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DIRECT STEP-DOWN SYSTEM HIGH CAPACITY S-FORMER (SILICON TRANSFORMER-RECTIFIER UNIT) FOR ALCAN AUSTRALIA LTD.

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I. INTRODUCTION

Reserves of bauxite, the source material for aluminum, of an estimated 3 billion tons have been discovered in Australia. In the area where the reserves were found, existing refinery plants are being enlarged and new facilities are being constructed by leading international aluminum companies.

Alcan Australia Ltd. is now building a plant with a proposed yearly output of 50,000 tons for which Fuji Electric has manufactured 4 silicon transformer-rectifier units (S-Formers) of dc 600 v, 32,000 kw to be used in the main dc power source for the dc 600 v, 160,000 amp pot line. These four S-formers, completed in one year, are outstanding products and amply demonstrate anticipated performance, as verified by test results. This paper gives an outline of the S-Former equipment.

II. OUTLINE OF RECTIFIER EQUIPMENT

1. Planning

In accordance with the main conditions of source voltage 132 kv, 50 Hz and pot line of dc voltage and current of 600 v ; 160,000 amp, Alcan presented 3 proposals : (a) a system which would step down the voltage from 132 kv to 600 v dc by means of a receiving transformer, voltage regulator and rectifier-transformer ; (b) two-stage step down using a combined receiving voltage regulating transformer ; and (c) a system with direct step down from 132 kv to 600 v dc using only one transformer.

When investigating these three proposals, the unit capacity of S-Former (rectifier equipment) was first examined. As reported previously, large unit capacities are economical. However, multiphase rectification was considered as a countermeasure against high harmonics and as a result 4 units including 1 stand-by unit were constructed. As investigations based on these three sugestions progressed, it became evident that the suggestions in order of value were $(c)<(b)<(a)$ and that the direct step-down system suggested in (*c*) would be the most suitable. However, at that time there was no direct step down system of rectifier equipment installed anywhere in the world which could convert directly from such a high voltage as 132 kv to a low dc voltage. In Japan, the largest capacity equipment could only convert from around 70 kv. Fuji Electric had made several direct step-down rectifiers from 66 kv for plants in Japan as well as 11,250 kw rectifier equipment for the Taiwan Plastics Co. Using this experience, as well as experience gained in the manufacture of about sixty 60 kv direct step-down transformers for low voltage/high current electric furnaces, Fuji Electric had considerable confidence in its ability to produce a 132 kv direct step-down S-Former and recommended the incorporation of proposal (*c*). After Alcan engineers had confirmed these past technical results and the features given below, the specifications of the 132 kv direct step-down system were drawn up and the purchasing order was issued to Fuji Electric. S-Formers were decided and production commenced.

2. Basic Electrical Specifications and Conditions

Receiver power source :	3-phase, 132 kv ± 5% 50 Hz neutral solidly grounded, 2-line receiving, short-circuit rating of power supply ; 7500 Mva
Electrolysis load :	Dc 600 v 160 ka Voltage control range; 0–600v
Rectifier equipment :	No. of S-Formers : 4 (including one stand-by) Unit capacity ; 53.4 ka, 600 v 32 Mw
Automatic control system :	Automatic constant current control (with kw limit)
Total number of rectification phases :	24
Location :	Main units are outdoor type Control switch boards only are indoor type

3. Outline of Main Circuitry and S-Former Arrangement

Fig. 1 is a one line diagram of the main circuits. The electric systems for the electrolysis power source can be classified broadly as follows :

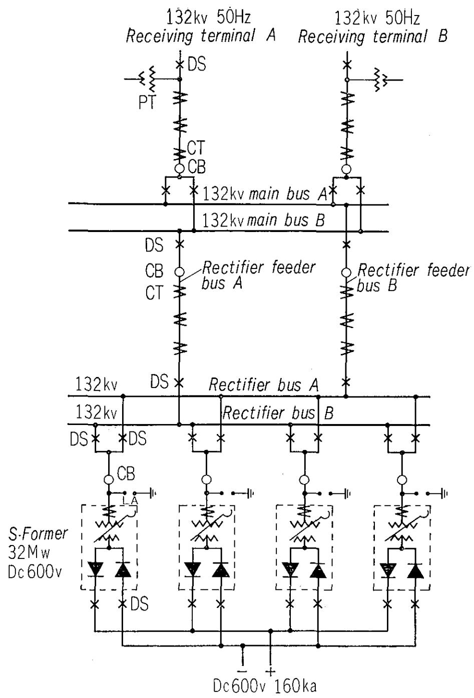


Fig. 1 One line diagram

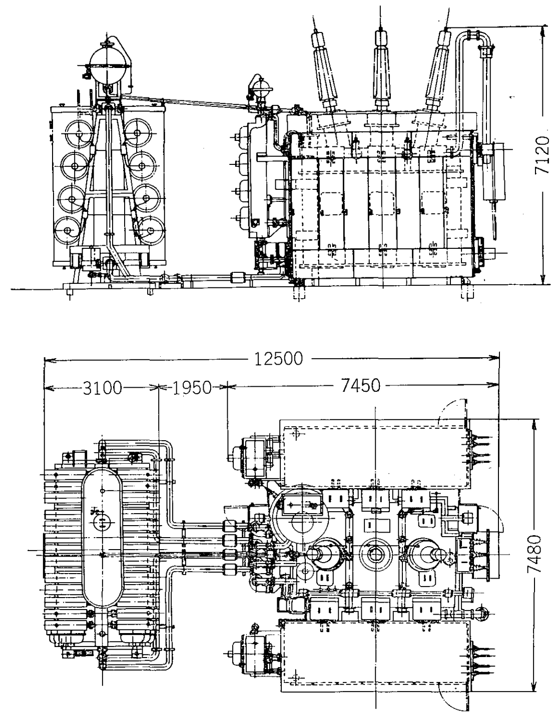


Fig. 2 Outline of S-Former

Receiving lines *A* and *B*
132 kv main buses *A* and *B*
Rectifier feeders *A* and *B*
Rectifier buses *A* and *B*
Rectifier units

The main systems are the *A* systems and the *B* are stand-by systems used during maintenance inspections or when there is a fault in any of the main systems. As can be seen from the drawing, the main components include only the 4 units of S-Former along with 132 kv circuit breakers, disconnecting switches, metering transformer and arresters. Startings / topping of the 4 rectifier units is performed collectively by means of a circuit breaker in rectifier feeder bus *A* (or *B*).

The 4 S-Formers are installed in a rectifier area 144 ft (44 m) wide and 49 ft (15 m) deep. There is a fire wall between each unit and Fuji Electric outdoor type oil-immersed dc disconnecting switches are located between the output terminal and dc bus in each unit.

III. S-FORMER SPECIFICATIONS

1. Unit Capacity

The S-Former unit capacity and ratings are as follows.

Ac side: 37,000 kva 132,000 v 50 Hz
Dc side: 32,000 kw 600 v 53,400 amp
Type: Outdoor type forced-oil forced air cooled system
Voltage regulation range:
100% control over 0∼600 v range using a combination of on-load tap changer, no-load tap changer and voltage control reactor
Standard: BS 171, IEC Pub. 146, JEM 1156

Fig. 2 shows an outer view of the S-Former. The 26.7 ka rectifier cubicles are closely coupled to each side of the rectifier transformer. A transformer cooling system with 2-stage ratings; forced oil forced air/forced oil natural air cooled, is located 2 m (6 ft) away from the transformer.

2. Transformer and Rectifier Specification Data

1) Transformer specifications

Connections:
- Ac side (primary): wye with neutral solidly grounded (±7.5° phase shift)
- Dc side (secondary): wye or delta
- Tertiary: wye

Rated capacity:
- Ac side: 37,000 kva
- Dc side: 4×9250 kva
- Tertiary: 11,000 kva

Voltage:
- Ac side: 138.6–132 (Rated)—125.4–118.8 kv (no-load tap changer)
- Dc side: 490∼258 v (27 taps)
  285∼53 v (27 taps)
- Tertiary: 10.86 kv

Ac test voltage:
- Ac side: 275 kv
- Neutral: 34 kv
- Dc side: 2.5 kv
- Tertiary: 50 kv

BIL (impulse voltage test):

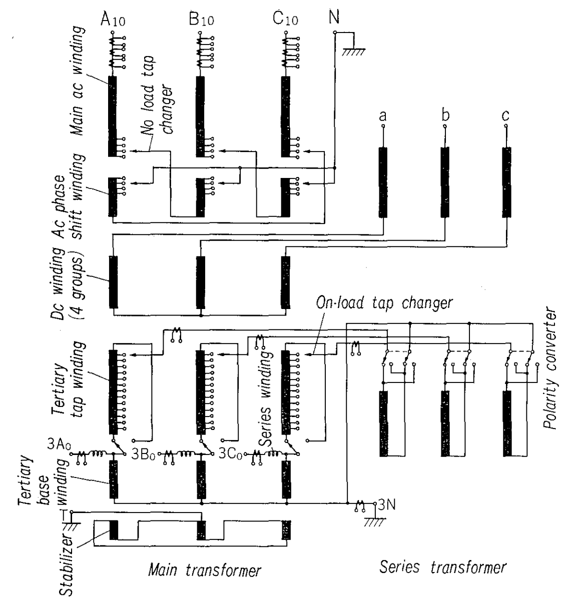


Fig. 3 Connection diagram of transformer

Ac side	Full wave	650 kv
	Chopped wave	750 kv

Saturable reactors: Dc 45 v (in tank)
Tertiary series reactor: 225 kva (in tank)

The connections of one of the four transformers is shown in *Fig. 3*.

2) Rectifier ratings

Dc voltage: 600 v
Dc current: 53,400 amp
Rated output: 32,000 kw Rating A (IEC)
Rectifier connections: 3-phase double-way
Silicon rectifier cells: Model Si 250.3
Diode arrangement: In series: 1
In parallel: 4 groups of 24

3) Dimensions and weight

Total weight including rectifier:
332,000 lbs. (151 tons)
Outline dimensions: See Fig. 2.

IV. FEATURES

This S-Former embodies many unique techniques developed from Fuji Electric's wide range of practical experience in the manufacture of liquid cooled rectifier systems for electrolysis, and transformer-rectifier for electric furnaces. The main features are as follows.

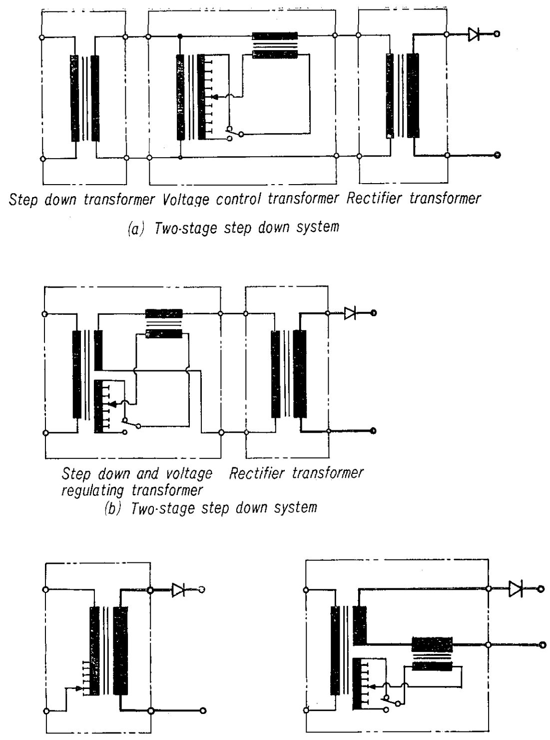
(1) This is the first low voltage/large current rectifier transformer (even including electric furnace transformers) ever manufactured with a direct step-down system 132 kv.
(2) The unit capacity of 37,000 kva/32,000 kw is the largest in the world for a rectifier transformer and rectifier.
(3) The voltage control range is very wide: 100% from dc 0 v to 600 v and control is stepless.
(4) The ac winding contains a phase shift winding and the dc winding can be used with two connections, wye or delta. The 4 units are capable of 24 phase rectification.
(5) By using the in-phase contra-polarity connection, low impedance and high efficiency are possible as well as an improvement in the power factor.
(6) In order to improve the power factor and eliminate high harmonic currents, a condenser and series reactor is connected in the tertiary circuit.
(7) The voltage control reactors (saturable reactors) are incorporated in a tank.
(8) The equivalent dc metering system using ac CT in the primary circuit of the series transformer and dc converter allows for highly accurate, economical measurement of the dc output current with no deterioration in the DCCT.
(9) A newly developed 3 DSCP type on-load tap changer is employed.
(10) The transformer and rectifier have been combined completly in a single unit which can be easily hoisted or transported. Except for the transformer cooling system, all structural components are incorporated within the S-Former.

V. PROBLEMS AND THEIR COUNTERMEASURES FOR THE DIRECT STEP-DOWN SYSTEM

1. Main Points of the Direct Step-Down System

Fuji Electric has named the system by which receiving voltages of 66 kv or over are decreased in one step to low values for use in electrolysis cells or electric furnaces, the direct step-down system.

With this system, when the secondary voltage control range is narrow, the secondary voltage can be controlled by altering the number of windings on the primary side as shown in *Fig. 5* (*c*) but if the voltage induced in each turn is varied over a wide range, the utilization rate of the core decreases and equal tap voltage can not be maintained between each of the voltage steps. Therefore, there are many cases when an indirect voltage control system as shown in *Fig. 4* (*d*) which controls the output voltage by connecting the secondary of a series transformer in series with the secondary of the main transformer and controlling the secondary voltage of the series transformer, is employed in direct step-down systems for rectifier or furnace transformers where wide range voltage control is required. When comparing the system in *Fig. 4* (*d*) with the two-stage step down systems using intermediate step-down transformers or voltage regulators as shown in *Fig. 4* (*a*) and (*b*), it is evident that the direct step-down system has a low loss and is more economical in terms of the number of cores and the total capacity of all of the transformers. As was mentioned previously, the direct step-down system is best in respect to rectifier equipment costs, area occupied, overall



(a) Two-stage step down system

(b) Two-stage step down system

(c) Direct step-down system

(d) Direct step-down system

Fig. 4 Comparison of the two-stage step-down system and direct step down system

efficiency, and maintenance costs. However, there are several possibilities why two-stage step-down systems are still used for large-capacity and large-current rectifier equipment. One is that on the secondary side of the rectifier transformer, the voltage is very low while the current is very high and there are many phase groups and therefore transformer construction and other matters can become very complicated.

If in the case of a direct step-down system the primary sides of the rectifier transformer were connected directly to the high voltage lines, the transformer would be subjected to direct surge voltages from lightning or other sources. Problems encountered in the rectifier transformer are a means of decreasing impulse voltage characteristics resulting from the increase of capacitance to ground of the primary winding wound beneath the secondary winding, and of limiting the transfer of surge voltage from primary to secondary windings, to which the silicon rectifier diodes are connected.

This probably results from the attitude of users to put most stress on reliability. However, a complete set of countermeasures as described below have been devised to do away with these problems and there is no need to worry about a decrease in reliability with the direct step-down system. From a collective point of view, the reliability of the 2-stage system which has several transformers connected in series is equal to the product of the reliabilities for each device, and therefore this reliability can more easily deteriorate than in the direct step-down system.

2. Construction of the Direct Step-Down System

In rectifier transformers which contain a series transformer it is not easy to make a connection with lead wires between the secondary winding of the main transformer which has a large number of three phase-groups and heavy current capacity and the secondary winding of a series transformer with the same number of three phase-groups and the same current capacity. Just as contact is about to be made, connection work becomes difficult and from the view point of workability the amount taken up by the connection leads increases remarkably when compared with the windings. Even when the current density is lowered, the amount of loss due to the leads is large and efficiency does not improve as much as it should. Therefore, there were many cases when the standard 2-stage step-down systems shown in *Fig. 4* (*a*) and (*b*) were more profitable for controlling the output voltage when the primary input voltage of the transformer was low.

When the direct-step down system is used and voltage control is to be over a wide range, it is necessary to find a connection method for the transformer secondary windings in order to achieve the features of the system, i.e. high efficiency and economy. Fuji Electric decided to used a method based on the figure-8 type ring-coil which had been employed in large capacity electric furnace transformers. The figure-8 type ring coil is a single coil formed by combining the cores of the main and series transformers in one unit, so that no connection leads are required between the two. The construction is also simplified and the equipment becomes more compact.

3. Improving the Lightning Resistance Ac Winding

Generally, the high voltage windings of rectifier and electric furnace transformers are arranged concentrically with the inner side of the low voltage windings. Therefore, the capacity to ground is larger than with external arrangements and the so-called impulse voltage characteristics $\alpha=\sqrt{C/K}$ (C: capacitance to ground, K: series capacitance) deteriorate. The initial potential distribution collects at the terminal attached by an impulse voltage and the voltage oscillation also increases. To improve the lightning resistance of the windings economically, it is necessary to place more emphasis on the improvement of α than on strengthening the insulation. Therefore, a static shield was provided and the series capacitance was increased by combining the windings in a special way. This same method can be employed in the direct step-down system.

Fig. 5 shows the arrangement of windings in this transformer. The ac (primary) 132 kv winding consists of three windings: the main winding, the tap winding and the phase shift winding. However the

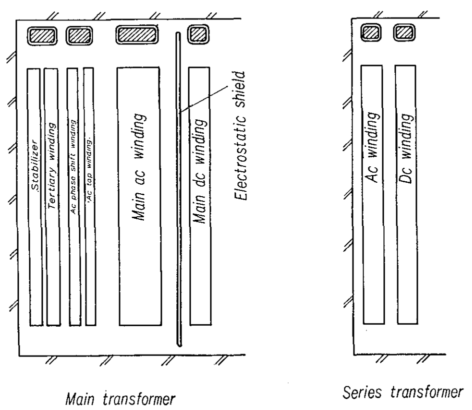


Fig. 5 Arrangement of windings

tap winding and phase shift winding which form the solidly grounded neutral are seperate and the main winding must be constructed to withstand an impulse voltage of BIL 650 kv. Therefore, Fuji Electric's unique interleaved disc winding on a common insulation system was employed. This type of winding is an improvement over the standard interleaved disc winding (high series capacitance winding). The impulse voltage characteristics are excellent and the safety factor in respect to insulation strength is high.

4. Suppression of and Protection Against Transferred Voltage

Since this S-Former is connected to 132 kv lines, surge voltage due to lighning and others causes can attack the ac winding directly and also be transferred to the dc side. In order to suppress this transferred voltage, it was necessary to confirm that such values are within peak reverse voltage of the rectifier diodes by various investigations and tests before production began.

The impulse voltage at the ac winding is transferred to the dc side as a superimposition of two phenomena: static and magnetic coupling.

The electrostatically transferred voltage appears on the dc side due to electrostatic voltage division. With the winding arrangement shown in *Fig. 7*, when the impulse wave with a peak value of V_1 penetrates from the ac side, the transferred voltage appearing on the dc side, V_2, can be expressed as follows:

$$V_2 = \frac{C_{12}}{C_{12}+C_{2E}} \times V_1$$

Therefore, to make V_2 small, C_{12} can be made small or C_{2E} can be made large. An effective way to make C_{12} small is to insert a static shield between the ac and dc windings as shown in *Fig. 7*. In this case, $C_{12}=0$ and therefore $V_2=0$. C_{2E} can be made large by connecting a condenser (surge absorber) of the required magnitude between the dc terminal and ground.

The magnetic transferred voltage is the same as in transformer theory when a surge voltage is in-

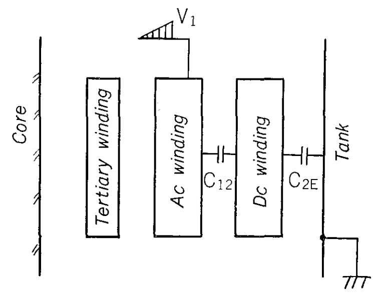


Fig. 6 Capacitance of transformer windings

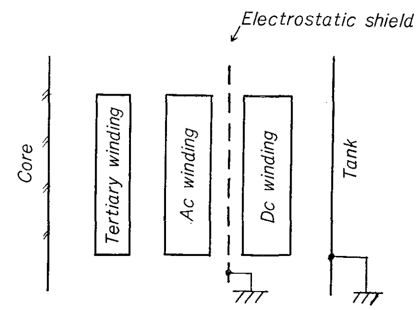


Fig. 7 Suppression of electrostatic transferred voltage

duced on the dc side by means of magnetic induction. When the number of windings on the ac and dc sides are N_1 and N_2 respectively, then

$$V_2 = k \cdot \frac{N_2}{N_1} \cdot V_1$$

where k: a constant determined by the connections, windings and oscillation period.

Using this equation and assuming that the dc rated voltage is 490 v and k=constant, a comparison of the magnetic transferred voltages at direct step-downs from 66 kv and 132 kV reveals the following.

For 66 kv direct step-down, BIL=350 kv and therefore:

$$V_2 = k \times \frac{490}{66{,}000} \times 350 = 2.6\,k$$

For the 132 kv direct step-down, BIL=650 kv and therefore:

$$V_2 = k \times \frac{490}{132{,}000} \times 650 = 2.4\,k$$

It is also clear from calculations with ac rated voltages of 22 kv and 11 kv that the larger the ac rated voltage, the smaller the magnetic transferred voltage.

Therefore, there is no need to worry when using the direct step-down system with voltages of 132 kv or higher. The value of k can easily be estimated by comparing the above two calculations. However, in practice, understanding the value of k is a major factor in assuming the value of the transferred voltage. The value of k is not easy to determine since it depends on the connections, winding construction, impressed voltage damping, oscillation wave damping and the oscillation period. However, for the past several decades, Fuji Electric has been compiling values measured under various conditions and has obtained considerable data from detailed analysis and investigations. Therefore, the value k can be estimated with a high accuracy.

This S-Former employs two means to suppress the surge transferred voltage: a static shield and a surge absorber. In order to confirm the effectiveness of these measures, impulse voltages were applied to the finished S-Former under many conditions and measurements were taken.

VI. CHANGING TO LARGE CAPACITY EQUIPMENT

1. Increasing the Unit Capacity

As the capacity of electrolysis equipment has increased in recent years, the unit capacities of rectifier equipment have gone up rapidly. This trend is especially evident in the aluminum reduction plants and chlorine industries. The unit capacity of the equipment described here (37,000 kva and dc output of 32,000 kw) has set a world record. If the capacity of the series transformer is included, the equivalent transformer capacity reaches 53,500 kva which is extremely high considering the previous levels. In Japan, the largest capacity in operation was about 21,000 kva which means an increase of about twice.

2. Dc Large Current Winding

As described previovsly, the so-called figure 8 type ring coil is employed in the dc (secondary) transformer winding so that the main transformer and series transformer windings are in a single unit. Since plate materials in the ring coil are used without modification, the construction is simple and the space factor is good. With this simple construction, transposition of the windings is easy. The conductor section modulus is large which makes it strong against mechanical forces which arise during short-circuits. Because of the cylindrical shape, the oil flows well and cooling is highly effective. The leads protrude in a simple manner from the ends of the windings.

In this transformer, the radial thickness of the ring coil has been divided into two parts because of the large capacity and a new system is used with 2 parallel winding. As a result, eddy current losses within the windings have been minimized and the efficiency is high.

The conductors are made of specially processed electric aluminum. For sometime, Fuji Electric has been a leader in the research and development of aluminum conductors and has considerable experience and data from the manufacture of rectifier and transformer windings. Aluminum is economical, easy to bend or weld and lightweight which means that it is used more than other materials such as copper for large current conductors.

3. In-Phase Contra-polarity Connection

As the capacities and current of transformer-rectifier units increase, magnetic flux due to the heavy ac currents cause an increase of effective conductor resistance, overheating in the region of the terminals and leads, current unbalance among diodes connected in parallel, an increase in the reactance drop and a decrease in efficiency etc. The usual means to prevent these disturbances were to arrange the reciprocal conductors as close together as possible and cancel their flux by means of the reciprocal currents. Previously, each phase of the secondary winding was kept disconnected and lead in parallel to the exterior of the transformer tank with the initial and final ends of winding close together. At the exterior of the transformer, the connections were formed as wye or delta. As an example, *Fig. 8* shows a bridge connection rectifier which is connec-

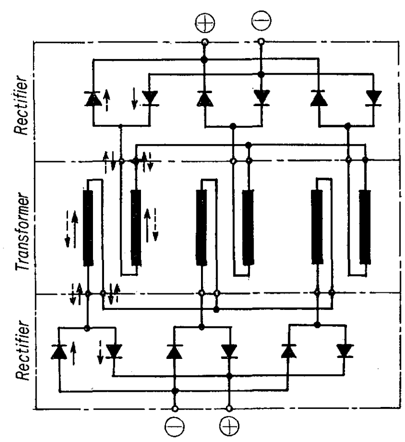


Fig. 8 Connection diagram for ordinary method (Bridge connection)

ted to a wye-connection transformer. In large current rectifier equipment, it is common to divide the windings into several groups because of the terminal current rating and also to improve the current distribution and have an appropriate number of diodes in parallel. The figure shows the windings divided into 2 groups. The direction of each phase of the current is shown in the drawing as → and ⇢. The difference in phase between → and ⇢ is 180°. Therefore, even if the current direction is reversed, the magnetic fluxes generated by the currents are not cancelled by each other.

However, with this method where all the winding connections are formed on the transformer exterior, the weight of the connetion bus between the transformer and the rectifier must be greater, the number of terminals in the transformer must be twice the number of windings, and difficulties arise in designing and manufacture of the terminal connection part. Since the reciprocal buses can not be lead into the interior of the bridge connected rectifier circuit, the reactance in the rectifier can not be reduced and such disturbances as current unbalance among diodes connected in parallel and overheating

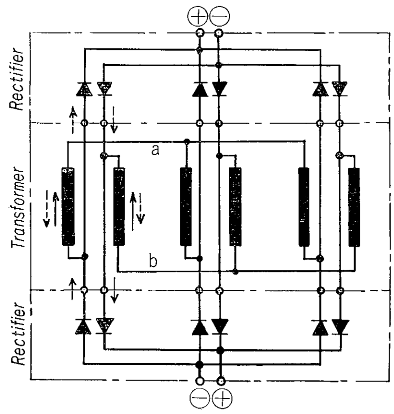


Fig. 9 Connection diagram of the same phase contra-polarity method (Bridge connection)

in the rectifier remain.

The in-phase contra-polarity connection method (Patent No. 476880) was devised by Fuji Electric to minimize these demerits in rectifier equipment connection. The principle of the method is shown in *Fig. 9.* For the above mentioned reasons, the rectifier connections and the groups of windings connected in parallel are arranged together and connected so as to acheive contra-polarity. In this method, the connections are made so that the magnitude of the currents in the rectifier arm (leg) and the adjacent leads are always equal at the same time and the current flows in opposite directions. As is evident from the figure, the magnetic fluxes generated by heavy rectifying current (diode arm current) can be cancelled in all positions from the transformer secondary winding to the dc terminals via the rectifier arms, and therefore the reactance can be reduced. The connections of each of the secondary windings can be made inside of the transformer tank, and therefore the connection buses can be much lighter and the loss also reduced.

With this special connection method, all problems arising due to large pulsating currents in the rectifier circuit can be minimized and when this construction is applied to the transformer-rectifier unit, the required number of buses can be reduced, and the efficiency and power factor improved.

VII. WIDE RANGE VOLTAGE CONTROL

1. Two-Stage Voltage Control

On the dc side of this equipment, the required range of voltage control is dc 600 v to 0 v. As shown in *Fig. 3*, a fixed winding and control tap winding make up the main transformer tertiary winding. Two-stage control, upper range and lower range, is performed by utilizing the reverse polarity between the tertiary windings. This method features minimum number of control tap windings and taps in the tap selector as well as a small on-load tap changer capacity. It is also possible to connect a condenser in the fixed tertiary winding so that it is not necessary to provide a separate winding for condenser connection.

Changing between the upper and lower control ranges is carried out by electrical operation in the no-load conditions. In each range, stepless control is possible by combining the on-load tap changer and voltage control reactor.

2. On-Load Tap Changer and Voltage Control Reactor

As the unit capacity increases, problems arise concerning high operating reliability and in an S-Former with an on-load tap changer the reliability of the diverter switch plays an important part. Fuji Electric employed the DSC 1 type on-load tap changer in a steel arcing furnace transformer where on-load switching conditions were more severe than in this case, and its reliability was then demonstrated. This DSC 1 type was a single phase unit, but in this S-Former the swich which is y-shaped and contained in steel cyrindrical case, is a 3-phase unit of type 3 DSCP. This new type 3 DSCP switch was formerly used in the transformer of a 66 kv 22 Mva steel arcing furnace, and is now operating satisfactorily. An outer view of this switch is shown in *Fig. 10* and the application curve is shown in *Fig. 11.*

The saturable reactors for stepless control of the

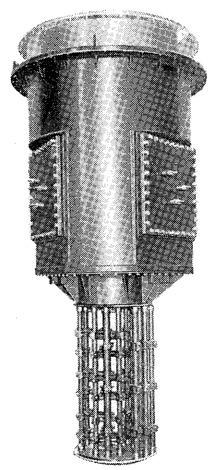


Fig. 10 3DSCP-type on-load tap charger

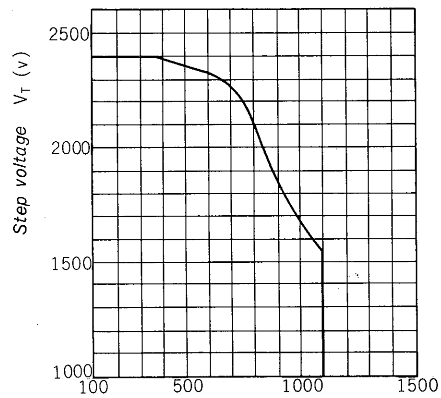


Fig. 11 Application curve of 3DSCP-type diverter switch

voltage between the taps are of the through type, and are installed compactly in a tank. These saturable reactors not only make possible stepless control of the dc output voltage in the $0\sim45$ v range but also contain a control winding to provide main circuit current balance between the rectifier groups and each phase.

VIII. SILICON RECTIFIER

1. Rectifier Diodes

This equipment employs standard Fuji pressure contact type diodes of type Si 250.3 with the following characteristics.

Repetitive PRV:	1400 v
Transient PRV:	1700 v
Forward voltage drop:	$\leq$1.0 v (300 amp normal temperature)
Rated mean forward current:	280 amp (single phase-half wave average)
$I^2 \cdot t$ limit:	280,000 amp$^2\cdot$sec.
Construction:	Pressure contact type

2. Rectifier Construction

In this S-Former, the 600 v 53,400 amp rectifier section is arranged in two 26,700 amp rectifier cubicles mounted directly on either sides of the transformer.

These cubicles are outdoor types with double construction to provide protection against climatic factors and dirt. The interior of the cubicle contains various parts such as the silicon rectifier diodes, fuses etc. which are protected against the entry of dirt and moisture. Two silicagel breathers are provided in the top of the cubicle to exhaust the internal air according to temperature variation. The outer cubicle is also of the outdoor type and in addition to keeping out rain, the outer surface of the cubicles are treated with a coat of silver aluminum paint to prevent the influence of solar radiation in the tropical area from penetrating inside of the inner cubicle.

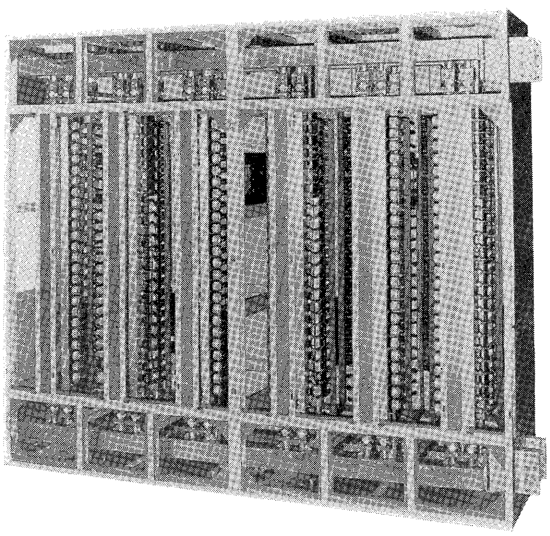


Fig. 12 Internal construction of the silicon rectifier cubicle

At the top and bottom of the inner cubicle, positive and negative current buses respectively pass through from left to right and between these, 24 oil cooling buses with rectifier diodes and fuses are arranged vertically (See *Fig. 12*).

The rectifier diodes are arranged in 4 groups of 3-phase double way connections corresponding to the number of dc windings in the transformer. Each group contains 1 series element and 24 parallel elements, and every two groups are combined by the in-phase contra-polarity connection. The 24 parallel diodes and their fuses are connected to one of the cooling buses. As shown in *Fig. 13*, the cooling buses are combined so that the current flows in the opposite direction in the same phase. As a result there is absolutely no influence of the magnetic field to the exterior in spite of the large rectifier current. Problems arising because of current unbalance between phases and local heating of the frame and panels inside the cubicle due to the magnetic fluxes are also eliminated.

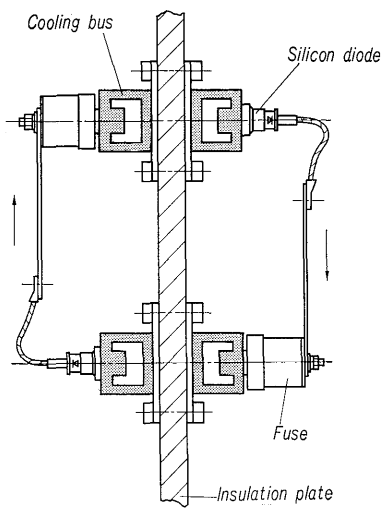


Fig. 13 Arrangement of the cooling bus

When 24 diodes are connected in parallel to each cooling bus, the bus length is over 2 m and generally there is a current unbalance in the parallel diodes which is large in the upper and lower diodes and medium in the middle diodes, due to the influence of mutual impedance between the parallel diodes. However in this equipment, bus arrangement for the ac input and dc output was investigated and as the test results given later show, the current unbalance has been improved by a geometrical arrangement on the cooling buses.

The protective fuses are round stud-type super rapid fuses of type SRF 3–700 (600 v 700 amp). One end is attached to the cooling bus with a screw and the other end is connected to the anode lead of

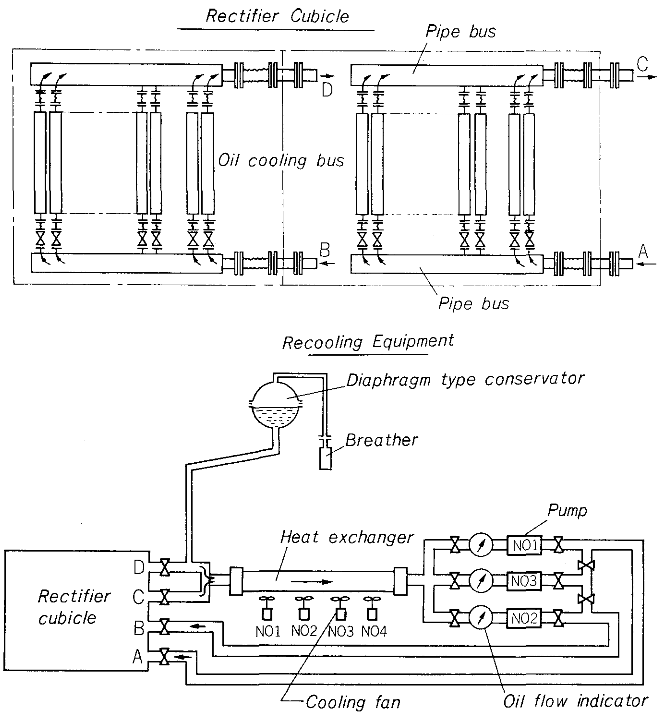


Fig. 14 Cooling diagram of silicon rectifier

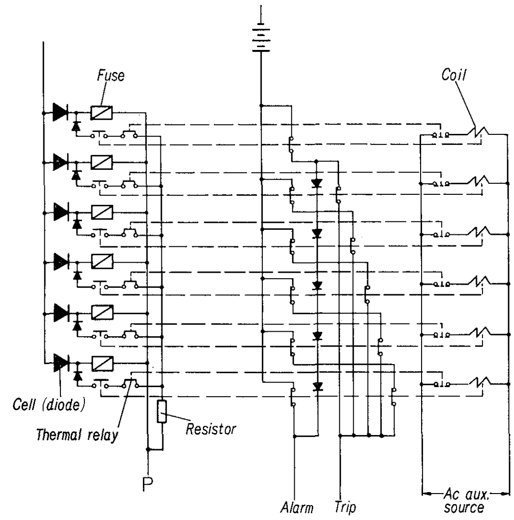


Fig. 15 Diode failure detector circuit

diodes (See *Fig. 13*).

The coolant in these oil buses flows through hollow portions inside the buses. With the oil-type cooling buses, lightweight alloy projecting type materials are used and the oil flow ducts (hollow parts) are made so that the cooling surface between the oil and metal is as large as possible. These ducts also contain turbulence plates and the cooling effect is very high.

The negative and positive dc buses arranged in the upper and lower parts of the cubicle are made of square shaped aluminum pipes. These also serve as oil pipes for the cooling buses.

Fig. 14 shows the rectifier cooling system. Of the three pumps, two are in use and one is a stand by.

Part of the cooling oil in the rectifier cubicle flows in each cooling bus. Heat generated by the rectifier diodes and fuses is absorbed and the oil again collects in the upper pipe of the cooling bus. In each cooling bus, there are a teflon bellows, adjustable valve, etc. The valve is used to control the oil flow so that there will be a large amount in the diode bus and a small amount in the fuse bus. As a result, it has been confirmed that the difference of the temperature rises in each bus is only about 1～2°C. One set of recooling equipment is provided in each cubicle and is attached directly to the outside wall of the cubicles.

Other auxiliary devices include a diode failure detection system, over-heat protection device, space heater, etc.

3. Rectifier Protection Equipment

1) Diode failure protection

In case a short-circuit should arise within a diode, the series connected super rapid fuse burns out, the faulty diode is cut off from the circuit and rectifier operation continues. The fuse itself contains a burn out indicator mark but because there are a large number of diodes and the cubicle is of the outdoor enclosed type, a diode failure detector circuit as shown in *Fig. 15* is provided which sends an alarm or a trip signal.

2) Cooling protection circuits

The cooling protection equipment consists of an oil low-flow relay and a dial type thermometer for supervising the temperature. A thermal switch attached to the diode cooling buses provides dual protection.

When the oil stops flowing in the cooling system or there is an abnormal temperature rise, a circuit breaker is tripped.

IX. TEST RESUITS

The S-Former underwent final tests based on BS 171, IEC Pub. 146 and JEM 1156 with the rectifier and transformer connected together. The results showed that anticipated values were fulfilled and the world's first 132 kv direct step-down system S-Former was successfully completed. The main test results are given below.

1. Impulse Voltage Test

In ordinary rectifier equipment, the impulse test is usually not performed but since this equipment is directly connected to 132 kv lines, the customer required this test. The test was conducted according to BS 171 which stipulated that full wave 650 kv be applied 3 times and chopped wave 750 kv 2 times to each of the 4 units. As previous investigations anticipated, there were no abnormalities in either the transformer or the rectifier equipment.

2. Loss Measurement

Test results showed that the overall rectifier efficiency at dc 540 v 160 ka operation was 98.3%. This was due to the use of appropriate winding construction, lead arrangement, rectifier construction etc. These results also proved the effectiveness of the in-phase contra-polarity connection method.

3. Temperature Rise

The rectifier and transformer equipment both contain individual forced oil forced air cooling systems but in the transformer only at a 75% load, can the cooling fan be stopped and forced oil natural cooling carried out.

The temperature rise tests were conducted under both conditions but the results in all cases showed sufficient agreement with the specified values and no ultimate over-heating or any other such abnormalities occurred.

Fig. 16 shows the results of a temperature rise test on the rectifier at 100% load. The cooling oil flowed partially in parallel through the cooling buses to which the diodes and their fuses were attached but because of a balanced distribution of flow, the temperature rise in all of the cooling buses was almost the same and results showed it to be well within the specified values.

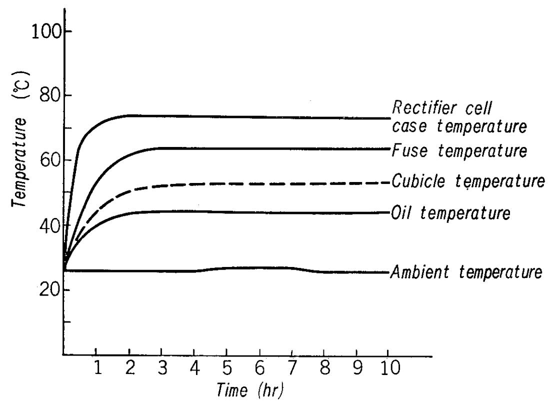


Fig. 16 Load test temperature rise

4. Rectifier Current Balance

The rectifier unit contains a large number of rectifier diodes attached to cooling buses and connected electrically in parallel. Instead of selecting the forward characteristics of the diodes to obtain proper current distribution in the parallel diodes, or connecting a balancer in series with the diodes, Fuji Electric design suppresses current unbalance by means of described in section VIII.

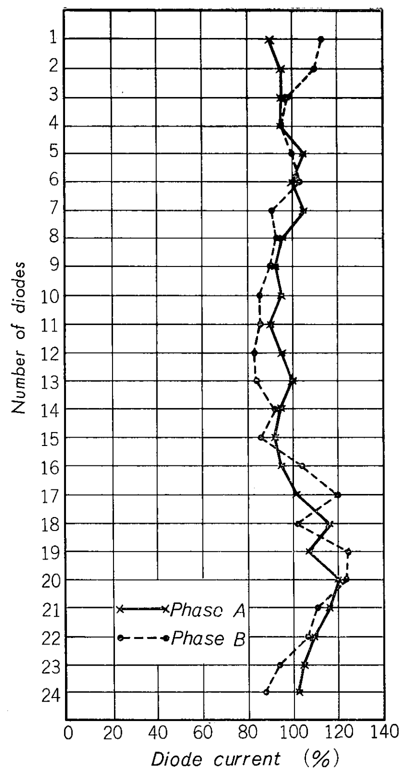


Fig. 17 Current balancing in parallel diode pass

As a result, the current distribution of each phase for the 24 diodes connected in parallel to the 2 m (6 ft) long cooling buses is satisfactory as can be seen from *Fig. 17* and the maximum unbalance was less than 25%. This value is satisfactory for protection even if one of the diodes is cut out.

X. CONCLUSION

This S-Former with two important characteristics: a direct step-down system from 132 kv and a unit capacity of 32 Mw, is of special significance in the manufacture of transfomer-rectifier equipment for electrolysis plants which are now increasing greatly in capacity. This equipment will no doubt serve as a guide for further developments.

On the basis of experience gained with this equipment, Fuji Electric is at present manufacturing 4 units with unit capacities of 37 Mw and 8 units with unit capacities of 45.5 Mw.

The authors would sincerely like to thank all the engineers of ALCAN who were so understanding in this work.