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LARGE CAPACITY SILICON RECTIFIER FOR ALUMINUM REDUCTION PLANT AT REYNOLDS METALS COMPANY

Shigeyuki Kobayashi
Akira Kamio
Toshiaki Hashizume
Harumi Miyama

I. FOREWORD

Recently, advances made in aluminum electrolytic reduction furnaces at aluminum reduction plants has been accompanied by an increase in the furnace current and currents of 150 ~ 180 kA are now generally used.

As a consequence, large scale aluminum reduction plants having a power consumption per aluminum reduction potline reaching 170 MW have been realized. The annual aluminum production of such a plant reaches 100,000 tons.

On the other hand, a number of new concepts are demanded for the rectifier equipment that supply the DC power required by aluminum electrolytic reduction furnaces.

The biggest factor is the rise in the cost of energy. The steady rise in the cost of energy ever since the oil shock of 1973 has had a subtantial affect on aluminum reduction plants, which consume large amounts of power. This also applies to rectifier equipments. Loss evaluation of rectifier equipments has steadily increased up to a level parallel with that of the cost of the rectifier equipments. Therefore, when studying the economy of an entire reduction plant, considering only the cost of the rectifier equipment is insufficient, but must also include loss evaluation. For this reason, as a result of the pursuit of economy, the design basis of rectifier equipments, especially the base for power loss, of recent reduction plants have changed considerably.

The second factor is the pursuit of reliability. This includes the following points:

(1) Improvement of the reliability of on-load tap changer.
(2) Securing of safety and rationalization of the insulation system of rectifiers whose DC output voltage has reached as high as 1,000V.
(3) Development of rational rectifier cooling systems.

The design and manufacture of the rectifier equipments delivered to the Reynolds Metals Company (U.S.A.), the world's leading aluminum reduction company, were based on the above points. The outline of the rectifier equipment is mentioned herein.

II. EQUIPMENT GENERAL

1. General Specifications

AC input: 3-phase, 115 kV ±5%, 60 Hz effectively grounded neutral system, two-parallel circuit

Potlines: 725 V, 70 kADC X 2 potlines

Number of rectifier units: 6 units (3 units per potline)

Unit capacity: 25,375 kW, 725 V, 35 kADC

Total rectifying pulse phase: 18 phases/potline, 36 phase/2 potlines

Voltage regulating range: 725 VDC at 35 kA down to 208 VDC at 0 A by rectifier transformer tertiary off-load taps and on-load taps.

Installation site: Rectifier units (S-Former) and local auxiliary cubicle installed outdoors.
Control panels, etc. installed indoors.

Ambient temperature: Minimum –25°C, maximum 45°C

Standard: ANSI C34.2 and C57.12

2. Summary of Installation

As shown in *Fig. 1*, 115 kV power from the electric power supply company is received by two-parallel circuit and is supplied to the diode rectifier units (hereinafter called "S-Former") from each Fuji SF_6 gas circuit breaker.

Disconnecting switches, current transformers, distribution SF_6 gas circuit breakers, and lightning arrester are installed at the 115 kV switchyard.

The S-Formers are installed between 6 m wide passages from the 115 kV switchyard and partitioned by a firewall as shown in *Fig. 3.* Six S-Formers are neatly installed in a 69 m wide, 10 m deep space.

The reduction potline requirement is 725 V, 70 kA DC. The S-Formers consist of three 725 V, 35 kA DC units and, even if one unit is shutdown, the other 2 units can supply 70 kA to the potline.

3. Features of S-Former

(1) A direct step down system (tertiary tap changing system with series transformer) is employed to directly step down the voltage from 115 kV to 725 VDC.
We have already delivered numerous rectifier transformers and furnace transformers having the direct step

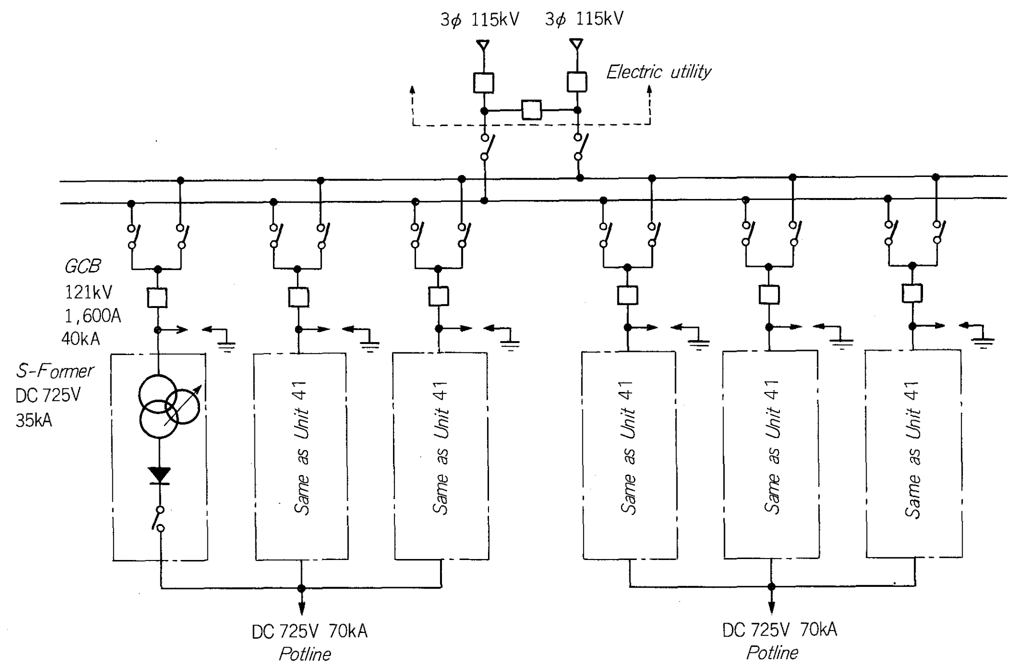


Fig. 1 Power system one-line diagram

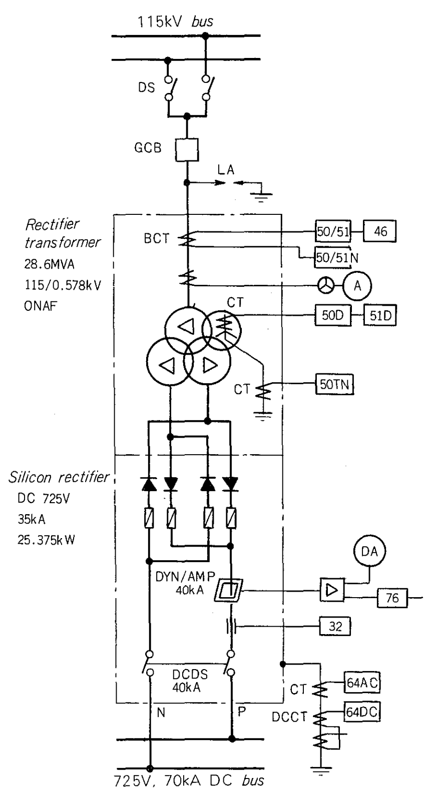


Fig. 2 S-Former one-line diagram

down system. On the direct step down system, since a separate step down transformer and voltage regulating transformer are unnecessary, losses are smaller and installation space is saved.

(2) Vacuum switch type on-load tap changer (hereinafter called VS-LTC) developed by Fuji Electric is used.
On this rectifier equipment, the saturable core reactors are not used, so voltage regulating is performed by tap changing only. Therefore, the on-load tap changer is required high frequency tap change. The VS-LTC is best suited to this application because it guarantees a switching life of more than 1,000,000 operation. The greatest advantage by using VS-LTC is a conspicuous reduction in maintenance as compared with the conventiònal Jansen type.

(3) The Fuji patented "in-phase contra-polarity connection system" is employed in the large current rectification circuit between the rectifier transformer DC windings and the rectifier in order to prevent local heating, reduce the commutating reactance, and improve the current unbalance among phases.

(4) Forced-deionized water cooling system with water to air or water to water heat exchanger has been frequently used so far. However, forced-air cooling system with air to air heat exchanger is employed for this rectifier according to customer demand. According to trial calculations, at the present time, forced-deionized water cooling system is more economical. But if the trend toward less maintenance and higher voltage potlines is taken into consideration, the development of the forced-air cooling system with air to air heat exchanger is significant.

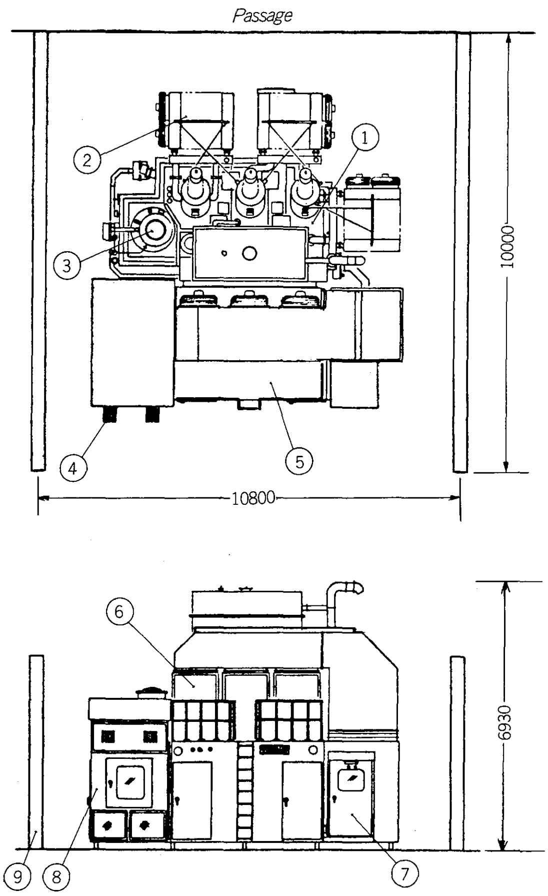
(5) Since a DC isolator cubicle and local auxiliary cubicle are integrated to the side of the rectifier cubicle, on-site installation work is simple and installation space is also extremely compact, as shown in *Fig. 3.*

III. SPECIFICATIONS AND DESIGN OF S-FORMER

1. Rectifier Transformer

1) Ratings

kVA rating: 28,600 kVA



① Rectifier transformer
② Cooler for transformer
③ On-load tap changer
④ DC terminals
⑤ Rectifier
⑥ Cooler for rectifier
⑦ Local auxiliary cubicle
⑧ DC isolator cubicle
⑨ Firewall

Fig. 3 Outline of S-Former

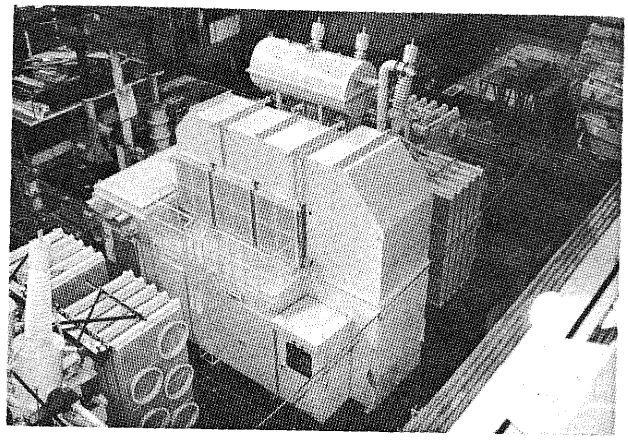


Fig. 4 Exterior view of S-Former

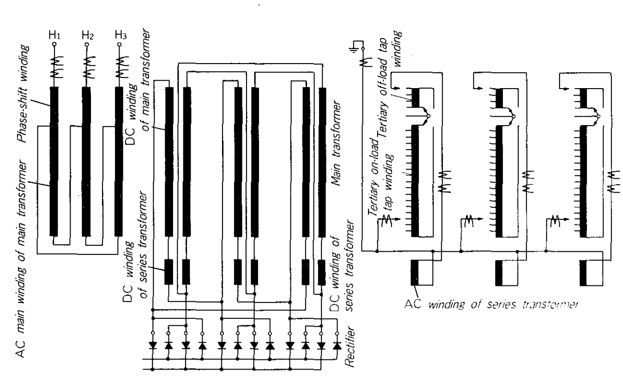
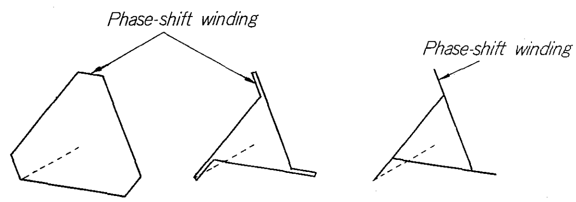


Fig. 5 Connection diagram of transformer



(a) Conventional system (b) New system

Fig. 6 Comparison of phase-shift winding connection

Number of phases: 3-phase
Frequency: 60 Hz
AC side voltage: 115,000 V
DC side voltage: 578 V
DC side tap voltage: 382 ± (3 X 57) ± 57 V
Off-load tap: ±3 X 57 V (57 V step, 7 taps)
On-load tap: ±57 V (3.56 V step, 33 taps)
Connection
- AC side: Wye, Wye + 10°, Wye – 10°, Delta, Delta + 10°, Delta – 10°
- DC side: 2 X Delta

Cooling system: Oil-immersed forced-air cooling system
Winding temperature rise limit: 55 deg. C
Basic insulation level
- AC side: BIL 550 kV
- DC side: AC 10 kV

Impedance voltage: 8%

2) Connection and voltage regulating system

Connection of one of the six transformers is shown in *Fig. 5*.

Required phase-shift angle is obtained by means of a phase shift winding provided on the AC side. As regards the phase-shift of the Delta winding, the equivalent capacity may be reduced than the convetional system shown in *Fig. 6* (a) by means of new single winding system. (Patent Pending, see *Fig. 6* (b).)

This unit employs a direct step down system that directly steps down 115 kV to the required low voltage.

Since the regulating range of the DC side voltage is wide, a system which adjusts the output voltage by adjusting the secondary voltage of the series transformer by tertiary tap voltage has been employed. The direct step down system of this unit has a smaller equivalent capacity than the two-stage step down system which requires a step down transformer and/or voltage regulating transformer between the electric utility and rectifier transformer. Therefore this system realizes lower losses, lighter weight, and higher economy, and a suitable on-load tap changer can be used. In addition, viewing the entire rectifier equipments, it is also advantageous from the overall point of view while

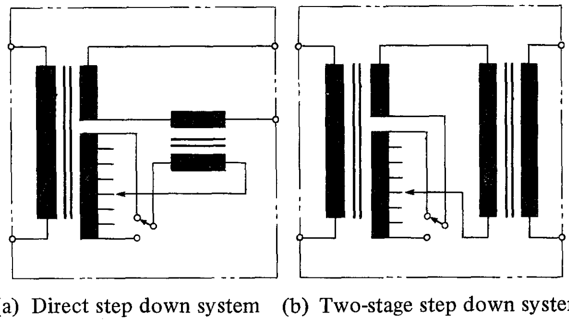


Fig. 7 Comparison of direct step down system with two-stage step down system

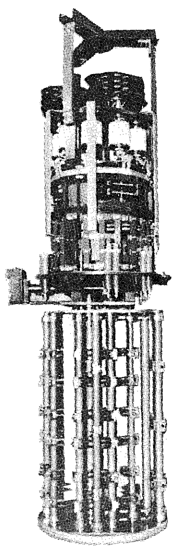


Fig. 8 Vacuum-switch load tap-changer

Table 1. Specifications of vacuum-switch load tap-changer

Model	VLN/B3 X 800/WF 9/30
Number of phases	3-phase
Regulating system	Neutral point-regulating system
Switching system	3 vacuum valves 1 resistance per phase
Insulation level	BIL 200 kV
Maximum through current	800 A
Maximum step voltage	2,500 V
Tap switching time	5 sec

reducing the installation space.

The on-load tap changer is the VS-LTC developed by Fuji Electric.

The specifications of the VS-LTC are given in *Table 1.* Its electrical switching life is 1,000,000 operations (that of the conventional Jansen system is about 200,000 operations), switching life has been improved remarkably and high frequency tap changing is possible. Moreover, since the maintenance interval is long and an oil purifier is unnecessary, it is more maintenance-free than conventional units. (The VS-LTC is described in detail is a separate article.)

The off-load taps are installed on the tertiary side, the same as the on-load taps, and 3-phase operation is performed by a motor driven mechanism.

3) In-phase contra-polarity connection system

At a large current rectification circuit, local heating around the conductors and terminals caused by the generated flux and increasing the current umbalance are produced. Therefore, in the past, the DC side of the transformer was opened, bus bars were arranged so that the fluxes cancelled each other, and connection was made Delta or Wye at the outside of the transformer tank as illustrated in *Fig. 9*.

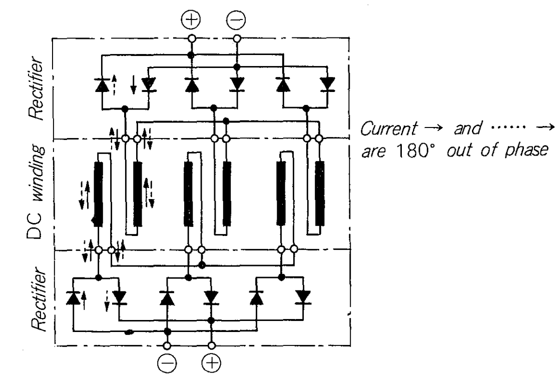


Fig. 9 Connection diagram of ordinary method (double way connection)

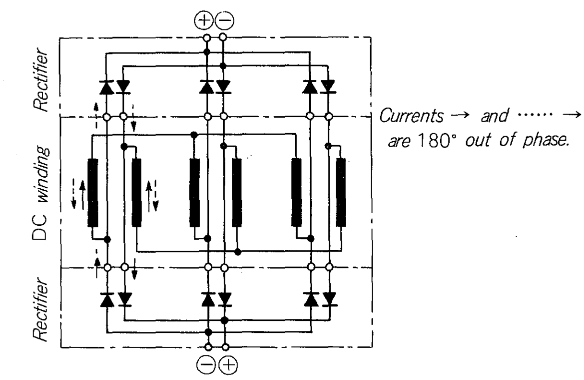


Fig. 10 Connection diagram of in-phase contra-polarity connection (double way connection)

Since our patented (No. 476880) In-phase Contra-polarity Connection system has no surplus bus bars protruding to the outside and the two parallel rectification circuits are of contra-polarity as shown in *Fig. 10*, fluxes of the same magnitude from the DC side bus bar of the transformer to the output terminal of the rectifier have a simultaneous and mutual cancelling affect. This not only prevents the previously mentioned troubles, but also makes a large contribution to improvement of the power factor and efficiency.

This system is not only applicable to double way connection, but also to single way connection.

4) Windings

The AC winding has been made a cylinder winding so that the main winding and phase-shift winding are arranged rationally. Moreover, the advantages of the previously

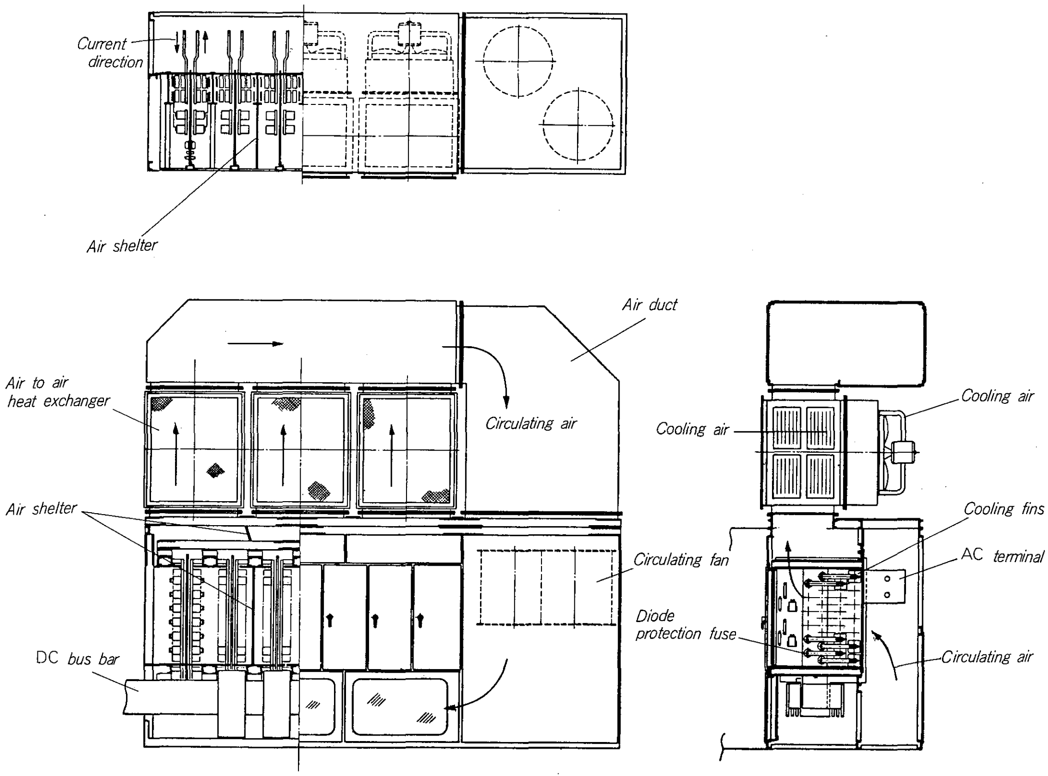


Fig. 11 Inner arrangement of rectifier

mentioned single winding system are utilized for phase-shift winding.

Since this equipment does not contain a saturable core rector, an current unbalance may be produced between units by the difference of voltage regulation, especially the commutating reactance drop, of each unit. Therefore, the interrelationship of the main winding and phase-shift winding of this equipment is suitably arranged and this objective achieved without changing the dimensions so that there is no variations in the reactance by the presence or absence of a phase-shift winding.

The tertiary tap winding is a parallel-cylinder winding containing the off-load tap, and ample strength against magnetic mechanical stress is provided by making the winding a single assembly with the AC winding and minimizing the shift of magnetic center at each tap. The DC winding is employed multi-parallel figure-8 type disc coils which is wound as a single assembly.

2. Diode Rectifier

1) Specifications

DC output: 25,375 kW, 725 V, 35,000 A DC

Connection: 6 phase double way

Diode used: Flat packaged type, Fuji Model ERP03-25

Cooling system: Forced-air cooling system with air to air heat exchanger

2) Construction

The rectifier has walk-in construction with a maintenance aisle at the front. The side is a cubicle housing the DC isolator. The local auxiliary cubicle is mounted at the opposite side as shown in *Fig. 3*.

The air to air heat exchangers consist of 3 units. They are installed at the top of the rectifiers together with the air duct. The air to air heat exchangers and rectifier body are divided into a top section and a bottom section to facilitate shipment and installation (Utility Model Pending).

As shown in *Fig. 11*, two groups of 6 phase double way rectification circuits are arranged in an in-phase contra-polarity connection.

3) Cooling system

Forced-deodinized water cooling system is frequently used as the cooling system for electrochemical rectifier systems. However, this rectifier has forced-air cooling system with air to air heat exchanger system that cools the diodes and fuses directly with circulating air. Since cooling water is not used, this system features:

(1) No care of corrosion and electrolytic corrosion.
(2) Special winterization is unnecessary, even in cold areas.
(3) Since there is no deionized water system, the cooling system is simple and maintainability is excellent.

The cooling air circulating fan is two centrifugal type axial flow fans and the circulating air is circulated through the route circulating fans → diodes → diode protection fuses → air to air heat exchangers → circulating fans, as shown in *Fig. 11*, and the heat generated from the diodes, diode protection fuse, bus bar, etc. is exchanged to the outside air by the air to air heat exchanger.

As shown in *Fig. 12*, the air to air heat exchanger is consisted of steel corrugated fins and flat plates stacked so that the fins intersect. Corrugated fins and flat plates are fastened by zinc galvanizing and surface corrosion resistance is secured.

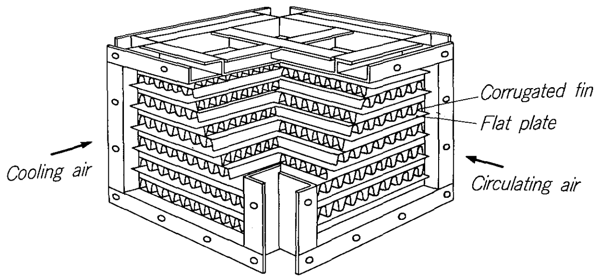


Fig. 12 Construction of air to air cooler

4) Diode cooling and assembling construction

The assembling construction of the diodes is shown in *Fig. 13*. Cooling fins are provided at both sides of the diode and the fins are connected and fastened directly to the bus bar by bolts through leaf springs. This eliminates the connection leads for connecting diodes with AC bus bar, and the bus bar serves as a cooling fin support and air guide (Utility Model Pending).

The circulating air enters from the rear as shown by the arrow, and is effectively passed over the cooling fins by the air guide (Utility Model Pending) and simultaneously cools the protection fuse. The air guide is constructed so as to be easily removed at diode replacement.

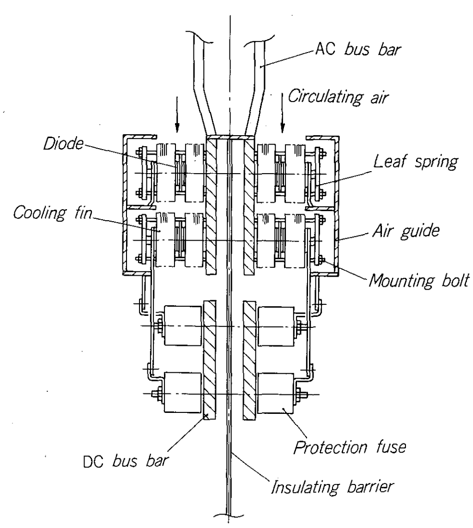


Fig. 13 Assembling construction of diode

5) Balancing of air flow

In this cooling system, minimizing the unbalance of the air flow between the air to air heat exchangers and between the cooling fins is extremely important. To solve this problem, the four rectification arms are made a single unit as shown in *Fig. 11* for each three-section air to heat exchanger and sheltered by an air shelter to minimize the effect of the head loss of the common air duct, and the diodes are arranged in a two row zig-zag pattern at the front and rear. (Utility Model Pending)

This zig-zag arrangement also contributes to improving the current unbalance among diodes, and a current balancer is not used.

6) Protection system

This rectifier provides the following protection system.

Fan trouble: Protected against overload and open-phase by thermal overload relay.

Low air flow: Low circulating air flow is detected by a differential pressure relay that monitors the static pressure difference at the air to air heat exchanger inlet and outlet.

Overtemperature: An abnormal rise of the circulating air temperature is monitored by means of a dial thermometer and resistance temperature detector, also a thermoswitch is provided at the cooling fins for back-up.

7) DC isolator cubicle

In addition to the DC isolator, the DC isolator cubicle also houses the direct current measuring system (DYN/AMP) and reverse current relay. The front door is equipped with an inspection window so that the inside can be inspected without opening the door. The inside of the cubicle is ventilated and cooled by a cooling fan through an air filter.

The DC isolator is a 1000 V, 40 kA double pole single throw type made by the Pringle Electrical Mfg. Co. and can be operated either by motor or manually (see *Fig. 14*).

A Halmar DYN/AMP head section and reverse current relay sensor are installed at the DC bus bar. The signal converter of each is housed in the local auxiliary cubicle.

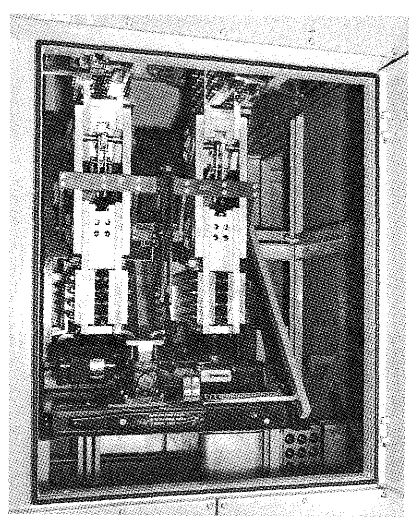


Fig. 14 Exterior view of DC isolator

IV. CONTROL, PROTECTION, METERING

1. Composition of Control Panels

The composition of the control panels per 2 potlines is as follows:

1) Main control panels (3 panels)

These control panels are in row with the existing panels in the central control room and are used for metering of the unit direct current and alarm indications, as well as for operation of the circuit breaker, DC isolator, off-load tap changer.

2) Tap operating panel (1 panel)

This panel is installed in row with the existing panels in the central control room and is used for gang control of the on-load tap changer for each potline and for individual control for each unit.

3) Protective relaying panels (6 panels)

These panels are installed in the distribution panel room near the S-Former and provide overcurrent protection, ground fault protection, etc.

4) Incoming control panel (1 panel)

This panel is installed in a row with the existing panels in the central control room and is used for control of the circuit breaker of the electric power supply company.

5) Local auxiliary cubicle (6 panels)

These cubicles are mounted on the side of each rectifier cubicle and provide fault indication in addition to cooling fan control, operation, and protection.

All the wiring between the S-Formers and each of the above control panels is routed through this panel to simplify wiring work.

2. Control System

The circuit breakers for each S-Former are simultaneously controlled for each potline by means of the gang control switch on the main control panel.

Automatic constant DC current control is not performed at this equipment, but is only manually controlled by on-load tap. On-load tap changer can be simultaneously controlled or individually controlled for each potline from the tap operating panel.

The S-Former cooling fan is controlled from the local auxiliary cubicle.

3. Protection System

When an overcurrent, ground fault, transformer pressure fault, or other serious fault occurs, a lockout relay is operated and each potline is tripped. In addition, only the faulty unit is tripped when rectifier overtemperature, off tap of the on-load tap changer and off-load tap changer, or other serious fault occurs.

DC side overcurrent protection is provided by DC overcurrent relay (76) on DYN/AMP output side and tertiary tap winding instantaneous type (50D) and inverse-time overcurrent relays (51D) (see *Fig. 2*). Moreover, a reverse current relay (32) installed at the DC bus bar in the DC isolator cubicle is capable of detecting short circuit faults at the power source side from this sensor within 1 ms.

4. Metering System

Direct current is measured at a ±0.2% accuracy by the DYN/AMP. The DYN/AMP has two outputs of 10 mV DC/kA and 0.2 A DC/kA. The unit direct current is monitored on the digital panel meter by metering and displaying the output voltage of the DYN/AMP. The total current of the potline is monitored and recorded on the high accuracy DC ammeter and DC ampere recorder at the customer's DC metering panel by totalizing the output current of each DYN/AMP by means of a totalizing shunt.

In addition, the winding hot spot temperature of each rectifier transformer and the rectifier cubicle air temperature are recorded by LEEDS & NORTHRUP multi-point recorders at the main control panels.

V. FACTORY TEST RESULT

The following satisfactory results were obtained from heat-run test and measurement of the current unbalnce among diodes, with the transformer and rectifier assembled, in addition to ANSI Standard tests.

1) Efficiency

Efficiency with the transformer and rectifier assembled was as high as 98.03%.

2) Impedance

As previously mentioned, minimizing the variations in the impedance among units is extremely important with this equipment. The results of measurement confirmed that this variation was an extremely small value of ±1% of average value.

3) Temperature rise

An ample margin relative to the specified values for both winding temperature rise and rectifier cubicle air temperature rise and the absence of locat heat were confirmed.

4) Current unbalance among diodes

The realization of an extremely low current unbalance rate of within 15% through the adoption of the in-phase contra-polarity connection system and zig-zag arrangement of the diodes was confirmed.

5) Air flow unbalance

A small circulating air flow unbalance rate of 5% between air to air heat exchangers and 10% between cooling fins was obtained.

6) Noise level

As a result of tests based on NEMA Standards, an adequately low noise level of 84.6 dBA relative to the customer's specified value of 90 dBA was obtained with the transformer and rectifier combined.

VI. CONCLUSION

Especially low running costs and high reliability were demanded of this S-Former. This demand was satisfied by applying vacuum switch type on-load tap changer, large capacity forced-air cooling type diode rectifier, and other newly developed technology based on our abundant experience.

At the completion of this equipment, we would like to thank the people of the Reynolds Metals Company who evaluated our technology and gave this opportunity to us. We will continue our effort in the future to meet our customer's needs.