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HIGH EFFICIENCY RECTIFIER EQUIPMENT FOR ELECTROLYSIS USE

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I. FOREWORD

The electrolysis industry is a typical high energy consuming industry. From the nature of its process, almost all the energy consumed by this industry is electric energy. From the statistics for 1977, the power consumed by electrolysis, centered about aluminum smelting and soda electrolysis, was about 6% of the total power generated in Japan, including that generated by local generators. The rise in the price of crude oil from 1973 has substantially pushed up the power generation prime cost of the oil fired power generation that occupies about 70% of the total power generated in the country. As a result, holding down the cost of electrolysis produced goods (aluminum, caustic soda, chlorine, copper, etc.) has progressed since then. Therefore, the electrolysis industry is making technological development efforts to produce the same amount with less power. For example, in aluminum smelting, research is being conducted on new method using aluminum chloride instead of alumina and a pilot plant having an annual production of 30,000 tons is said to be already operating in America. This method is expected to provide a power saving of more than 20%.

On the other hand, the direct-current required by electrolysis is generally supplied from an AC power system through a converter (rectifier). However, the process that converts the AC power to DC consumes about 2 ~ 10% of the required power as losses. This losses is estimated to be about 1.5×10^9 kWh a year and reducing it is considered to be the mission of our electrical engineers.

II. TECHNOLOGICAL MOVEMENT AS VIEWED FROM POWER CONSUMPTION

The conversion efficiency of rectifier is defined in JEC-178 as follows:

$$\text{Conversion efficiency} = \frac{\text{(rated output of rectifier equipment)}}{\text{(rated output of rectifier equipment)} + \text{(total loss by conversion)}} \times 100\%$$

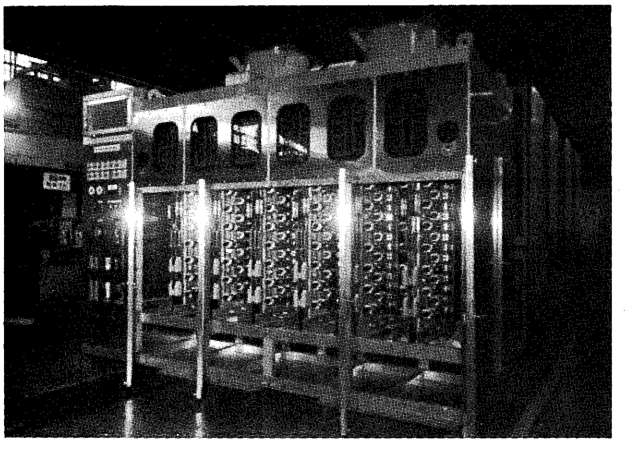


Fig. 1 Exterior view of silicon rectifier

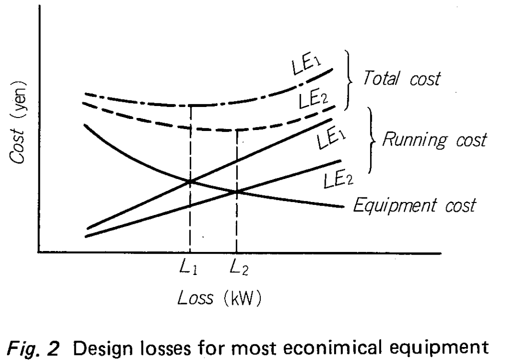


Fig. 2 Design losses for most econimical equipment

What value should be selected as conversion efficiency? Considering loss evaluation rate as a judging criteria is a convenient method. This method is not in general use in Japan yet, but has been used in America and Europe for some time, and is a technique used to consider facilities having the lowest total cost, including the equipment costs and running costs.

If the equipment is designed for larger losses, the cost will be lower naturally. On the other hand, the running power cost rises in direct proportion to the losses.

Fig. 2 shows that when the loss evaluation is LE_1 (yen/kW), L_1 kW equipment is most economical and when LE_2, L_2 kW equipment is most economical as viewed from the standpoint of total cost. The loss evaluation rate is determined by the electric charges, facility investment interest, and the number of years of depreciation. Taking America as an example, energy that cost 100 ~ 200 dollars/kW in 1970 rose to 600 ~ 1000 dollars/kW in 1978. Because the rise in energy cost is accompanied by a rise in loss evaluation rate, the current trend is toward the design of low loss (high efficiency) rectifier equipment such as that shown in *Fig. 2*.

As the simplest example, consider the conductor that connects the rectifier to the electrolysis tank. What is the most economical current density of the bus, that is, the cross sectional area (S) of the conductor? Total cost C is expressed by Eq. (1).

$$C = AS + B/S \quad \cdots\cdots\cdots\cdots \quad (1)$$

(A and B are proportion constants.)

First term is the facility cost, including the material cost and work cost, and can be considered to be almost proportional to the cross sectional area S. Second term is the power cost due to loss (running cost) and is inversely proportional to S.

To find S at which C in Eq. (1) is minimal:

$$\frac{dC}{dS} = A - \frac{B}{S^2} = 0 \qquad \therefore S = \sqrt{\frac{B}{A}}$$

This shows that the total cost is minimum when the facility cost and running cost in Eq. (1) are equal. It also shows that when the rise in energy cost exceeds the rise of facility costs (proportional to A), S becomes large and low-loss design is more economical. Considering the entire rectifier equipment, the factors that determine the total cost and loss are still more complex, but the loss level to which the equipment should be designed can be found by basing on this concept. Therefore, grasping the suitable loss evaluation beforehand is important when designing new facilities and is considered to be related to a saving of total resources.

Table 1 shows the conversion efficiency of recent typical facilities.

Table 1 Example of conversion efficiency

Application	Rectifier ratings	Efficiency
Aluminum 1	805V 38,000A 6units Primary voltage: 36kV (excluding the voltage regulator)	98.95%
Aluminum 2	725V 35,000A 3 units Primary voltage: 115kV	97.89%
Soda 1	266V 80,000A Thyristor Primary voltage: 13.2kV	97.50%
Soda 2	400V 3 x 10,800A, Thyristor Primary voltage: 13.8kV	97.40%

III. SPECIFIC MEASURES FOR ACHIEVING HIGH EFFICIENCY

Semiconductor rectifier equipment consists of a rectifier transformer, semiconductor rectifier, accessories, and auxiliaries. An electrolysis cells generally require low voltage and high current; and their capacity is steadily increasing. Therefore, from the standpoint of capacity of electric power required and the influence of higher harmonics, etc., power must be supplied directly from a higher voltage system, and a rectifier transformer is essential to convert this power directly to low voltage, high current power.

Most of the losses generated by a semiconductor converter are from the transformer and rectifier. However, since the rectifier loss is virtually governed by the inherent characteristics of the diodes and thyristors, improvement of the efficiency of rectifier equipment is largely owed to the transformer and its circuit construction is an important point in power saving studies.

The following section describes analysis of loss generation and power saving method for each element comprising rectifier equipment.

1. Rectifier transformers

The losses generated in a transformer comprise no load loss and load loss. The loss ratio (R = load loss/no load loss) depends upon the transformer impedance, etc., whereas it is about 4 for a power transformer, it is about 10 for a rectifier transformer. The reason for this is that a rectifier transformer handles a large current and much loss is generated in the high current leads, accordingly stray loss also increases. Therefore occupied by the load loss become higher for the rectifier transformer. In other words, improving the efficiency of a rectifier transformer can be said to be reducing the load loss.

1) No load loss

The no load loss is the loss generated only when the transformer is excited and is mainly the iron loss of the silicon steel plates forming the core plus the small winding resistance loss caused by the exciting current and insulators dielectric loss, etc. The iron loss consists of hysteresis loss and eddy current loss, and its ratio for grain oriented silicon steel is 1:1 in the normal magnetic flux density range at the power frequency.

The key to reducing the no load loss is selection of the core material, the arrangement of the core magnetic path, laminating method, jointing method, and clamping method and has the following points:

(1) Low silicon steel plate is used. Loss of grain oriented cold rolled silicon steel plate is becoming lower and lower, and plate up to minimum loss G6A (below M2H by ANSI) class is currently being used. Since class G9 (M4H) ~ G12 (M8) is generally used, which material to select is determined by the relationship between energy cost and material cost.

(2) The maximum flux density is suitably selected. Iron loss depends considerably on the maximum flux density is selected too low, the core cross sectional area must be that much larger and not only core weight but also winding weight are increased. Therefore, this is not necessarily a good method. Because its disadvantages are large in a rectifier transformer having a high

loss ratio, as previously described, usually, a flux density of 1.7 ~ 1.8T is selected.

(3) A magnetic path is designed in order not to disturbs the flux. When magnetic flux flows in the rolling direction of grain oriented silicon steel plate, minimal loss is obtained. Therefore, the core magnetic path is made suitable and to connect the legs and the yokes, a 45 degree joint construction is adopted using the plates with same width for legs and yokes. Recently, attention has been focussed on amorphous silicon steel plate as an energy saving core of the future. Such a core is still in the laboratory investigation stage and it application to large capacity transformers is not matured, but its use as a transformer core is expected in the future.

2) Load loss

Load loss is the loss generated by the flow of load current in a transformer and consists of:

(1) Resistance loss caused by the resistance of the windings and internal connection leads.
(2) Eddy current loss in the conductor caused by the leakage flux in the winding.
(3) Stray load loss generated in structural parts, tanks, and other metal structures other than the winding.

Since the DC winding of a rectifier transformer is a low voltage, high current winding and a large current also flows in the leads from the DC winding to the low voltage bushing, the resistance of the leads is rather large compared with the windings and their resistance loss is large. Moreover, because the current is large, the conductors are also large in size and the eddy current loss in the lead conductors and the stray loss of surrounding structures are comparatively large. To reduce the eddy current loss and stray loss caused by the large current, two large current leads are placed close together so that current flows in the leads in opposite directions. In other words, the stray loss can be substantially reduced and the eddy current loss in the lead conductors can also be decreased by eliminating the leakage flux to adjacent structures by constructing the leads so that the generated flux be canceled each other. The patented in-phase contra-polarity connection system (*Fig. 3*) used by Fuji Electric uses this principle. This connection system effectively cancels the magnetic flux at any parts from the large current leads inside the transformer to the DC output terminals of the rectifier and is extremely effective in reducing losses.

The following methods are generally used to reduce load losses.

(1) The current density is reduced and a material having a low inherent resistance is used. What should be noted when reducing the current density is that simply making the cross section of the conductor large increases the eddy current loss in the conductor and does not necessarily reduce the total loss. Therefore, the conductor must be made smaller by dividing it into several parts. *Fig. 4* shows the relationship between winding current density and loss. This figure shows that the current density i bringing minimum loss depends on the conductor thickness b and the number of wires m arranged in the radius direction and that the loss increases at current densities below this value. In other words, if the physical arrangement of the winding conductors is decided, the minimum loss current density is accordingly determined. Moreover, many conductors arranged in parallel are used in the low voltage, high current winding and consideration must be taken so that the current between the parallel conductor is not unbalanced.

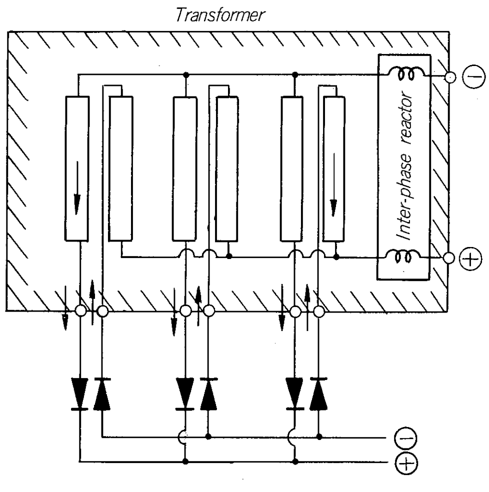


Fig. 3 In-phase contra-polarity connection

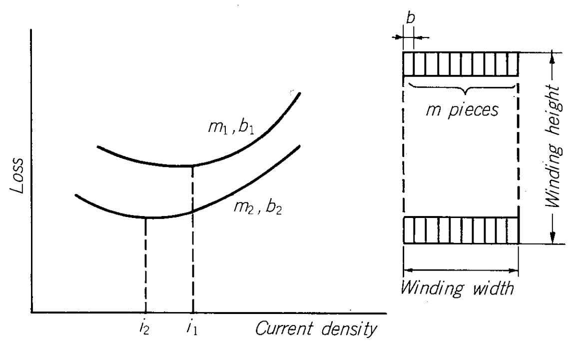


Fig. 4 Winding current density for minimum losses

(2) To reduce the eddy current loss, the conductor should be divided into small pieces with appropriate cross section.
(3) To reduce the stray loss, the structures near the large current leads are made of nonmetallic or nonmagnetic materials.
(4) An appropriate impedance is selected. Generally, the load loss is made small by selecting a small impedance, that is core machine. However, this also has limits and an appropriate value is selected by matching it with the short circuit strength and manufacturing cost.
(5) Transformer tank is magnetically shielded, by aluminum plate or silicon steel plate as required, to reduce the stray loss.

2. Semiconductor rectifier

The losses of a semiconductor rectifier are:

(1) Losses in silicon semiconductors
(2) Losses in protection fuses
(3) Losses in conductors and heat sinks
(4) Losses in surge suppression circuits
(5) Other ancillary devices losses

About 70 ~ 90% of these losses is generated in silicon semiconductor elements. Therefore, selecting the numbers connected in series and the suitable circuit arrangement is an important factor in improving efficiency.

The losses of a semiconductor element comprise:

(1) Losses in conduction period (Forward losses)
(2) Losses in blocking period
(3) Switching losses when turn-on or turn-off

Only the forward losses be considered for line-commutated convertor used at the commerical power frequency. This forward characteristic is nonlinear as shown in *Fig. 5*, but practically it is expressed in linear formula.

$v_F = V_0 + R_d \cdot i_F$

V_0 and R_d are the values shown in *Fig. 5*.

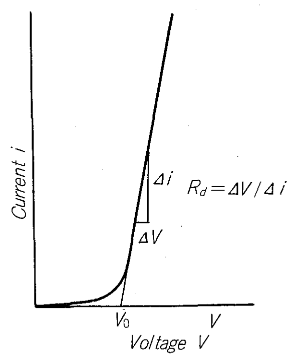


Fig. 5 Forward characteristic of power semiconductor

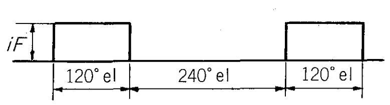


Fig. 6 Current on power semiconductor

The current waveform of the semiconductor elements in a 6 pulse converter can be approximately square wave with 120 °el conduction as shown in *Fig. 6.*

The voltage drop waveform of the semiconductor is also the same as the current waveform, and if the current is I_d, the voltage drop will be,

$V_F = V_0 + R_d I_d$

with the same waveform, the power loss is,

$P_F = I_d V_F + R_d I_d{}^2$

Generally, V_F is a value of 1.5 ~ 2.5V in the practical range. Since the loss will be doubled if the number of series elements is two, reducing the number of series elements by using high withstand voltage elements is advantageous. However, since the high withstand voltage elements have generally thicker base, the V_F tends to be higher.

Element loss is not proportional to the square of the current, such as normal resistance loss, but is mostly proportional to the current, because the characteristics of the semiconductor element is nonlinear, as previously mentioned. Reducing the current substantially reduces the transformer load losses, but the circumstances are different for a semiconductor element.

Next is the surge adsorber loss. What must be noted here is that the loss changes considerably when the control angle is changed, especially in case of thyristors. The loss in capacitors is small, but since the terminal voltage of a thyristor changes like that shown in *Fig. 7*, and capacitor discharge current flows with sudden voltage changes, the re-resistance loss is fairly high. This value changes greatly by changing the control angle and becomes maximum at control angle $\alpha = 90°$el.

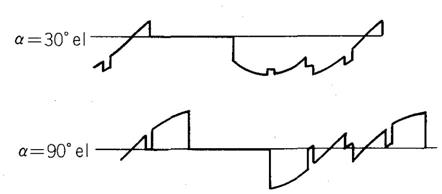


Fig. 7 Voltage waveform across thyristor

3. Losses generated by ancillary devices

Items to be noted are voltage control reactors frequently used in diode rectifiers, inter-phase reactors used in single way connection, gate control devices at the thyristors, and the ancillary devices for cooling. The losses generated by these devices are rather small compared with the losses of the transformer and semiconductor elements, but should be made as small as possible.

1) Voltage control reactor

Usually, a through type saturable core reactors are used as shown in *Fig. 8*. To obtain better characteristics, grain oriented silicon steel plate is used as the wound core.

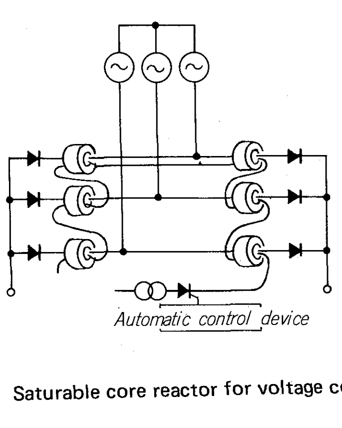


Fig. 8 Saturable core reactor for voltage control

2) Inter-phase reactor

Since the frequency of the voltage applied to the inter-phase reactor is three times of the power frequency, the iron loss is much higher than that of a transformer. Therefore, the flux density must generally be made lower than that of a transformer because of the core temperature rise.

When the inter-phase reactor is inserted between two 6-pulse converters having different phases, the iron loss increases further, since the frequency will be 6 times the power line frequency. In the case of thyristor converters, the voltage applied to the inter-phase reactor changes with firing angle changes and, therefore, careful attention must also be given to the iron loss. The iron loss increases as the control angle approaches 90 °el.

Winding of the voltage control reactor or the inter-phase reactor carries large current, therefore conductor has large cross section and makes only 1 or 2 turns. The loss can be reduced by making the length of this conductor as short as possible by some suitable arrangement.

4. Voltage control system selection

The demand for wide range voltage control is the biggest feature of electrolysis rectifier equipment for the following reasons:

(1) When starting the electrolysis cell line, the current must be gradually raised to the rated value.
(2) At normal operation, the number of cells changes due to maintenance.
(3) Electrolysis cells will be added in future steps.
(4) A constant current must be supplied to the cell line even when the AC voltage fluctuates.
(5) The electrolysis power is sometimes limited by process side factors.
(6) When DC power is supplied to cell-line by several units, the share of the load must be balanced among the units.
(7) A constant current must be supplied for load changes such as the anode effect at aluminum smelting pots.

To satisfy the above conditions, the voltage control is achieved by combining the methods shown in *Table 2*.

Especially in the case of a diode rectifier, the connection method for tap changing at a transformer has a considerable affect on conversion efficiency.

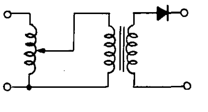
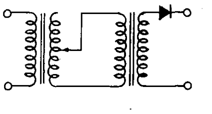
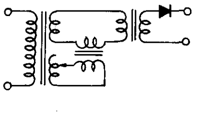
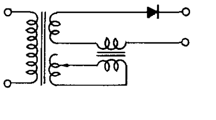
Table 3 shows the voltage control connection methods. Since several transformers are combined in any case, the generated loss increases as the number of transformers and the total sum of the self-capacity increases.

On the other hand, in case of thyristor rectifier, though power factor may be lower, the conversion efficiency can be higher than the diode rectifier because of very simple construction of the transformer.

Table 2 Voltage control methods

Method	Description
No voltage tap changing	Provided at the primary of the transformer. Applicable to the case when the switching frequency is low and short time interruption of the power supply will not affect the operation. Inexpensive.
On-load tap changing	Rough control of the output voltage is performed while load current is flowing. The step voltage is selected so as not to affect current change. Extremely expensive.
Voltage control reactor	Fine voltage control is performed. Normally used in combination with on-load tap changer and having a voltage control range of 2 ~ 3 taps for automatic control.
Thyristor	0 ~ 100% voltage control is possible by controlling the firing angle. To prevent power factor reduction, it is normally combined with no-voltage tap.

Table 3 Combination of diode rectifier and voltage regulating transformer

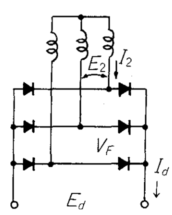
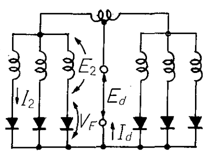
Scheme	Connection diagram	Description
Voltage regulating auto-transformer and rectifier transformer		The self-capacity of the voltage regulating transformer becomes smaller as the voltage control range becomes smaller.
Voltage regulating transformer and rectifier transformer		Two transformers, with full capacity required. The voltage control range cannot be made too wide. Tap may be at the primary side.
		Wide voltage control range is possible. Three transformers are required and increases both the space and loss.
Taps are provided at the reactifier transformers in combination of series transformer		A wide voltage control range is possible and the capacity of the series transformers can be at most half of the reactifier transformer.

5. Connection scheme selection

There are various kinds of rectifier connection. However, bridge connection and single way connection are generally used with electrolysis power supplies. *Table 4* lists the features of each method.

In the rectifier equipment for large current supply, number of elements are connected in parallel, since the maximum allowable current is 800 ~ 1600 Amps per element. In the single way connected rectifier, the loss generated and the number of elements required are half of those in bridge rectifier, because the current duty on element is half of that in bridge rectifier though an inter-phase reactor needed and its lead loss added, and the single way connec-

Table 4 Comparison of rectifier connection

		3-phase bridge	6-phase single way
Connection diagram			
Character istics	No-load DC voltage	$E_{d_0} = 1.35\,E_2$	$E_{d_0} = 1.17\,E_2$
	Secondary current	$I_2 = \sqrt{2/3} \cdot I_d$	$I_2 = 1/2\sqrt{3} \cdot I_d$
Semiconductor element maximum voltage		$\sqrt{2} \cdot E_2$	$\sqrt{2} \cdot \sqrt{3} \cdot E_2$
Loss generation	Semiconductor elements	$2 \times V_F \times I_d$	$V_F \times I_d$
	Transformer	Simple construction, low lead loss	Complex, high lead loss
	Inter-phase reactor	NO	YES

tion should be used within the range of the output voltage possible with one series element as far as the semiconductor element voltage allows.

6. Cooling method selection

There are many methods of cooling rectifier equipment, such as water cooling, air cooling, etc. From the standpoint of equipment design, if the cooling efficiency is good, a higher loss generation is allowed for the temperature rise limit at which equipment life and reliability are maintained and "improved cooling efficiency = power saving" may not always hold true. However, the fact if cooling is efficient, the equipment can be made more compact and less material, especially conductors, is used and low loss design is possible. Cooling ancillary equipment loss, utility power loss, and effective use of water resources in the case of water cooling and other resource saving factors are also important points.

When the secondary cooling of a transformer is air cooling, the ancillary equipment losses can also be reduced by operating and stopping the cooling fan or controlling the number of running units according to the state of the load.

7. Unit construction method

In aluminum smelting, etc., the load requires a DC current of 100 ~ 200 kA and two or more rectifier equipment are generally installed because of single unit capacity restrictions. The phases of the multiple units are shifted and multi-phase rectification is performed as a harmonic countermeasure. Selection of the number of these divisions can be viewed from the standpoint of total power loss evaluation. However, it is generally decided from the standpoints of the above single unit capacity limit, harmonic countermeasures, cost, etc. When a standby unit is provided and all the units are normally operated, such as in the case of aluminum electrolysis, the load per unit becomes (N—1)/*N* and efficient operation is possible, especially to the transformer.

8. Structural considerations

Since electrolysis rectifier equipment is low voltage, high current equipment, the generated losses must be reduced by making the conductors carrying the high current shorter. Especially, to make the high current conductors that connect the rectifier transformer and semiconductor rectifiers as short as possible not only reduces the loss but is also effective in improving the power factor. It is also important to accomodate the voltage control reactor, series transformers, inter-phase reactors, etc. in the same tank and to minimize the large current leads unless there is a limitation for transportation.

IV. CONCLUSION

Energy saving is an old story, but since the exterior of electrolysis rectifier equipment and its design standards have changed considerably, we have outlined this equipment here. The authors will be happy if it serves as reference in future planning.