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ELECTRICAL EQUIPMENT FOR THERMAL POWER STATION

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I. INTRODUCTION

The demand for electric power in Japan has grown rapidly in recent years, along with economic growth and development. Previously, Japan's principal sources of electric power were hydroelectric power which utilized its abundant water resources. However, in past 4 or 5 years, huge thermal power stations has been constructed replacing the hydroelectric power stations one after another and, with a view toward improved efficiency, equipment capacity is being greatly increased.

This article presents a brief outline of Japan's largest 3-phase, 3-winding transformer; the extra-high voltage, on-load tap changing 345 Mva transformer; and the extra-high voltage pantograph type disconnecting switches which were delivered to the recently constructed Chita Thermal Power Station of the Chubu Electric Power Co., Ltd., one of this country's leading electric station which boasts of high output capacity.

II. 345 MVA EXTRA-HIGH VOLTAGE, ON-LOAD TAP CHANGING TRANSFORMER

1. Specifications

Type: 3-phase, outdoor use, forced oil circulated, fan cooled, core type, with on-load tap changing equipment.

Frequency: 60 cps

Capacity:
- Primary 300,000 kva
- Secondary 300,000 kva
- Tertiary 90,000 kva

Voltage:
- Primary 275R ± 8 × 3.125 kv (17 taps) (⅄ connection)
- Secondary 154 kv (⅄ connection)
- Tertiary 33 kv (△ connection)

BIL:
- Primary: Line side 1050 kv, neutral point 200 kv
- Secondary: Line size 750 kv, neutral point 550 kv
- Tertiary: 200 kv

Impedance voltage:

Between primary and secondary
13.95% (300,000 kva base)

Between secondary and tertiary
3.94% (90,000 kva base)

Between primary and tertiary
8.71% (90,000 kva base)

Total weight: 363,000 kg

Transporting weight: 240,000 kg

Oil quantity: 91,500 ℓ

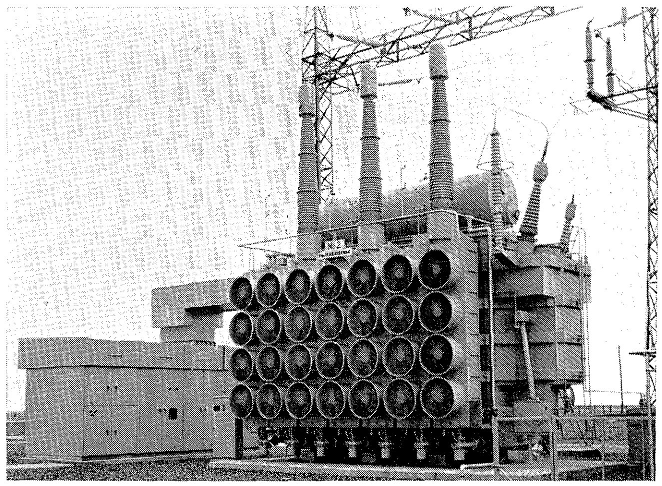


Fig. 1 Transformer external view

Fig. 1 shows the 275 kv, 345 Mva on-load tap changing transformer and *Fig. 2* shows its external configuration.

2. Construction Features

1) Core

Since this transformer was transported by ship, there were no particular limitations on size; therefore, Fuji standard construction for high capacity transformers, the 3-limbed core with cooling ducts, was applied. Highest grade oriented silicon steel core sheets G10 were used for the core.

Since there is a general tendency for the ratio of the cross-sectional area to the length of the magnetic path to increase in high capacity transformer cores, oil cooling ducts were added as a precaution to prevent the magnetic unbalance between parallel magnetic paths from becoming excessive. For this reason, the magnetic flux distribution in each magnetic path was determined by means of a computer and the

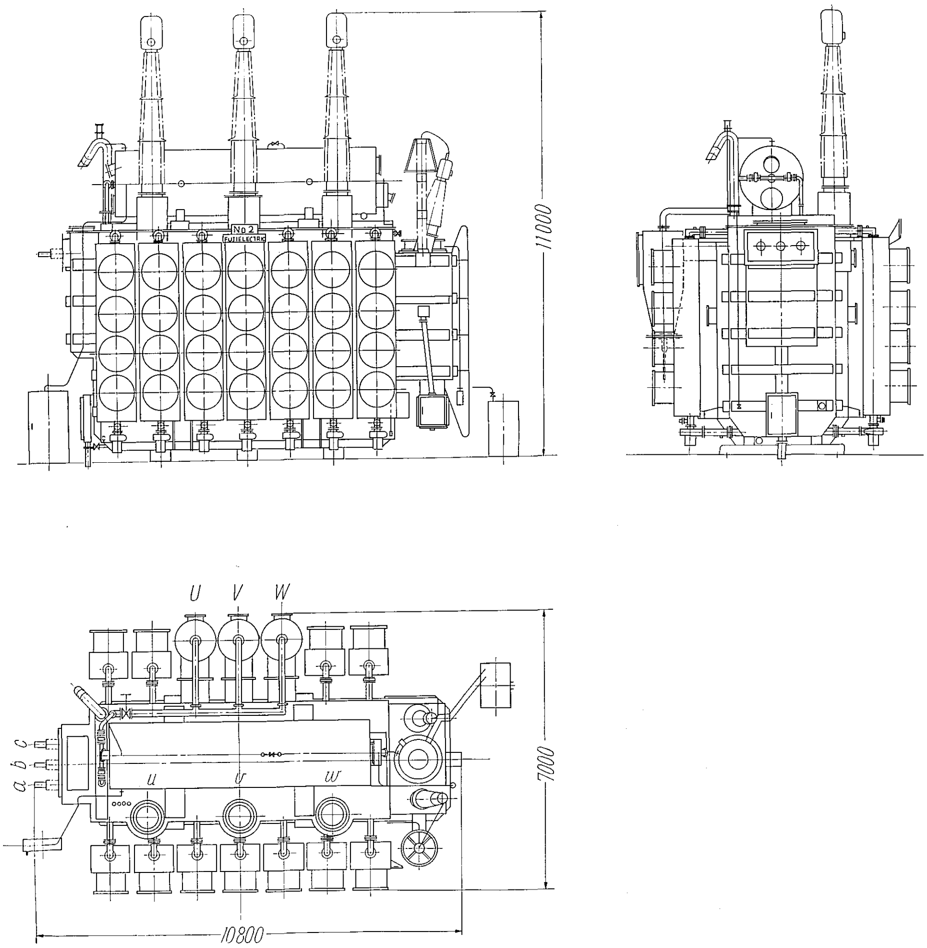


Fig. 2 Transformer configuration

cross-sectional areas were designed on the results.

2) Windings

Respective windings used were as follows: For the 275 kv primary windings: Oscillation-free cylindrical layer winding, parallel wound cylindrical layer tap winding, according to Fuji standard practice for its extra-high voltage transformers. For the 154 kv secondary winding: Special twin-disc winding having excellent impulse voltage characteristics and suitable for passing comparatively large currents. For the 33 kv tertiary winding: Cylindrical block windings suitable for low voltage, large current applications. Tertiary, secondary and primary windings are concentrically arranged, in that order, from the center of the core.

The oscillation-free cylindrical layer windings used for the main primary winding have been used in numerous extra-high voltage large capacity transformers manufactured by our company. Since this type of winding has frequently been described in this journal and its excellent capabilities are well known, a detailed description is not required. The tap winding has been connected to the neutral point of this cylindrical layer winding, making it possible to make both coarse and fine tap adjustments. The coarse tap winding is constructed in exactly the same way as the cylindrical layer winding, while the fine tap winding is a parallel wound cylindrical layer type. Like the cylindrical layer winding, it also demonstrates excellent surge voltage characteristics due to the high series capacitance between adjacent windings. Moreover, the respective arrangement of the conductors has been carefully planned so that radial leakeage flux for all tap positions is minimized; hence, axial mechanical force produced during short circuiting has also been sufficiently suppressed. Since the tap winding is arranged close to the main winding, the space factor for the high voltage winding on the core window is also favorable. This means that it can be constructed without provisions for excessive increase winding outside diameter and material even when an extra-high voltage, large capacity transformer with no-voltage tap changing equipment is converted to one with on-load tap changing equipment. This is significant when large capacity equipment is to be transported by railway in " Fahrbar " form.

Having been used in the 345 Mva transformer delivered to Electric Power Development Co., Nagoya SS, the special twin-disc windings used in the secondary side have proven to have superior surge voltage characteristics. Furthermore, due to its comparatively simple construction, fine workability and other outstanding features, this type of winding is widely used for numerous medium and low voltage windings for large capacity transformers.

3) Measures applied to decrease stray load loss

Up to the present time, our company has made extensive effort to decrease the stray load loss on large capacity transformers and all previous experience has been used to the maximum possible extent with regard to this transformer. For example, in designing large capacity transformers, the effective load losses (direct current loss + eddy-current loss) produced in each part of the windings have been computed in detail and minute determinations have been provided to obtain the most suitable conductor dimensions and arrangement.

In determining the effective load losses in each part of the transformer windings, the winding space was first divided into several small sections, and the leakage flux in the surrounding area and its direction were determined. Finally, the effective load losses from conductor dimensions and arrangement within these sections was computed. Transformer leakage flux can be determined by the Beaver-Adams method, i.e. by replacing the windings with several thin, straight current sheets, applying Biot-Savart's law to each small section and finally integrating the results throughout the entire windings. It goes without saying that, in this connection, the effects of core legs, yokes, tanks, etc., can be computed from the current sheet image. In actual transformers, current sheets may number as many as 10, and computations become tedious when higher order images are involved. Effective load losses in the conductor within the divided sections can be determined by applying Dictrich's method. Since computations for determination of effective load losses also becomes extremely complicated, a computer was used to solve these losses along with leakage flux. Using this method in the designing process, stray load losses to the extent of their distribution were accurately determined, thus providing data to be used in providing the most suitable conductor dimensions and arrangement and in preventing particular portions from becoming overheated.

Fig. 3 shows an example of computations for leakage flux distribution and eddy current loss distribution in the winding of a three winding transformer. It shows the condition under which the impedance test was performed between the primary and secondary.

Adequate consideration has also been given to decreasing not only the stray load loss from the windings, but also those from the frame, tank, and other structural components. The construction has been made lighter and more rational without sacrificing mechanical strength, and considerable study was made with regard to appropriate positioning of the shielded core, etc., thus providing improvement in anticipated results.

4) Tertiary current limiting reactor

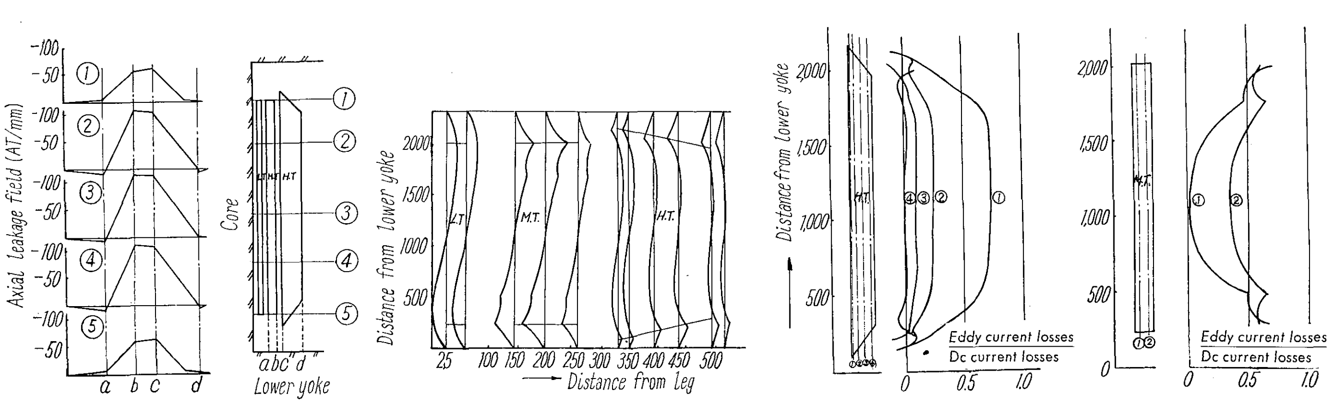
Generally, in comparison with the other windings of the 3-winding transformer, capacity as well as the short-circuiting current limiting impedance of the tertiary windings have a tendency to diminish; therefore, considerable attention must be given to its short-circuit strength. In order to suppress the short-circuit capacity of the tertiary winding, particularly for large capacity transformers, impedance between the secondary and tertiary windings must not be diminished. This is also true in many cases insofar as the impedance between the primary and secondary windings are concerned. When only the short-circuit strength of the transformer itself is concerned, it is sometimes effective to merely increase the winding capacity of the tertiary to greater than that normally required. However, to suppress the short-circuit capacity of the tertiary side, there is no alternative except to increase the tertiary impedance.

Methods of increasing the impedance are:

(1) Increasing the width of the tertiary winding as well as the distance from the winding facing the tertiary winding.

(2) Connecting an additional impedance to the tertiary winding.

In (1), while setting the impedance between the primary and secondary windings at a safe value, the impedance between the secondary and tertiary must be increased; therefore, the distance between the secondary and tertiary windings must be increased. As a result, the diameter and height of the primary and secondary windings, and of the core window, are enlarged. Consequenlty, the material required for the windings, the tank, etc., and the quantity of oil must also be increased. When low grade insulation is applied to the face of the tertiary winding, the distance between the secondary and the tertiary windings should be made slightly larger than



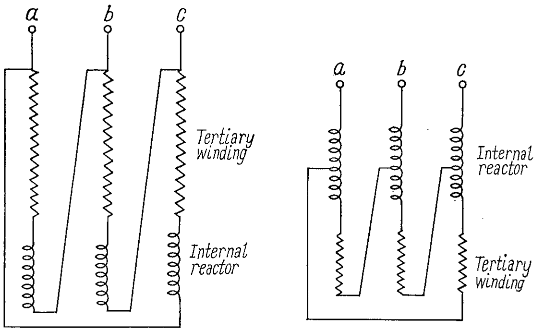
(a) Distribution of axial leakage field

(b) Distribution of radial leakage field

(c) Distribution of eddy-current losses in high voltage windings

(d) Distribution of eddy-current losses in medium voltage windings

Fig. 3 Distribution of leakage field and eddy-current losses in the winding



(a) Installation (b) External and internal diagram of Δ winding

Fig. 4 Tertiary current limiting reactor

normally required to provide improved insulation; therefore, additional, unnecessary space is provided within the transformer. Moreover, when limitations, such as the requirement for transportation in assembled form, are imposed with respect to extra-high voltage, large capacity transformers, dimensions and weight not only become a problem, but also uneconomical.

By comparision, method (2), as illustrated in *Fig. 4*, consists of connecting a reactor in series with each phase of the tertiary winding. The increase in material involved with the use of the reactor is considerably less than in method (1). The reactor winding is similar to the transformer winding without core. It is snugly fastened to the frame in one corner of the transformer tank. The reactor winding is enclosed with magnetic sheet shielding to reduce stray load losses due to reactor leakage flux. Through mutual arrangement of the transformer windings, as a design standard, our company has insured that a reactor having the required impedance, corresponding to the customer's order with regard to the short-circuit capacity of the tertiary circuit, can be connected to the tertiary side. Increase in the limiting capacity of on-load tap changing transformers has also been successfully provided with provisions for railway transportation in assembled form. The method of incorporating this current limiting reactor has been applied to 15 transformers manufactured by our company since 1960.

In order to keep the relationship between the zero sequence impedance and the positive sequence impedance of the primary as well as the secondary winding at the appropriate value in the 70/70/20 Mva transformer delivered to the Shikoku Electric Power Co., Matsuyama Power Station, a portion of the reactor was inserted in the tertiary △ winding and the remaining portion was positioned outside the △ winding, as shown in *Fig. 4* (*b*). Using this method, it is only necessary to connect the reactor to the outer portion of the △ connection when increase in zero sequence impedance is to be prevented due to earth conditions in the system to be connected. This well illustrates one of the excellent features of incorporating a tertiary current limiting reactor.

In the delivered 345 Mva transformer, mutual impedances between each winding have been fixed so as to suppress tertiary short-circuit capacity to about 2500 Mva. Of the 3.94% impedance between the secondary and tertiary windings, the impedance of the transformer itself was 2.86%, while that of the reactor accounted for 1.08%.

5) On-load tap changing equipment

Newly developed 3DSC 1 type on-load tap changing equipment has been installed in this transformer. This tap changing equipment is directed at $4150/\sqrt{3}$ volt between terminals and a current of 900 amp and is suitable for use in transformers having extra-high voltages up to the magnitude of 400 Mva.

This tap changing equipment uses a 2-resistor switching method, a double 4 node link mechanism, and contacts which have long service life and which have proven results since having been introduced approximately 10 years ago.

In this tap changing equipment, 3 single phase diverter switch are arranged in a Y form on the lower portion of a suspended insulating cylinder. In this application, since there is an excellent space factor within the cylinder, the device is compact, and since the impulsive forces occurring during switching operations are equally distributed along the cylinder circumference, the mechanical strain applied to the insulating cylinder is minimized.

Since the diverter switch chamber is large than previously provided, a large oil filtration device has been attached. Furthermore, a conservator for the diverter switch chamber has been installed along with the main conservator to prevent oil within the chamber from deteriorating.

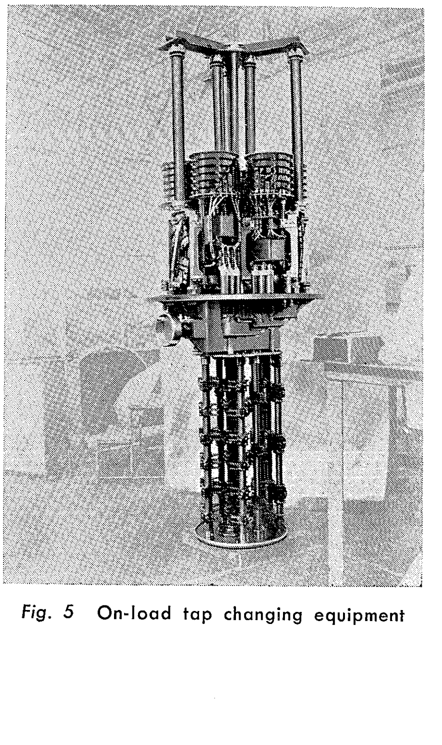


Fig. 5 On-load tap changing equipment

Endurance tests were performed to the extent of 200,000 electrical and 800,000 mechanical operations. As a special feature of the electrical endurance test, with the unbalanced phase transformer acting as a power source, actual load and test conditions were brought into conformity.

Aside from these tests, tests were also conducted on overcurrent switching by imposing 1.5 times the passable current, and on short-circuit current conduction by imposing 10 times the passable current, in ascertaining its excellent capabilities.

6) Elephant head

In consideration of protection against salt contamination, the 275 kv extra-high voltage side is connected directly to the cable by an elephant head.

A direct method used only by our company is used in the elephant portion, isolating the cablehead chamber from the transformer, i. e., applying a through insulation type of construction. The purpose of this through arrangement is to complete separation of the elephant chamber from the transformer while assembling and performing maintenace checks. Therefore, wall pierced bushing in oil are not used and simple construction consists of insulators, and is, therefore, featured by being smaller and lighter than other types. Recent improvements have been applied to the insulator construction and tests have been conducted beforehand on models to determine the extent of its capabilities. The elephant type cablehead has been made extremely compact and light through the incorporation of these improvements.

Fig. 6 shows the elephant type cablehead. The lower portion of the case is mounted firmly on a concrete stand, so that transformer vibrations are completely prevented from being transmitted to the cable and the lead sheath.

7) Forced oil circulated, fan cooling device

A large, appropriate size cooling device has been devloped and installed in this transformer. Fuji Electric's standard U-fin radiator tubes, cooled by a large fan, are used for the cooling tubes. Cooling capability as high as double that provided by previous cooling devices has been obtained. By comparison to previous devices, the construction has been made considerably simplier, and vibrations in each component have been greatly reduced, thus increasing the life of bearings, shafts, and other components easily affected by vibration, greatly increasing the reliability of auxiliary equipment.

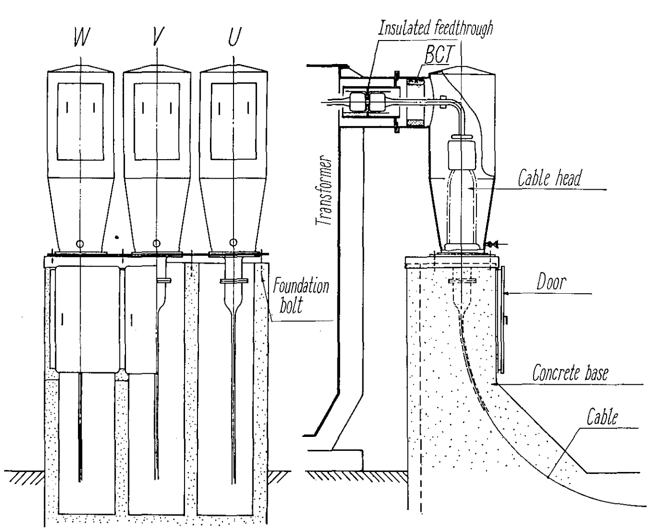


Fig. 6 275 kv elephant-type cablehead

8) Transportation

Since this transformer was transported by ship, there were no dimensional limitations. It was the first transformer in the 300 Mva class in Japan to be transported fully assembled with on-load tap changing equipment. Since the tap leads did not have to be connected to the transformer at the installation site, unnecessary exposure was avoided and, consequently, increased transformer reliability was provided. Absolute protection was insured during transportation against shock or vibration resulting from acceleration as a result of having made numerous measurements and providing adequate shock absorbers both outside and inside the transformer.

III. EXTRA-HIGH VOLTAGE PANTOGRAPH TYPE DISCONNECTING SWITCH

1. Specifications

This disconnecting switch is used as the bus line section switch for the 275 kv single bus line. Its description, ratings, and principal features are presented as follows:

Type: Indoor use, single pole, single throw, pneumatic operated, pantograph type disconnecting switch (HF 273 B/250/4000D).

Rated voltage: 300 kv

Rated current: 4000 amp

Rated short time current: 53 ka (2 sec)

Frequency: 60 cps

BIL: 1050 kv

Operating pressure: 15 kg/cm^2·g

Distance between phases: 4.5 m

Height: Shown in *Fig. 8*

Weight: Approximately 1100 kg (without stand)

The exterior is shown in *Fig. 7*.

2. Construction

Fig. 8 shows the external diagram of this disconnecting switch. The disconnecting switch can be classified into: fixed contact b_2, suspended from bus line a_1; conduction path c_2; the intermediate operating mechanism d; supporting porcelain insulator e; operating porcelain insulator f; and pneumatic operating device h_1.

1) Fixed contact

The fixed contact b_2 is simply constructed, since

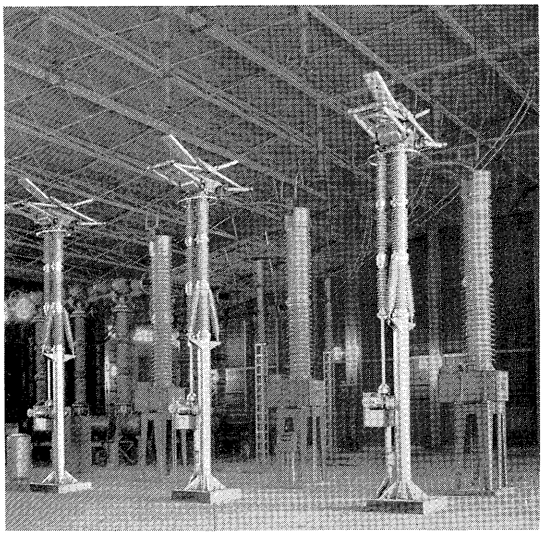
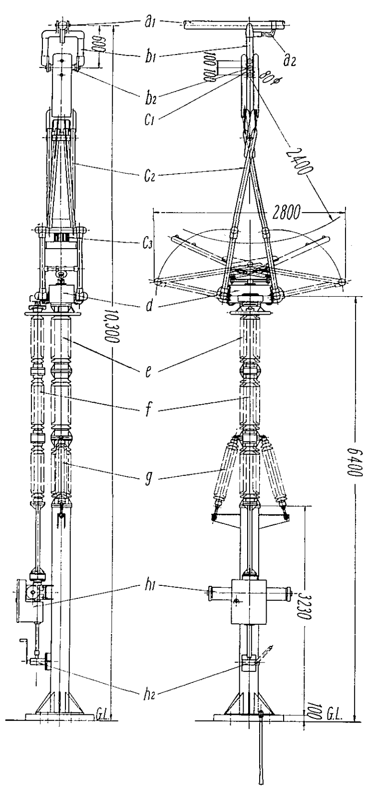


Fig. 7 300 kv 4000 amp pantograph type diconnecting switch



a_1: Bus line
a_2: Flexible conductor
b_1: Fixed contact suspension
b_2: Fixed contact
c_1: Moving contact
c_2: Conduction path
c_3: Flexible conductor
d: Intermediate operating mechanism
e: Supporting porcelain insulator
f: Operating porcelain insulator
g: Suspension porcelain insulator
h_1: Pneumatic operating device
h_2: Manual operating device

Fig. 8 Diagram of 300 kv 4000 amp pantograph type disconnecting switch

the bus line a_1, to which the fixed contact b_2 is suspended is installed indoors and is made of heat resistant aluminum pipe, and there are no effects from wind pressure, ambient temperature rise, conduction, etc., which might result in loosening of the transmission line. A ⊓ shaped aluminum pipe is bolted to the heat resistant aluminum pipe from which the fixed contact b_2 is suspended. Conduction is accomplished through a flexible conductor by-pass a_2.

2) Conduction path

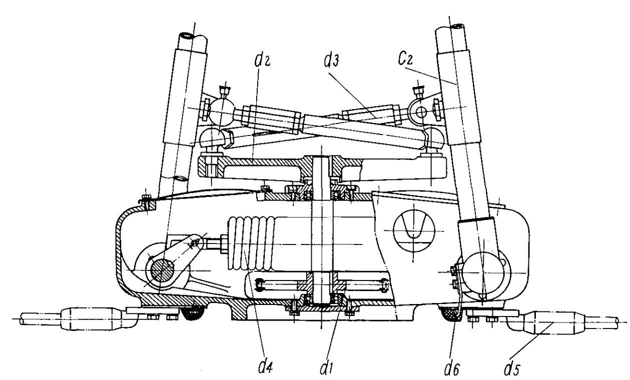
Since the rated current is 4000 amp, the conduction path is constructed entirely from non-corrosive aluminum alloy pipe, except for moving contact c_1, and pipe joints are electrically connected by flexible conductor c_3.

3) Intermediate operating mechanism (*Fig. 9*)

Rotation of the operating porcelain insulator f is transmitted to operating lever d_2 by chain d_1, resulting in expansion and contraction of conduction path c_2 due to the action of pull rod d_3. Only a very small amount of driving force is sufficient at the end of this operation, since the pull rod is near the dead point. A balancing spring d_4 is provided within the intermediate operating mechanism to balance the weight of the conduction path so that the required driving force is more or less maintained at a constant rate. However, the conduction path itself normally overcomes the spring tension so that even if the operation of the disconnecting switch is temporarily interrupted, the mechanism will return to a completely open circuit position.

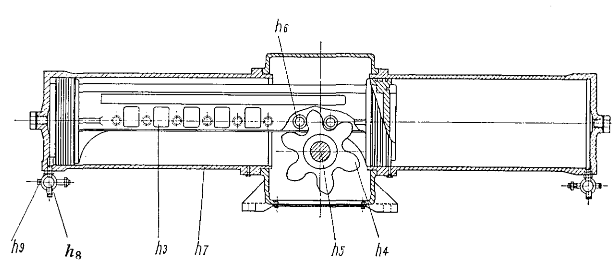
4) Pneumatic operating device (*Fig. 10*)

The straight line motion of the two throw piston,



d_1: Chain
d_2: Operating lever
d_3: Pull rod
d_4: Balancing spring
d_5: Lower terminal
d_6: Flexible conductor
c_2: Conduction path

Fig. 9 Intermediate operating mechanism



h_3: Piston
h_4: Gear
h_5: Shaft
h_6: Roller
h_7: Cylinder
h_8: Adjusting needle
h_9: Inlet of air supply pipes

Fig. 10 Pneumatic operation device

h_3 is changed to rotating motion of the operating porcelain insulator by the gear h_4. During the closing operation, the cylinder on the open pole side acts as an air dashpot, and when opening the cylinder on the closed pole side acts as the air dashpot, reducing the shocks that occur at the end of each stroke.

5) Additional feature

This disconnecting switch includes a manual operating device h_2 for emergency use. Furthermore, protection against salt contamination has been provided for porcelain insulators, although the equipment is for indoor use, since this is a marine industrial region. Since there is considerable electromagnetic force during short-circuiting (short-circuit current 53 ka), a suspension porcelain insulator *g* is attached to the supporting porcelain insulator *e*.

Aside from the construction features described, this equipment has several advantageous functional features, such as: when the circuit is open, the disconnecting switch is in a complete no-voltage condition, facilitating maintenance checks; the supporting porcelain insulators for the disconnecting switch also serve the dual purpose of maintaining the lower conductor; various arrangements are possible; and other favorable points.

3. Test result

1) No load operation test

After a continuous 1000-time no load operation test was performed, there was almost no change in closing or opening performance characteristics. *Fig. 11* shows the operation performance characteristic curve for rated control voltage and rated operating pressure after continuous 1000 operation test. The minimum operating pressure also remained nearly unchanged before and after the continuous 1000 operation test, reflecting values of 7.7 to 8.0 kg/cm²·g for the closed circuit and 6.5 to 6.6 kg/cm²·g for the open circuit.

2) Temperature rise test

Table 1 shows the final temperatures of the main conducting components with a 4000 amp alternating current having been imposed. There is a sufficient margin for temperature rise above the values prescribed for disconnecting switches in JEC-165.

3) Voltage withstand test

No difficulties were encountered during the performance of the withstand test applicable to the rating of this disconnecting switch. Moreover, the minimum corona starting voltage at closed circuit was 265 kv and minimum corona extinction voltage was 245 kv, while those for the open circuit were respectively 260 kv and 240 kv. Furthermore, no corona was produced even in the ground phase voltage with one line grounded.

4) Current switching characteristics

The test circuit used will be omitted due to space limitations. The test of charging current interrup-

Table 1 Data on Temperature Rise

Measuring Point	Temperature Rise (°C)
①	35.0
②	28.0
③	28.5
④	22.5
⑤	29.5
⑥	19.5
⑦	21.0
⑧	26.5
⑨	22.5

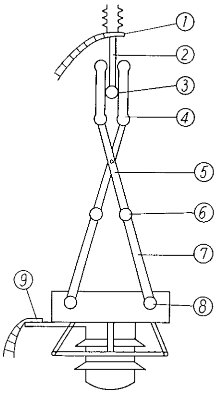


Table 2 (a) Characteristics of Breaking Capacity of Charging Current

E_t	I_c	P	t_a	S	α	β	f_o
173	0.87	15	1.4	690	34.5	1.78	135
173	0.87	15	1.44	920	46.0	1.90	135
173	0.38	15	1.38	770	38.5	1.86	135
173	0.65	15	1.54	970	48.5	1.78	150
173	0.65	15	1.54	950	47.5	1.96	150
173	0.65	15	1.46	800	40.0	1.60	150
173	0.43	15	1.54	950	47.5	1.91	190
173	0.43	15	1.52	920	46.0	1.93	190
173	0.43	15	1.50	860	43.0	1.80	190

Table 2 (b) Characteristics of Making Capacity of Charging Current

E_t	I_c	P	t_a'	S'	β	f_o
173	0.43	15	0.58	100	1.33	190
173	0.87	15	0.58	100	1.47	135
173	0.87	15	0.59	100	1.50	135

Et: Test voltage (kv)
Ic: Breaking or making current (amp)
P: Operating pressure (kg/cm²·g)
ta: Total breaking time (sec)
S: Extinction point (mm)
α: Proportional opening distance (proportion of S to effective open pole distance, %)
β: Abnormal voltage factor (multiplier with respect to $173\sqrt{2}$ kv normal peak valtage to ground)
fo: Restriking frequency of re-arcing (cps)
ta': Discharge time forerunning operation (sec)
S': Position of the above (mm)

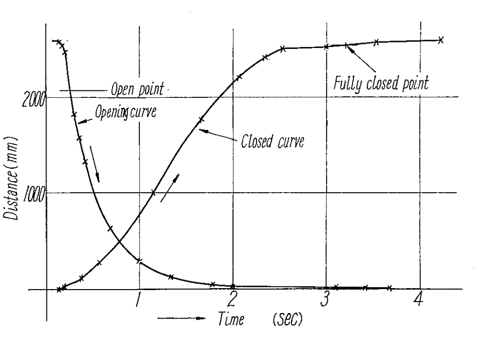


Fig. 11 Relationship between stroke and closing and opening time

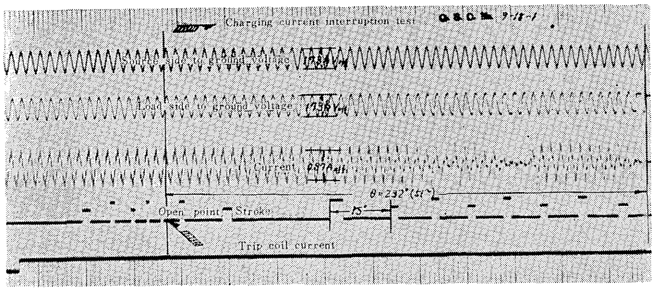


Fig. 12 (a) Typical oscillogram of charging current interruption

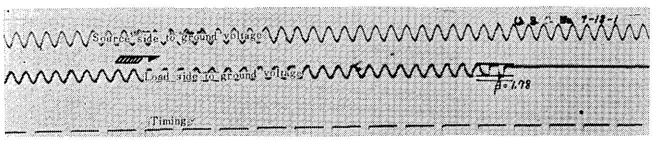


Fig. 12 (b) Typical oscillogram of overvoltage on charging current interruption

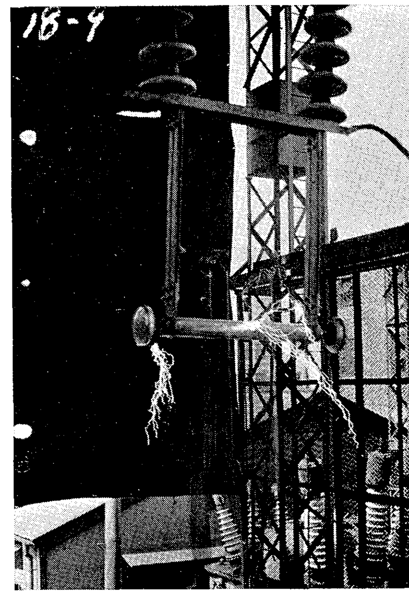


Fig. 13 Charging current interruption test

tion was conducted indoors with a charging voltage of 173 kv (300 kv/$\sqrt{3}$) and breaking currents of 0.43 amp, 0.65 amp, and 0.87 amp.

Table 2 (*a*) shows the proportionate opening distance, the arc time and overvoltage factor when the charging current is interrupted. *Table 2* (*b*) shows the closed distance, the discharge time and overvoltage factor when the charging current is making.

Fig. 12 (*a*) shows the oscillograms 0.87 amp charging current interruption, *Fig. 12* (*b*) shows the oscillograms of the over voltages for the same instant, while *Fig. 13* shows the arc conditions at that state. As can seen from these test results the number of occurrences of re-arcing is less than in horizontal rotating disconnecting switches ; hence the overvoltage factor tends to be smaller.

This is due to the slow opening velocity of the pantograph type disconnecting switch. There is almost no re-arcing, and breaking is accomplished through " piecemeal natural extinction " with rearcing.

5) Short time current test and others

A short time current test was performed using 56 ka (2 sec), measuring the contact resistance before and after the test and determining that there was no change.

Aside from these tests, excellent results were also obtained from leakage tests.

IV. CONCLUSION

In the foregoing discussions, an outline has been given of Japan's largest 3-winding transformer, the 345 Mva extra-high voltage on-load tap changing transformer, and the extra-high voltage 4000 amp pantograph type disconnecting switches.

In designing and constructing electric power system equipment with increasingly higher voltage and capacity, the experience gained with the electrical equipment previously described can be put to full use, particularly in Japan where plans are underway for 500 kv power transmission, scheduled for finalization within the next few years.