down the arc using electromagnetic power is chosen for the purpose of developing an electric relay with a new design and high efficiency.

Studies have been conducted to observe the connection of two electrodes and how the application of a magnetic field to them at a right angle can reduce the sustained-period of the arc. In contrast, our study has developed a relay making the disappearance of the arc possible at an earlier stage. This is developed by applying a radial component magnetic field to electrodes in order to add force to the arc so that the arc turns along a circle in a certain direction. This paper describes the results of evaluating the effects of this type of relay and the performance of a high-speed shutdown.

2. AN ELECTRIC RELAY WITH A RADIAL COMPONENT MAGNETIC FIELD

In this section, a newly developed method to reduce the disappearance time when using a high-voltage DC relay is described. The high-voltage DC relay is an important element for developing electric vehicles and devices using high-voltage high-current power. The method used here is: the arc shifts by the application of a magnetic field to the generated arc; the arc length is extended because of electromagnetic force being added; the sustaining voltage of the arc is elevated and this makes the disappearance of the arc possible at early stage. The sustaining voltage is caused by situations where the temperature remains high at the contact point and a large amount of electrons is generated from the contact point. Shifting the root of the arc by rotating the arc itself in the magnetic field also has a considerable effect in making the arc disappear at an early stage.

The unique feature of this newly invented DC relay is the method of application of a magnetic field in the neighborhood of the poles. It is well known that the method of applying a magnetic field to one direction and using the generated unidirectional electromagnetic force in order to make the arc disappear at an early stage as shown in Figure 1. Here, the arc current, *I*, between the poles is shown. The unidirectional external magnetic field, *B*, is applied perpendicular to the current *I*. The arc is moved in the direction of the arrow with the product of *I* x *B*. The newly invented relay also uses electromagnetic force; however, the configuration of the magnetic field lines are different with the conventional method. A radial component magnetic field which is formed by setting a magnet in an electrode as shown in Figure 2 (a,b,c) makes it possible to disappear the arc much faster than the conventional one. Magnetic field lines of a permanent magnet which is embedded into the electrode is bent by a ring-shaped iron magnetic circuit (F). A radial component of the magnetic field is formed by this magnetic circuit. In this method, the arc driving force is not influenced by where the arc is generated. This generates azimuthal force and rotational force on the arc, and it leads to the disappearance of the arc.

Figure 3 is a photograph of the relay produced according to the concept described above.

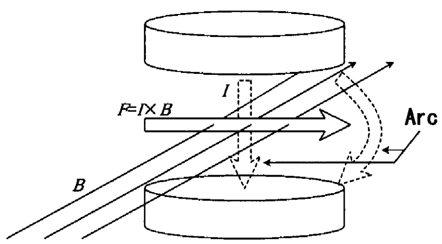
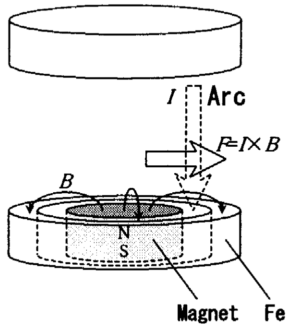
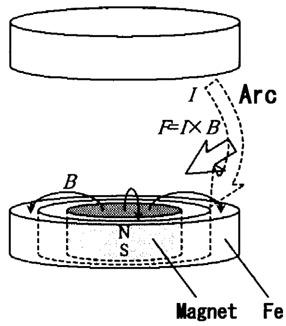


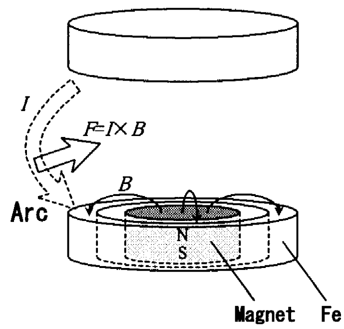
Fig. 1 A method for arc driving with the magnetic field applied to one direction



(a) early phase



(b) mid phase



(c) later phase

Fig. 2 The new method of arc driving by a radial component magnetic field

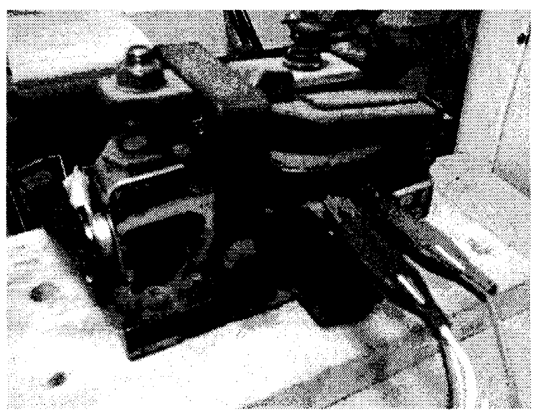


Fig. 3 A photograph of the newly produced high-voltage DC relay

3. EVALUATION OF THE PERFORMANCE OF THE NEW RELAY

After a current is applied between the electrodes of this high-voltage DC relay, the electrodes are opened to generate an arc. The time variations of the inter-electrode current, inter-electrode voltage and the sustained-period of the arc are measured by an oscilloscope, and comparisons are made for parameters including the issue of whether the application of a magnetic field exists. The sustained-period of the generated arc and the endurance of the electrode are important points for the relay's performance. The two steps shown below is used to evaluate the relay's performance.

(1) Using a pulsed power supply circuit, DC current is applied. Then detach the relay electrodes mechanically, and generate an arc between the electrodes. A pulsed power supply is used to energize the current instead of DC power supply because: it is difficult to create a large amount of power to 400V/1000A with a stationary current; and to assure safety, just in case the arc cannot be cut.

(2) Measure the sustained-period of the arc. Figure 4 shows the circuit of the evaluation device for relay performance. In order to storage energy, a capacitor of 0.3[F] is used.

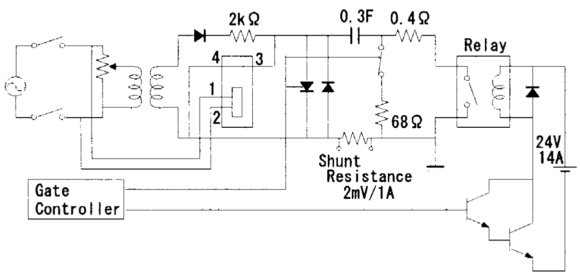


Fig. 4 Circuit diagram of the evaluation device for relay performance

The electrodes is opened mechanically 70ms after turning the electric current on, and an arc is generated. The energizing current of the relay and the waveforms of voltage between the relay electrodes are measured by an oscilloscope. The sustained-period of the arc is read from the waveforms.

In the experiment, the arc-sustained-period is measured with applied voltages of 40V, 60V, 80V, 100V and 120V. A series resisitor of 0.4 [Ω] is connected to the relay circuit. Thus the energized current to the relay is 250A in the case of 100V test voltage. The time-constant τ obtained from the capacity of C=0.3 [F] and resistance R=0.4 [Ω] used in the evaluation test is:

$$\tau = CR = 0.12[s] = 120[ms] \quad (1)$$

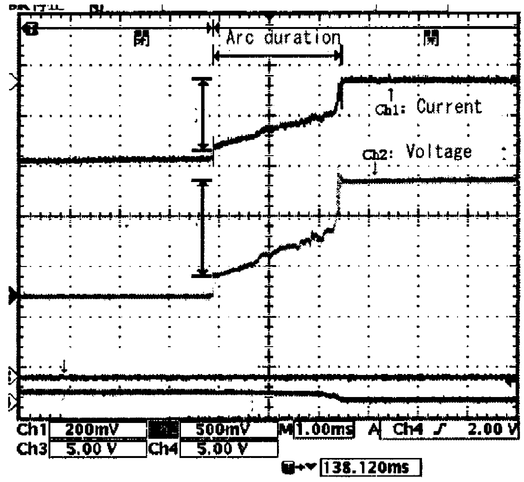


Fig. 5 An Example of the measured arc (Upper Trace: Current (200A/div.), Lower Trace: Voltage (50V/div.)

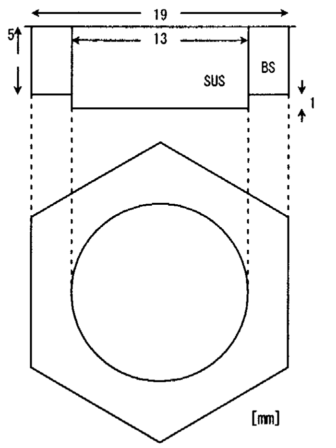
and the time constant τ is long enough to the arc sustained-period. Thus the initial current is considered to be stationary. Figure 5 shows the time variation of the arc current and arc voltage (voltage between electrodes) measured by an oscilloscope.

Figure 5 is the result for a case when a test voltage of 100V/250A, series resistance 0.4Ω and a magnet with a diameter of 8mm are set at the lower electrode of the relay electrode. The horizontal axis is time (1ms/div). The vertical axis is Ch1: relay current (200A/div), Ch2: voltage between electrodes. In this case, the arc-sustained-period is approximately 2.5ms.

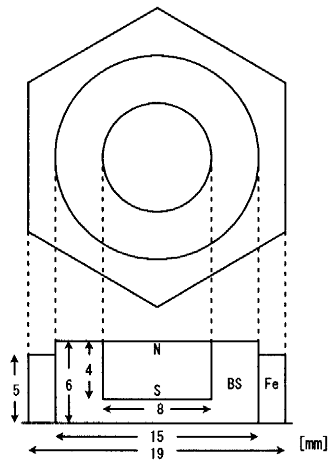
4. STRUCTURE OF THE ELECTRIC RELAY

Figure 6 shows the structure of the electrode of the produced relay. The "upper part" indicates the movable part of the electrode in Figure 2, and the "lower part" indicates the fixed part. The relay used for the movable part is one that already existed, and the relay used for the fixed part is one produced particularly for this study. As for the relay itself, a high-voltage DC relay "24VCD CONTACTOR" from NIPPON YUSOKI., LTD. is used, and the experiment is conducted by attaching the experimentally produced electrode system to it. Samarium-cobalt magnets with diameters of 8mm and 10mm are used, and the effect of the magnetic field is also studied. The contact part of the upper electrode is made of stainless steel, SUS304. The contact part of the lower electrode is made of brass, and an iron-ring is set around it. A radial component magnetic field is created by the magnets placed inside the contact parts.

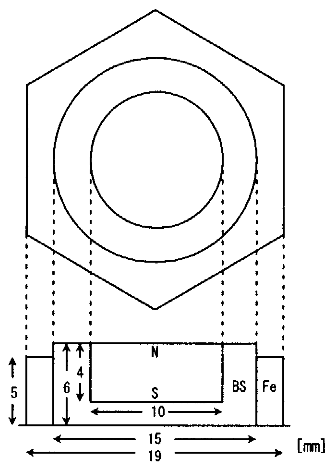
Lower electrodes are made in two sizes with 8mm and 10mm diameters. Figure 6 (b) is the fixed part of the relay electrode for 8mm and (c) is for 10mm. The one shown in Figure 6 (a) is used for both upper electrodes. The distance between the upper and lower electrodes



(a) Upper (movable)

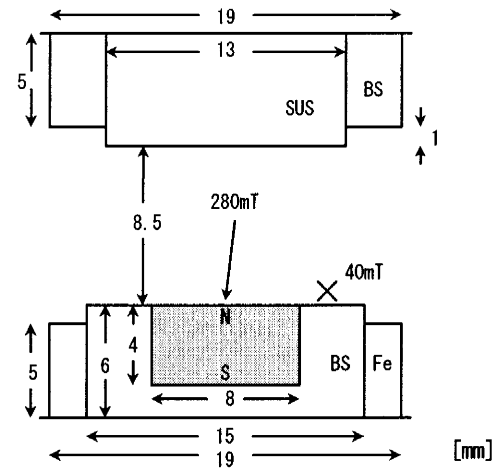


(b) Lower (fixed)

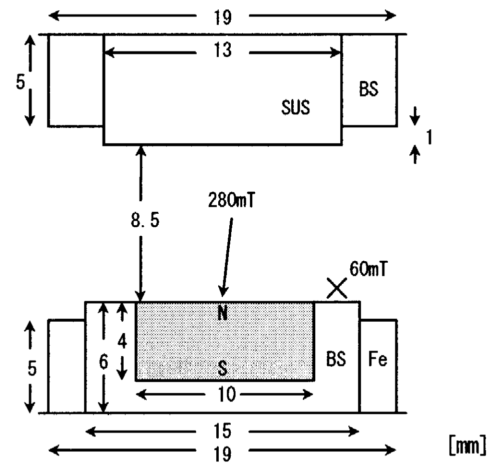


(c) Lower (fixed)

Fig. 6 Contact point (for diameter 8mm and 10mm magnets)



(a) 8mm magnet



(b) 10mm magnet

Fig. 7 Electrode with magnet (8mm or 10mm in dia.)

varies from 8.5mm to 19mm, depending on area. The values of magnetic field by magnets in diameters of both 8mm and 10mm are same and 280mT at the surface of the center of the magnets. When these are placed in electrodes, the magnetic field at the contact point of the lower electrode where the arc is generated is about 40mT for the one with a diameter of 8mm (Figure 7 (a)), and it is about 60mT for the one with 10mm (Figure 7 (b)). Since magnets are insulators, an arc is not created at the upper part.

5. RUSULTS

The results of the study using the experimentally produced relay is described here.

5.1 The case where a radial compound magnetic field is applied

Results are obtained by measuring the arc sustained-period with a relay to which a radial compound magnetic field is applied. A series resistance of 0.4Ω is connected to the relay. When 100V is applied, 250A of electric current is expected to flow in the beginning at the electrodes. Figure 8 shows the results of measured arc sustained-period in a case where a magnet with a diameter of 8mm is in place and a radial compound magnetic field is applied. Figure 9 shows the results of

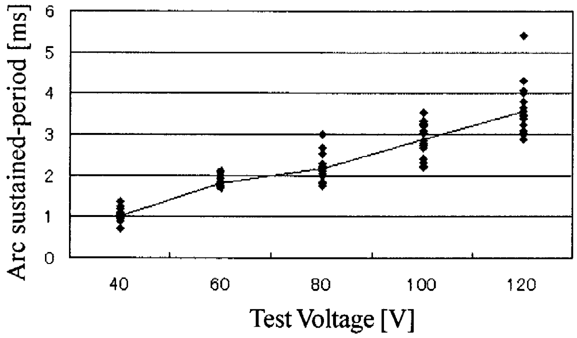


Fig. 8 Relation between the test voltage and arc sustained-period (with 8mm magnet)

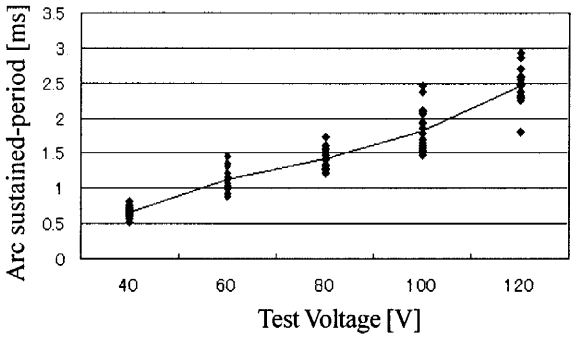


Fig. 9 Relation between the test voltage and arc sustained-period (with 10mm magnet)

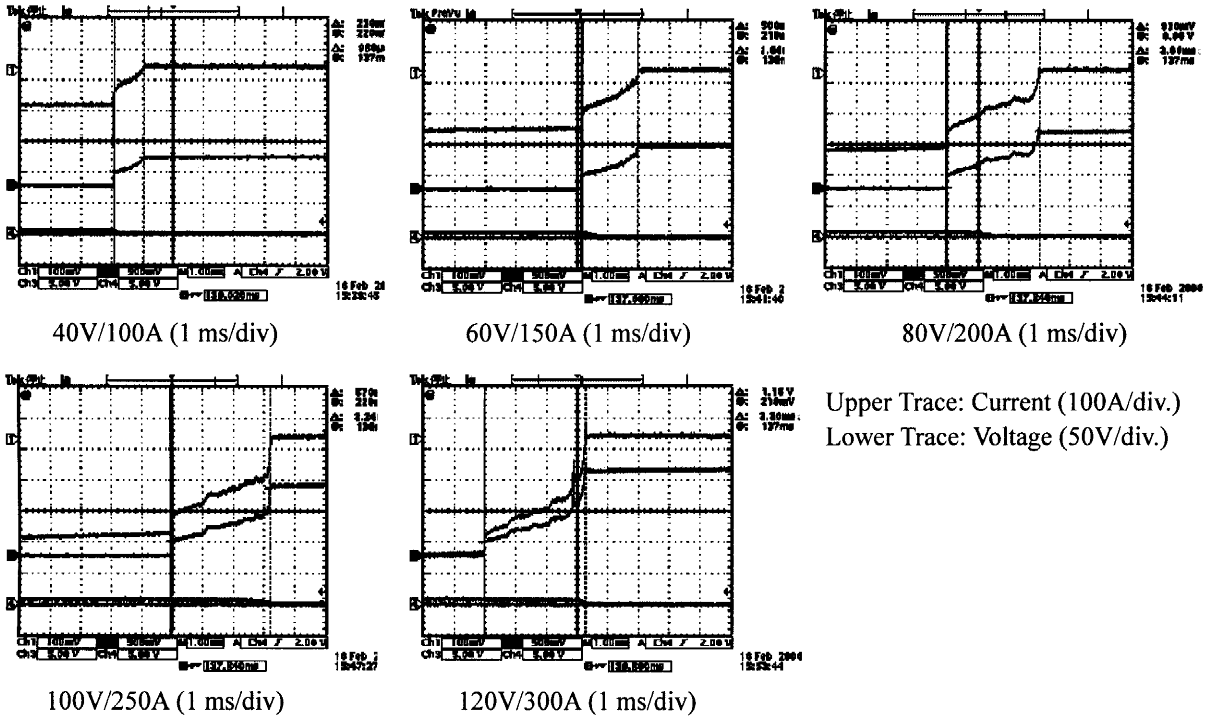


Fig. 10 Waveforms in the case of a 8mm magnet

measurements obtained from the case where a magnet with a diameter of 10mm is in place. Figures 10 and Figure 11 show examples of measuring waveforms in each case. For each case the experiments are conducted 20 times.

5.2 The case where a radial compound magnetic field is not applied

In order to study the effects of a magnetic field for the experimentally produced relay, the relay is opened without applying a radial compound magnetic field and the arc sustained-period for the charging voltage is measured. The results are described below. Similarly to the case where a magnetic field is applied, a 0.4Ω series resistance is connected to the relay. When 120V is applied, 300A of electric current is expected to flow at the beginning in the electrodes. Figure 12 shows the results of measured arc sustained-period when a magnet with a diameter of 8mm is not in place and a radial compound magnetic field is not applied. Figure 13 shows the results obtained from measurements when a magnet with a diameter of 10mm is not in place. Figures 14 and 15 show examples of measuring waveforms in each case. The experiments are conducted 20 times with 8mm relay and 7 times with 10mm relay. The line in the figure shows the average value.

Examples of measured waveforms are shown in Figure 14 and in Figure 15. The test voltage and energized current are shown.

5.3 The case where a unidirectional magnetic field is applied

In order to check the usefulness of the radial compound magnetic field, a conventional relay set-up to with a uni-

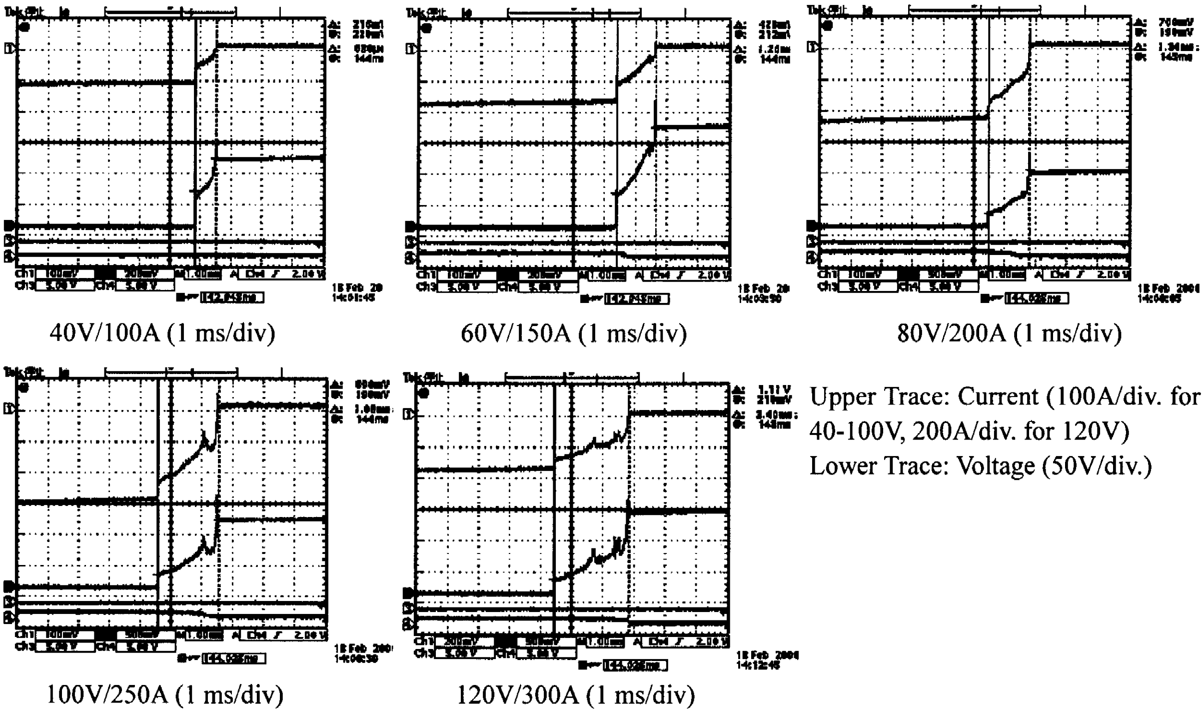


Fig. 11 Waveforms in the case of a 10mm magnet

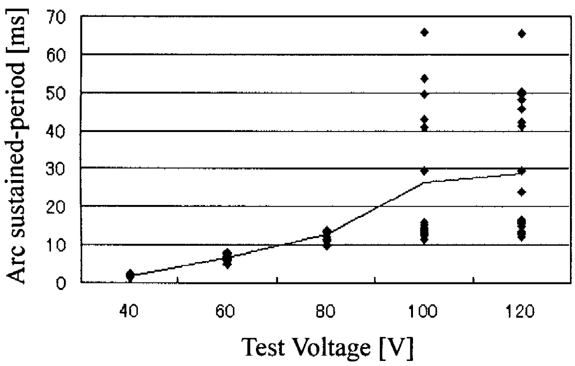


Fig. 12 Relation between the test voltage and the arc sustained-period (without 8mm magnet)

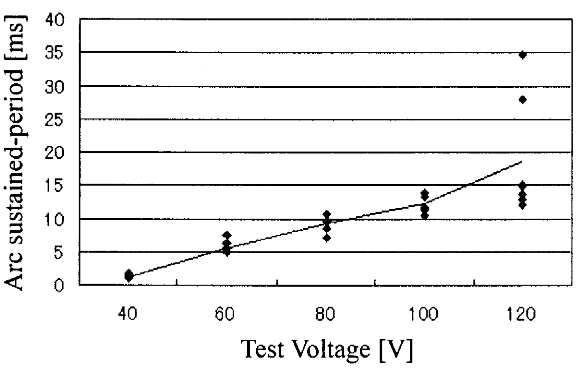
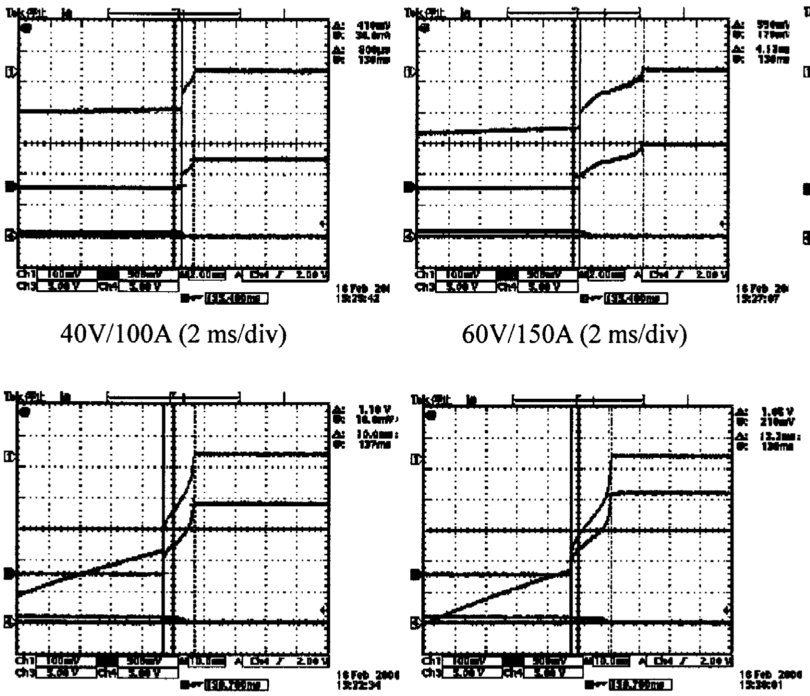


Fig. 13 Relation between the test voltage and the arc sustained-period (without 10mm magnet)

directional magnetic field is used for the comparison. The electrodes in Figure 7 (a) are used at both the movable and fixed parts of the electrode. And a pair of 8mm-diameter magnets is placed between the relay electrodes in order to generate an almost unidirectional magnetic field between the electrodes. The distance between the magnets is 25mm, and the relay electrode is placed almost at the center. With the set-up in Figure 8 (a), at the point where 40mT of magnetic field is detected, the density of the layout above is also about 40mT. The reason why a unidirectional magnetic field is formed by using the same magnet is to equalize the magnetic energy around the contact points. Figure 16 shows a distribution chart for the results obtained by measuring the arc sustained-period with the layout described above, and Figure 17 shows examples of measured waveforms. The experiments are conducted 7 times.

5.4 The case where a radial compound magnetic field is set in reverse direction

In order to study the impact of the direction of the magnetic field, experiments are conducted by setting magnetic poles in the reverse direction. In this case, the arc receives electromagnetic power in the opposite direction from the one shown in Figure 2. A distribution chart of the results of measuring the arc sustained-period is shown in Figure 18, and examples of measured waveforms are shown in Figure 19. An 8mm magnet is used and the experiments are conducted 7 times.

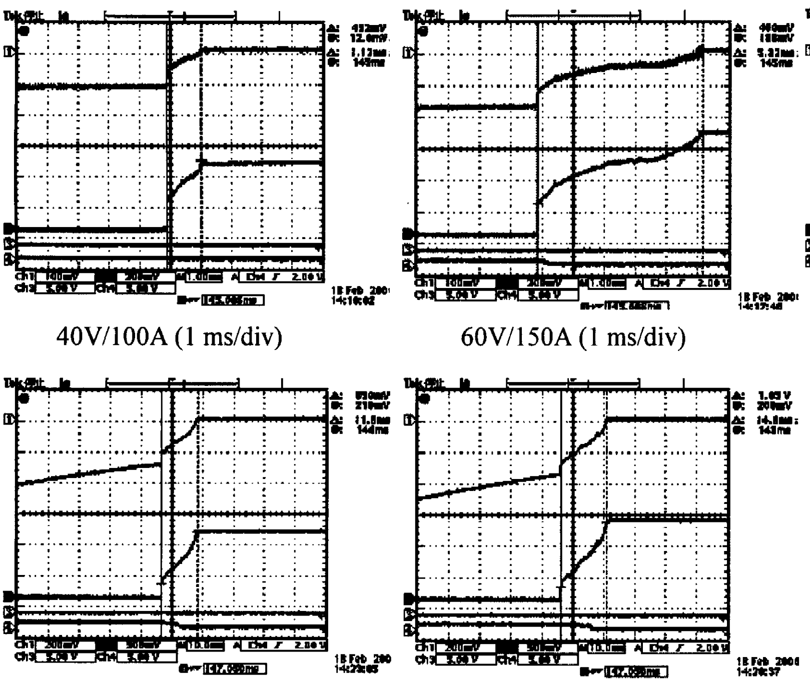


40V/100A (2 ms/div) 60V/150A (2 ms/div) 80V/200A (4 ms/div)

100V/250A (10 ms/div) 120V/300A (10 ms/div)

Upper Trace: Current (100A/div.)
Lower Trace: Voltage (50V/div.)

Fig. 14 Waveforms in the case without 8mm magnet



40V/100A (1 ms/div) 60V/150A (1 ms/div) 80V/200A (4 ms/div)

100V/250A (10 ms/div) 120V/300A (10 ms/div)

Upper Trace: Current (100A/div. for 40-80V, 200A/div. for 100-120V)
Lower Trace: Voltage (50V/div.)

Fig. 15 Waveforms in the case without 10mm magnet

5.5 The case where the polar character of the electrodes is set in the opposite direction

Because the magnet is set only at the lower part for the experimental relay, there is a considerable difference in the distribution of the magnetic field between the upper and lower areas of the electrodes. Because of this, one can guess whether an electron which forms the arc flows from a movable part or a fixed part. In other words, one can guess that differences occur in the arc sustained-period because of the polar character of the electrodes. In order to study this, experiments are conducted by setting the polarity in the opposite direction. In this case,

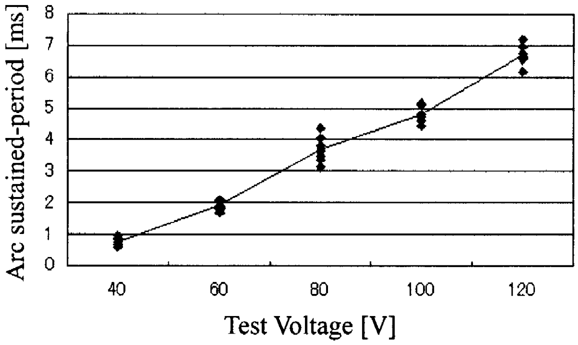


Fig. 16 Relation between the test voltage and arc sustained-period (with the application of unidirectional magnetic field)

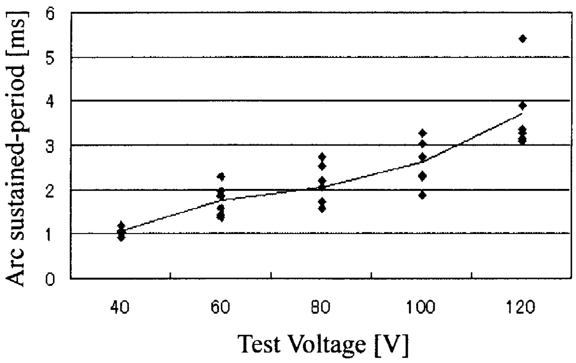


Fig. 18 Relation between the test voltage and the arc sustained -period (8mm magnet in reverse direction)

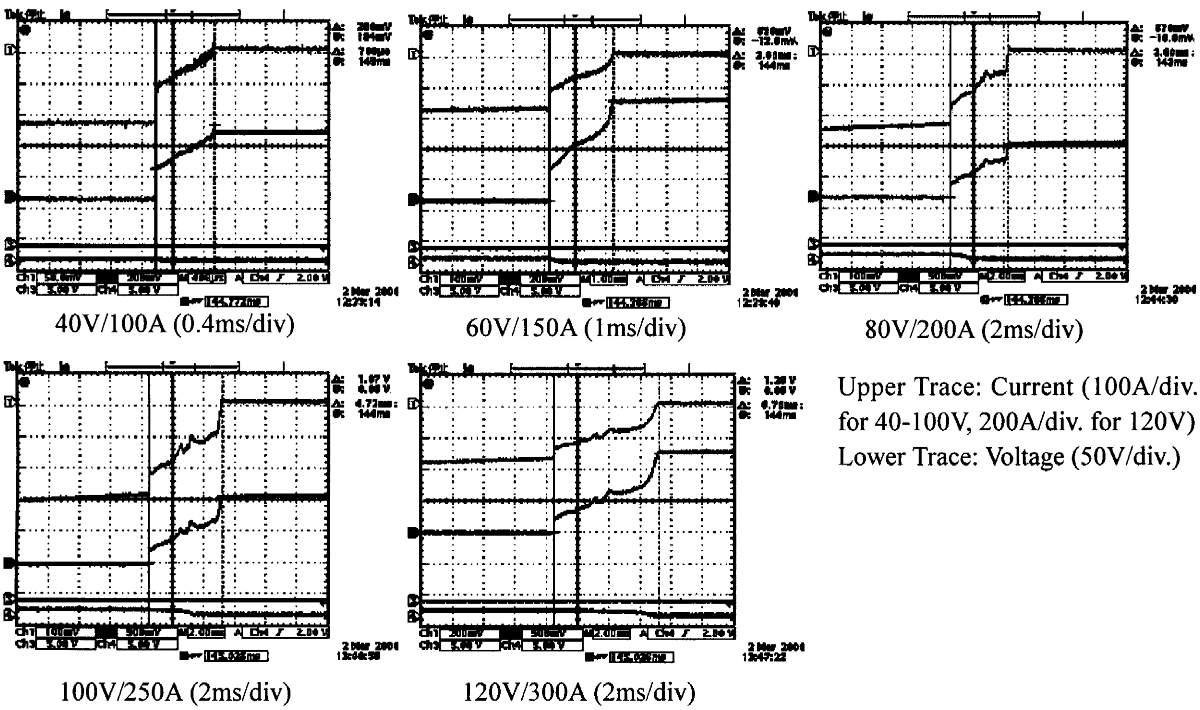


Fig. 17 Waveforms at arc shutdown when unidirectional magnetic field is applied

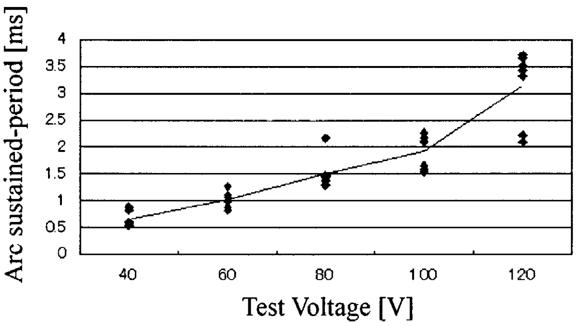
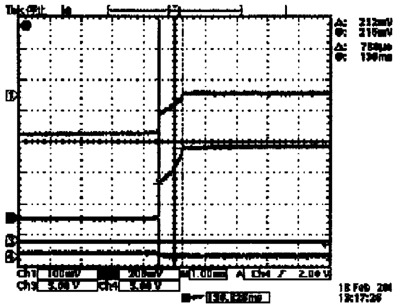


Fig. 20 Relation between the test voltage and the arc sustained- period (polar character in the opposite direction)

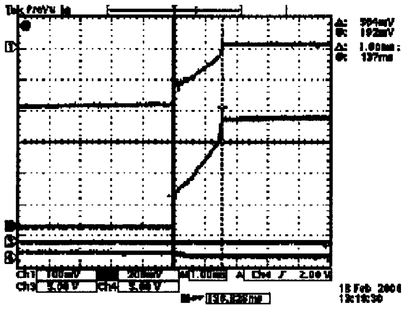
the electric current flows upward, which is opposite from the one shown in Figure 2, and the direction of the circular motion is also opposite. Figure 20 is a distribution chart of the results of measuring the arc sustained-period, and Figure 21 shows examples of measured waveforms. An 8mm magnet is used and the experiments are conducted 7 times.

5.6 The case where the arc current is changed

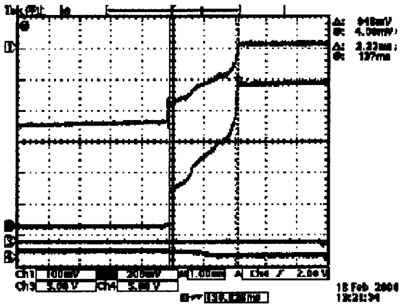
Experiments are conducted to study the impact on the arc sustained-period when relay currents differ but the applied voltage is the same. A series resistance of 0.4Ω connected to the relay electrodes is changed to 0.2Ω. By changing the resistance to 0.2Ω, the arc current becomes two times greater than when the arc current is 0.4Ω. Figure 22 is a distribution chart of the results of measuring the arc sustained-period in the case described above, and Figure 23 shows examples of measured waveforms. An 8mm magnet is used and experiments are conducted 7 times.



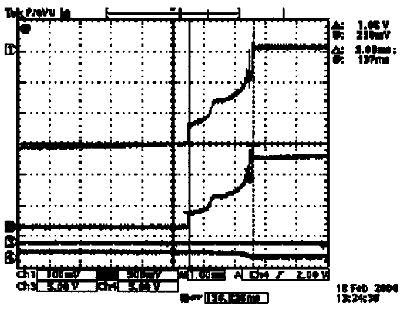
40V/100A (1 ms/div)



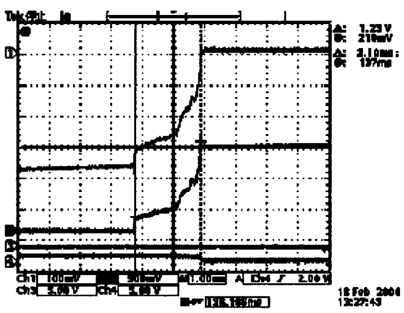
60V/150A (1 ms/div)



80V/200A (1 ms/div)



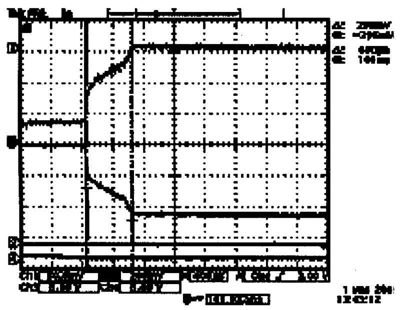
100V/250A (1 ms/div)



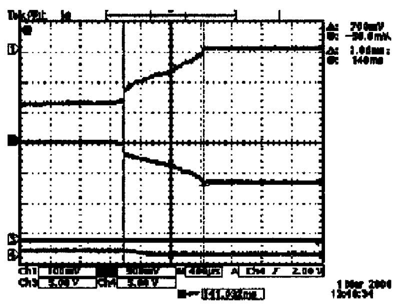
120V/300A (1 ms/div)

Upper Trace: Current (100A/div.)
Lower Trace: Voltage (50V/div.)

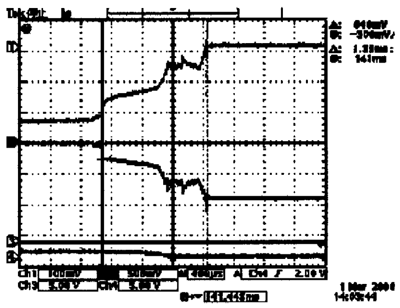
Fig. 19 Examples of waveforms when 8mm magnet is set in reverse direction



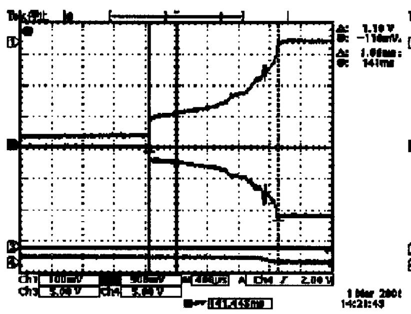
40V/100A (1 ms/div)



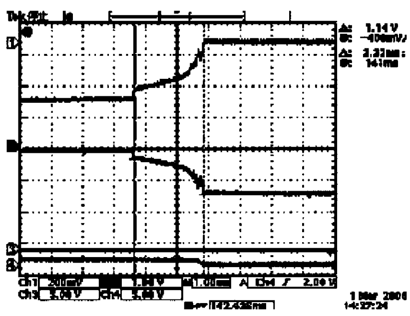
60V/150A (1 ms/div)



80V/200A (1 ms/div)



100V/250A (1 ms/div)



120V/300A (1 ms/div)

Upper Trace: Current (100A/div. for 40-100V, 200A/div. for 120V)
Lower Trace: Voltage (50V/div. for 40-100V, 100V/div. for 120V)

Fig. 21 Examples of waveforms in the case where the polar character of the electrodes is set in the opposite direction

6. DISCUSSION

The results of this experiment are discussed below.

6.1 The difference between cases with and without a magnetic field

The performance of the newly developed relay is the main theme of this study concerning magnetic fields. Figure 24 shows the results of comparing the arc sustained-period in cases with and without a radial compound magnetic field. An 8mm in dia. magnet is used for this experiment.

When the test voltage is as low as 40V, there is no great

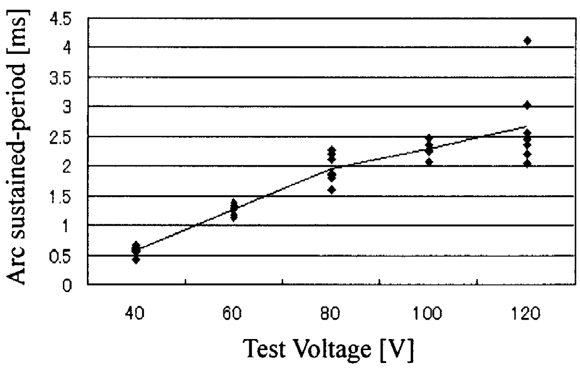


Fig. 22 Relation between the test voltage and the arc sustained -period (0.2Ω series resistance)

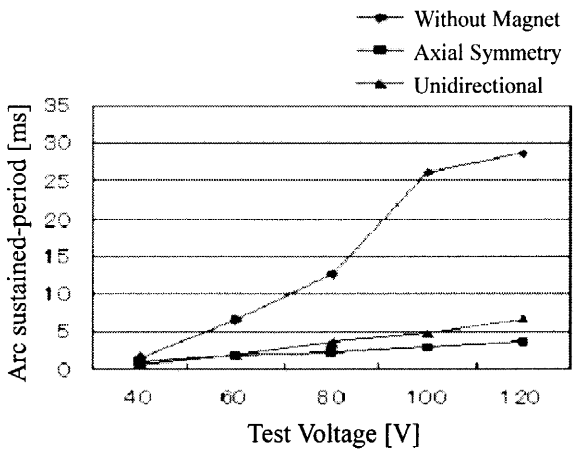


Fig. 24 Difference of the arc sustained-period in cases with and without a magnetic field

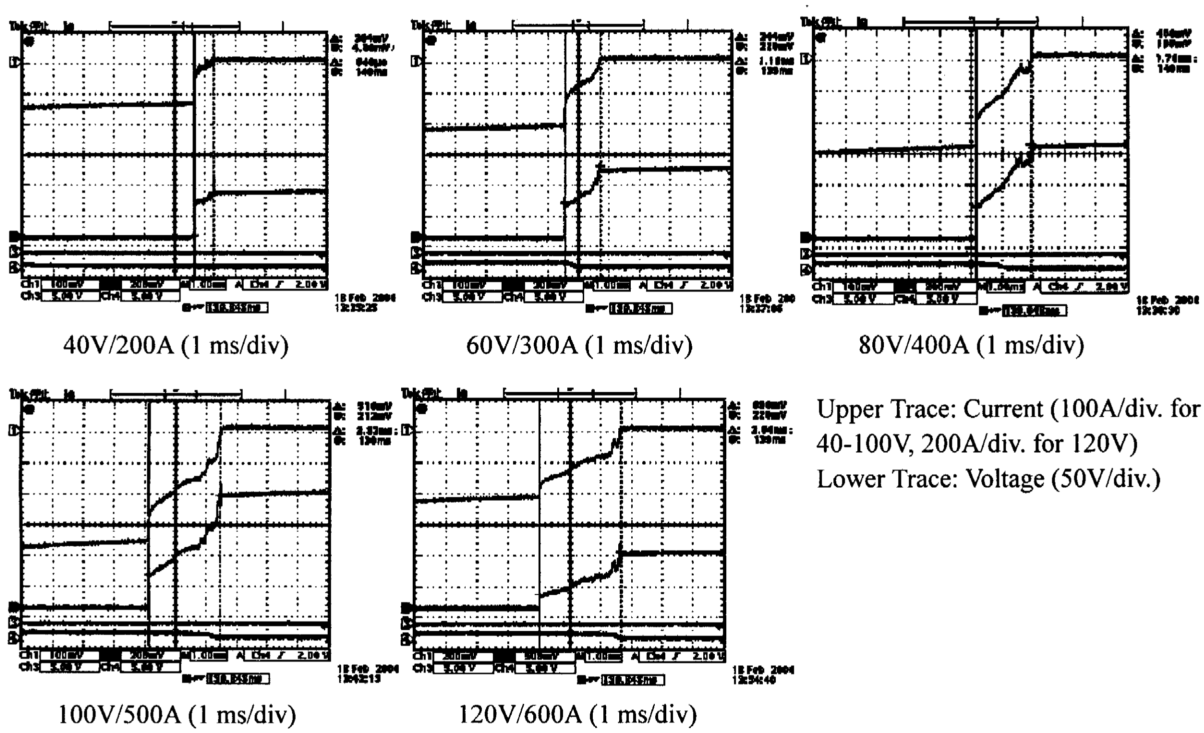


Fig. 23 Examples of waveform when the series resistance is 0.2Ω

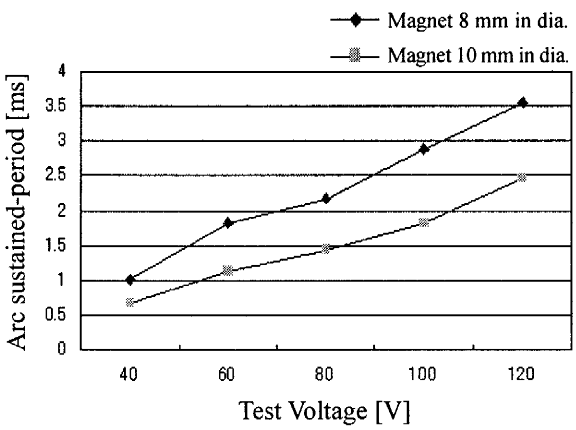


Fig. 25 Difference of the arc sustained-periods influenced by the strength of the magnetic field

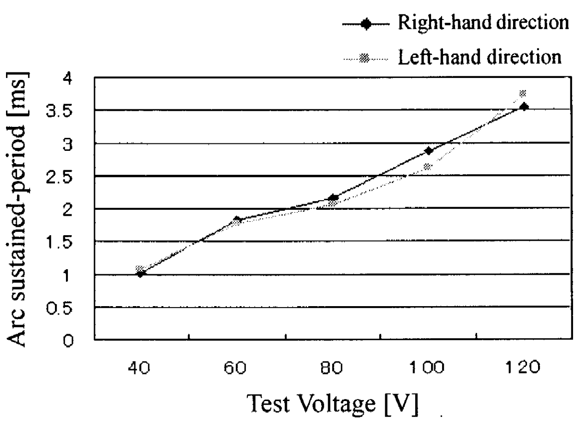


Fig. 26 Difference of the arc sustained-periods caused by the directions of the magnetic field

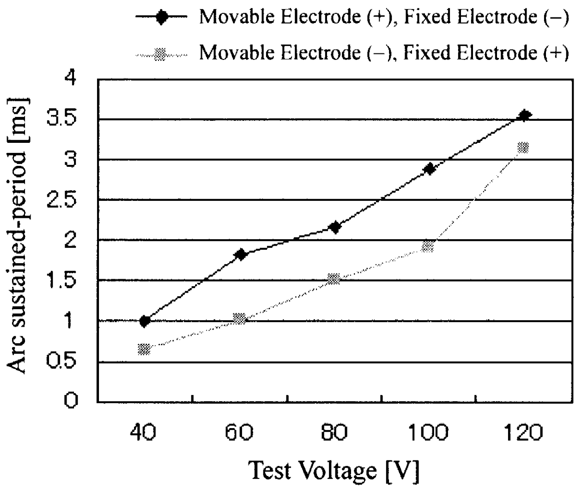


Fig. 27 Difference of the arc sustained period depending on differences in the polar characters

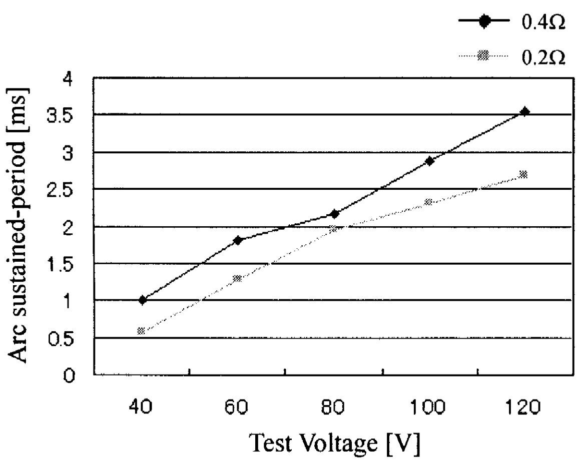


Fig. 28 Differences of the arc sustained-period caused by different values of the energized current according to changes in the series resistance

difference, but as the test voltage increases, the excellence of this relay, which uses the newly developed radial compound magnetic field, becomes more obvious. Apart from the fact that the difference of the arc sustained-period is large, when the test voltage is high, as shown in Figure 13, the arc sustained-period varies considerably in the case with no magnetic field. In the case where the test voltage is 100V, while taking the fluctuation of the arc sustained-period into consideration, the arc period is shortened from 1/10 to 1/20 by applying a radial compound magnetic field. In order to indicate a comparison, Figure 24 shows the characteristics of the arc sustained-period when generating a unidirectional magnetic field by using two magnets of the same size. The results show that, as to the density of the magnetic flux, a radial compound magnetic field is more effective than a unidirectional magnetic field for reducing the arc sustained-period.

6.2 The difference caused by the strength of the magnetic field

In order to discuss the impact of the strength of the magnetic field, the results obtained by comparing the arc sustained-periods for both a 8mm magnet (density of magnetic flux 40mT) and a 10mm magnet (density of magnetic flux 60mT) are shown in Figure 25.

When a magnet is large, in other words, when the density of the magnetic flux at the area where the arc is generated is large, the arc sustained-period becomes short. In addition, when the magnet is changed from 8mm to 10mm, the arc sustained-period is reduced by up to 3/5 when the test voltage is 100V.

6.3 The difference caused by the direction of the magnetic field

Figure 26 shows a comparison of the arc sustained-periods among cases where electromagnetic power is received at the right-hand and left-hand direction of the electrodes of an arc according to the directions of the magnetic fields.

Since no significant difference is observed in the graph, it is considered that neither the size of the electrodes used in this experiment nor the test voltage will impact on the directions of the magnetic field.

6.4 The difference caused by the difference of polar characters

Figure 27 shows a comparison between the case of an arc current flowing from a movable part to a fixed part and the case of it flowing in the opposite direction, of which differences in the directions are caused by the difference in the polar character of the electrodes.

It is found that the arc sustained period is reduced when the arc current flowed from the fixed part to the movable part (upward direction). The results show that the arc sustained period is shortened more when the electron which sustains the arc is generated at the upper (movable) pole of the magnet, and this result remains an issue for future study.

6.5 The difference caused by the variation of energized current value in a relay

When the series resistance is changed from 0.4Ω to 0.2Ω, a comparison of the arc sustained period is made when the size of the energized current in a relay is doubled under the test voltage. Figure 28 shows the results.

As the energized electric current is greater, the arc sustained-period becomes shorter. When a magnetic field is applied, the arc driving force, I x B, becomes proportionately greater as the arc electric current is stronger, and thus the arc sustained-period becomes short. In other words, when a magnetic field is applied, it is best to make the energized electric current large in order to shorten the arc sustained-period further.

7. CONCLUSION

As to the development of a high-voltage DC relay, which the widespread use of electric vehicles is making more important, one of the issues relating to such development is the problem of the high-speed shutdown of the arc generated when the circuit is opened. In this study a new relay has been introduced, using the idea of extending the arc length and reducing the sustained-period by the application of electromagnetic power to the arc. This relay has electrodes to which a radial compound magnetic field is applied. Its performance is found to be excellent in evaluation experiments.

That is, experiments for evaluating performance confirmed that the effect of a radial component magnetic field on the electrodes is significantly valid for reducing the arc sustained-period, and that the period becomes shorter as the size of the magnets increases. With this, the efficacy of the experimentally produced relay, to which relay electrode is applied with a radial compound magnetic field, has become clear. In comparison to a conventional relay using a unidirectional magnetic field, the radial compound magnetic field is also found to be efficient. It has also grown clear that the greater the arc current becomes, the shorter the arc sustained-period becomes. Thus it is found that this relay is significantly efficient for unusual accidents of circuit with a high current.

For future reference, the experiments for evaluation in this study are conducted with an experimental voltage which is up to 120V. But it is necessary to conduct experiments with a range of voltage of several hundreds for the actual application of a high-voltage DC relay used for vehicles. The advantages of this relay, which uses a radial component magnetic field, are that damage to the electrodes is small and that high endurance is expected, since the point of electrode where the arc generates moves because of the arc rotation. Validation of this point is also a future issue. Furthermore, in the future, it will be necessary to conduct comparative assessments between the arc behaviors using computer simulation and with the actual arc behavior video-recorded by high-speed cameras for cases where a radial compound magnetic field is applied.

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