UDC 621.311.6 : 669.714.7

POWER EQUIPMENT FOR ALUMINUM ELECTROLYSIS

By Tatsuo Mizushima
First Industry Technical Sect., Central Technical Dep't.

Sadao Tsuji
First Power Technichal Sect., Central Technical Dep't.

I. INTRODUCTION

The electro-chemical industry occupies a considerable large percentage in the section of the electric consumption, above all the aluminum electrolysis plant is the largest scale one as a unit of electrical consumption in all industries.

In this field, new establishment of the equipment has very rarely been seen since the termination of the War II with exception of rehabilitation or partial extension. In response to the sudden progress of the recent aluminum demand, Nippon Light Metal Co., Ltd. has participated the extension of Kambara Factory and Sumitomo Chemical Co., Ltd. has established Nagoya Factory. For both plants, we have received complete orders on receiving and silicon rectifier equipments as shown in *Table 1*, as electrical sources for their new production plants, for which we have recently supplied the most up-to-date equipment. On this oppotunity, we wish to introduce the contents of the electrical equipment for aluminum electrolysis.

***Table 1* Specification of equipments**

Customer	Nippon Light Metal Co.		Sumitomo Chemical Co.
Receiving equipment			
Receiving voltage	Three phases 154 kV 60 c/s and 77 kV 60 c/s		Three phases 154 kV 60 c/s
Capacity of transformer	154 kV 35,000 kVA 2 sets 77 kV 35,000 VA 1 set		50,000 kVA 2 sets
Secondary voltage	11 kV		20 kV
Rectifier equipment	Silicon rectifier	Silicon rectifier	Silicon rectifier
Capacity	30,600 kW	44,880 kW	78,000 kW
Voltage	450 V	660 V	650 V
Current	68,000 A	68,000 A	120,000 A
Remarks	Completed in March, 1961	Completed in May, 1962	Completed in July, 1961

II. SPECIAL CHARACTERISTICS OF EQUIPMENTS FOR ALUMINUM ELECTROLYSIS

1. Equipment Capacity

The principle of aluminum electrolysis is that, making use of cryolite as solvent of alumina powder, direct current is flowed from graphite anode to cathode so as to educe pure aluminum on the cathode. The electric power consumption to produce one ton of aluminum amounts so much as 16,000–18,000 kWh. As capacity of electric equipment of 2.5–3 kVA, including reserve capacity, is needed to produce annually one ton of aluminum, the total capacity should be about 90,000 kVA to produce annually 30,000 t. Consequently, the receiving voltage should be 77 kV or 154kV. 5–10% of the power to supply for general load such as motor, illumination etc. and 90–95% for electrolysis must be distributed rationally and economically, never causing any harm interference among themselves.

2. Operation without Interruption

As mentioned above, the aluminum electrolysis occurs in a melted condition of mixture of alumina powder and cryolite. The melted condtion is maintained at about 1,000°C by heat produced by resistance loss of the electric current in the furnace. Therefore, if the electric current is reduced or interrupted for some time due to some trouble of the power source, the temperature in the furnaces drops gradually and finally the electrolysis bathes coagulate and lose its conductivity, incurring a fatal damage of the electrolysis. Hence the electric current must be maintained continuously without interruption after the operation is once started. For that purpose, reserve equipments of main machines and apparatus for receiving and rectifying are absolutely required, and periodical checking and maintenances of them should not be neglected.

If one rectifier unit got inoperable due to some trouble, remaining units should supply the minimum power required for safety operation of the bathes.

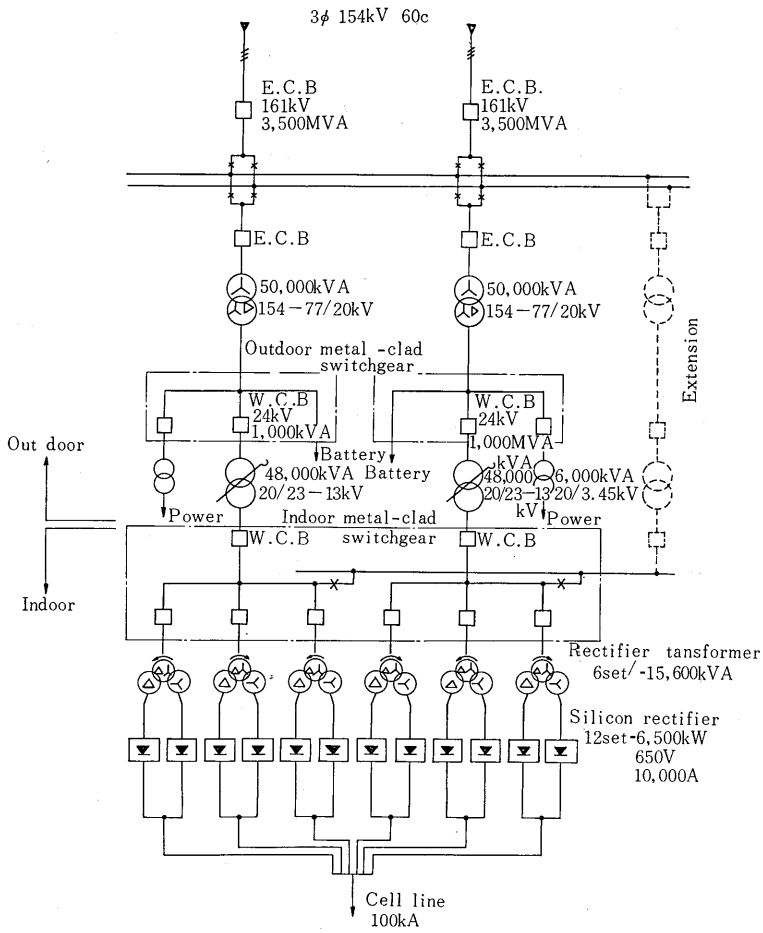


Fig. 1 **Skeleton diagram of electric source of Sumitomo Chemical Co.**

3. Range of Voltage Regulating

The running voltage per cell is usually 4.6–5 V, and the current capacity varies according to the type of cell from 40 to 120 kA. Taking into consideration the scale of production, adequate number of cells are to be connected in series to the DC source.

But at the beginning of operation, for each cell, baking of anode graphite, preparing of electrolysis bath and other troublesome procedures must be completed. So, it is practically impossible to set from the beginning all equipments in operation at a stroke.

It is advisable, therefore, to set at the beginning a few cells in operation, and to increase gradually number of cells with completion, advancing by degree to the final stage. Hence, the output voltage of the rectifiers must be under free controll ranging practically from zero to the rated value.

4. Fluctuation of Load Current

As the electrolysis proceeds and alumina in the furnace decrease, a gap may be made between the anode and electrolysis bath, causing the electric current to flow through it as an arc.

In consequence of it, the terminal voltage in the cell may rise rapidly so much as 30–50 V, equal to the arc voltage. This phenomenon is called anode effect. If this occurs, the load resistance increases rapidly so much equal to the arc resistance and, if the source voltage is constant, the current would be reduced so much.

The anode effect can be made disappear by adding alumina and stirring it. But if the anode effect occurs in many cells, the cumulative reduction of electric current during the period of anode effect would be tremendous, causing the reduction so much of the efficiency of electrolysis factory established on a big capital. A means for preventing this plight is to provide a higher output voltage of the rectifiers equivalent to the anode effect, to be raided automatically when the anode effect takes place. To achieve this purpose, the efficient voltage regulators and the automatic control devices should be provided. But when the anode effect disappears, the regulators must be able to tolerate the overload current before the automatic devices set in action.

The relation between the voltage and current on this case is as follows:

In normal operation,

$$I_d = \frac{E_{D_0} - E_\alpha - N \cdot E_p}{R_r + N \cdot R_C} \quad \cdots\cdots (1)$$

wherh E_{D_0}: No load output volage of rectifiers,

E_α: Automatic control voltage,

E_p: Decomposition voltage (Counter voltage) per cell,

N: Number of cells,

R_r: Apparent inner resistance of rectifier equipments,

R_C: Inner resistance per cell.

when an anode effect occured,

$$I_{\alpha'} = \frac{E_{D_0} - E_\alpha - (N \cdot E_p + E_A)}{R_r + N \cdot R_C} = I_\alpha - \frac{E_A}{R_r + N \cdot R_C} \quad \cdots\cdots (2)$$

where E_A is the volage of anode effect.

When E_α becomes 0 by action of the automatic control device to compensate E_A,

$$I_{\alpha''} = \frac{E_{D^0} - (N \cdot E_p + E_A)}{R_r + N \cdot R_C} \quad \cdots\cdots (3)$$

Before the automatic device functions immediately after disappearance of an anode effect,

$$I_{\alpha'''} = \frac{E_{D_0} - N \cdot E_p}{R_r + N \cdot R_C} = I_\alpha + \frac{E_d}{R_r + N \cdot R_C} \quad \cdots\cdots (4)$$

The overload capacity of the silicon rectifier must be investigated as its own object.

III. RECTIFIER EQUIPMENTS

The rectifier equipment for aluminum electrolysis is the biggest one among all its uses. In our country today, rectifiers of equipment capacity of 500,000 kW in total are operating day and night at five works of three companies. But most of them were installed befor War II, and are of the type of multi anode mercury-arc rectifier.

It is a matter of course that this time silicon rectifiers, which surpass all other types with respect to price, efficiency, reliability, size, cooling device, maintenance etc, were adopted, and actually they are proving fully their merits by the results of the operation. Particularly, the silicon rectifier supplied to Sumitomo Chemical Co. is the greatest in the world now in operation.

1. Construction of Main Circuits

Differing from mercury-arc rectifiers or contact convertors which are restricted, to some degree, in output according to the standard type, a silicon rectifier of any capacity can theoretically be adopted. But when the installation consists of rectifiers of n series and the output is secured by $n-1$ series, for example, in case of Sumitomo's equipment of 100 kA the capacity of each series and the total capacity of the installation for various n will be listed as follows:

n	Capacity for each series	Total capacity
2	100 kA	200 kA
3	50 kA	150 kA
4	33.4 kA	133.4 kA
5	25 kA	125 kA
6	20 kA	120 kA
7	16.5 kA	116.7 kA
8	12.5 kA	112.5 kA

In order to make commutating impedance uniform and to obtain polyphase rectifier circuit, it is perferable to adopt even number of n. Besides, taking into account of installation cost and occupying area, a schedule of 6 series, 20,000 A was adopted. In the case of Nippon Light Metal Co., 4 series, 17,000 A was adopted.

(1) In each case it was so planned that the rectifier transformers have two secondary windings, one is star, the other is delta connection, and each of them was connected with a silicon rectifier of three phases bridge connection, and a 12 phases rectifier circuit was built.

(2) By changing over of the star-delta connection in the primary coil of the rectifier transformer the output voltage can be changed over to $1 : 1/\sqrt{3}$; and by adding the phase-shifting coils, the phase of voltage is shifted $-7.5°$, for a half of the transformers and $+7.50$, for another half, making 24 phases rectifying in total.

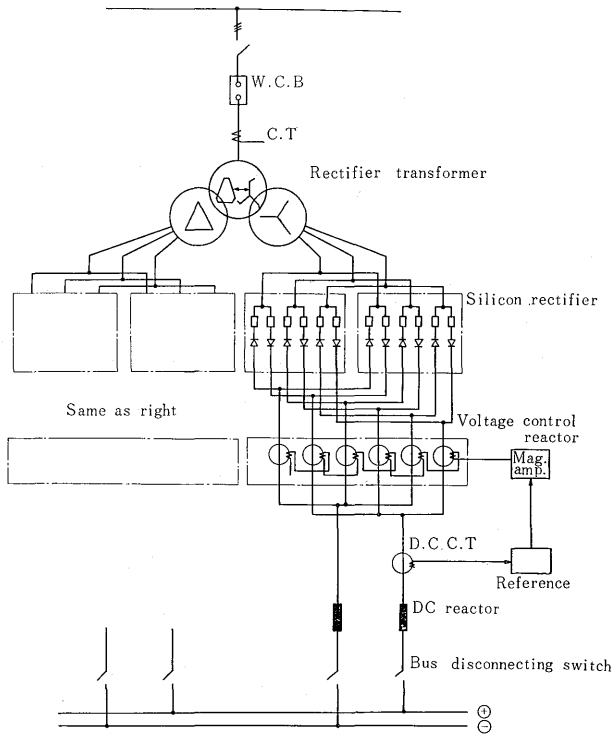


Fig. 2 Skeleton diagram of rectifier equipment

(3) No circuit breaker was installed in the output circuits of rectifiers, but, with a main circuit breaker on AC side which was prepared for a lump switching-in and breaking of load; and the output voltage is regulated collectively by load ratio transformer.

(4) The voltage control reactors of each rectifier circuit were inserted on the output side of rectifier, and paying attention to the arrangement of conductors between the transformers, rectifiers and reactors. The required voltage regulation was attained by availing the reactance of them.

2. Over-load Capacity and Protective Coordination

The short time overload capacity of rectifiers is based on the number of parallel path of silicon rectifier elements. To minimize the cost and occupying area of the installation, the number of them should be restricted to a minimum of requirment. For this purpose, following two conditions were fulfilled with reserve capacity of 10%:

(1) No protection device should operate against the overload immediately after disappearance of the anode effect in the cells before the automatic control devices function.

(2) At an accident due to shortcircuit on the output side or like that, destruction of the rectifier elements and protection fuses should be prevented by cut off of AC input and the capacity must be big enough to bear the

Table 2 **Specification of rectifier equipments**

Customer	Nippon Light Metal Co.		Sumitomo Chemical Co.
Rating of plant			
Number of phases	24	24	24
Number of series	4	4	6
Voltage	450 V	660 V	650 V
Current of machine	4×17,000 A	4×17,000 A	6×20,000 A
Working current	51,000~55,000 A	51,000~55,000 A	100,000 A
Voltage control range	0~450 V	0~660 V	0~650 V
Automatic control system	Constant current	Same as left	Same as left
Cooling system	Open air cooling	Same as left	Same as left
Silicon rectifier			
Number	8 sets	8 sets	12 sets
Unit capacity	450 V 8,500 A	660 V 8,500 A	650 V 10,000 A
Overload capacity	135% continuous	135% continuous	125% continuous
Connection	Three phase bridge	Same as left	Same as left
Number of series elements	1	2	2
Number of cubicles	8 sets (8 cubicles)	8 sets (16 cubicles)	2 sets (24 cubicles)
Cooling system	Air cooling	Air cooling	Air cooling
Rectifier transformer			
Number	4	4	6
Type	Indoor use, forced oil circulated, air fan cooled	Same as left	Same as left
Capacity	9,160 kVA	13,400 kVA	15,600 kVA
Load ratio transformer			
Number	2	1	2
Type	Outdoor use, oil immersed self cooled	Same as left	Same as left
Self capacity	6,030 kVA	9,000 kVA	14,600 kVA
Output	31,500/63,000 kVA	47,000 kVA	48,000 kVA
Voltage	11 kV/11 kV±2.2 kV or 11 kV±1.1 kV	11 kV/11 kV±2.2 kV	20 kV/18 kV±5 kV
Voltage control reactor			
Number	8	8	8
Current	8,500 A	8,500 A	10,000 A
Controlling voltage	56 V	72 V	72 V
Turbo fan			
Number	6	6	10
Capacity	8.7 m^3/sec	13 m^3/sec	13 m^3/sec
Motor	8.5 kW	15 kW	15 kW
Speed	680 rpm	680 rpm	680 rpm
Total efficiency			
Not incl. of DC bus	97.6%	97.7%	97.7%
Incl. of DC bus	97.4%	97.4%	97.2%
Dimension of substation building			
Width	30 m	30 m	43.2 m
Depth	20 m	20 m	23.8 m

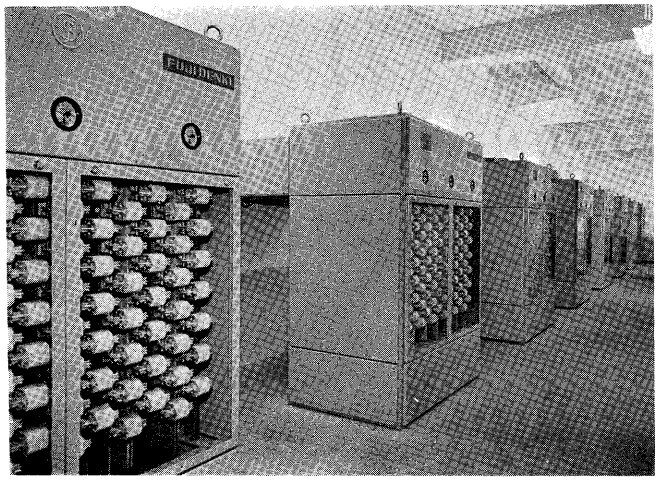


Fig. 3 Silicon rectifier of 450 V 68,000 A for Nippon Light Metal Co.

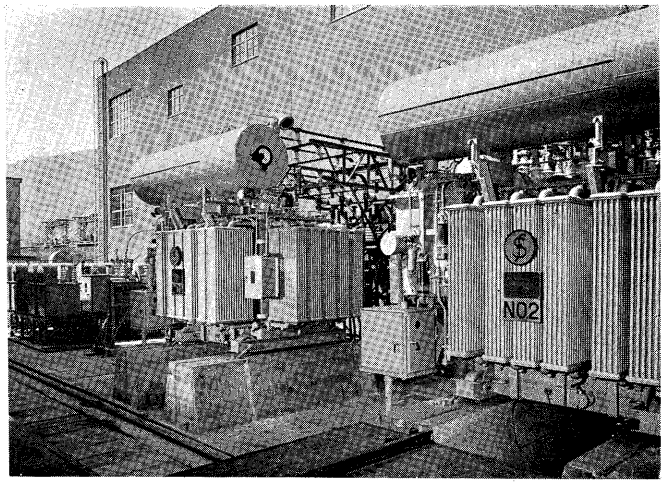


Fig. 4 Load ratio transformer for Nippon Light Metal Co.

after-flow of electrolysis current dut to great inductance of bus of electrolysis plant.

The protection devices:

(1) Inner shortcircuit of rectifiers, namely, short-circuit current caused by puncture of rectifying elements, should be cut off by high-speed fuses connected in series with the elements.

(2) Against overload or outer shortcircuit, AC circuit breakers should be cut off with inverse time-limit over current relays which begin to operate at some higher value (point) than the overload due to anode effect in the cells as mentioned in (1), and with high speed over-current relays which operate at still higher value. In the Sumitomo's installation, assuming possibility of bolted shortcircuit in the DC main bus, the small type of high speed shortcircuiters, which had been developed for contact convertors, were utilized to control the voltage control reactors to the maximum limit in a very short time, enabling the control of shortcircuit current.

3. Silicon Rectifiers

The rectifying elements used for each equipments were manufactured in our Company as our standard having the following ratings

Type: Si 150 F
Surge break down voltage: more than 1,500 V
Maximum working voltage: 425 V (effective value)
Rated current: 200 A (mean value)
Backward characteristics: less than 3 mA at 1,000 V

These elements are connected in three phases bridges, and number of series is one for 450 V and two for 660 V.

In the installation of Nippon Light Metal Co., 168 sets of these elements, and in that of Sumitomo Chemical Co., 192 sets, together with the fuses, are contained in an aluminum-clud cubicle. The elements in the cubicle were arranged in geometric symmetry, back to back in the front and back side of the cubicle, and they can be inspected through a window of plastic glass. The accident rate of the rectifier elements have practically been zero. And as the reserve capacity, 10 percent extra rectifying elements was provided. Consequently, there is no reason for adopting tray system of complicated construction. By simple and clear arrangement of the elements, even without aid of balancing reactors, the unbalance factor can be kept under 20%. Accessories of the cubicle are only three electric fans of 420 W and dial type thermometers.

4. Voltage Regulating Devices

How to regulate the voltage continuously and economically, 100% to 0, was a problem racking our brains at the fundamental planning. Finally it was achieved by combining the following four methods:

(1) Rough control of 1 : 0.58 by star-delta changing of secondary connections in the receiving

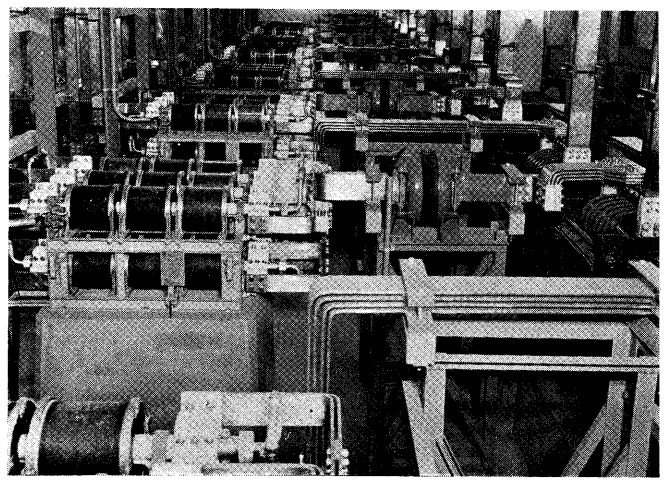
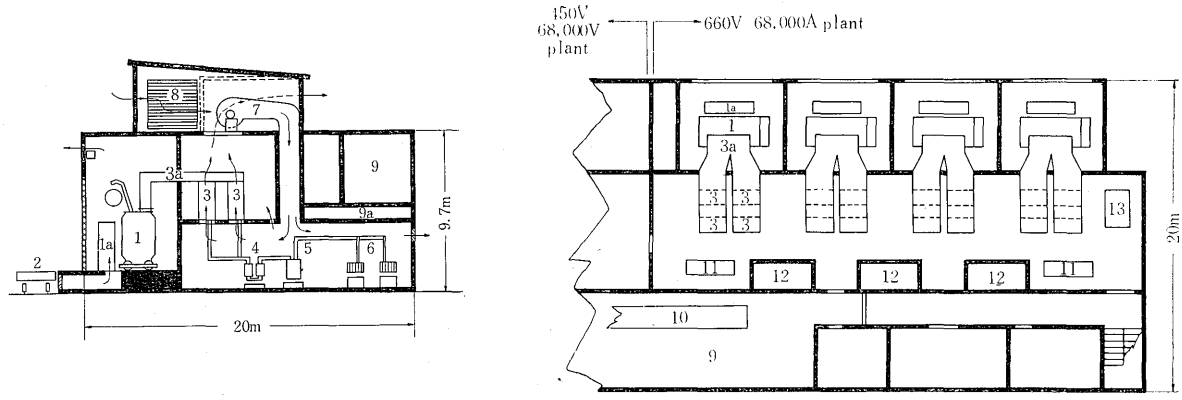


Fig. 5 DC machine room for Nippon Light Metal Co.



1. Rectifier transformer
1a. Cooler of rectifier trans
2. Transporter of rectifier trans
3. Silicon rectifier
3a. Bus duct
4. Voltage control reactor
5. DC reactor
6. DC main bus
7. Blower
8. Air filter
9. Switchboad room
9a. Wire basement
10. Switchboad
11. Automatic control cubicle
12. Air duct
13. Lifting hatch

(a) Section (b) Layout

Fig. 6 Machine arrengement of 660 V 68,000 A equipment for Nippon Light Metal Co.

transformer or of 1 : 0.5 by secondary tap change.

(2) Rough control of 1 : 0.58 by delta-star changing of primary connections in the rectifier transformer.

(3) Fine control of 1–2% steps by load ratio transformer.

(4) Stepless control by voltage control reactor.

The change over is done in (1) and (2) on off load, and in (3) and (4) under loaded.

The seasonal or daily fluctuations of receiving voltage were compensated by the on load tap changer of the receiving transformers.

5. Cooling System

The electricity loss in the rectifier room is about 820 kW in the instance in the Sumitomo's plant. In this value, the loss of the connecting bars and that of the main bus of 100kA are included, but that of the rectifier transformers is not included. The cooling system of the rectifier room must be planned taking into account not only this loss but also solar heat penetrating through the wall of the building.

Following three methods of the cooling system were experimentally compared :

(1) Enclosed rectifier room, the air in the room is cooled by a water cooled heat exchangers.

(2) Enclosed air circulating silicon rectifiers, cooling air is circulated and cooled by a water cooled heat exchangers.

(3) The whole rectifier room is open and have ventilation facility.

To prevent spoiling of the equipment and erosion by harmful gases, the method (1) is ideal. But, as it was difficult to get good water enough, and moreover, to minimize maintenance of cooling water facilities the method (3) of open system of air cooling was adopted.

As *Fig. 6* shows, intakes of fresh air and outlets were placed alternately on the roof of the rectifier room ; cooling air was pushed into the ground floor of the building through automatic air filters with turbo-fans ; the air which got heated through the main buses and rectifiers is exhausted from the roof in the different direction than the intakes. Assuming the maximum temperature of the atomospharic air reaches 35–38°C, it was planned to keep the equip-

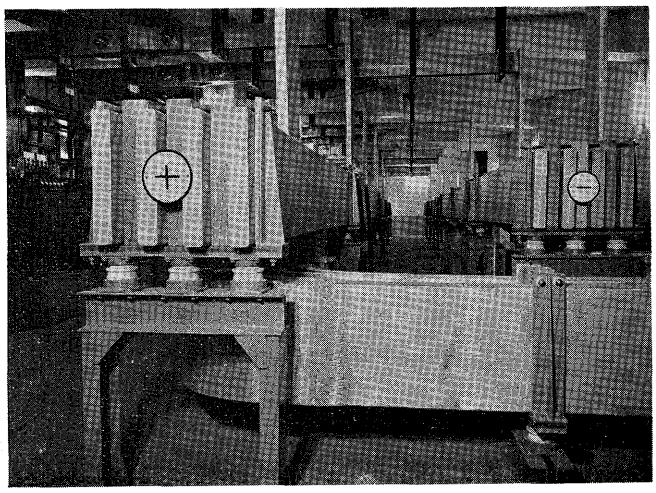


Fig. 7 DC bus of 450 V 68,000 A equipment for Nippon Light Metal Co.

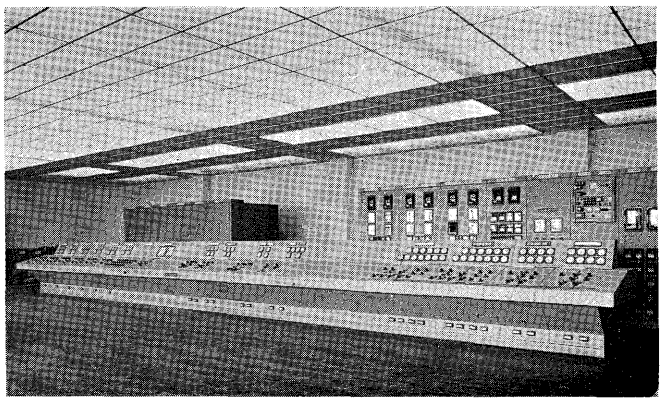


Fig. 8 General control board of 650 V 120,000 A equipment for Sumitomo Chemical Co.

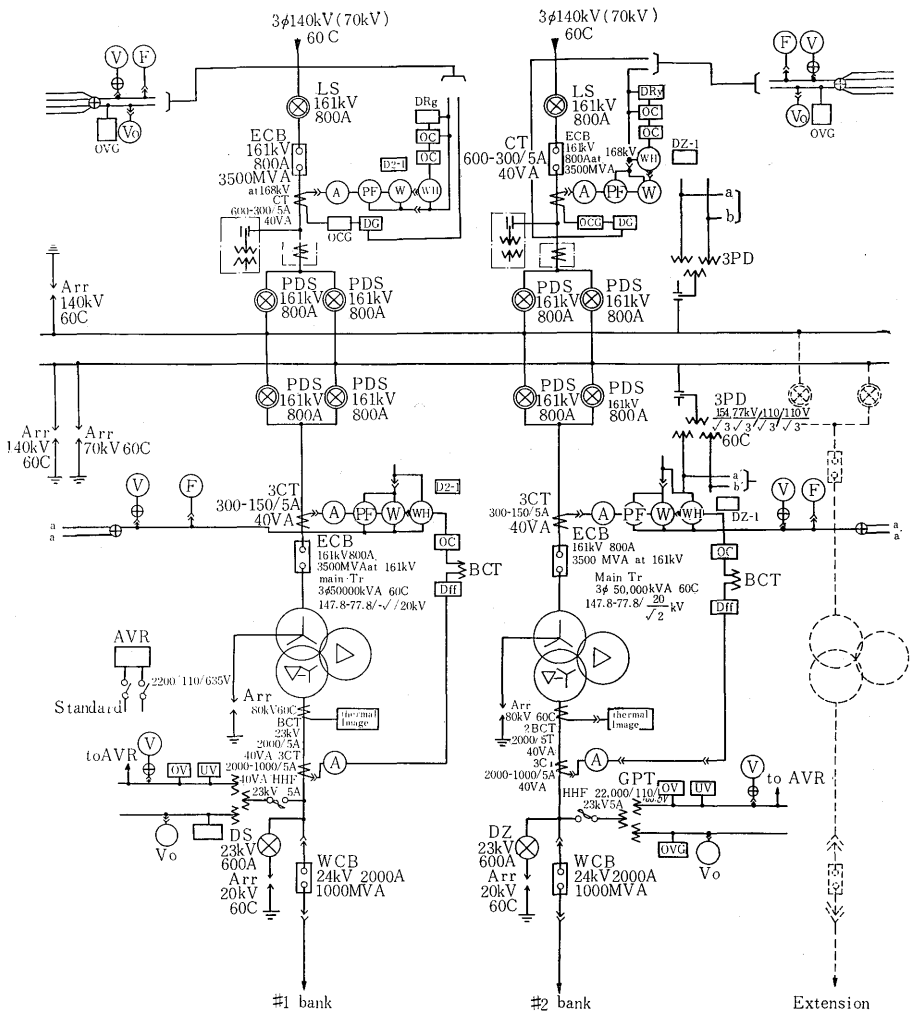


Fig. 9 Single line connection of receiving equipment for Sumitomo Chemical Co.

ments cool enough by operating two thirds of the number of fans.

6. Others

(1) AC circuit breakers.

Water circuit breakers of accurate operation and of non-combustible quality were used; and the interupting capacity of each breaker is 1,000 MVA. These were installed in the compartments of ferro-concrete building in Nippon Light Metal Co., and in metal-clad switch cubicles for indoor use in the Sumitomo Co.

(2) Connecting bars and DC main bus.

Execpting for a part, aluminum was used as main bus bar; and all the jointing parts but the terminals of machines and apparatus were welded.

(3) Switch boards

It was planned that one man could control both receiving and rectifying on the single switch board. In the equipments of Nippon Light Metal Co., as DC main bus is laid out in the floor below the switch boards room, aluminum plate was used as material of the boards to avoid the influence of strong magnetic field of the bus, and special caution was paid against accumulation of harmful magnetic flux around the meters and relays.

(4) Measuring of direct current.

In the plant of Sumitomo Chemical Co., making use of DC current transformer of 100 kA with hole generator, DC power can be measured directly.

IV. RECEIVING EQUIPMENTS

The characteristics of receiving equipment of Sumitomo Chemical Co. will be described here.

1. Capacity of the Substation

As the skeleton diagram of *Fig. 9* shows, power of 140 kV is received from two transmission lines and stepped down with two transformers, the capacity of which is each 50 MVA.

As one more transformer is going to be increased in near future, in order to facilitate the extension works and to enhance reliability, the main bus of 140 kV was made of double system.

2. Voltage Adjustment

The receiving transformers have on-load tap changer, and they supply the constant voltage automatically to the rectifier plant; and two kinds of output voltage, 20 kV and 11.56 kV, can be obtained by changing over the secondary connection to the star-delta.

And, moreover, by change of the primary connection, P.C.T. and lightning arresters, the substation equipment can be utilized for both 140 kV or 70 kV power receivings.

3. Machine Arrangement and Steel Structure

Nagoya-shi, where this works was established, was attacked in the fall of 1959 by a violent typhoon (Ise Bay Typhoon). By experience of this typhoon, the substation was planned to escape from destruction even if flood rises 2.4 meters above the ground level; the building site of the substation is all raised 1.4 meter by laying earth on it, and, moreover, the main apparatus was installed on a base 1 meter high.

Steel structures and wires can withstand the wind of 50 m/s.

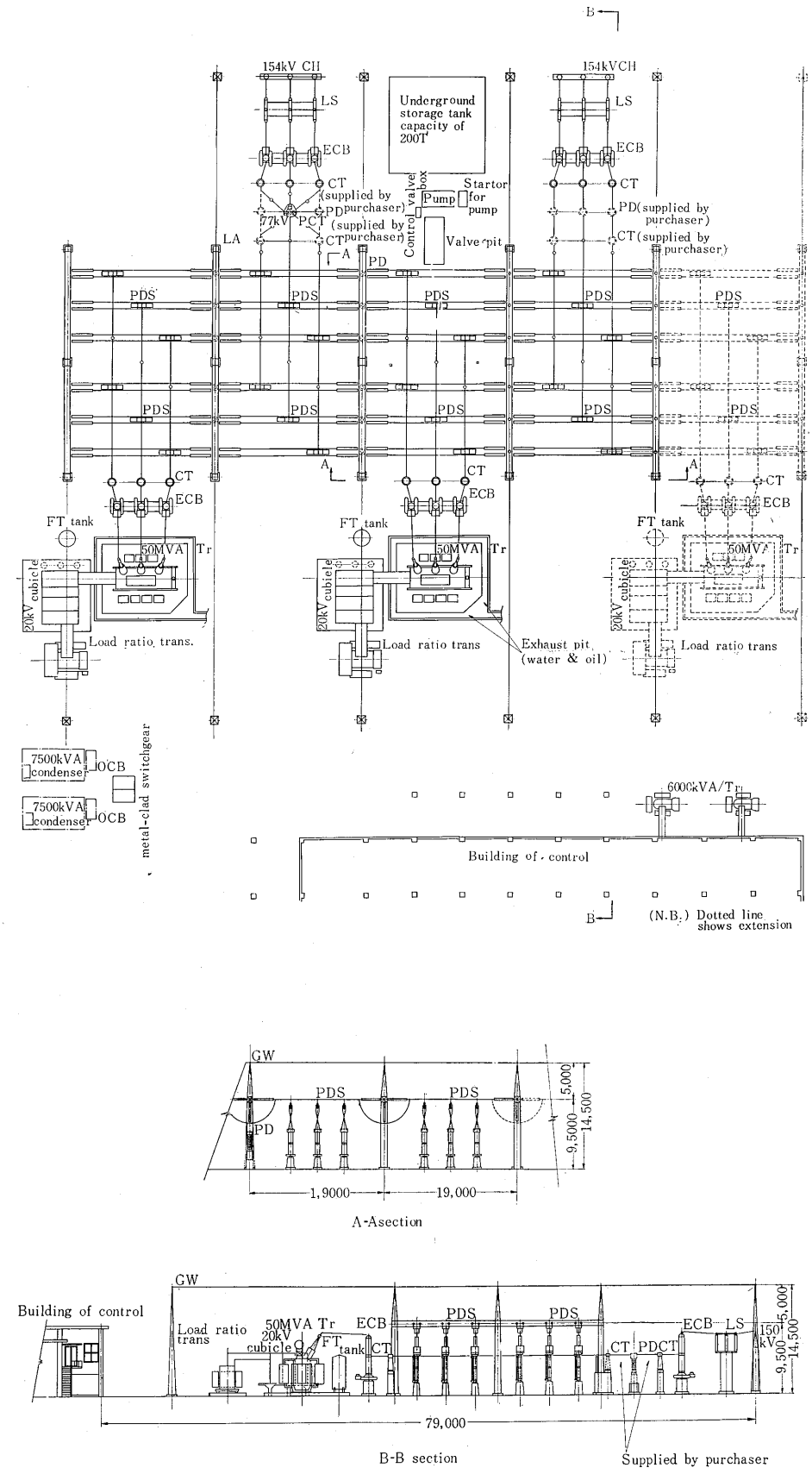


Fig. 10 Machine arrangement of receiving equipment for Sumitomo Chemical Co.

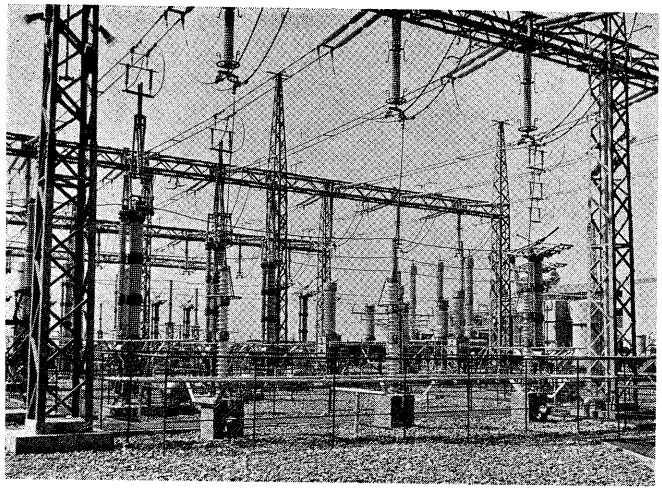


Fig. 11 General view of receiving substation of Sumitomo Chemical Co.

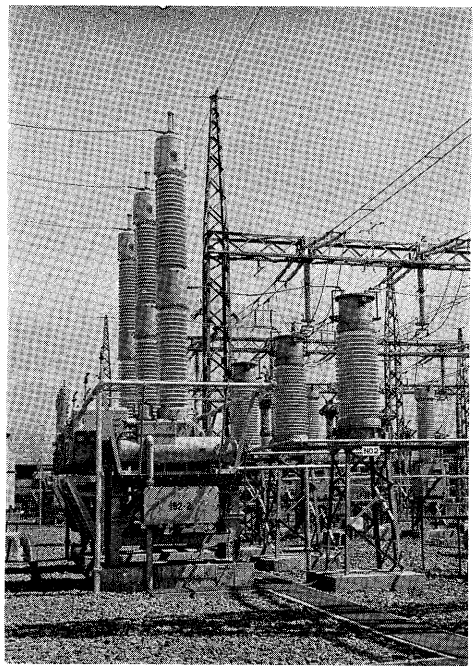


Fig. 13 154 kV circuit breaker and current transformer for Sumitomo Chemical Co.

4. Other Characteristics

As this works is situated near the town, to make noise nuisance as little as possible, the receiving transformers are provided with screan wall for sound absorbing, consequently, the noise can be kept below 64 phon. And, as it is near the sea shore, to protect against typhoon, splay-nozzle washing devices are provided.

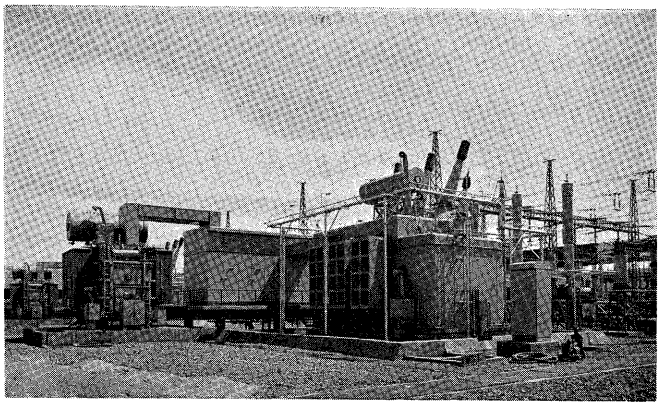


Fig. 12 Receiving transformer, 20 kV cubicle and voltage regulating transformer of Sumitomo Chemical Co.

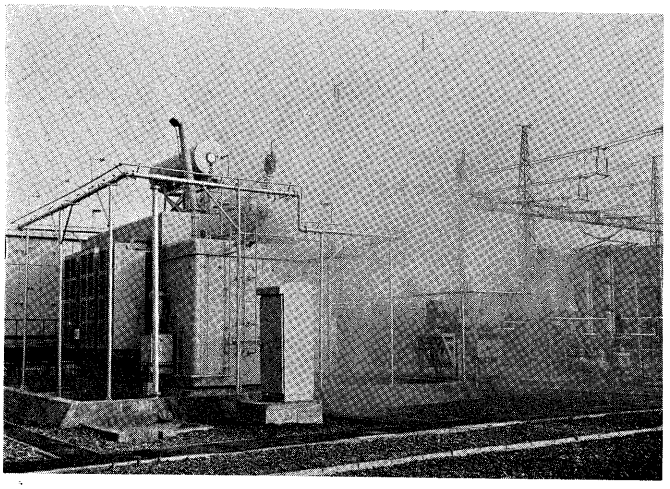


Fig. 14 Driving condition of splay nozzle washing device at Sumitomo Chemical Co.

V. CONCLUSION

It is yet a short time since the silicon rectifier began to be used in practice, but it has given full play to its efficiency, price, size, reliability, durability and other merits surpassing all other rectifiers or convertors of any type; its sole defect of being unable itself to regulate the voltage was rid of by aid of the rational and economical voltage regulating reactor, consequently, stable automatic control of higher response than mercury-arc rectifiers has become possible.

It is our great pleasure, by utilizing fully past experiences in existing plants, to have decided the protection and control system and achived such marvelous operation results which dispel completely traditional notion heretofore obtained of DC substation.