SILICON RECTIFIER EQUIPMENT FOR ELECTROLYSIS SERVICE

By

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I. ELECTROLYTIC INDUSTRY AND CONVERTER EQUIPMENT

Direct current is utilized for various kinds of services and the largest consumers for direct current power are electrolytic industries which produce various kinds of substances by electrolysis process. The followings show their typical kinds of business.

1) Sodium chloride electrolysis:
   produces caustic soda and chlorine gas by electroliyzing salt-water
2) Alminium refining:
   produces alminium by electrolyzing alminium oxide (almina) by means of cryolite as medium
3) Water electrolysis:
   produces hydrogen gas by electrolyzing water (main parts of this equipment are for ammonium composition)
4) Metal electrolysis
   produces electric copper, electric zinc etc. by electrolyzing copper sulphate, zinc sulphate etc.

Besides the above there are hydrogen peroxide production, magnesium refining, metallic natrium production, sodium chlorate production etc. In table 1 capacity of converter equipment and approximate power required to produce unit weight of respective products of the typical electrolytic industries in

Table 1. Capacity of rectifying equipment for electrolysis industry and electric source unit

Kinds of Industry	Capacity of rectifying Equipment	Ratio of Capacity	Electric Power Consumption
Sodium Chloride Electrolysis	Approx. 340,000 kW	28.8%	3,300～3,400 kWh/t
Aluminium	〃 370,000 kW	31.3%	16,000～18,000 kWh/t
Water Electrolysis	〃 360,000 kW	30.5%	4～5 kWh/m^3 (H_2)
Electric Copper	〃 18,000 kW	1.5%	340～350 kWh/t
Electric zinc	〃 60,000 kW	5.1%	3,500～4,000 kWh/t
other	〃 32,000 kW	2.8%	—
Total	〃 1,180,000 kW	100%	—

Note: Approximate figures in March 1959.

Table 2. Ratings of electrolytic cell and capacity of rectifying equipment

Kinds of industry		Decomposition voltage (V)	Operating voltage (V)	Current (A)	Rectifying equip. capacity kW per 1000 t/month
Salt	Mercury method	3.1～3.2	4～4.8	10～100	4,600～4,800
	Diaphram method	2.3	3.6～4	1～10	3,600～4,000
Alminium		1.6～1.7	4.6～5	40～100	22,000～25,000

Japan are shown.

The trunk equipment of these electrolytic industries are electrolytic cells. In table 2 are shown approximate figures on voltage per electrolytic cell, typical current values of the existing equipments in Japan and capacity in kW required to produce respective products 1,000 t monthly.

In these electrolytic plants, various kinds of rectifying equipment are operated contineously throughout day and night without any exceptional case (though there are very few plants which still use DC generators), we find very rarely such a machine as rectifying equipment among so many kinds of heavy current electric machines to have so rapidly improved and developed. At beginning motor-generators were used, nextly rotary converters, and then multianode mercury-arc rectifiers, single anode mercury-arc rectifiers, contact converters, and after gelmanium rectifiers the present silicon rectifiers have attained to this purpose. More over the electrolytic equipment itself has gradually changed its content according to its technical improvement and its content trends to be changed in a wide range in order to utlize most effectively new type of the machine whenever any new type of a rectifying equipment is developed.

The production amounts of the electrolytic products are propotional to

electrolytic current × no. of electrolytic cell × electrolysis efficiency × operation factor.

When a production amount is decided the combination for current of the electrolytic cell and numbers of the electrolytic cell can be selected optionally within a certain limit, so it is advisable to select the most favourable combination for voltage (numbers of cell) and current as a rectifying equipment.

The silicon rectifier has quite different characters from various kinds of rectifier hitherto developed and also posseses many excellent characteristics such as good efficiency, extremely wide range of application etc., among of which the most important features as a rectifying equipment for electrolytic service are

1) Efficiency
2) Reliability (running stability and operation factor)
3) Eretion charge

we wish to compare these features with those for single anode mercury-arc rectifiers and contact converters represented a championship in the past.

II. COMPARISON WITH SINGLE ANODE MERCURY-ARC RECTIFIERS AND CONTACT CONVERTERS

1. Efficiency

The electric power being one of the most important factors in the electrolytic industry, the efficiency of a rectifying equipment composing electric source must be the highest.

Table 3 and 4 show comparison for losses at the same output (kW) and the different voltage and Fig. 1 shows a relation between voltage and efficiency

Table 3. In case of 2,400 kW 200 V 12,000 A

Kinds of machine	MR	KU	Si
Connection	6 phase double star		
Transformer loss (kW) (incl. inter phase reactor)	42	42	42
Main loss (kW)	220	6	18
Saturable reactor loss (kW)	—	15	4
Auxiliaries loss (kW)	20	10	6
Bus bar loss (kW)	10	9	7
Total loss (kW)	292	82	77
Efficiency (%)	89	96.6	96.9

Table 4. In case of 2,400 kW 400 V 6,000 A

Kinds of machine	MR	KU	Si
Connection	6 phase double star	3 phase bridge	
Transformer loss (kW) (incl. inter phase reactor)	40	34	34
Main loss (kw)	110	6	18
Saturable reactar loss (kW)	—	15	4
Auxiliaries loss (kW)	15	10	6
Bus bar loss (kW)	5	6	4
Total loss (kW)	170	71	66
Efficiency (%)	93.4	97.2	97.3

Note: MR......Single anode mercury-arc rectifier
KU......Contact converter
Si......Silicon rectifier

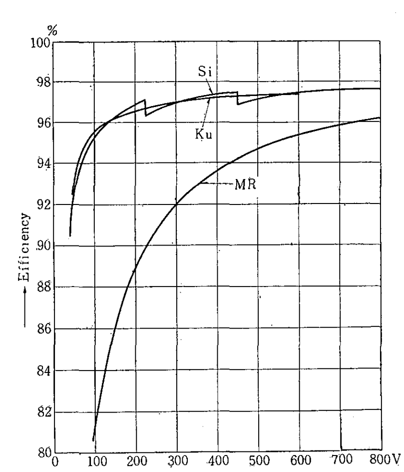


Fig. 1. Total efficiency curves for MR, KU & Si

at the same current value.

In general, the lower the voltage is the worse the efficiency becomes, however the silicon rectifier maintains neary the highest efficiency at any case. Moreover its erection area being small, the losses of bus bars connecting respective machines and apparatus are made minimized.

2. Reliability

The present silicon rectifier may be considered that it has attained nearly such level that its essential defects never occur.

Even if any of silicon elements should be broken down the operation will not be interrupted and is able to be continued by means of the protection system as described here-in-after, accordingly it stands to reason that it is required 100% operation factor.

3. Installation cost

So far as rectifier proper concerned, the silicon rectifier is the lowest cost and within a certain limit of voltage and current the contact converter may only compete against the silicon rectifier, however if its simple accessories device and interchangerability of plant projection which is able to compose an equipment with any optional voltage and current according to a combination of silicon elements are taken in account even the contact converter is no match for the silicon rectifier.

III. FUJI SILICON RECTIFIER ELEMENT

A fundamental constitution of Fuji silicon rectifier element is shown in Fig. 2. The silicon element of Fig. 2 consists of main part of high purity silicon single crystal plates with thickness approximate 0.3 mm, for which impurities and electrodes are composed in order to form N & P junction. The silicon piece is contained inside a copper case, being interrupted entirely from open air. Inside the case fully dried inactive gas is filled up. Fuji silicon rectifier elements are classified into many kinds of size as shown in Fig. 3. Table 5 shows electrical output ratings obtained by one unit for both series numbers

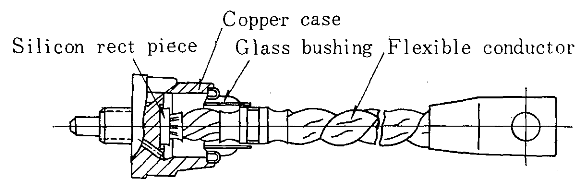


Fig. 2. Construction of silicon rectifier element

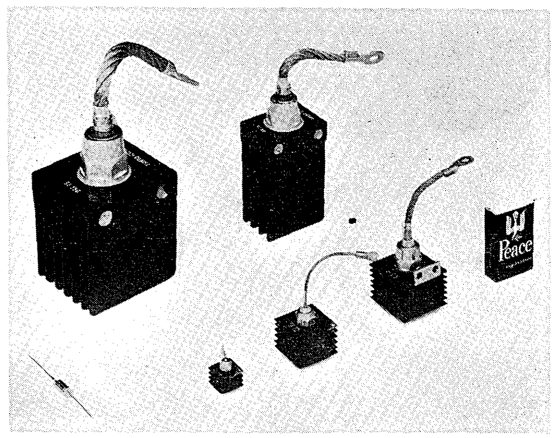
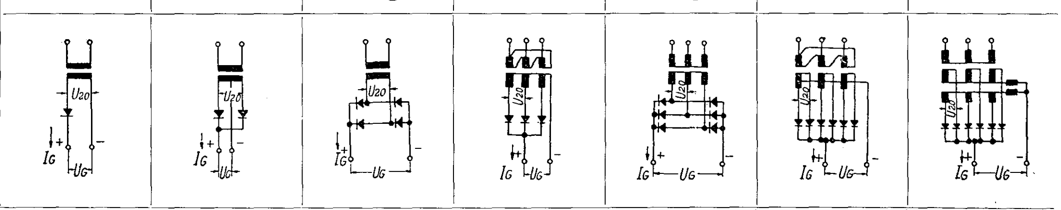


Fig. 3. Series of silicon rectifier element

Table 5. Electric ratings of silicon rectifier element

		Single phase half-wave		2 phase		Single bridge		3 phase star		3 phase bridge		6 phase star		3 phase double star	
Connection System															
Numbers of si elements for fundamental constitution		1		2		4		3		5		6		6	
Type	U_{20} (Effective value)	U_G (V)	I_G (A)	U_G (V)	I_G (A)	U_G (V)	I_G (A)	U_G (V)	I_G (A)	U_G (V)	I_G (A)	U_G (V)	I_G (A)	U_G (V)	I_G (A)
Si 1	475	210	0.5	210	1	420	1	315	1.5	630	1.5	310	2.5	270	3
Si 5	380	170	2.5	170	5	340	5	255	7.5	505	7.5	250	12.5	220	15
Si 12	—	—	9	—	18	—	18	—	27	—	27	—	45	—	54
Si 25	—	—	20	—	40	—	40	—	60	—	60	—	100	—	120
Si 50	—	—	40	—	80	—	80	—	120	—	120	—	200	—	240
Si 50F*	—	—	80	—	165	—	165	—	250	—	250	—	450	—	500
Si 150F*	380	170	200	170	400	340	400	255	600	505	600	250	1,000	220	1,200

and parallel numbers when used various connection systems.

IV. RATINGS AND CONNECTION SYSTEM OF RECTIFIER ELEMENT

1. Rating of rectifier element

The output current of the electrolytic rectifying equipment being always more than several thousand amperes, the larger the output current is, the more preferrable the rectifier element used for it is.

On the other hand, the output voltage is available from several ten volts to several hundred volts according to the service and scale of production.

In this case it is not right way that according to output voltage any rectifier element with permissible inversed voltage equivalent to it is selected and applied.

It means permanent breaking-down for the silicon rectifier element, when abnomal over voltage beyond permissible value enters into the rectifier circuit, quite different from mercury-arc rectifier or contact converter which rectification ability is temporarily interrupted.

Various kinds of abnormal voltages generated in the rectifier circuit are considered and their magnitutes are mostly dependent upon the output value of the rectifier rather than the value of rectifier voltage.

The silicon rectifier elements are equipped with surge absorbing condensers connected in parallel to protect against surge voltage and the surge energy absorbed in condensers are proportional to the square of permissible inversed voltage (PIV), accordingly they are quite safe against abnormal voltage with large energy expecting in the rectifying equipment of the large output.

Moreover as a rule in order to eradicate the breakdown troubles from the elements the permissible inversed voltage or surge breakdown voltage shall ensure suitable high value under co-ordination with the other machines and apparatus even in case the output voltage of the rectifier is low. Consequently the rectifying element used in our electrolytic silicon rectifying equipment is adopted only one kind of the under-described rating even in case of low output voltage of rectifier and for the higher output voltage several pieces of element are connected in series.

2. Ratings of rectifying element

Type	:	Si 150F
Cooling system	:	Forced air cool
Surge breakdown voltage	:	Above 1,500 V
Maximum input voltage	:	425 V (effective value)
		600 V (peak value)
Rated input voltage	:	380 V (effective value)
		540 V (peak value)
Rated output current	:	200 A (mean value)
Inverse current	:	Less than 3 mA at 1000V
Forward voltage drop	:	Less than 1.1 V

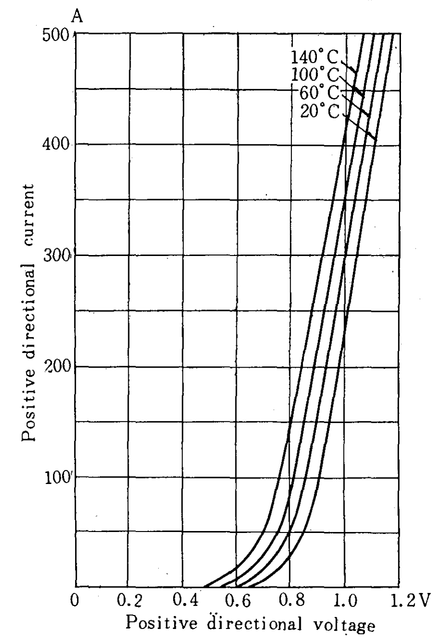


Fig. 4. Typical forward characteristic curves of Si 150

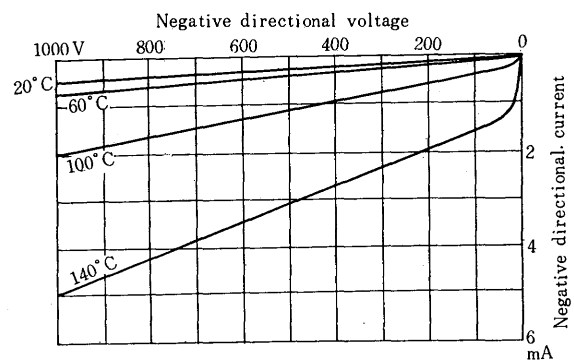


Fig. 5. Typical reverse characteristic curves of Si 150F

The typical forward characteristics and reverse characteristics at various temperatures are shown in Fig. 4 and Fig. 5.

3. Connection system

The silicon rectifiers can be used for various kinds of connection system and can constitute the rectifying equipment of optional valtage and current by selecting optionally numbers in series or numbers in parallel.

However in general AC receiving and distributing systems are 3 phase and under considerations of rectifier transformer windings, utility factor of rectifier elements, economy of conductors connecting between rectifier transformer and rectifier, arrangements of the equipment etc. almost all the rectifying equipments are constituted either of the following,

1) 3 phase bridge connection (hereafter call DB)
2) Double star 6 phase connection (hereafter call DSS)

Table 6 shows comparison of one fundamental circuit of rectifier element used in both series and parallel. (When more than two elements connected in series input voltage (E_2) per element is to be reduced by about 10% and when more than two elements connected in parallel output current (I_d) per element is to be reduced by about 20%.)

The difference between (a) and (b) in connection DSS is—(a) is used when two sets of 3 phase half-wave rectifier are only conncted while the load current exceeding the exciting current of interphase reactor is flowing and the rectifier elements are never applied voltage higher than 3 phase line voltage, (b) is used when even under no load two sets of 3 phase half-wave rectifier circuit are connected at DC side and the rectifier elements are applied voltage two times of phase voltage (namely $2/\sqrt{3}$ of line voltage). The connection (a) is actually adopted in the electrolytic rectifiying equipment and it is mostly the case that connection DSS is able to be utilized up to the higher output voltage.

Simplifying the comparison of DB and DSS the following conclusion is obtained.

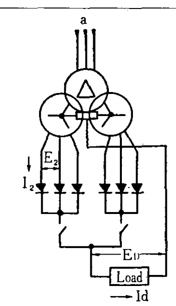
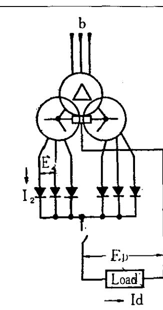
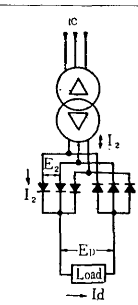
1) DSS is adopted in case
   up to output voltage (ED)=225 V

Required numbers of rectifier element and power losses of rectifier element for DSS being 1/2 of those for DB, DSS is more advantageous than DB even if output of the transformer becomes larger and the interphace reactor is needed in case of DSS.

2) DB is adopted in case
   output voltage (ED)=225V～450V

Within a range of output voltage between bellow 400V and above 225V, both DB with one series element and DSS with two series elements can be used. In both cases numbers of rectifier element and power loss are entirely same, however DB is more advantageous with regard to its transformer

Table 6. Comparison of fundamental connection of rectifiers

Connection	6 phase double star (DSS)		3 phase bridge (DB)
Connection diagram			
E_2 E_{D0} 1) E_D	380 Veff. 257 V ca. 225 V	380 Veff. $\times \frac{\sqrt{3}}{2}$ =330 Veff. 222 V ca. 220 V	380 Veff. 514 V ca. 450 V
I_d	1,200 A		600 A
I_2 I_2'	347 A —		347 A 490 A
Output ($I_d \cdot E_D$)	270 kW	240 kW	270 kW
Transformer primary capacity	325 kVA	280 kVA	325 kVA
Transformer secondary capacity	460 kVA	395 kVA	325 kVA
Silicon Voltage drop Silicon loss	1.1 V 1.32 kW		2.2 V 1.32 kW
2) Ratio of weight of connection Conductors for rectifier and transformer	112%		100%

Note: 1. Assumed voltage regulation 12.5%
2. DB is assumed 100%, at the same output current

output and construction. However if one of rectifier elements should break down an internal short circuit occurs in case of DB (one series element) but in case of DSS with two series elements short circuit does not occur even if one element breaks down, consequently when an internal short circuit is protected by means of a short-circuiter (refer to the chapter of protection system described here-in-after) DSS is sometimes used by the reason of such operation.

Above 400V DSS is provided with three series elements so DB is more advantageous.

3) Above output voltage (ED)=450 V

DB is more advantageous than DSS because capacity of the transformer becomes smaller and its construction is simple. However in a special case when an existing mercury-arc rectifier is replaced with a silicon rectifier DSS connection is sometimes adopted in order to utilize the existing transformer as it is.

V. CHARACTERISTICS OF ELECTROLYTIC LOAD

The operating voltage (ED) in case of a lot of electrolytic cells connected in series as described in I is expressed by the following formula

$$ED = N \cdot E_p + I_d \cdot N \cdot R_c \cdots\cdots\cdots\cdots (1)$$

Where,

N : Numbers of electrolytic cell connected in series

E_p : Decomposition voltage per cell

R_c : Internal resistance per cell

Note : $R_c = \dfrac{\text{term. volt. of cell} - \text{decom. volt.}}{\text{current of electorolytic cell}}$

I_d : Current of electrolytic cell and output of rectifier (ED) is

$$ED = E_{D0} - E_a - I_d \cdot R_r \cdots\cdots\cdots\cdots (2)$$

Where,

E_{D0}: Output voltage at no load of rectifier

R_r: Apparent internal resistance

Note : $R_r = \dfrac{\text{no load voltage} - \text{rated voltage}}{\text{rated current}}$

E_a: Control voltage by saturable reactor (refer to the next page).

Further

$$E_{D0} = k \cdot E_2 \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Where,

E_2 : Secondary line voltage of rectifier transformer

Note : $k = 1.35$ in case of DB

$k = \dfrac{1.35}{2}$ in case of DSS

(neglecting the exciting current of interphase reactor).

Therefore by combinaton of the above formula (1) the relation between valtage and current when rectifier is supplying power to electrolytic cells is expressed by the following formula.

$$E_2 = \frac{1}{k}\{N \cdot E_p + E_a + I_d \cdot (N \cdot R_c + R_r)\} \cdots (4)$$

or

$$I_d = \frac{k \cdot E_2 - E_a - N \cdot E_p}{N \cdot R_c + R_r} \cdots\cdots\cdots (5)$$

Beside the above in the alminiuum electrolytic equipment according to progress of electrolytic process air gaps being formed, arc will generate between anodes of electrolytic furnace and electrolytic bath, consequently it happens sometimes that the terminal voltage of electrolytic furnace rises by arc voltage. This phenomena is called Anode Effect and the arc voltage attains to 30—50V. Because a lot of electrolytic furnaces are connected in series it sometimes happens that not only one furnace but more than two furnaces break out the anode effects simulteneously. At this time if operated at the same voltage the electrolytic current will decrease, which current (I_d') will be calculated from formula (5) as follows,

$$I_d' = \frac{k \cdot E_2 - E_a - N \cdot E_p - n \cdot E_a}{N \cdot R_c + R_r}$$

Where n : Numbers of furnace, generating anode effect

E_a: Voltage of anode effect

Load of electrolytic cells and voltage-current characteristics of rectifying equipment as above are shown in Fig. 6 taking one example of NaC*l* electrolysis by mercury method. As known by this curve as there exists a back voltage in the load of electrolytic cell the rate of current change when voltage variates is larger in this case than usual resistance load and voltage regulation $\left(\dfrac{E_{D0} - E_D}{E_{D0}}\right)$ of a rectifying equipment gives great influences on this relation. Namely this has such meaning that when some changes occur in the source or load voltage regulation of the rectifying equipment must be selected large even sacrifying powerfactor to a

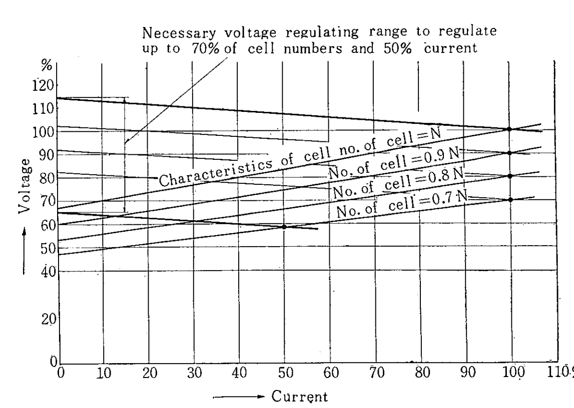


Fig. 6. Voltage-current characteristics of electrolytic cell in case of NaCl electrolysis by mercury method

certain degree in order to minimize transitional changes of current of the rectifying equipment.

VI. VOLTAGE REGULATING SYSTEM

1. Object of voltage regulation

The characteristics of voltage and current of the electrolytic cells are as discussed in the preceeding chapter and as production of electrolysis products as described in Chapter I is proportional to the product of electrolytic current and numbers of electrolytic cell, voltage regulating system of the rectifying equipment is most important on the stand point that it controls directly production amount of an electrolytic works and at the same time it occupies large parts in the installation cost, for which it must be carefully discussed case by case.

The silicon rectifier can not make any voltage regulation by itself, which is the only one as essential weak point compared with the other types of rectifier, and it causes the great increase of installation cost and at the same time the lowering of efficiency to require too wide range of voltage regulation aimlessly, on the contrary too small range of voltage regulation gives extremely inconveniences to the management of electrolytic works, which results in loading the excessive burden on the rectifier.

The reasons and main objects for which voltage regulation should be carried out for the load of ordinary electrolytic cells are as follows.

1) To regulate the electrolytic current (I_d).
2) To keep constant the electrolytic current, compensating variations of source voltage (E_2).
3) To keep constant the electrolytic current when numbers of electrolytic cell (N) are changed.
   (Various cases are expected such as when one part is cut off or short circuited owing to damages or repair of electrolytic cells, when one part is separated owing to curtailment of works operation, when operation begins without waiting completion of all electrolytic works and electrolytic cells gradually finished are put on the group of cell, when the source equipment is constructed in the large scale expecting the final form and electrolytic factory will be extended to 2 times, 3 times at suitable chances.)
4) To keep constant the electrolytic current, compensating variations of conditions (R_c) of the electrolytic cells.
   (The internal resistances of cells variate according to temperature and density of electrolytic liquid, quality of electrode materials or electrode distances and in alminium electrolytic plant anode effects are to be considered)
5) For starting
   (In some kinds of electrolytic cells back voltage can not be obtained at the time of starting and it takes sometimes long time to generate it, in such case some means to limit starting rush current is necessary)

Various requirements as above can be satisfied by

1) regulation of input voltage of rectifier or
2) regulation of control voltage (E_a) of saturable reactor

from the relation shown in formula (5) of the preceeding chapter.

In a special case

3) by means of change of connection system of rectifier

regulating range can be extended more.

2. Regulating method of input voltage (E_2)

Output current of the rectifier for electrolysis is large accordingly secondary current of the transformer is also large, it is very difficult to regulate input voltage of the rectifier on secondary side of the transformer, so that it is almost all the cases to regulate it on the primary side.

1) Tap change on primary side of rectifier transformer

Together with the following saturable reactor, under-load changing system is mostly used. So long as it is not inconvenience in practical use no-voltage changing system is more ecconomical.

The amount of tap coils being inversely proportional to the lower limit value of the range of voltage regulation, if the regulating range is required wider, the size of transformer becomes larger and also the arrangement of coils becomes very difficult. It is usually a limit that the lower limit valve of voltage regulation is 60~70%.

The numbers of tap are sufficient with about 11–21 in case of combination with the saturable reactor.

2) Voltage regulating transformer

When it is difficult to provide taps because the rectifying equipment consists of more than two transformers or the primary windings of the rectifier transpformer are provided with phase shifting windings or the induced voltage per turn is restricted specially, a voltage regulating transformer is inserted on primary side of the rectifier transformer. The regulating range is usually selected ±10–20% and numbers of tap step are 17 or 21.

Capaicity of voltage regulating transformer is as follows:

$$\text{Input capacity of rectifier transformer} \times \frac{\text{regulating voltage}}{\text{primary rated voltage of rectifier transformer}}$$

3) Change of primary connection of rectifier transformer

The rough regulation of 100%∼50% can be made by changing over series/parallel of primary windings but when a wide range of regulation is required star-delta connection change over is most ecconomical and widely used. By this method, a rough regulation of $1 : 1/\sqrt{3}$ can be carried out, for instance when regulating taps 100–70% are provided on the primary winding,

100∼70% by primary delta connection
58∼40.5% by primary star connection

two steps of regulating range are obtainable.

The change over of connection is done by changing connection with 6 primary bushings or by changing over manually or electrically with change over switch inside the transformer.

According to the respective conditions, suitable method can be selected.

4) Induction regulator

This has such merits that the stepless regulation is obtainable compared with various kinds of method described above. However for high voltage and and large capacity it is difficult to manufacture it, even if combined with series transformers the cost becomes very expensive and also the loss becomes large, so being replaced by the following saturable reactor, it is only used for comparatively small capacity of the equipment at present.

5) Change over of primary bus bar voltage

As a special case, when required very wide range of voltage regulation, more over two kinds of bus bar voltage for instance 10 kV and 3 kV or 6 kV and 3 kV are obtainable, which is utilized because of its simple method.

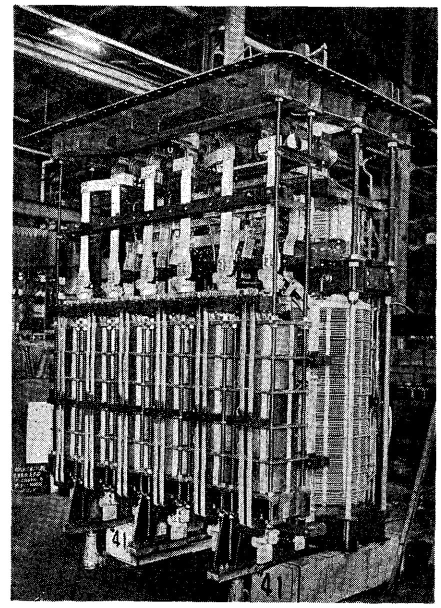


Fig. 7. Accomodated saturable reactor in transformer

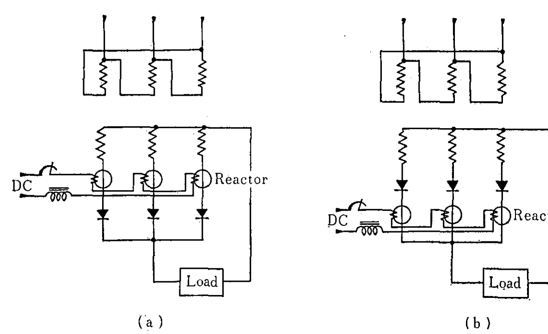


Fig. 8. Connection method of saturable reactor with rectifier

3. Voltage control (E_a) by saturable reactor

This reactor has such simple construction that a conductor of AC side of the rectifier passes through a center of iron core wound with oriental silicon steel bands in a cylindrical form and equipped with small DC control windings.

By combination of this reactor, the only weak point which voltage control can not be made by itself has been eliminated and the silicon rectifier is able to make smooth voltage regulation by small control power, quite same as the mercury-arc rectifier or contact convertcr, whereby it has now become to posses the most excellent merits as an electrolytic rectifying equipment. Fig. 7 shows a reactor mounted upon transformer and Fig. 9 shows an outline of its operation principle.

The connections of rectifying circuit when used this reactor are shown in (a) and (b) of Fig. 8 (to symplify, 3 phase half wave connection is described but the principle is quite same as in the connection of either DSS or DS) in either case its performance is same. However when a short circuiter is used in the protective device in order to limit the short circuit current, connection (a) is adopted and in the other cases either (a) or (b) may be selected according to the arrangement of the machines and apparatus or design of transformer.

The main coils of this reactor are conductors of pipe form passing through the center of iron core of cylindrical form as described above, in which currents of respective rectififying arms flow. So long as the rectifier is making a regular rectifying action, these currents form rectangular wave flowing only in one direction during $2/3\pi$ every AC cycle. On the other hand, in the control winding (small auxiliary windings with less than several turns) DC control current flows which induces m.m.f. in opposite direction of m.m.f. induced by main winding current. As understood by Fig. 9 the iron core of the reactor changes its flux from the bias point to the satulated point and AC voltage supplied to the rectifier circuit being absorbed by the reactor only

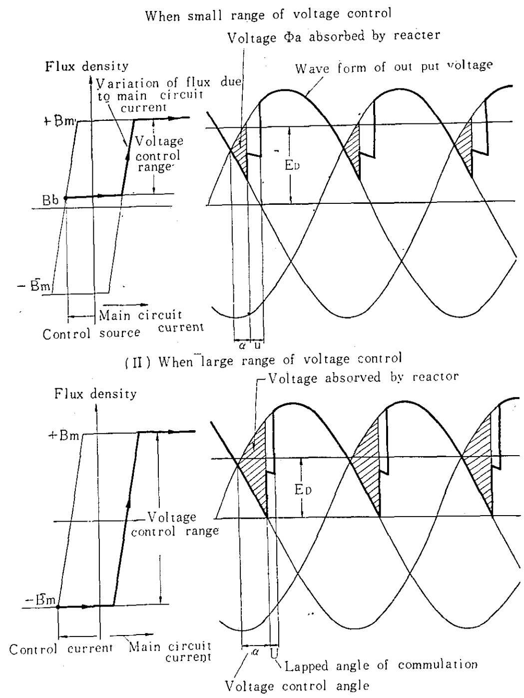


Fig. 9. Action of saturable reactor for voltage control

the amount changed by this flux, output voltage of the rectifier decreases by this amount. In (I) of Fig. 9 bias current is small so it shows an action of iron core and wave form of voltage in the rectifier circuit in the case of small range valtage control, (II) shows the same in case of bias current making maximum voltage control.

Voltage ϕ_b induced in main windings when flux density of reactor changed from B_b to $+B_m$,

$$\phi_b=\int_{B_b}^{B_m} N\cdot q\cdot dB=N\cdot q\cdot(B_m-B_b)$$

where N: Numbers of main winding

q : Sectional area of iron core.

This equals to ϕ_a in voltage wave form of Fig. 9, ϕ_a is also expressed,

$$\phi_a=\sqrt{2}E_2\int_0^{\alpha}\frac{\sin\theta d\theta}{\omega}=\frac{\sqrt{2}E_2}{\omega}(1-\cos\alpha).$$

On the other hand controlling value of voltage E_a of rectifier in case only angle α has been controlled

$$E_a=k\cdot E_2(1-\cos\alpha)$$

(k: refer to chapter IV-(3))

in result the following formula is introduced

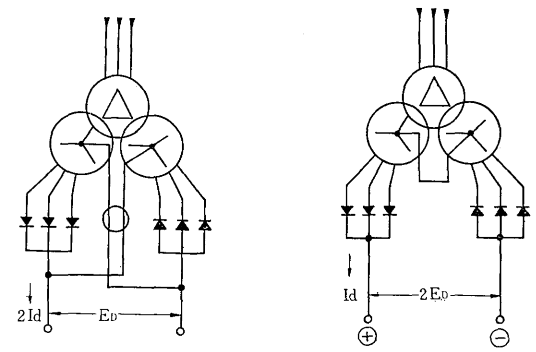
$$E_a=k\cdot\frac{\omega}{\sqrt{2}}\cdot q\cdot(B_m-B_a)$$

As understood from this formula the controlling value of voltage has no relations with secondary voltage of rectifier transformer or amount of rectifier output current but is decided by amount of B, namely amount of DC current value of reactor control winding.

Control AT necessary for controlling all the range of reactor is usually less than several ten AT and with very small control power and also by completely statical system the voltage control for large output is possible and moreover with combination of magnetic amplifier described herein-after automatic regulation for constant current or constant voltage can easily be carried out.

4. Change of connetion system of rectifier

This system is sometimes utilized when numbers of the electrolytic cell are extended to 2 times or the rectifying equipment is used being changed its service different from its beginning. In such cases, the most simple method is as shown in Fig. 10



(a) 6 phase double star conncction　　(b) 3 phase bridge connection

Fig. 10. Changing of voltage and current by change of connection in rectifier

3 phase bridge connection (DB) and 6 phase double star connection (DSS) are to be changed over and by change of connection of DC bus bar the voltage is able to change over in ratio 2 : 3 and the current in ratio 1 : 2 respectively.

Due to the change over output of the rectifier (product of voltage and current, i. e. kW) and regulating ratio of the voltage regulating device are not changed. The efficiency is also not changed.

5. Relation between voltage regulation and power factor

The power factor of the rectifying equipment is expressed by a ratio of rectifier output to apparent input of rectifier tranformer as follows,

$$\text{Power factor}=K\left(\cos\alpha-\frac{\omega\cdot I_d\cdot L}{\sqrt{2}\cdot E_2}\right)$$

Where K: Factor

0.955 for 6 phase rectifying

0.988 for 12 phase rectifying

a : Voltage control angle by saturable reactor

I_d: DC output current

L : Leakage reactance of each phase of rectifier circuit

Consequently power factor decreases in response to the increase of the rate of voltage control by saturable reactor or power factor decreases in response to the decrease of input voltage (E_2) of the rectifier. In general the lower voltage and the larger current in the equipment are, the more influence due to reactance of AC conductors connecting the rectifier and the transformer becomes, therefore lowering of power factor is unavoidable Fig. 11 is a typical example illustrating the relation between output voltage and powerfactor in case tap change over of transformer, tap change over of voltage regulating transformer and voltage control by saturable reactor are combined with.

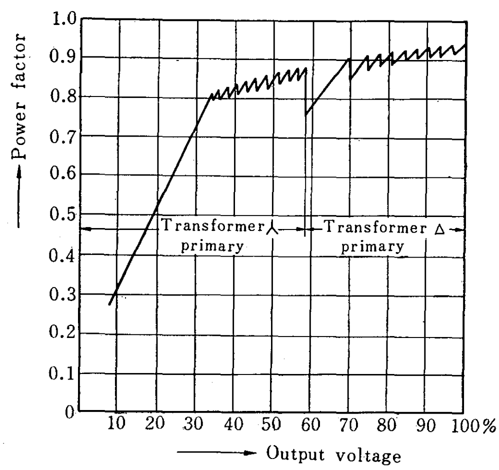


Fig. 11. Relation between output voltage and power factor

VII. AUTOMATIC REGULATION (E_α)

As explained in the preceeding chapter, such causes as voltage variation of source, variation of electrolytic cell conditions etc. which make electrolytic current variate are compensated by means of voltage regulation of rectifying equipment and moreover automatic control is mostly carried out in order to maintain always a constant electrolytic current.

The voltage regulation in this case must be carried out steplessly under loading or at extremely slight step from the nature of load.

The higher the sensibitity is, the more frequently it operates, so that the regulating device must be as robust as possible to withstand sufficiently the operation duty.

As one of methods to fully satisfy this requirement a combination of saturable reactor and magnetic amplifier as explained in the receeding chapter is most populary utilized.

The principle diagram is shown in Fig. 12. Output current of rectifier detected out by DCCT is compared with standard value and its differential value is applied to magnetic amplifier, whereby saturable reactor is controlled by output current proportional to its input, namely load current increases (decreases) → input of magnetic amplifier increases (decreases) → reactor control current increases (decreases) → reactor control voltage increases (decreases) → rectifier output voltage decreases (increases) → load current decreases (increases)

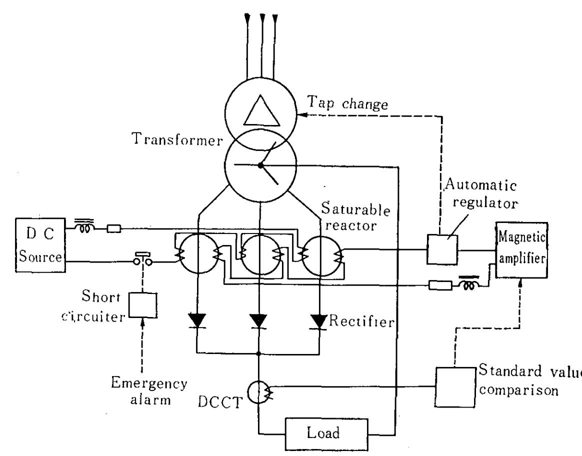


Fig. 12. Automatic adjusting circuit of constant current

This device has usually a sensibility ±1% and response rate 0.5 sec. approximately. Moreover by means of staturable reactor it is not possible to raise output voltage of rectifier more than equivalent value to control voltage $E_\alpha = OV$, on the contrary if control voltage becomes larger power factor becomes lowerer as described in the preceeding chapter, so that as explained in Fig. 12 an automatic controller inserted in the reactor control circuit detects control current to have attained the upper limit and the lower limit (namely, detection for fully and excessively building up of control voltage), and then transformer taps can be made to change over autmatically.

When the silicon rectifier is operated in parallel with such machines as mercury-arc rectifier or contact converter which often happens back fires, it will be in danger to come into the same trouble, getting reverse current component and load current of the machines operated in parallel when back fire has broken out. By ordinary automatic control it can not response to such a rapid change. For such case, one more control winding being equipped on saturable reactor, a high speed relay or a small size high speed shortcircuiter being made to operate with relation to backfire of mercury arc rectifier or operation of shortcircuiter of contact converter, for this control winding a sufficiently high DC voltage is applied, whereby it can be made to lower suddenly the output voltage of rectifier nearly to the decomposition voltage of electrolytic cells.

The silicon rectifiers delivered to Nihon Carbide Industry Co. and Kanegafuchi Chemical Industry Co., explained here-in-after are equipped with such quick magnetic control device and are so planned that they never be interrupted operation even if the short circuiter of the contact converter may operate when under parellel operation with the existing contact converters.

VIII. PROTECTIVE DEVICE

Various kinds of method hitherto developed in general for silicon rectifier may be applicable for the protective device of silicon rectifiers for electrolysis, however the under mentioned items must specially be taken care for electrolytic service.

1) Full load operation, contineously day and night is a fundametal rule, when accidents interruption of operation must be avoided as much as possible.

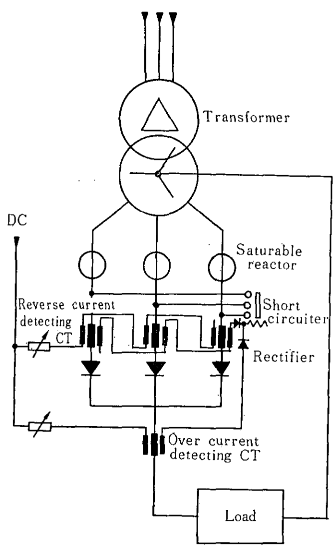


Fig. 13. Protection system by short circuit device

Due to interruption of operation, some disturbances are mostly given for process of chemical action after electrolytic process.

2) In the melting electrolysis of alminium or magnesium if interruption of operation continues for long time or output is lowered the electrolytic furnace will get deadful loss due to freezing of bath.

3) The electrolytic equipment generally requiring considerably large current, it includes a lot of rectifying elements in parallel, more over it is mostly the cases that some sets of the same kind or the different kind of rectifying equipment are operated in parallel.

4) Due to counter e.m.f. existing in the electrolytic cells reverse current from the electrolytic cells must be considered when internal short circuits occur in the rectifier.

The followings are outlines of protection system which are often adopted in the silicon rectifier for electrolysis.

1. Internal short circuit protection (in case of breakdown of rectifier element)

Either of the following methods is used

1) Short circuiter

Reverse current when element breaks down, being detected by reverse current C.T., is made to actuate the short circuiter and short circuit current in rectifying circuit produced due to break down of element is made to shift AC side of rectifier, whereby the other sound elements are protected from breaking down.

This method is a protection system peculiar to the contact converter and is the simplest and most ecconomical means for the heavy current equipment. The AC short circuit current due to short circuiter is considerably damped down by means of saturable reactor, however it must be interrupted by AC circuit breaker. The operation must be stopped even temporarily until causes of accidents are taken off. It is a weak point in this system that it neccesitates circuit breakers on DC side in order to cut off reverse current from electrolytic cells or machines in parallel.

However when operated in parallel with contact converters or in a special case when we are to expect short circuits being happened very often on DC bus bars, because suitable cooperation on protection can not be obtained by any other means, this short-circuiter is sometimes used for short circuit protection for DC side as described here-in-after. In this case in order to simplify the equipment the short-circuiter is also mostly used common for the protection against internal short circuits.

2) Fuses

For every rectifier element a fuse being inserted in series, when an element is broken down, it is rapidly fused by the short circuit current and the damaged element is cut off from the circuit.

The fuse used is of high speed fuse with high sensibility and short circuit current is interrupted within extremely short time, so even if breaking down of element the source or the rectifier arms of the neighbouring phases get scarecely any shocks.

Further if numbers of element in parallel are considered some surplus even when some of elements are cut out from the circuit by some accidents the operation can continue as it is. Moreover in this case any reverse current circuit breakers are not necessary so it is a standard protection system most widely used.

Fig. 14 shows outline of fuses for 200A and 350A (each effective value) and Fig. 15 shows their fusing characteristics.

Fig. 16 shows a rectifier cubicle equipped with

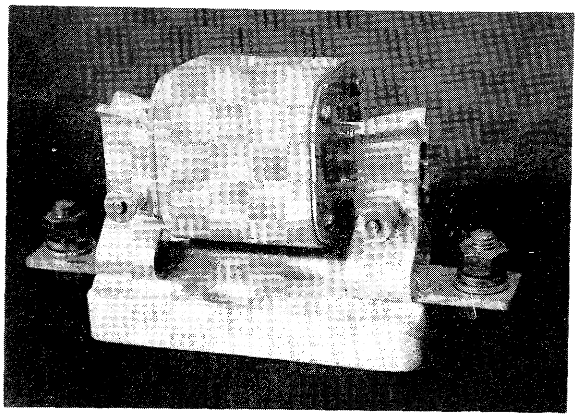


Fig. 14. 200 A, 350 A Fuji super rapid fuse

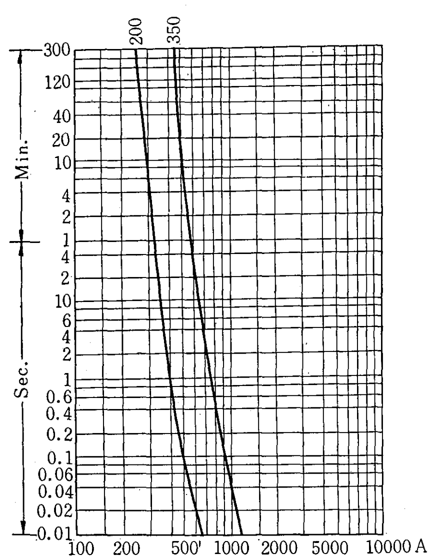


Fig. 15. Current time characteristic curves of 200 A, 350 A Fuji super rapid fuse

fuses.

3) Detecting device for voltage unbalance of series element

For the rectifier connected more than 2 rectifier elements in series even if one of elements is damaged short circuit defect does not follow instantly. In this case the damaged element does not get any reverse voltage from the rectifier circuit and most part of it is applied to the sound series elements. Therefore the voltage partially charged to each element connected in series being detected, if the charged voltages become considerably unbalanced, an alarm is given and short circuit defects can be prevented beforehand.

This devicecan be applicable in the case either the short circuiter or the fuses is used.

2. Over load protection and external (DC side) short circuit protection

In general the rectifying equipment for electrolysis is designed for contineous rating and the silicon rectifier element itself has small heat capacity com-

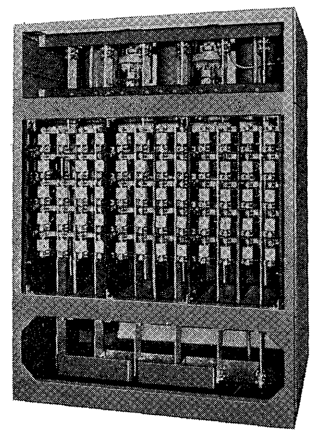


Fig. 16. Rectifier cubicle using fuse

pared with the transformer and other machines, consequently overload capacity is also small. Therefore the other machines and apparatus are used practically without any trouble against load variations as described in Chapter V even if they are designed and manufactured, taking the rated current as a base, however the silicon rectifier is not sufficient only to rely upon overload capacity of the rectifier element itself so the numbers of element in parallel must have some surplus to the requsite numbers calculated on the base of the rated output current. This is quite necessary in order not to release off the circuit breakers on source side or load side at random in case of load variation which may usually happen on electrolytic load.

Surplus numbers of parallel elements are enough to select around 10% for ordinary electrolytic load however when operated in parallel with the rectifiers which happen very often backfires or when used for such loads as alminium electrolysis in which current changes very severely owing to generation and erasure of anode effect, further detailed dicussion must be made case by case.

One example of protective co-ordination for silicon rectifier having over load capacity as above and protective device for over load and short circuit is shown in Fig. 17 and kinds of over load and short circuit protective device is shown in Table 7.

It must be discussed at each time how to combine the protective device, however in such low voltage and heavy current equipment as the up-to-date NaCl electrolysis equipment by mercury method it is mostly the case to be satisfied with combination of A,B and F in Table 7, in which case DC side circuit breakers are not necessary and installation cost can considerably be saved. Even when operated with contact converter or mercury-arc rectifier in parallel up to nearly 300V it is mostly the case to be sufficient with the combination of A,C and E or A,C and F. In this case even if machine operated in parallel gets backfire quick magnetic control

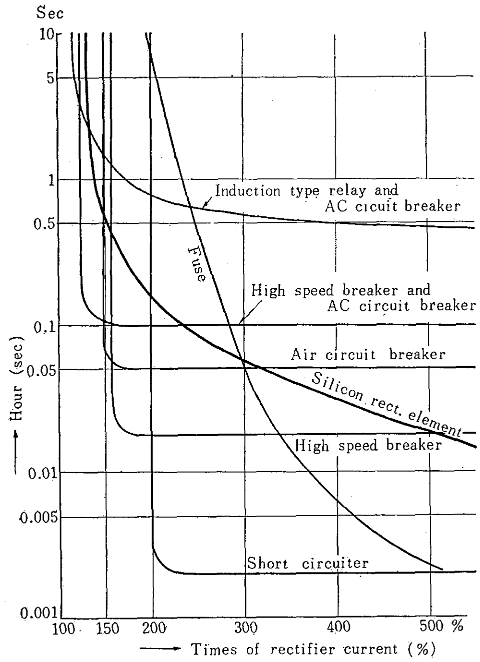


Fig. 17. Example of protection for electrolytic rectifying equipment

Table 7. Kinds of overload and short-circuit protective device

Protection system	Circuit breakers	Results
A. Inverse time limit over load relay B. High speed short circuit relay	AC Primary side	Automatic reclosing is possible
C. Air circuit breaker D. High speed circuit breaker	DC side	same as above
E. Shortcircuiter	AC Primary side	Operation is temporarily stopped
F. Tuse	Interior of rect. circuit	Operation continues as it is

device described in the preceeding chapter can be attached in order to continue the operation under no interruption.

IX. STANDARD CUBICLE AND FUNDAMENTAL CONSTITUTION

Up to the preceeding chapter the fundamental connection, voltage regulating system etc. have been repeatedly discussed, which results being summarized the following kinds of electrolytic rectifying equipment based on the standard cubicles and standard groups are constituted.

1. Stadard cubicles

Fig. 18 and Fig. 19 show outlines of standard cubicles.

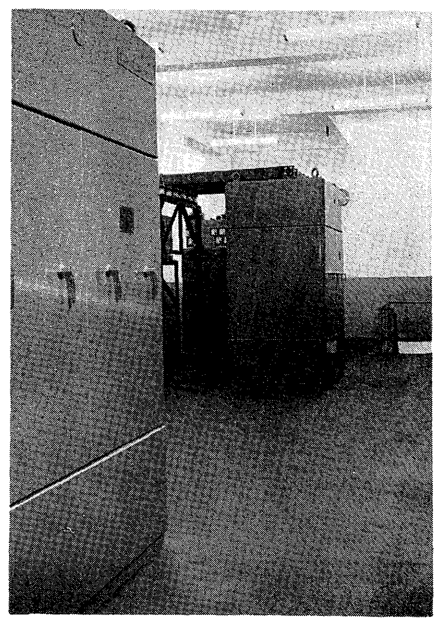


Fig. 18. Example of silicon rectifier cubicle

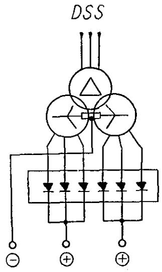
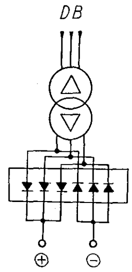
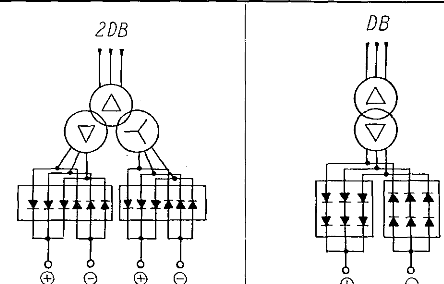
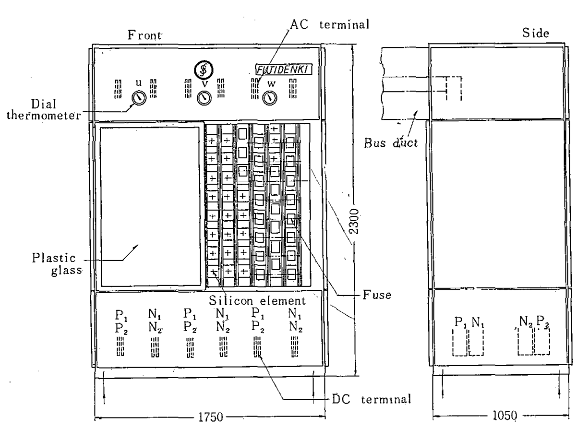
Connection System	DSS 		DB 		2DB 		DB	
Voltage E_D	Ca. 225 V		Ca. 450 V		Ca. 450 V		Ca. 820 V	
standard output	8,000 A	16,000 A	4,000 A	8,000 A	8,000 A	16,000 A	4,000 A	8,000 A
	16,000 A	20,000 A	5,000 A	10,000 A	10,000 A	20,000 A	5,000 A	10,000 A
	12,500 A	25,000 A	6,250 A	12,500 A	12,500 A	25,000 A	6,250 A	12,500 A

Fig. 19. Fundamental constitution and standard output of silicon rectifying equipment for electrolysis

Each rectifier element is arranged symmetrically against AC and DC bus in order to make current distribution and cooling conditions uniform and cubicles are used non-magnetic materials such as alminium, stainless steel etc., and used very little of steel lest the current distribution should be disturbed due to local magnetic fields. Moreover it is carefully considered for the insulating materials in the important parts to use strong heat resisting and corrosion resisting special plastics lest the insulation should be broken down due to injurious gases at chemical factories.

Table 8. Kinds and output current of standard cubicle

Form	Dimension	1,750 (width)×800 (depth) ×2,300 (height) mm	
	Connection / No. of elements	3 phase bridge	6 phase double star
I	60	4,000 A	8,000 A
	72	5,000 A	10,000 A
	96	6,250 A	12,500 A
II	Dimension	1,750 (width)×1,050 (depth) ×2,300 (height) mm	
	Connectioh / No. of elements	3 phase bridge	6 phase double star
	120	8,000 A	16,000 A
	144	10,000 A	20,000 A
	192	12,500 A	25,000 A



Outline of cubicle

Cooling is forced air cooling system and on the upper part of the cubicle three fans (each 150 W small size) are equipped, moreover there are provided cooling air inspection valves and fuses, bypass condensers of rectifier elements etc. are all contained inside the cubicle.

There are 2 kinds of dimension for cubicle and according to numbers of element contained various kinds of output are obtainable as shown in Table 8.

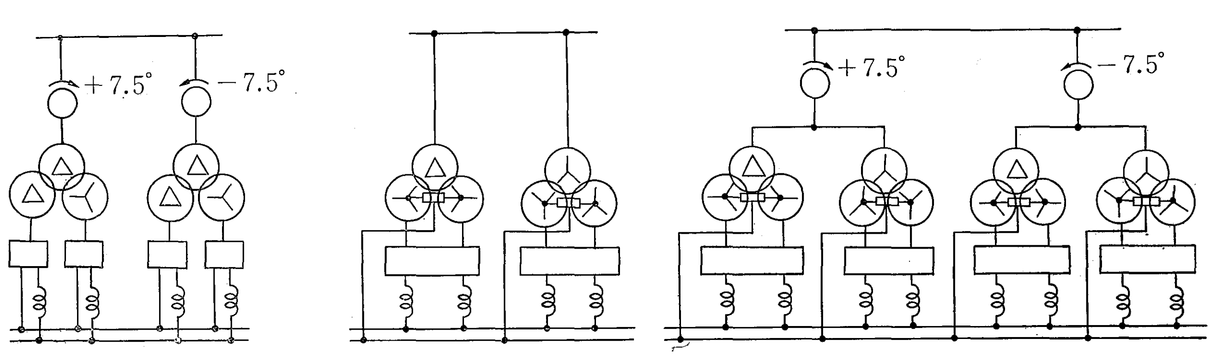
Moreover output current values shown in this table have been taken in account of overload capacity as discussed in the preceeding chapter and margin by which any hindrances on operation do not cause owing to fusing of one part of fuses.

2. Fundamental constitution of rectifying equipment

Application range of output in case the standard cubicles are combined with rectifier transformer ond used for the fundamental connection systems are shown in Fig. 19.

When the capacity of equipment is too large and is not sufficient with independent fundamental constitution it is possible to connect several cubicles with one transformer further it is also possible to arrange this fundamental constitution composing of more than 2 systems in parallel, however what system to be adopted must be decided under consideration of various conditions whether or not to adopt multiphase rectifying system, capacity of spare unit, erection method of machines and apparatus.

When many of these fundamental constitutions are installed in parallel if needed to minimize higher harmonic wave disturbances it is sometimes the case that multi-phase rectifying system is adopted, shifting the phase of rectifying voltage of each system in the



a DB 24 Phase b DSS 12 Phase c DSS 24 Phase

Fig. 20. Multi-phase rectifying system of large capacity equipment

Table 9. Manufactured examples of silicon rectifying equipment for electrolysis

Customer	AC Voltage (V)	Frequency (c/s)	Out put (kW)	Voltage (V)	Current (A)	Connection	Application	Delivery
**Kao Soap Co., Ltd.	11,000	60	2,640	660	4,000	3 phase bridge	Nitrogen	9, 1959
Nippon Light Metal Company Ltd.	10,000	60	4,400	220	20,000	6 phase double star	Soda	10, 1959
*Nippon Carbide Industry Co., Ltd.	3,300	60	3,600	300	12,000	〃	〃	12, 1959
*Kanegafuchi Chemical Industry Co., Ltd.	3,300	60	3,780	315	12,000	〃	〃	3, 1960
*Kureha Chemical Industry Co., Ltd.	3,300	50	6,480	270	24,000	〃	〃	3, 1960
Shin-etsu Chemical Industry Co., Ltd.	11,000	50	6,480	180	36,000	〃	〃	2, 1960
*Tuurmi Soda Industry Co., Ltd.	20,000	50	3,000	250	12,000	〃	〃	3, 1960
*Toyo Soda Manufacturing Co., Ltd.	3,300	60	6,000	300	20,000	〃	〃	3, 1960
Sumitomo Chemical Co., Ltd.	11,000	60	78,000	650	120,000	〃	Alminium	Under Construction
Hokuriku Salt Chemical Industry Co., Ltd.	3,300	60	2,640	220	12,000	〃	〃	〃
Tokai electro-chemical Co,. Ltd.	3,300	50	1,800	300	6,000	3 phase bridge	Hydrogen peroxide	〃

* Mark set is operated in parallel with existing contact converter.

** Mark set is operated in parallel with existing marcury arc rectifier.

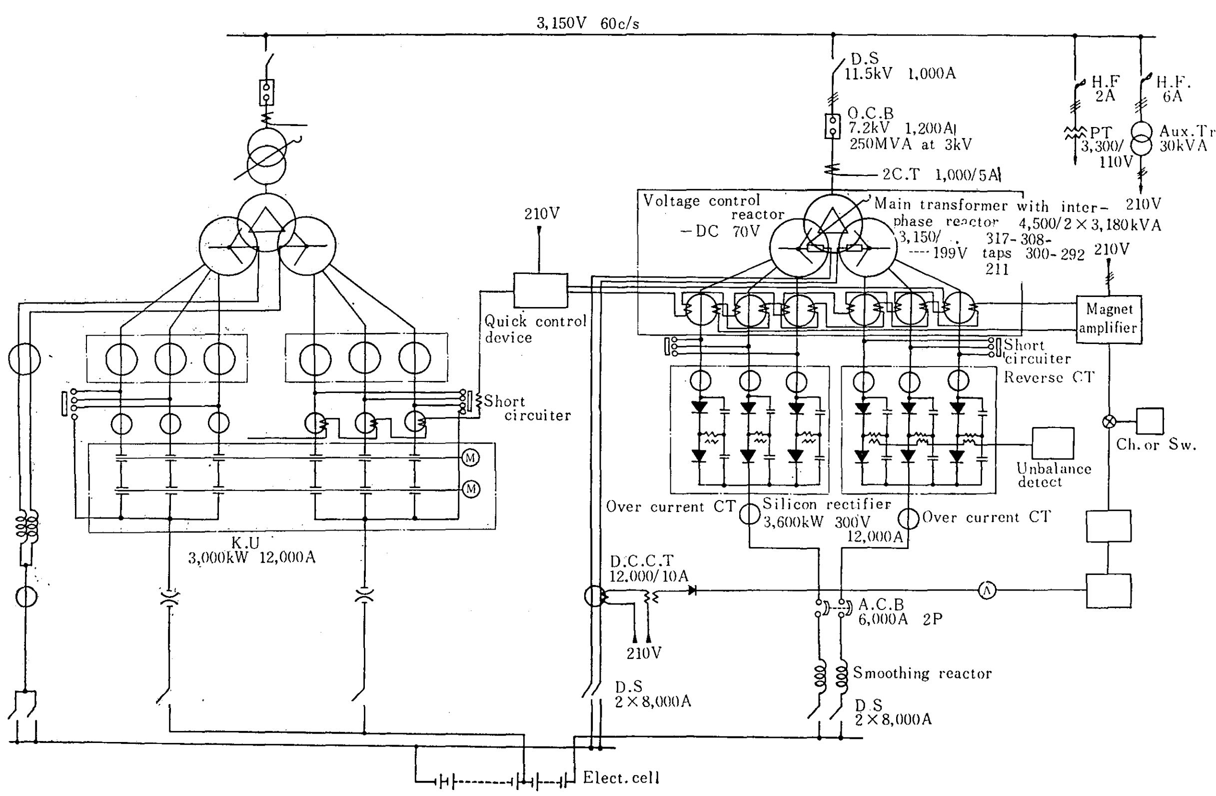


Fig. 21. Connection diagram of 300 V 12,000 A silicon rectifier equipment for Nippon Carbide Industries Co., Inc.

quite same as in the case of mercury-arc rectifier or contact converter. Fig. 20 shows few methods.

X. MANUFACTURED EXAMPLES ETC.

1. Manufactured examples

Electrolytic silicon rectifying equipments actually delivered and under manufacturing are shown in Table 9. Among of these we wish to introduce few examples as follows.

1) Delivered to Nihon Carbite Industry Co. (Electrolytic equipment of NaCl electrolysis by mercury method)

As shown in skelton diagram Fig. 21 silicon rectifiers are parallel operated with the existing contact converter shortcircuiters as protective device being used for protection against internal short circuits and external short circuits and over load switching off in done by DC side air circuit breaker, further quick magnetic control devices are provided in order that the rectifier sets continue operation under no interruption even in case of actuation of short-circuiter of contact converter.

2) Delivered to Hokuriku Seien Co. (Electrolytic equipment of NaCl electrolysis by mercury method)

Fig. 22 shows skeleton diagram for the plant. The equipment does not include other machines and is a typical example of fundamental constitution of the silicon rectifier. As protective device fuses are used for protection against internal short circuits and AC circuit breakers together with high speed relays are used for protection against external short circuits.

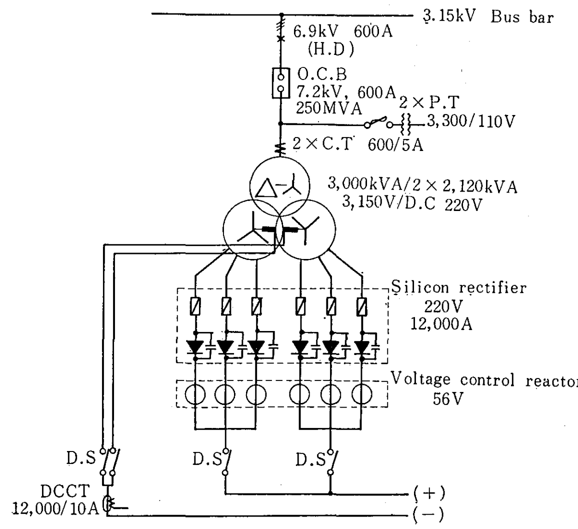


Fig. 22. Skeleton diagram of 210 V 12,000 A silicon rectifier equipmemt for Hokuriku Seien K.K.

3) Delivered to Nihon Light Metal Co. (Alminium electrolytic equipment)

Fig. 23 shows skeleton diagram for the plant. The equipment consists of 4 fundamental groups each having one element in series for 3 phase bridge connection, output voltage 450 V, valtage regulating range 0–450 V and is operated contineously with automatic constant current control, compensating load variation due to anode effect.

2. Operation system, Cooling system and others

For the silicon rectifier itself, nothing is needed

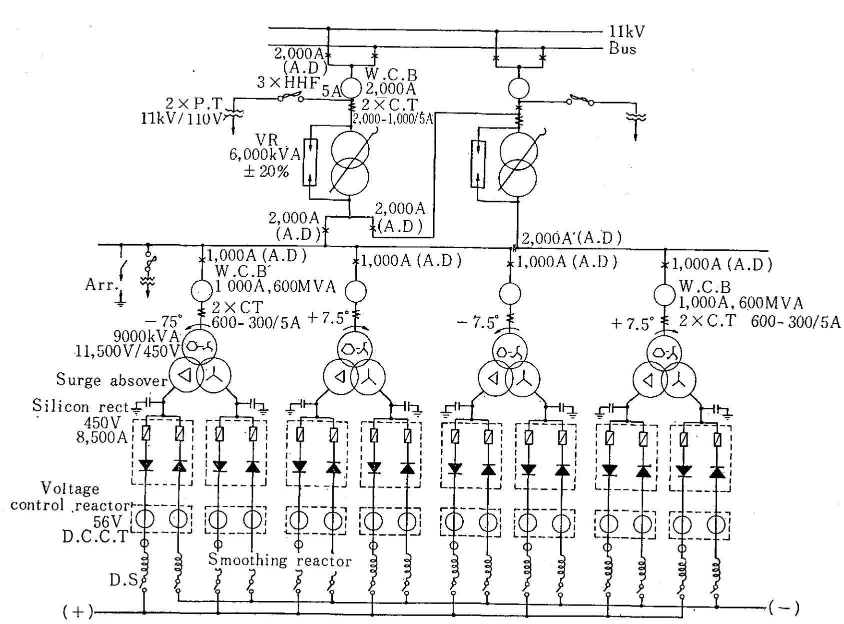


Fig. 23. Skeleton diagram of 450 V 68,000 A silicon rectifier equipment for Nippon Light Metal Co.

to attend and regulate usually, so it is possible to make the equipment no-attendent operation.

Consequently if the connecting method between rectifier and transformer is taken care it is quite sufficient to consider only the electrolytic factory as a subject for arrangement of rectifiers but not consider the electric room. However at the places where corrosive gases, moisture or dusts exist muchly it is preferable to have the rectifier room enclosed and to make cooling air enclosed circulation through a heat exchanger from the points of soiling of insulating materials for connecting conductors.

Further it is also possible to connect the rectifying equipment to the receiving line of 60kV, 70kV extra high tension (so-called one stepping down system) for which we wish to report at next chance.