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RUPTURING PERFORMANCE OF D-C HIGH SPEED AIR CIRCUIT BREAKER

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I. RUPTURING TEST OF D-C HIGH-SPEED AIR CIRCUIT BREAKER AT THE NIPPON LIGHT METAL CO.

1. Introduction

In coordination with the simulated arc-back test conducted on mercury rectifiers at Kambara Works of the Nippon Light Metal Co. the description of which was given in the separate paper, interrupting test of arc-back current has been made on a high-speed air circuit breaker for reverse current protection and the general description of the same will be made as follows.

The high-speed air circuit breakers for reverse current protection employed in the test are of the Siemens Co., manufactured in 1939, rated 750 V, 6,000 A and compressed-air operated under operating air pressure of 4.5 kg/cm^2. There are, in all, twenty six circuit breakers of the same type being equipped in the factory and two of them were used for the test.

2. Purpose of test

The purpose of the test was primarily to investigate arc-back current characteristics of the mercury rectifier as observed at the instant of arcing-back, and the test of a circuit breaker itself is rather of secondary consideration. Incidentally, however, from the results obtained, it can be said that the test has proved to be most successful. Because the mechanical time of the circuit breaker under test and its total fault time have happened to be just what should be in value so that, over 20 ms or more, the wave form of arc-back current was studied with considerable accuracy. Thus, in a sense, the purpose of the test was satisfied and at the same time, valuable information was also obtained concerning the use of the circuit breaker in a d–c system.

3. Results of tests

Out of the test results, a few representive examples of information are shown in the oscillograms T–5, T–6 and T–8. The principal items are extracted in Table 1.

Tabe 1. Test results of high-speed air circuit breaker

Test number	T–5	T–6	T–8
Arc-back current (breaking current) maximum value	21,000A	36,000A	10,900A
Rate of rise of current	2.24×10^6 A/s	2.64×10^6 A/s	2.64×10^6 A/s
D–c voltage	640 V	645 V	645 V
Recovery voltage maximum value	1,610 V	1,620 V	845 V
Mechanical time	4.8 ms	4.9 ms	4.0 ms
Total fault time	24.0 ms	23.0 ms	14.8 ms

The circuit breakers employed in the test, as already mentioned, were manufactured in 1939 and has been in use for nearly twenty years. Therefore, if compared with those of our latest type produced based on research and improvement effected ever since the World War II, their quality, in respect to performance can never be excellent. Actually, however, the test results, shown in Table 1, testifys that the function to protect equipment is not yet enfeebled and sufficinently maintained. In the photograph, Fig. 1. is shown an arcing that is blowing upward from the arc chamber at the instant of interruption.

4. Meaning of test

In a survey of the test results, it was made apparent that for the satisfactory solution of problems concerning the duty of a high-speed circuit breaker and the type of tripping system in general,

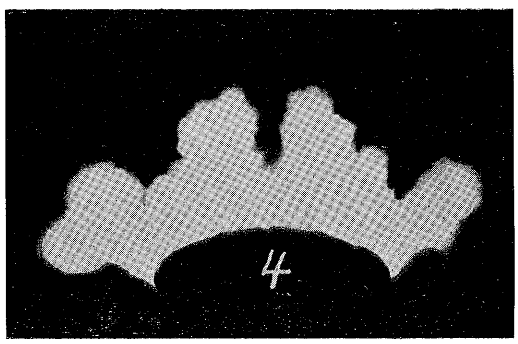

Fig. 1. Arc of d–c high-speed air circuit breaker

the following two items as described must be taken up. Thus, through these tests, major difficulties concerning the circuit breaker have been brought to light and even in this fact alone is found a meaning of the test made.

1) Problem of recovery voltage

In comparison of the two oscillograms T-5 and T-6, a difference is noted in the wave forms of arc-back current and recovery voltage but will be neglected here as it is already described in full in the separate paper. In short, whenever a faulty rectifier has an arc-back induced on any anode other than the first fault anode, the condition is represented by T-6, while otherwise, by T-5. According to the oscillogram, recovery voltage rises approximately twice as high as d-c out-put voltage and gives an impression that the condition of interruption is extremely severe. A close investigation, however, discloses that it is not true. It is because that in the simulated arc-back test, even after current has been interrupted, short circuiting still continues between the anodes and cathodes by means of starting thyratron. With actual circuit, in addition to a high-speed circuit breaker and in the path of arc-back current, is connected in series an arc-back rectifier having one pole which makes arcing-back. It is supposed that this rectifier, when the high-speed circuit breaker finishes interruption, simultaneously recovers its rectifying ability and shares the oscillating voltage load, thus alleviating the interrupting condition. As to the correct rate of voltage sharing, data are not available from these tests, therefore confident conclusion can not be drawn at this stage. It seems that there is still a room left for further investigation in this respect.

2) kind of tripping system

In this test, it was observed that when the main circuit current reverses its normal direction, there exists a zero-current time, though of a very short duration, as shown in Fig. 2. Taking advantage of this turn-over time, if the circuit breaker in its operating state is made self-held at normal load current and is changed to be set at its minimum tripping current of 600 A by scale (point Bin Fig. 2) instead of at −600 A, reverse current, (point A in Fig. 2), the contact opening point of the breaker shown in Fig. 2 represents the time shortened by 3 ms approx. Strictly speaking, the rate of change of current at points A and B differs, therefore, proper time t_o is not necessarily equal to each other. Similarly, it is conceivable that arc-back current at each arc-initiating point (point C and D respectively in Fig. 2) may differ in value, and so will it be with the rate of rise of arc voltage at the terminals of the circuit breaker. But assumed all these factors are about equal for immediate purpose. Then with the minimum current tripping system, the total fault time is shortened about 3 ms and the maximum value of arc-back current is decreased from I_m to I'_m which signifies an improvement in the function of protection.

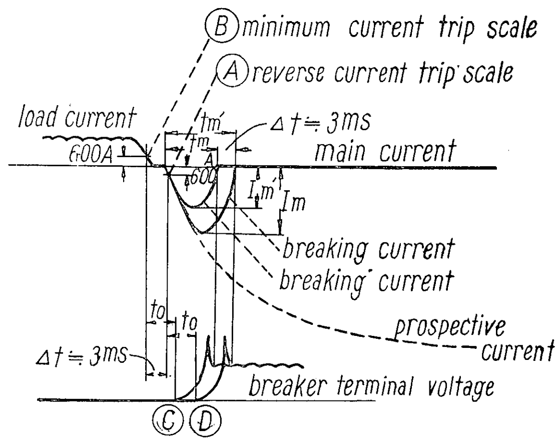

Fig. 2. Variation of breaking current due to difference of trip current scale

This example is best illustrated in a case like an electrochemical plant where the electrolytic bath is operated with practically constant load. Under such circumstances, the circuit breaker is held by normal load current and of the minimum current tripping system.

5. Conclusion

To evaluate the d-c high-speed circuit breaker as a protective device against arcing-back for use in the electrochemical plant having many large-capacity rectifier units, various tests were made and the results of arc-back current interrupting test and the interrupting conditions of arc-back circuit, in particular, have been so far described.

Basing on these valuable informations obtained through these tests, design effort will be further made for rationalization of the protective device for large-capacity d-c systems to be used not only in electrochemical plants but also in electric railways or various industries.

Throughout the planning and test, valuable assistance has been extended by the members of the Nippon Light Metal Co. both the main office and field factory, for which hearty appriciation is expressed.

II. RUPTURING TEST OF D-C HIGH SPEED AIR CIRCUIT BREAKER AT OUR WORKS

1. Introduction

In the last ten years, a considerable number of d–c high-speed air circuit breakers of our makes have been delivered as a protection instrument for d–c source or circuit for use in various fields such as electric railways, electrochemical or industrial power plants. User's requirements and any such informations have been taken into consideration and continuous effort for improvement made. Of course, improvement in construction is important in order to effect simplified inspection and maintenance. The still more important and for which our utmost effort has been concentrated is an improvement in the rupturing performance of short-circuit current, which must be the objective of all the engineers concerned. Hereunder are outlined some of the problems which have been recently taken up in connection with the d–c high-speed circuit breaker and also the results of the test conducted independently on our product at the Japanese National Railways Research Laboratory and our own Company.

2. Increase of fault current in d–c high power system and its countermeasure

In this country, the electric railway substations (particularly of the Japanese National Railways) face the problems of fault short-circuit current which is conspicuously magnified as the result of a capacity increase of d–c source, necessitated by the transportation reinforcement trend of recent years and the question of interrupting of the high-speed circut breaker that is used as a protective instrument has come to the front. Fortunately, it was recognized among the circles concerned that in order to determine its interrupting capacity, the first thing to do is to ascertain the nature of fault current.

As one of the signs of the movement, at Nippori Substation of the Japanese National Railways, experiments are in progress with railway service normally maintained and by means of a magnetized steel piece, measurement is being taken of the induced arc-back current of a mercury rectifier. A part of the result has been published in a journal 'Electric Railways'. According to the journal, it is stated that with more than three mercury rectifiers of 1,500 V, 3,000 kW in parallel-running, arc-back current reaches from 25 kA to 35 kA.

Since prewar days, d–c systems of extremely large capacities have been used in electrochemical works and the magnitude of arc-back current has been also a matter of problems. Since the last year, for the first time in this country, our Company, assisted by the Nippon Light Metal Co. has undertaken, as described in Part I, artificial arc-back tests on the mercury rectifiers, which is a pioneer work of this kind in the country, and taken an initiative in the study of the problem. The maximum value of arc-back current in this case was 36,000 A (at d–c voltage 645 V)

Regardless of whether be it used on electric railways or in electrochemical plants, arc-back current induced on the mercury rectifier is interrupted by the reverse current protecting high-speed air circuit breaker, usually inserted on the side of the cathode and its value is to be easily determined by the location of impedance on the source side (that is, of the substation), the capacity and number of the installations in parallel arrangement. Actually, however, the fact is not so and even to this day, practically no means have been found to make this arc-back current value clear the reason is that the short-circuit phenomena of the circuit containing mercury rectifiers are fundamentally so difficult to clarify reliable numeric values by caluculations alone. Furthermore, the artificial test in the field requires a large-scale preparation and the test was practically impossible for the reason of that it may hamper commercial operation. Therefore, information that has been made public in Japan to date concerning the arc-back current values are only those two mentioned above.

In spite of this, now that enormous power is being actually handled, establishment of the countermeasure for the safety and maintenance is the most pressing need of today. One or two years since, on the basis of the experiment just mentioned and reasoning, the parties concerned are jointly studying the fault current characteristics displayed at the instant of arcing-back, on mercury rectifiers of the principal Japanese National Railways substations.

If conclusion is reached, the nature of arc-back current will be clarified and so will be with the duty of the protecting circuit breaker. Under the circumstances, the following test was made on the standard type high-speed circuit breakers, currently in use for the study of rupture performance.

3. Results of test by the Japanese National Railways

Last year, at Ninomiya Branch, Electric Safety and Maintenance Seminar of the Japanese National Railways Technical Laboratory, interrupting tests were made on a number of the high-speed circuit breakers (rated 1,500 V, 3,000 A) of different makers of current use. Tests were repeated about 40 times on various circuits of prospectve short-circuit current 5–50 kA and total inductance of circuit 0.5–8 mH at test voltage of 1,500 V d–c. In this test, the superiority of our product has been proved in the following respects.

1) Current limiting action is particularly excellent. For instance, with a circuit of prospective short-

circuit current of 50 kA and total inductance of 0.5 mH, the actual breaking current is only 19.1 kA

In Fig. 3 is shown a general form of interrupting phenomena of the d-c high-speed circuit breaker with the symbols used in reference to the following statement of the test results.

test voltage $E_o = 1{,}500$ V.

prospective short-circuit current $I_o = 50{,}000$ A.

actual breaking current $I_c = 19{,}100$ A.

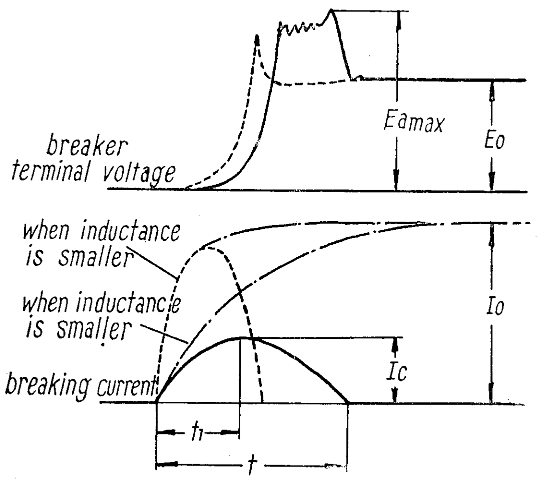

Fig. 3. Phenomena occured on interrupting operation of d-c high-speed air circuit breaker

rate of rise current $\frac{di}{dt} = 3 \times 10^6$ A/s

reverse current trip scale = 400 A.

time to peak current $t_1 = 9.3$ ms.

total fault time $t = 23.5$ ms.

peak value of arc voltage $E_{a\ max} = 2{,}100$ V.

From the above, it is apparent that the current limiting action is sufficiently effective and the function of protection is excellent. This means that with our product, mechanical time is exceedingly short, which is due to the action of the reaction coil—the most remarkable feature of our makes—and that the rate of rise of arc voltage is comparatively large.

2) Arc voltage in surprisingly stabilized after its peak value has been reached, that is, arc quenching action is reliable and its arcing time is stabilized. These features were observed most conspicuously when a circuit of large inductance was interrupted.

3) Main contacts, damaged on their surface, produce practically no difference in their current-carrying capacity. Similarly, arcing contacts, inspite of repeated interruption over 40 times, were found in a state sufficiently serviceable for further use.

Through these tests, rupturing performance which has been rather ambiguous, was clarified.

For the purpose of comparison, if interruption is made on two short-circuited circuits having equal prospective short-circuit current but different inductance L, as shown in Fig. 3 ; then, for less inductance L the actual breaking current I_c is large as shown by the dotted line in Fig. 1 but time to peak current t_1 and total fault time t are small. Similarly, for larger inductance L, I_c is small but t_1 and t are large as shown by the heavy line in the same figure.

The entire aspects of this test will be published in a separate paper, therefore, no further detail be given herein.

4. Test results at our Company

In above test by the Japanese National Railways, the total inductance of the circuit was 0.5 mH, therefore, the maximum value of the rate of rise in current was

$$\left[\frac{di}{dt}\right]_{t=o} = \frac{E}{L} = \frac{1{,}500}{0.5 \times 10^{-3}} = 3 \times 10^6 \text{ A/s.}$$

A next proposition is then to try on the circuits having the rate of rise of current greater than this value and to study the effect on the current limiting action and the extent of the damage that might be incurred on the contacts and arc chamber. Tests were made at our Kawasaki Plant on a high-speed circuit breakers of our current standard type, rated 1,500 V, 3,000 A, (appearance of the same is given in Fig. 4)

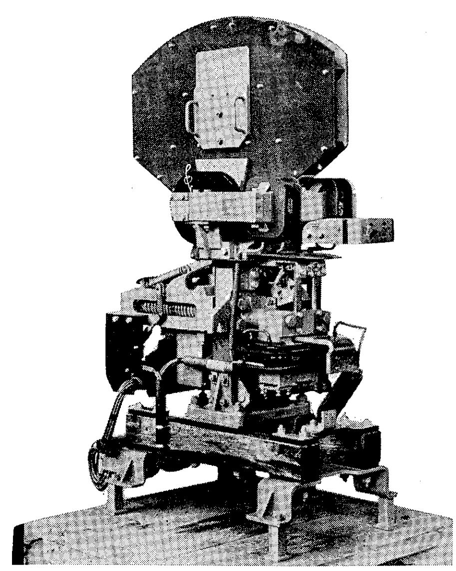

Fig. 4. D-c high-speed air circuit breaker 1,500 V 3,000 A

Principal information derived from the tests is the classification A of Table 2.

The classification B of the table is given for reference purpose to indicate the change in the current limiting action at a change on the reverse current trip current scale.

Table 2. Test results of d-c high-speed air circuit breaker

Classification	Test number	Test voltage E_0 (V)	Prospective short circuit current I_0 (A)	Actual breaking current I_c (A)	Rate of rise of current (A/s)	Reverse current trip scale (A)	Time to peak current t_1 (ms)	Total fault time t (ms)	Peak valve of arc voltage $E_{a\ max}$ (V)
A	A—1	1,760	15,200	14,560	13.7	400	6.5	12.8	2,010
	A—2	1,780	33,500	32,000	17.2	400	6.6	18.0	2,150
	A—3	1,850	43,400	40,700	17.5	400	9.3	18.0	2,260
B	B— 1	1,500	25,000	24,900	5.8	400	8.7	15.7	2,410
	B— 2	1,500		24,400		800	8.2	15.6	2,260
	B— 3	1,500	25,000	16,100	3.0	400	9.3	17.1	2,560
	B— 4	1,500		18,700		800	10.0	19.0	2,390
	B— 5	1,500	25,000	14,600	2.7	400	10.1	21.9	2.540
	B— 6	1,500		14,000		800	10.1	20.1	2,720
	B— 7	1,500	25,000	11,600	1.54	400	11.3	25.6	2,680
	B— 8	1,500		12,100		800	12.2	29.5	2,700
	B— 9	1,500	25,000	9,950	1.16	400	12.2	33.8	2,570
	B—10	1,500		11,300		800	13.4	38.8	2,570
	B—11	1,500	25,000	9,170	0.91	400	12.1	41.0	2,570
	B—12	1,500		9,500		800	13.6	43.1	2,570
	B—13	1,500	25,000	8,150	0.8	400	12.7	42.7	2,500
	B—14	1,500		8,750		800	13.6	53.0	2,520

1) On test A.

The circuit under test contained one set of mercury rectifier equipment of 4,000 kW as a source and was short-circuited on the d–c side at 1,800 V approx. The transformer for the mercury rectifier was of small impedance but strong against large current.

As indicated in Table 2. the maximum value of test current, that is, actual breaking current value, reached 40 kA which is closely comparable with that of the fault current obtained in the test at Nippori Substation of the Japanese National Railways already mentioned. Inference can be drawn, then, that this circuit-breaker can be employed at Nippori Substation with greater satisfaction.

To speak of some of the features observed as the results of interruption, the circuit-breaker itself showed no objectional signs for further use ; damages incurred on the main contacts were as slight as that of 10–20 kA interruption but damages suffered on the arcing contacts were very severe, that is, the amount of wears was large. Inspite of the considerably large amount of wear on the surface, as compared with that caused by 10–20 kA interruption current, the damages in the direction of thickness were rather

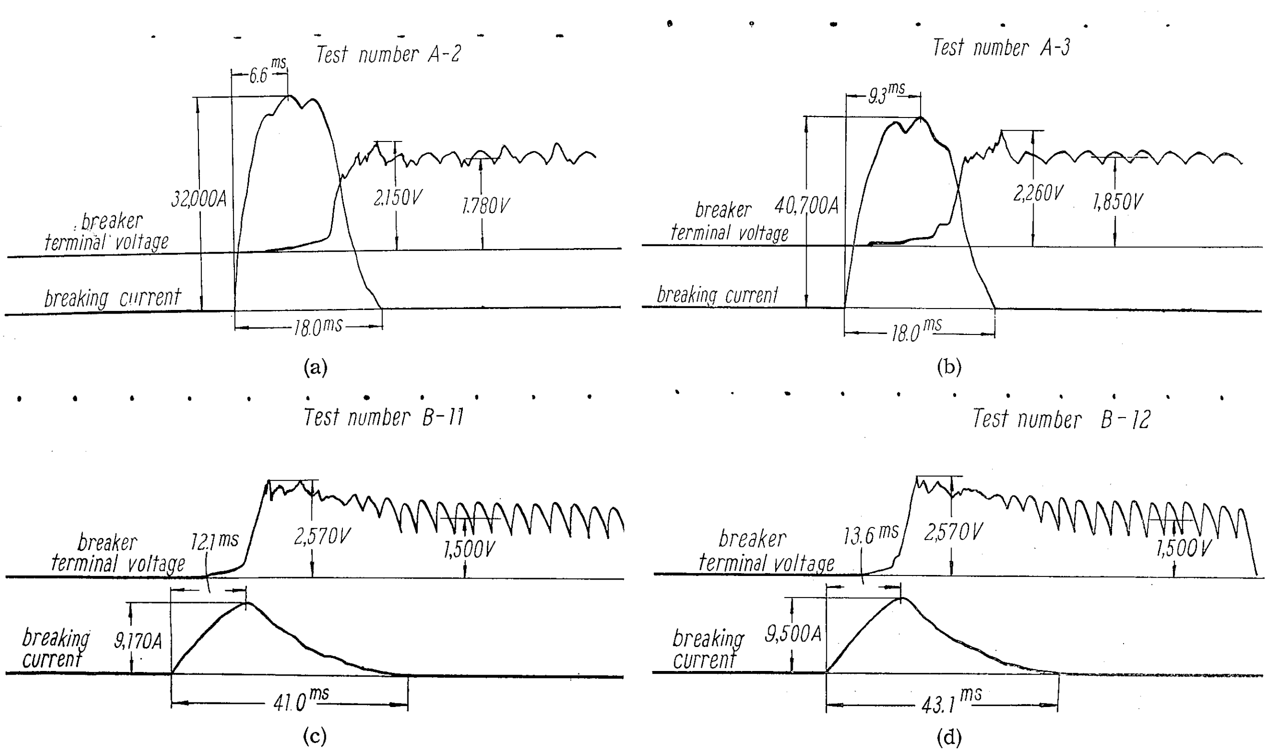

Fig. 5. Oscillogram of interrupting tests of d–c high-speed air circuit breaker

slight. From this fact inference can be made that the life of the arcing contacts is not seriously affected.

Contamination of the arc-quenching chamber was somewhat heavier under the same condition. With regard to insulation resistance and in other respects, however, practically no difference was observed when the test were completed. So was it with the mechanical parts.

In Fig 5, a and b are shown oscillograms respectively of the breaking current 32 kA, test number A–2, and that of 40 kA, number A–3. It is to be noted that if the rate of rise current is exceedingly high and in excess of 17×10^{6} A/s, current limiting action is greatly reduced (as in the case of 10–20 kA interruption current) but the total fault time is somewhat greater than that of 10–20 kA interruption current. All this is due to the fact that the circuit breaker employed in the tests was designed with specific purpose of minimizing interrupting time for actual breaking current of 10–20 kA and constructed with special care, for instance, in gap dimensions, in shape, size and arrangement of the barriers for lengthening arc, with the secondary blow-out magnet also specified on the same basis. In other words, if test is made with the actual breaking current exceeding 30 kA, the optimum condition is lost and the amount of conductive gas generated by arcing is increased in proportion to the increase in the current value, resulting in an elongated time required by the magnetic blow-out action for the disposal of gases,. This itself does not means that the circuit breaker in question is unsuitable for 30–40 kA interruption. On the contrary, the circuit breaker has shown sufficient margin in capacity, discharging its duty of interruption with certainty. Also, in spite of the rate of rise in current which is considerably high, self-holding phenomena due to the inversion of flux of the holding magnet was not observed at all.

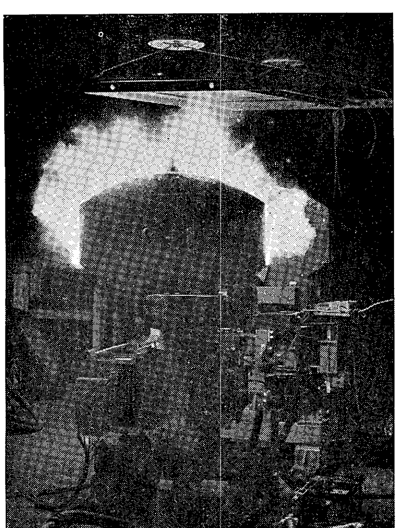

Fig. 6 Arc of d–c high-speed air circuit breaker on interrupting of 40 kA

In Fig. 6 shown a photograph of the arc spouting from the arc quenching chamber as observed in the course of test A–3 (breaking current being 40 kA)

In this case, the distance the arc spouted was 320 mm upward and 220 mm sideway on both directions.

2) On test B

Test was made on a set of 2,000 kW mercury rectifier equipment as a source and the circuit was short-circuited on the d–c side at 1,500 V. The purpose of the test was to investigate the extent to which a circuit breaker is affected in respect to current limiting characteristics when the setting value of the reverse-current trip-current scale is changed. By the way, the arc-quenching chamber used in the list was not of the latest type now in use. As a result, a slightly longer time is obsrved in the total fault time, particularly in arcing time as compared with the results of the test by the Japanese National Railways mentioned above.

In comparison of the reverse trip currents with the scale set at the values 400 A and 800 A, it is apparent that the current limiting action is, as a rule, not sensitive with the 800 A setting and a difference, if any, is surprisingly slight between the two cases. This difference, however, is practically negligible if inductance of the circuit is small. What are most influential in regard to current limiting effect of a circuit breaker are the wave-form of current and various errors such as irregularity in the operating condition of the circuit breaker. Therefore, if the reduction the current limiting effect as noted in Table 2 is acceptable, a greater advantage will be gained with the scale set at as closely as 800 A. Because in that case, not only the same interrupting characteristics is maintained but the excitation of the holding magnet is strengthened, resulting in the increase of reliablity in the closing and opening operations. Therefore, as far as the high-speed air circuit breaker for reverse current protection is concerned, if used in an unattended substation, a greater benefit will be gained in respect to maintenance by setting the current trip scale at values as high as possible.

In Fig. 5, c and d are the oscillograms of the test numbers B–11 and B–12 respectively.

5. Conclusion

Recently the problem of protection of d–c large capacity system is being seriously taken up and its importance is gradually recognized. Investigation of the characteristic of the circuit itself and study of the circuit breaker and its testing equipment as well is being carried on in parallel. In an effort to provide information concerning the subject, the results of test conducted by our Company have been outlined. Should this be accepted as a contribution in the study of the problem of protection of d–c system in general, it will give us pleasure.