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SYNCHRONOUS AIR BLAST CIRCUIT BREAKER FOR 1 CYCLE INTERRUPTION

By Yoshio Nitta

Nobuaki Kiyokuni

Development Dept.

I. FOREWORD

In recent years the scale of the electric power transmission system in Japan has been ever expanding to meet a remarkably increasing power demand. With its overall regional expansion, plus the network system expansion in areas where the power demand is concentrated and load density is high, our power transmission system is becoming more and more complicated.

As part of the overall regional expansion of the power transmission system, cooperation among the different regions has been strengthened to improve the interchange of power among all and thus reduce auxiliary power costs. With regard to the network system in those areas of highly concentrated demand, distribution line networks at individual substations are being improved to eliminate accidental failure of electric power.

The demand for better system protection equipment, such as high-speed reliable fault-checkers, and fault-interruption and reclosing devices, is increasing. Furthermore, system separation in case of accident is needed in order to secure the smooth operation of this magnified and complicated power system. In response to this demand, the development department of Fuji Electric has been making an all-out effort to create unique protection equipment during the last few years. Thus a Synchronous Air Blast Circuit Breaker for 1 Cycle Interruption (synchronous ABB) has been achieved for the first time in the world.

Contact drive by electromagnetic repulsive force is fully utilized in this effective and original mechanism. This mechanism has the remarkable ability of being able to open contacts and break current in less than one cycle after the trip signal is given. The following advantages are expected when the synchronous ABB is introduced into the power supply system.

1) Faster fault clearance

Much faster fault clearance is possible. A comparison between the conventional ABB and the synchronous ABB fault duration times is given in *Table 1*.

Table 1 **Comparison of High Speed ABB and Synchronous ABB Fault Duration Times**

Classification	Occurence of Fault to Trip Signal	Trip Signal to Interruption	Total Fault Duration
Conventional ABB	30 to 40 ms	40 to 50 ms	70 to 90 ms
Protective Relay +Synchronous ABB	30 to 40 ms	10 to 15 ms	40 to 55 ms
Transistor Relay +Synchronous ABB	20 ms>	10 to 15 ms	35 ms>

2) Higher reliability and stability of system

The stability of those single power transmission systems, which are usually observed in the early 500 kv class power supplies, is rather poor. Therefore the quickest possible recovery of original condition, by eliminating troubles that happen in the system, is essential. Faster fault clearance through introduction of the synchronous ABB is very desirable in this respect. This synchronous ABB permits a more economical power supply because the transformer impedance can be higher for the same degree of stability.

3) Shorter reclosing time

The high speed reclosing time can be remarkably shortened because de-ionization is much faster when fault duration becomes less than two cycles. The possibility of phase-to-ground faults causing phase-to-phase faults is reduced. Influence upon the load also decreases to a large extent.

4) Advantage when used as system separation breaker

Increasing the power capacity of a given system usually necessitates installation of new circuit breakers of larger capacity to substitute for the original ones. If this synchronous ABB is used for the purpose of interconnecting and disconnecting related systems during faults, the short-circuit current will be reduced and limited to within the capacity of the original breakers. Thus use of the original breakers in a given system becomes possible despite the capacity increase. This provides an important economic advantage.

5) Easier repair of damage

The degree of damage to power lines and transformers is directly related to fault duration. The shorter the fault duration, the easier the required repair becomes. Dangerous explosion of oil-filled devices such as transformers, etc., will become less probable.

The construction, general principles of operation, and the main test data are given in the following.

II. RATINGS

The unit breaking voltage of this synchronous ABB is 84 kv and the standard series of ratings, based on this unit, is shown in *Table 2*. The rated operating pressure of this breaker is 15 kg per sq. cm-g and its breaking ability is guaranteed over the pressure range of 85% to 110% of this value.

As the breaking capacity, that of asynchronous conventional interruption is guaranteed as well as that of synchronous interruption. Capacity of synchronous interruption only increases in the manner 300 kv 15,000 Mva to 300 kv 25,000 Mva.

III. PRINCIPLES OF SYNCHRONOUS INTERRUPTION

Generally speaking, when a high voltage ac circuit is interrupted, an arc will continue after the contact is opened at least until the current passes through zero naturally. The longer the arcing time, the more arc energy is consumed between the contacts in the form of heat. Thus the interruption becomes more difficult due to the fact that this deteriorates recovery of dielectric strength between contacts at the passage of the zero current point. Therefore, interruption with the shortest arcing time possible is desired with any ABB. However, conventional ABB's in general have a much longer arcing time because interruption is attempted without regard to the ac phase, Even though the case is such that the contacts are opened just before the zero current point, it is difficult to obtain enough contact separation by the next zero current point. Therefore, even if the arc is extinguished temporarily at the zero current point, the transient recovery voltage produces an arc again and the arc current continues until the next zero current point; thus arcing time is ineviatably prolonged.

In this synchronous ABB, the electrode contacts open with almost no time lag after a pulse signal is given, and the opening of the contacts is exactly synchronized to just before the zero current point; thus interruption is made with a constant, very short arcing time until the zero current point. This almost ideal type of synchronous interruption is attained by the combination of an electromagnetic repulsive drive system which gives adequate separation of the contacts in a very short time, and a synchronous pulse-generator that produces synchronous pulses regularly at a fixed interval just before the zero current point.

This synchronous ABB is schematically shown in *Fig. 1* and *Fig. 2*.

Using the output of a current transformer, this synchronous-pulse generator continuously produces synchronous pulses that are timed just before the zero current point. When a trip signal is given, a pulse is transmitted to the live parts of the syn-

Table 2 Ratings of Synchronous ABB

Voltage (kv)	168	240	300	500
Continuous Current (amp)	2000	2000	2000	2000
Breaking Capacity (Mva)	7500	10,000	15,000	25,000
Making Current (ka)	70.3	65.6	78.8	78.8
2-Second Current (ka)	25.8	24.0	28.9	28.9
Make Time (sec)	0.1	0.1	0.1	0.1
Total Break Time (∿)	1	1	1	1
Operating Pressure (kg/cm^2g)	15	15	15	15
Control Voltage (v) (dc)	100	100	100	100
Test Voltage (kv) Dry (1 min) Wet (10 sec) (ac)	325	395	460	745
Impulse (kv)	750	900	1050	1675
Duty Cycle	0-0.35 sec-CO-1min-CO			

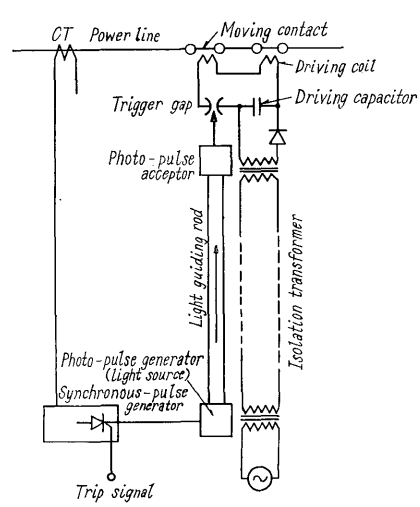


Fig. 1 Schematic of synchronous ABB

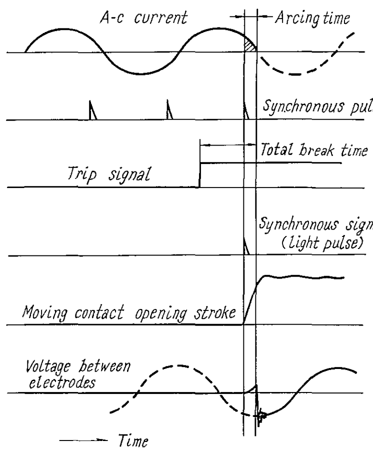


Fig. 2 Process of synchronous interruption

chronous ABB by a photoelectric relay. Receiving this pulse signal, the live part of synchronous ABB opens the contacts without delay through the electromagnetic repulsive drive system and completes arc interruption at the zero current point. Through such construction, the time required for interruption is limited to its theoretical minimum and arc energy becomes less than one tenth that of conventional high speed ABB's.

IV. CONSTRUCTION AND OPERATION

Fig. 3 is a photograph of a 300 kv 15,000 Mva synchronous ABB and *Fig. 4* is an illustration of its construction.

To the supporting insulator on the air tank is mounted a double-flow nozzle arc-extinction chamber.

In this highly compressed air region, the breaking contacts are installed. Into this part parallel resistors are inserted for the purpose of voltage equalization and surge reduction. In series with this

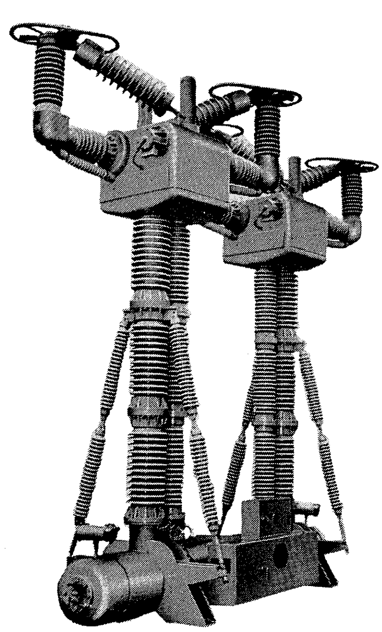


Fig. 3 300 kv 15,000 Mva synchronous ABB

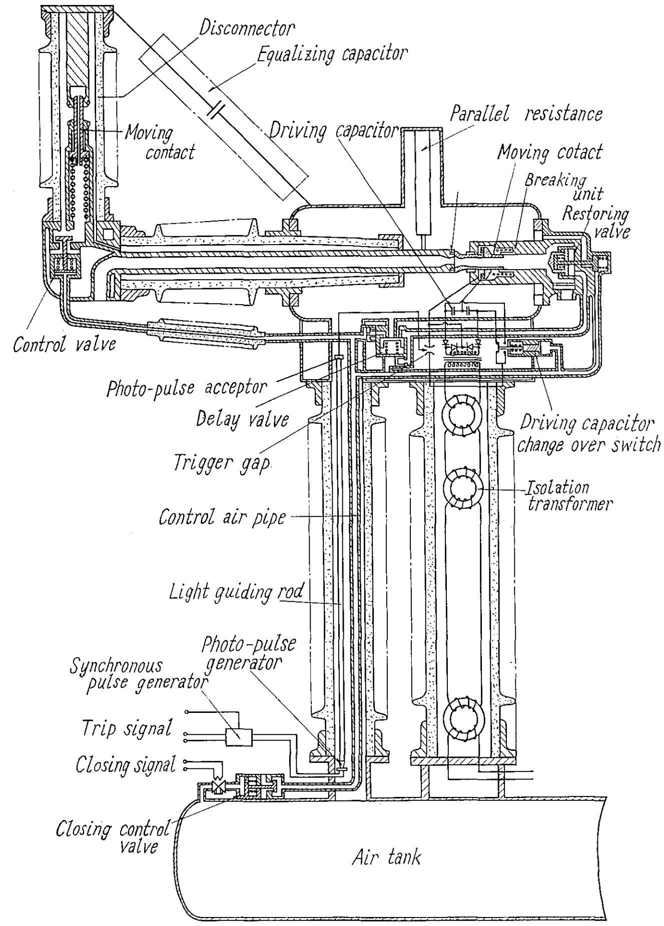


Fig. 4 Construction of synchronous ABB

breaker is a disconnector which also has a nozzle. The blast from this nozzle disconnects the current to the parallel resistors. The moving contact drive capacitor is placed next to this arc extinction chamber. This capacitor is charged by a charging device through the isolation transformer which is contained in the supporting insulator and is locked by a supervisory device so that it cannot initiate operation below a certain voltage. The photo-pulse acceptor, trigger gap, driving capacitor change-over switch, etc. are all placed in the cabinet of the live part of the synchronous ABB.

The construction of each part and operation are illustrated in the following.

1. Breaking Operation

When a trip signal is given, it enters at first into the synchronous pulse generator.

1) Synchronous-pulse generator

The synchronous-pulse generator is a device which produces periodic pulses just before the zero current point of the power current that flows in the ABB. When a trip signal is given, this pulse is fed to the photoelectric relay as a synchronous signal pulse. The principles of this device are shown in *Fig. 5.* It produces a pulse at the crossover point of the output of current transformer and peak value of its

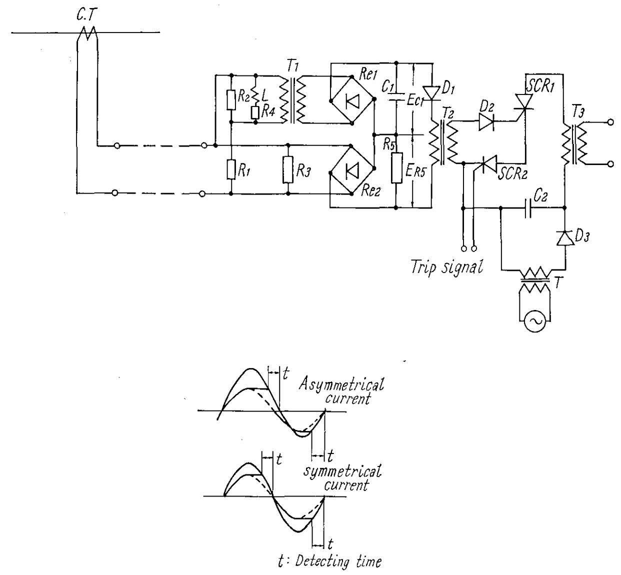


Fig. 5 Synchronous-pulse generator

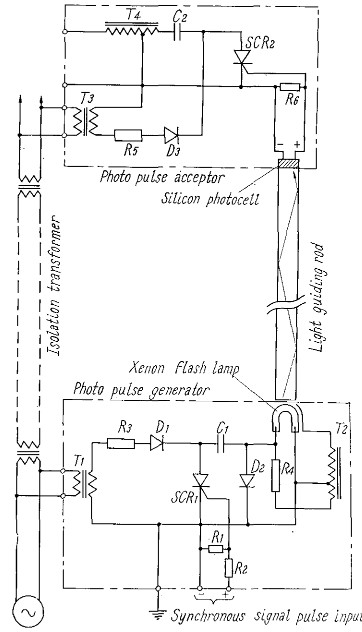


Fig. 6 Principles of photoelectric relay

a-c component which is reduced at 70% of its original value. This is done by the fact that current flows through D_1 to T_2 when $E_C > E_R$. When this current flows, a voltage pulse is produced in the secondary side and this is the synchronous pulse.

When a trip signal is given, SCR_2 becomes " on ". With the following synchronous pulse SCR_1 becomes " on ". Then by the discharge of C_2, a synchronous signal pulse is produced at the secondary side of T and fed to the photoelectric relay.

The required time between the synchronous pulse and the zero current point, namely the detecting time, is 2 ms at present. This time has little variation, even when the current that flows in case of an accidental short-circuit contains a fair d-c component. This is due to the function of the d-c component attenuator which consists of L and R_4. The detecting time was determined by the time required to provide adequate separation of the moving and fixed contacts. With this synchronous ABB, the detecting time is actually arcing time. If a trip signal is given when current is not flowing in the ABB, the pulse will automatically be produced approximately 25 ms later.

An ordinary current transformer for general instruments can be used in this synchronous ABB.

2) Photoelectric relay

This is a device which transmits a synchronous signal pulse from the synchronous-pulse generator to the high voltage part of the ABB, using light as the medium. It consists of a photo-pulse generator, a light guiding rod, and a photo-pulse acceptor. General principles of this device are shown in *Fig. 6*.

The photo-pulse generator is a device which converts synchronous signal pulses into photo-pulses, without a time lag by use of a *SCR* and a xenon flash lamp.

Photo-pulses are transmitted to the live part through the highly effectively light-guiding rod, which makes use of the complete boundary reflection of an acryl resin rod of high transparency.

As this light-guiding rod has a few hundred times better light transmitting efficiency than the ordinary insulation pipe, the following photo-pulse acceptor can be simplified and thus increases the reliability of this part. The transmitted photo-pulse is converted by the photo-pulse acceptor to a high voltage pulse sufficient to ignite the trigger gap. The photo-pulse acceptor supplies this high voltage pulse to the trigger gap through the circuit shown in *Fig. 6*.

3) Breaking unit

The moving contact drive system of the breaking unit, which makes use of electromagnetic repulsion, is the most significant characteristic of this synchronous ABB. With the development of this system, synchronous interruption became possible. The external view of the contact driving device is shown in *Fig. 7*, and its fundamental construction is shown in *Fig. 8*. The driving capacitor is charged from the ground potential side through the isolation transformer. This charge is the energy source for driving contact. The moving contact has a nozzle and the fixed contact also has one. Together they comprise a double-flow nozzle, a part of which forms a short-circuited ring that is tightly coupled electromagnetically with the driving coil.

The equivalent circuit of this part is shown in *Fig. 9*. When the switch S is closed, in other words when the trigger gap is ignited, the charge of the driving capacitor C is discharged through the driving coil L ; thus, current I_1 flows, and I_2 that is induced by I_1 flows in the short-circuited ring. As I_1 and I_2 have opposite directions of current flow, an electromagnetic repulsive force F is exerted between the

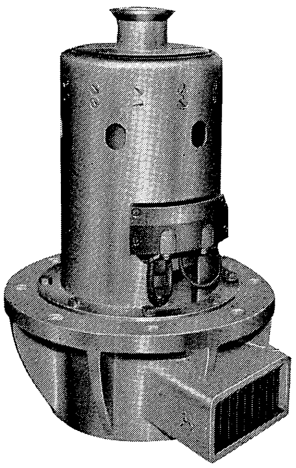


Fig. 7 External view of breaking unit

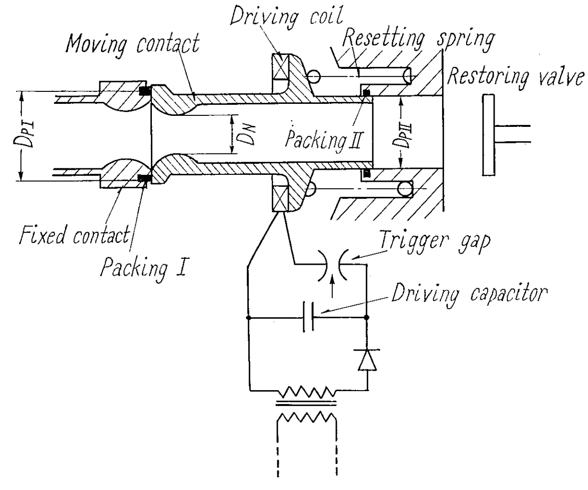


Fig. 8 Fundamental construction of the breaking unit

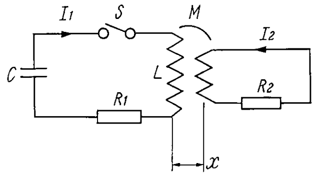


Fig. 9 Equivalent circuit of the driving mechanism

fixed driving coil and the short-circuited ring. This value of F is given in the following equation.

$$|F| = \frac{\partial}{\partial x}(M \cdot I_1 \cdot I_2) \doteqdot I_1 \cdot I_2 \cdot \frac{\partial M}{\partial x}$$

x: distance between the driving coil center and the short-circuited ring center

M: mutual inductance between the driving coil and the short-circuited ring

I_1 shown in above equation, which is the discharging current that flows in the driving coil, F which is the produced force, v which is the speed at which the moving contact is driven, and s which is the stroke of the moving contact are shown in *Fig. 10.* The momentary maximum force that works on the moving contact reaches from several tons to scores of tons.

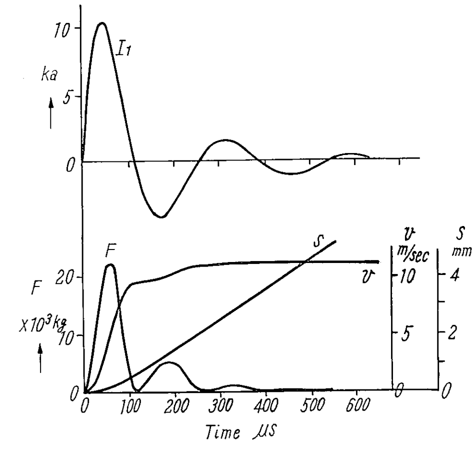


Fig. 10 Waveform of the discharging current and driving characteristics

Therefore, the maximum acceleration that the moving contact receives is as great as 10^4 g or more. Thus the time lag between the start of discharge and separation of the moving contact is measured within scores of μsec. Furthermore, due to this great acceleration, a sufficient separation distance is achieved in an extremely short time. The repulsive force drives the moving contact for only about 200 μs. However, by making use of the fact that the moving contact also functions as the releasing valve of the blast air, a simple and secure construction is obtained which maintains large contact pressure when the contact is closed and also holds the moving contact stable at the separated position. For this purpose the effective inside diameters of packing *I* and *II,* namely D_{PI} and D_{PII}, and the nozzle diameter of the moving contact D_N are designed to have the following relationship;

$$D_{PI} > D_{PII} > D_N$$

As a result, the compressed air can operate for the above mentioned purpose.

The time lag between feeding a synchronous signal pulse to the photo electric relay and the completion of the moving contact separation is decided by these factors; namely, the ignition time of each *SCR,* the time required to reach necessary light intensity, the response time of the silicon photo cell, the time required for the pulse transformer to develop the required voltage, and the delay between the trigger gap ignition and the moving contact separation. This total time lag is approximately 100 μs, and can be neglected when compared to the 2 ms detecting time.

4) Contact separation at the disconnector and stopping the air blast at the breaking unit

Fig. 11 shows the opening and closing operations of the breaking unit and its restoring valve. In this synchronous ABB, interruption is accomplished by an air blast of 2 ms. Therefore the restoring valve, which is placed at right angles to the moving contact nozzle, maintains a certain clearance with the exhaust so that it does not affect the breaking

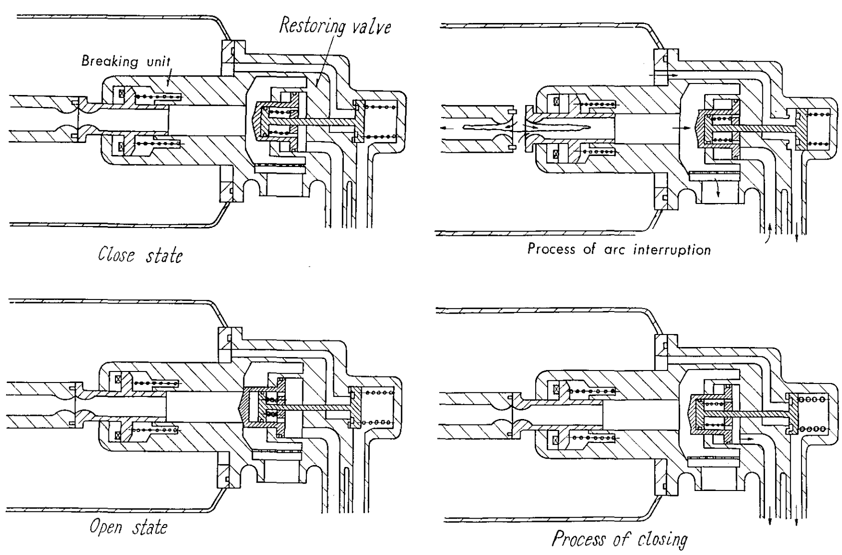


Fig. 11 Schematic diagram of the opening and closing operation

ability. As a result of the moving contact separation, high compression air is blast out of both the moving and the fixed nozzles. The restoring valve is moved to the right, as shown in the illustration, by the blast air pressure, and the air in the arc extinction chamber is blast into the control air pipe. The control valve in the disconnector is operated by this air in the chamber and releases the high pressure air which separates the moving contact and, finally, breaks the resistor current paralleled to the breaking unit. As the moving contact moves one stroke, it closes the nozzle. A time lag exists between the operation of the moving contact at the breaking unit and the operation of the moving contact at the disconnector, which is determined by the propagation velocity of the high pressure air and the operation piping. As the result, approximately two cycles after the separation of the moving contact at the breaking unit, the moving contact at the disconnector separates.

The operation of the delay valve, which is connected to the control air pipe, also passes high pressure air to the restoring valve through other piping after the moving contact at the disconnector is completely separated. The valve moves to the left and completely closes the exhaust located at the moving contact side. By this action, the moving contact is restored to its original position by the resetting spring and the air blast is stopped. In addition to the delay valve the change-over switch and the closing valve are also connected to the control air pipe.

5) Driving capacitor change-over switch

Two driving capacitors are provided to permit high speed reclosing operation. One of the two is used alternatively at each interruption. The switch operation is automatically done at high speed by the flow of high pressure air in the control air pipe.

2. Closing Operation

Following interruption, air travels from the tank at the live parts to the closing valve which is placed at the ground side (on the air tank). The closing operation is accomplished through operation of this valve which releases the air in the control air pipe to the outside. With the operation of this valve, the restoring valve is restored to its position, the contacts at the disconnector close, and one closing operation is completed. Trip free is also available with ease by merely operating this closing valve.

As has been stated, the characteristic operation of this synchronous ABB has been attained by the application of an electromagnetic repulsive drive system and semiconductor circuits such as the synchronous pulse generator, photoelectric relay, etc.

Thus the reliability of the synchronous ABB depends upon the reliability of these parts. To attain high reliability of these parts, only silicon semiconductor elements are used in this synchronous ABB. These are highly stable against heat and used with sufficient safety factors. Electrostatic and electromagnetic shielding is strictly made. Moreover, the double system (parallel-equipped system) is adopted to approach perfect shielding.

Life tests and malfunction tests have confirmed the reliability of this synchronous ABB.

V. CHARACTERISTICS

As stated in III. this synchronous ABB has many features, not obtainable in conventional types, that result from the adoption of its all-new system and construction.

1. 1 Cycle Interruption

The time required for interruption ranges between 0.2 cycle and 0.75 cycle according to the current phase at the moment a trip signal is given. Considering the case when there is large d-c component owing to an accidental short-circuit, this figure is the theoretical minimum value.

Synchronous interruption is from several times to scores of times faster than interruption by conventional types.

2. Excellent Short Line-fault Clearing Ability

Since the arc energy is extremely limited and due to the original structure of contacts, this synchronous

ABB has an excellent dielectric recovery after interruption. Therefore short line-faults are easily handled, eliminating what has been a problem recently.

3. Low Contact Erosion and Easy Maintenance

Not only is contact erosion very low, owing to the limited arc energy, but also the voltage of breaking unit is very high. This reduces the total number of breaking units and simplifies maintenance.

4. Lower Switching Surge

As an air blast accompanies opening of the disconnector, the parallel resistance at the breaking unit can be lower; this limits switching surges.

5. Less Air Consumption

Since a constant pressurized type is used, and as the moving contact acts also as the air blast valve, arc extinction is done effectively with a minimum of air.

The voltage per breaking unit is high, thus lessening the total number of breaking units. Accordingly, air consumption is reduced to about half that of conventional types.

VI. TEST DATA

Testing during development of this synchronous ABB included those tests which are normally made on conventional types and such tests, based on the characteristics of the synchronous ABB, as induction tests and mechanical strength tests under impact acceleration. The test data is given in the following.

1. Breaking Test

1) Short-circuit breaking test

Through the long term company test, and the direct interruption test (which was conducted by the Takeyama High Voltage Power Laboratory) excellent breaking ability was confirmed; and, at the same time, the equivalence of our testing method was substantiated.

Breaking characteristics per unit point of interruption in case of a short-circuit are shown in *Fig. 12.* It is clear that our synchronous ABB has much better characteristics than required by the JEC–145 rating (Japanese circuit breaker standard).

Fig. 13 shows an oscillogram of a short-circuit interruption conducted at the High Voltage Power Laboratory, Takeyama.

2) High-speed reclosing duty test

The data is shown in *Table 3. Fig. 14* shows an example of our company test.

3) Short line-fault interruption

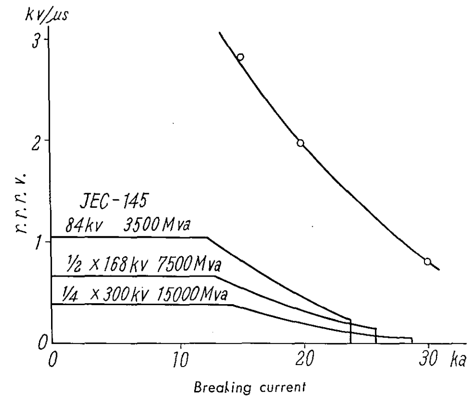
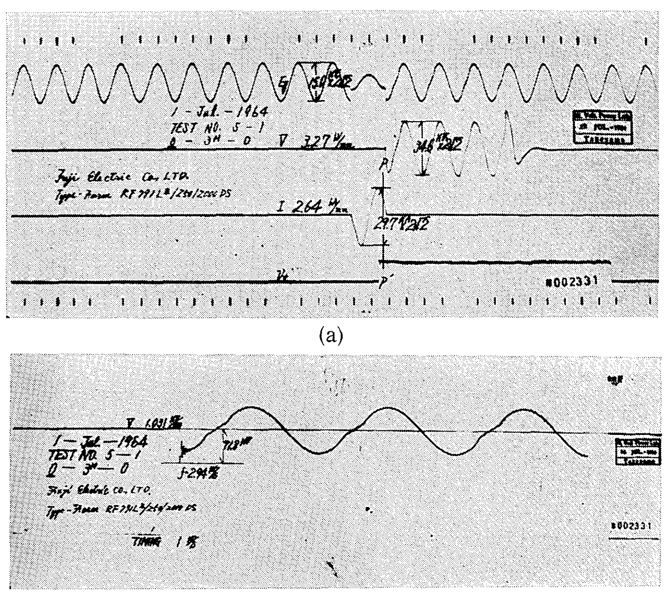


Fig. 12 Breaking characteristics (per unit breaker) of the synchronous ABB



(a)

(b)

Fig. 13 Oscillogram of a short-circuit interruption conducted at High Voltage Power Laboratory, Takeyama

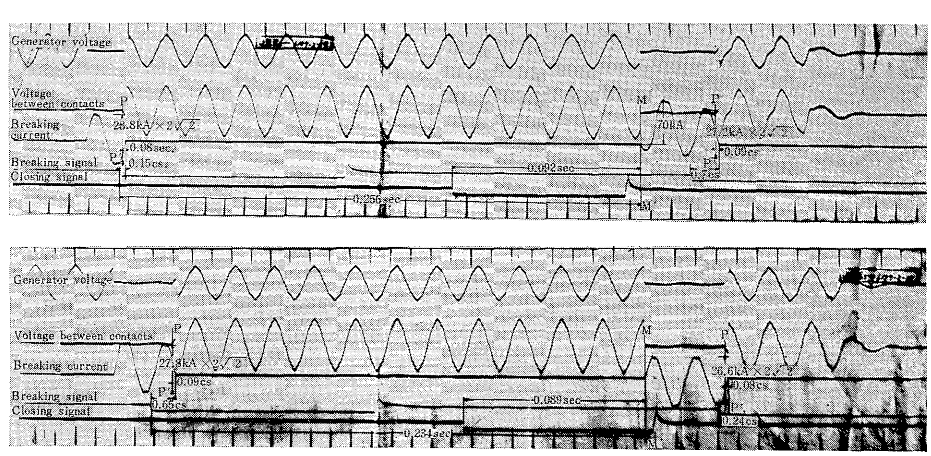


Fig. 14 Oscillogram of high-speed reclosing duty

Table 3 Results of Breaking Test

Supplied Voltage (kv)	Breaking Current (ka)	Dc Component of Breaking Current (%)	Transient Recovery Voltage (kv)	Freq. of Restriking Voltage (kc)	Duty Cycle	Arcing Time (~)	Total Break-time (~)	Peak Making Current (ka)	No. of Breaking Units	Operating Pressure (kg/cm²g)	Test Circuit	Remarks
43.1	16.8	3.0	91.1	9.1	"O"	0.09	0.29	—	1	15	Takeyama Direct Test	
14.5	13.8	1.5	119.5	9.8	"O"	0.08	0.35	—	1	15	Fuji Equivalent Test	
36.0	29.7	8.0	71.8	2.9	"O"	0.09	0.25	—	1	15	Takeyama Direct Test	
14.5	28.0	9.0	122	4.4	"O"	0.08	0.58	—	1	15	Fuji Equivalent Test	
35.7	29.7	1.5	83.7	0.5	0~ 0.35 s "O-CO"	0.10	0.32	—	1	15	Takeyama Direct Test	High-speed reclosing
36.0	28.0	3.5	79.61	0.5		0.10	0.31	46.2	1	15		
46.0	32.3	90.0	137.5	1.3	"O"	0.55	0.55	—	1	15	Fuji Equivalent Test	Asynchronous (evolving fault)
72.4	13.9	9.0	143.0	0.5	"O"	0.10	0.33	—	1	15	Takeyama Direct Test	Out of phase interruption
19.5	30.0	24.0	38.5	6.5	"CO"	0.10	0.13	83.0	4	15	Fuji Direct Test	
225.0	1.2	0	350	2.0	"O"	0.17	0.17	—	4	15	Fuji Direct Test	Asynchronous

From the test data when using a single frequency, transient recovery voltage circuit, the breaking current is 20 ka and the rate of rise of restriking voltage (r.r.r.v.) is 2 to 3 kv/μs at 30 to 40 kc/s per unit, thus, interruption is extremely well done. This data also shows that this synchronous ABB has very good characteristics even when r. r. r. v. is high and the first peak voltage is comparatively low as in the case of short line-faults.

4) Asynchronous interruption

If an accidental short-circuit (or any evolving fault) occurs when the moving contact is being separated, interruption which is synchronized with the zero current point is impossible. However, it was confirmed that interruption is done without problem even in such cases. An example is shown in *Table 3*. *Fig. 15* shows an example of evolving fault interruption. In this case the moving contact was purposely separated with a simultaneous trip signal. The current which had a 90% overlapping d-c component and an asymmetrical value of 52 ka was interrupted within a half cycle.

5) Disconnector closing test

All of the disconnector making tests were done as CO test. There was no problem of contact damage. *Fig. 16* shows an example.

6) Interruption of charging and small lagging currents

Charging current breaking test were made until the condition of 80 amp at 12.7 kg/cm²g, which is the minimum operating pressure where reignition easily takes place. In every case, interruption was done without having reignition. This is due to the excellent dielectric recovery characteristics and the

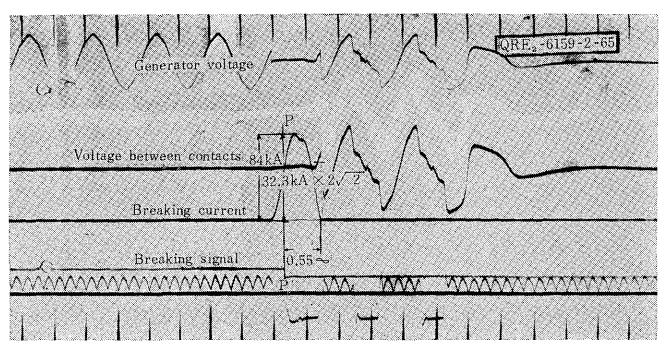


Fig. 15 Oscillogram of evolving fault interruption

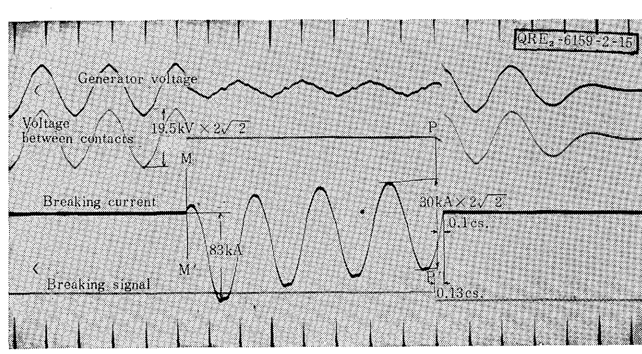


Fig. 16 Oscillogram of CO operation

parallel resistance at the breaking unit.

In breaking small lagging currents such as transformer exciting current and circuit shunt reactor current, abnormal voltage can be produced during interruption of high arc extinction ability owing to the high circuit inductance. The test was done by breaking the specific reactor currents at their most normal current severing values with an operating pressure of 16.5 kg/cm^{2}g. As a result, the overvoltage factor was always under 1.65 within the range of 12 to 128 amp.

2. Other Tests

1) Insulation test

Insulation in open state of this synchronous ABB is kept by the disconnector. During the unit disconnector test, at standard frequencies it withstands sufficiently 160 kv at 5 kg/cm^{2}g. At 7 kg/cm^{2}g the interior insulation becomes better than the exterior insulation. Against impulse, it withstands 400 kv at 7 kg/cm^{2}g. Above 10 kg/cm^{2}g the interior insulation becomes better than the exterior insulation. No insulation problems exist anywhere within the working range.

2) Induction test

Semiconductors are used in the pulse generator, photoelectric relay, and other places. Various induction tests, such as impulse voltage, large impulse current impression etc., were made under operating conditions. No malfunction or abnormal performance was found. Appropriate shielding and grounding have eliminated induction problems.

3) Test using artificial power line

By building the synchronous pulse generator into an artificial power line, fluctuations of the time required from a synchronous signal pulse to the zero current point (namely, fluctuations of detecting time, and their influence on breaking characteristics) were tested under various possible fault conditions. In all cases, fluctuations were found to be very little and had no bad influence on the breaking characteristics.

4) Endurance test

Performance tests of the breaking unit, the disconnector, and the various control valves were repeated 10,000 times. A life test was also conducted on the electrical circuits. The trigger gap, which uses arc-proof material, was confirmed to withstand more than 10,000 operations.

5) Moving contact drive test

The moving contact of the breaking unit is separated with an acceleration of approximately 10,000 g with energy that comes from the contact drive capacitor.

Based upon this fact, mechanical strength tests and life tests were conducted to determine the optimum shape, material, and method of working of the contact.

VII. SUMMARY

This synchronous ABB was completed through the development of our original technology. This synchronous ABB reduces the time required for interruption to its theoretical minimum value. This results from the combination of electromagnetic repulsion, synchronous pulse generation, photoelectric relaying and other improvements. Thus this synchronous ABB has many advantageous characteristics, such as short fault duration, less damage from fault occurrences, increased stability of the power transmission system, possible shortening of reclosing time, etc.

These advantageous characteristics are also applicable to its use as a breaker for the purpose of power transmission system separation.

Its superb performance has been confirmed by thousands of tests under every possible condition of interruption.

Finally, through the practical application of the original electromagnetic drive system, and the detecting and control system utilization of successfully tested semiconductor circuits, it can be safely said that this synchronous ABB has shown the way in which further development can be made in this field.