STATIC FREQUENCY CHANGER FOR RAYON INDUSTRY

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INTRODUCTION

There has been a trend of employing static mercury frequency changers in place of rotary machines on account of reduced installation costs, high efficiency, easy operation and maintenance resulting in a great saving of expenses and feasibility of stable converted power through grid control. Practical examples of application for power supply use are: those delivered by Toshiba to Nichinan Works, the Japan Pulp Co. and to Kamaishi Works, the Fuji Steel Manufacturing Co., one built by Mitsubishi for the Mitsubishi Mining Co. Takashima Coal Mine and one at Hanaoka Mine of the Dowa Mining Co. supplied by Fuji. They are all in satisfactory operation, but the mercury rectifiers are all provided with vacuum pumps, being used for connecting the systems having commercial frequencies of 50 cycles and 60 cycles.

In the building of pumpless, sealed mercury rectifiers, our company took the initiative and since then the field of their application has been markedly enlarged and an opportunity of general employment for power services has been afforded by them. As an example, a static mercury arc power converter to be used as a power source of pot motors for rayon industry by changing 50 cycles to 150 cycles has come to an actual load operation at Nobeoka Works, the Asahi Kasei Kogyo Co. As this is a world record product as a static unit of 50~150 cycles power conversion, painstaking effort has been taken in its design. The principle and features of this static frequency changer will be given herein together with the outline of the apparatus.

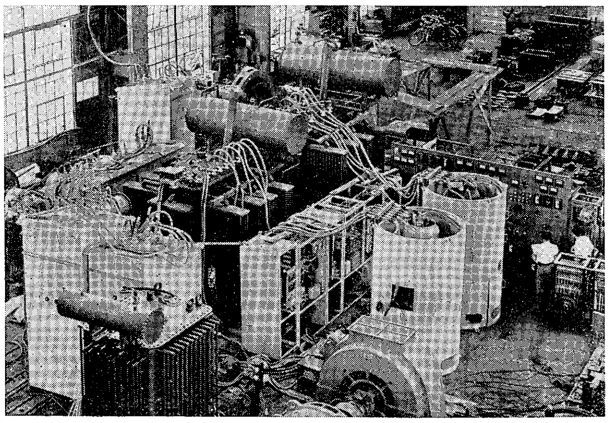

Fig. 1. Static frequency changer for rayon works

I. PRINCIPLE OF STATIC MERCURY ARC FREQUENCY CHANGER

(1) Mercury arc power rectifier and inverter

Operating principle of the mercury arc power rectifier is briefly given in reference to 3 phase half wave rectifier circuits as shown in Fig. 2.

Generally D. C. winding voltage is given by the following equation.

$$e_{21}=e_{22}=e_{23}=\sqrt{2}\,E_2$$

Then, no load D. C. voltage E_{d0} without grid control is shown below.

$$E_{d0}=\sqrt{2}\,E_2\frac{\sin(\pi/p)}{(\pi/p)} \quad \cdots\cdots\cdots\cdots\cdots(1.\ 1)$$

where p is the number of phase of the unit, when operating with a grid control for phase angle of retard α,

$$E_{d\alpha}=E_{d0}\cos\alpha \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(1.\ 2)$$

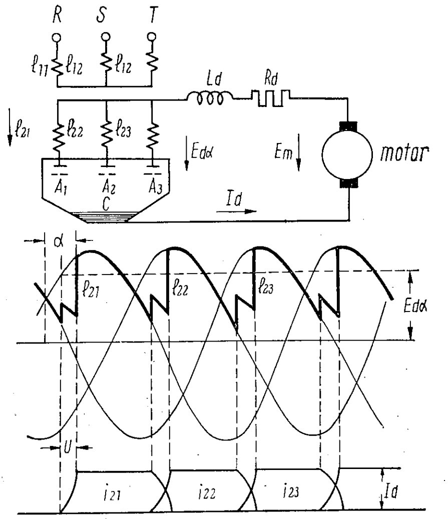

Fig. 2. Performance of rectifier

Let X denotes commutating reactance of unit, R the resistance of the circuit and E_a the arc drop. The characteristics of D. C. output voltage E_{dr} and D. C. output current I_d are represented in general by the following equation.

$$E_{dr}=E_{d0}\ \cos\alpha-\frac{p}{2\pi}XI_d-RI_d-E_a \quad \cdots\cdots\cdots\cdots(1.\ 3)$$

If rated D. C. current is denoted by I_{dN}, and let $i=I_d/I_{dN}$, and $E_x=p/2\pi XI_{dN}$, and also the resistance of the circuit and the arc drop is ignored, the foregoing equation is represented as follows.

$$E_{dr}=E_{d\alpha}-E_x\cdot i$$

the D.C. output current flows owing to the difference between D. C. output voltage E_{dr} and motor counter electromotive force E_m and is obtained by the following equation.

$$i=\frac{E_{d0}\ \text{con}\ \alpha-E_m}{E_x} \quad \cdots\cdots\cdots\cdots\cdots\cdots(1.\ 5)$$

According to Equation (1.2), the A.C. output voltage is changed easily from full voltage to zero voltage ($\alpha=90°$) by grid control, the relation being illustrated by curves in Fig. 3. In the case

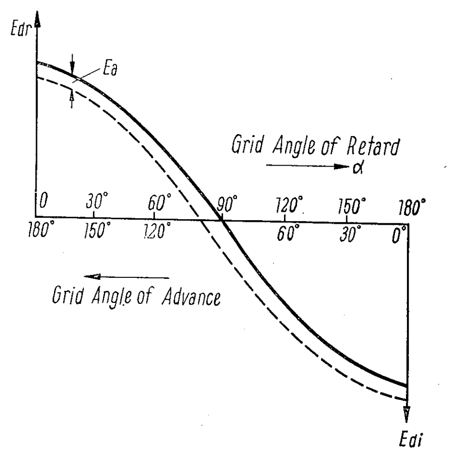

Fig. 3. Curves between D.C. voltage and grid phase angle

of inverter, if this grid angle of retard is further proceeded beyond 90°, the D.C. output voltage of this rectifier becomes in an opposite direction. If the direction of this electromotive force E_m is changed to a generator electro motive force E_g, power is inversely fed to A.C. circuits from D.C. circuits. This principle is shown in Fig. 4 with 3 phase half wave rectifier circuit. If the phase angle of retard is represented by a angle of advance γ as in Fig. 3, the following relation is available.

$$\gamma=180°-\alpha \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(1.\ 6)$$

Therefore, substituting each equation of rectifier with Equation (1.6) and changing the sign, equations of inverter are to be obtained. That is, if D.C. output voltage is denoted as E_{di}

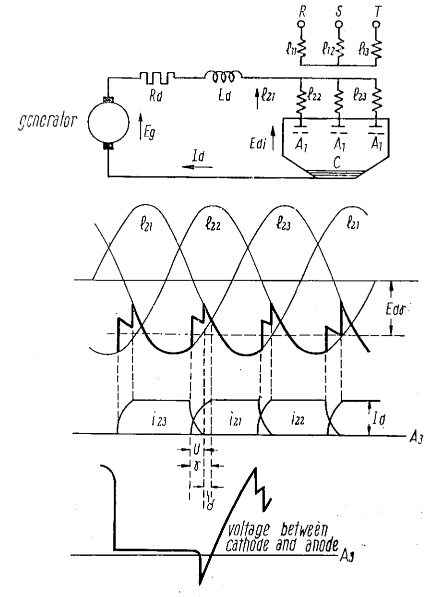

Fig. 4. Performance of inverter

$$E_{di}=E_{d0}\ \cos\gamma+\frac{p}{2\pi}XI_d+RI_d+E_a \quad \cdots\cdots\cdots(1.\ 7)$$

$$E_{di}=E_{d\gamma}+E_x\cdot i=E_{d0}\ \cos\gamma+E_x\cdot i\cdots(1.\ 8)$$

However, in the case of inverter if the angle of overlap during commutation is denoted by u as shown in Fig. 4, the following equation is a necessary condition for the above.

$$\delta=\gamma-u>\delta_0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(1.\ 9)$$

δ_0 is the term, what is called the recovering time of control ability, i.e., a necessary time for the recovery of grid control ability after extinction of anode current, being peculiar to rectifiers. When $\delta=\delta_0$ no commutation is carried out, resulting in the failure of commutation and producing the short circuit of D.C. circuits. Therefore, a rectifier having small δ_0 for the inverter so as to make $\delta>\delta_0$ in operation. Further, it is necessary to make the commutating reactance of the system including transformers small and keep the angle of overlap u small. This commutation failure limit is available from the next equation.

$$\cos(\gamma-u)=\cos\gamma+2E_x\cdot i/E_{d0}\cdots\cdots(1.\ 10)$$

$$\gamma_m-u=\delta_0$$

$$\text{con}\ \delta_0=\cos r_m+2E_x\cdot i/E_{d0} \quad \cdots\cdots\cdots(1.\ 11)$$

Then D.C. output voltage and current characteristics are represented by substituting the above equation to Equation (1.8).

$$E_{di}=E_{d0}\ \cos\delta_0-E_x\cdot i \quad \cdots\cdots\cdots\cdots\cdots(1.\ 12)$$

They are represented by dotted lines in Fig. 5.

(2) **Static Frequency Changers**

Static frequency changers are the combination of the rectifier and inverter mentioned above as shown in Fig. 6. If the voltage regulation of

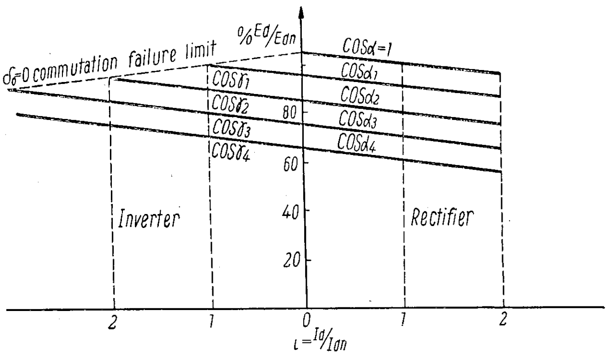

Fig. 5. Characteristic curves D.C. voltage and current

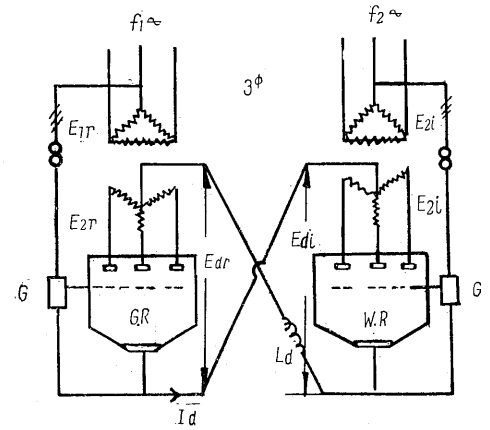

Fig. 6. Connection diagram of static frequency changer

two converters are the same, their characteristics are represented by following equations.

$$\left.\begin{array}{l} E_d = E_{d\alpha} - E_x \cdot i = KE_{2r} \cos\alpha - E_x \cdot i \\ E_d = E_{d\gamma} + E_x \cdot i = KE_{2i} \cos\gamma + E_x \cdot i \end{array}\right\} \quad (2.\ 1)$$

$$i = \frac{E_{d\alpha} - E_{d\gamma}}{2E_x} = \frac{K(E_{2r}\cos\alpha - E_{2i}\cos\gamma)}{2E_x} \quad \cdots\cdots (2.\ 2)$$

If D.C. converted power is denoted by W.

$$W = E_d\, i_d \cdots\cdots (2.\ 3)$$

That is, the converted power varies in response to the fluctuation of both system voltage E_{2r}, E_{2i} when the phase angle of grid α and γ are constant, but they can be kept constant irrespective of the voltage and frequency variation by automatically controlling the phase angle of grid. In case of failure, interruption of fault current can be made by grid arc quenching and reclosing will be done quickly.

There are varied systems to make automatic grid control of frequency changers. Generally they are divided to constant D.C. voltage control, constant D.C. current control and constant D.C. power control. In order to make a commutation failure limit wide with D.C. output kept constant, D.C. constant current control is extensively used. The state of varied controls is theoretically obtained from the following equation.

$$\left.\begin{array}{l} E_{d\alpha} - E_{d\gamma} = 2E_x \cdot i \\ E_{d\alpha} + E_{d\gamma} = 2E_d \end{array}\right\} \quad \cdots\cdots (2.\ 4)$$

$$\frac{\left(\frac{E_{d\alpha}}{E_{dN}}\right)^2 - \left(\frac{E_{d\gamma}}{E_{dN}}\right)^2}{4\left(\frac{E_x}{E_{dN}}\right)} = \frac{E_d I_d}{E_{dN} I_{dN}} = \frac{W}{W_N} \quad (2.\ 5)$$

Where $W_N = E_{dN} I_{dN}$ is rated D.C. converted power. For example, if commutation failure limit is obtained when $E_x/E_{dN} = 5\%$, $\gamma = 35°$ with respect to rectifier inverter, it will be noted from Fig. 7 that constant D.C. current control gives the largest commutation failure limit.

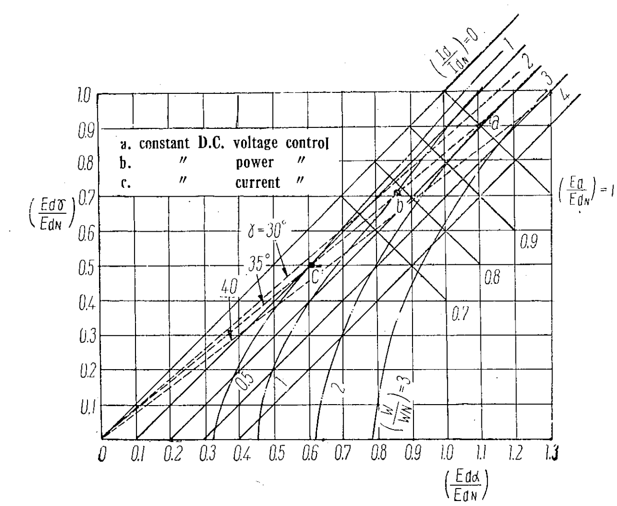

Fig. 7. Performance of static frequency changer

(3) Required Reactive Power

There is a defect with respect to static frequency changer that lagging reactive power necessary for inverters must be supplied from the A.C. system even when the capacity of output side of the A.C. system is not large. The required lagging reactive power P_b is available from the following equation.

$$P_b = W \tan\phi \cdots\cdots (3.\ 1)$$

$$\cos\phi \doteqdot \cos\left(\gamma - \frac{u}{2}\right)\cos\left(\frac{u}{2}\right)$$

$$\doteqdot \cos\left(\gamma - \frac{u}{2}\right) \quad \cdots\cdots (3.\ 2)$$

$$\cos\phi = \cos\gamma + e_x = \cos\delta_0 - e_x \cdots\cdots (3.\ 3)$$

where $e_x = E_x / E_{d0i}$

These relations are readily available from Figs. 8 and 9.

Since this reactive power increases in proportion to converted power, the output of parallel rotating machines is reduced and the voltage of system is also reduced.

Then γ, u, δ_0 must be made small as much as possible for the purpose of minimizing the reac-

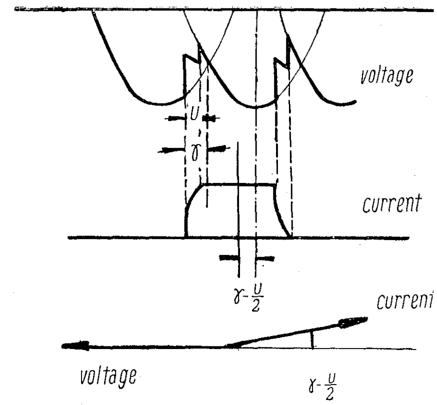

Fig. 8. Power-factor of inverter

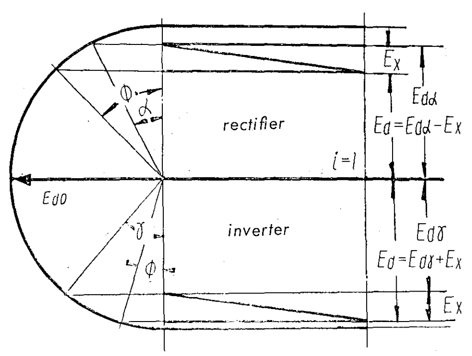

Fig. 9. Power-factor of static frequency changer

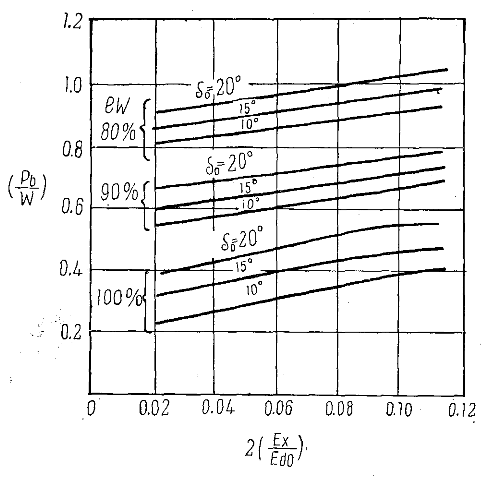

Fig. 10. Required γ active power curves

tive power. In this case the voltage fluctuation of the A.C. output system affects the most, the values when the voltage drop of the A. C. output system is represented by

$$e_w = 100\%,\ 90\%,\ 80\%$$

with respect to the recovery time of grid control ability $\delta_0 = 10°$, $15°$, $20°$, are illustrated in Fig. 10.

Increase of required reactive power accompanying to the voltage drop of the A.C. output system is related to the increase of D.C. output current, so if the rectifier is given the grid-automatic control

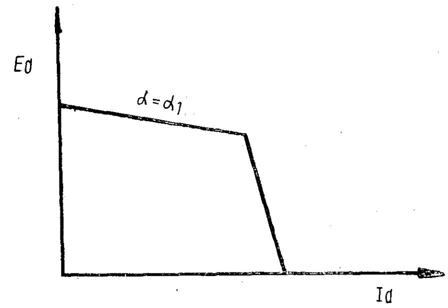

Fig. 11. Characteristic of D.C. current limitting

with promptness to control the current as shown in Fig. 11, the required reactive power does not increase, not giving much effect on the A.C. system. This indicates that quick grid automatic control is a prime requisite. Aside from it, it is a practise extensively applied to put static condensers in divided units depending on the required reactive power.

(4) Parallel Operation of Rotating Machines

When the static frequency changer is viewed from the A.C. output side, its characteristics greatly differing from those of rotating machines are noticed. A.C. Output voltage E_2 of frequency changers has relation with apparent input voltage E_1, and apparent internal impedance $\dot{Z}_1$ as shown in the following equations.

$$\dot{E}_2 = \dot{E}_1 - \dot{I}_1 \dot{Z}_1 \quad \cdots\cdots (4.\ 1)$$

$$\dot{E}_1 = \frac{\cos\alpha}{\cos\gamma} E_1 e^{jo} \quad \cdots\cdots (4.\ 2)$$

$$\dot{Z}_1 = \frac{R}{K^2 \cos\gamma} e^{-j\gamma} \quad \cdots\cdots (4.\ 3)$$

$$R = \frac{KE_1 \cos\alpha - KE_2 \cos\gamma}{I_d}$$

Fig. 12 shows this relation, in which E_1, $I_1 \cdot Z_1$ are always on the same phase and power factor $\cos\gamma$ is always constant when γ is constant. Then, the share of load with rotating machines is determined by the voltage regulation, the more stable load-share being possible with the smaller γ and the smaller value of x_g/Z_1.

(5) Features of Static Freuequency Changers

The following features are given as compared with the conventional rotary frequency changer.

a) As there is a definite relation between the frequencies of two systems in the conventional rotary frequency changer, changing-over the pole number or Krämer speed control is required to change the output frequency. But in the static frequency changer, there is a D.C. intermediate circuit between two A.C. systems, which gives flexibility in the coupling of two A.C. systems, and fluctuation of frequency in one system does not affect the other system.

b) The conventional rotary frequency changer necessitates a speed regulator to adjust the converted power, whereas the static frequency changer is capable of regulating it with precision and ease by grid control.

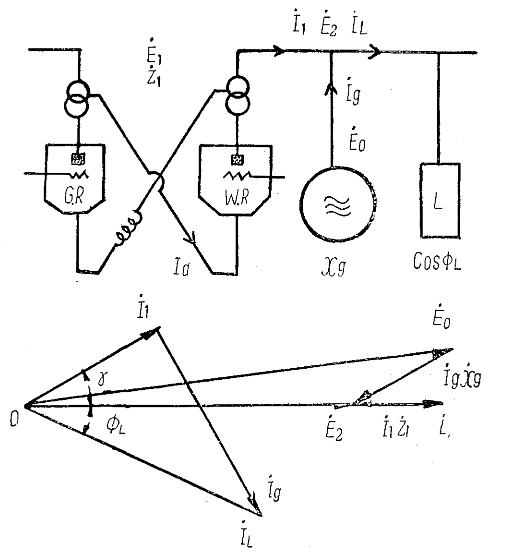

Fig. 12. Performance of parallel running

c) Starting devices are not required. The static frequency changer is started by simply applying control voltage to the grid after closing A.C. circuit breaker. No such troubles of synchronizing or stepping out are to be feared with ease of stop, operation and maintenance.

d) Should any faults occur inside the static frequency changer or either of the A.C. systems, fault current can be interrupted by grid control and the apparatus can be restarted readily with ease, giving little disturbance to the A.C. system.

e) Because of using a mercury arc rectifier, the efficiency is quite good and does not lower even at a light load, i.e., overall conversion efficiency is favourable.

f) Being a static apparatus, it makes little vibration and noise. Installation and transportation are easy. From the viewpoint of foundation and other allied problems, building of substations is greatly facilitated.

g) Reverse electromotive force exists at the output A.C. system of the apparatus, and excitation is necessary. Lagging reactive power must be supplied and its magnitude is to be determined by the fluctuation and control method of the frequency changer

h) Higher harmonics occur on the side of A.C. input and of output system in their voltage and current. Therefore, necessary precaution must be taken to avoid induction disturbance to communication lines and radio receivers.

II. STATIC FREQUENCY CHANGERS FOR RAYON INDUSTRY

A frequency changer delivered to Nobeoka Works, the Asahi Kasei Company, as a power source for pot motors of rayon industry is used to supply 1,500 kW converted power from 50∿ 3,300 V A.C. input side to frequency 130–140–150 cycles 2,680–2,890–3,100 V A.C. output side system. As for load, several tens of pot motors are thrown in at a time or it happens that a few hundred kW load in one group is cut off. But fluctuation of regular load is small and stable. Machines running in parallel are several units of asynchronous-asynchronous type and asynchronous-synchronous type frequency changers.

Because of small capacity and high frequency in output A.C. side system, a number of considerations were given with adoption of new system, their outline being given as follows:

(1) Mercury Arc Rectifier

The mercury-arc-rectifier is of air cooled pumpless sealed type convenient for the maintenance and operation, and is of multi-anode type which has perfect grid control characteristics. The control grid construction is of double grids construction. Since the apparatus is to be operated at 150 cycles, reduction of recovering time of grid control ability is taken into account especially as compared with the case of 50 cycles operation, and this time is designed short. Temperature regulators consisting of cooling fans, anode heaters and cathode heaters are of automatic operation, requiring no attendant. The rectifier is housed by a protective cylinder, which dispenses with protecting fence. The appearance is as shown in Fig. 13.

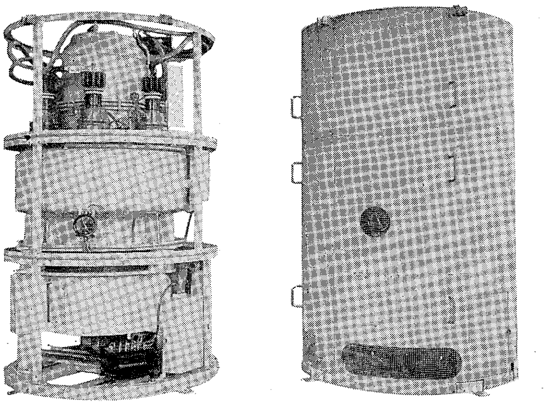

Fig. 13. 1,500 kW, 1,500 V air-cooled pumpless, sealed mercury arc rectifier

(2) Transformer for Mercury Arc Rectifier Use and Others

Transformer is outdoor use, oil-immersed, self-cooled with interphase reactors, for use with rectifier, having the following specification.

Rated Capacity	2,300 kVA
Rated Voltage	3,400–3,250–3,100–2,950–2,800/1,920 V
Rating	Continuous
Rated Current	428/294 A
Connection	△/⅄Y
Rated Frequency	50 cycles

Transformer outdoor use, oil-immersed, self-cooled with interphase reactor, for use with inverter, having the following specification.

Rated Capacity	1,900 kVA
Rated Voltage	3,100/1,878–1,820–1,770–1,720 V
Rating	Continuous
Rated Current	354/248 A
Connection	△/⅄Y
Rated Frequency	150 cycles

1–Series reactor, outdoor, oil-immersed, self-cooled 3 phase, having the following ratings.

Rated Capacity	850 kVA
Rated Voltage	1,210–933–695–490 V
Rating	Continuous
Rated Frequency	50 cycles

1–D.C. reactor, outdoor, oil-immersed, self-cooled, with the following ratings.

Rated Current	1,000 A
Rated Inductance	20 mH
Impedance:	Transformer for rectifier 16.4%
	Series reactor max. 39%
	Transformer for inverter 2.4%

Apparent internal impedance of frequency changer Z_1 is taken sufficiently large for the steady parallel operation with other rotary frequency changers. The transformer for inverter use is so constructed to have specially small impedance, with due consideration to the reduction of overlapping angle u and to the enlargement of margin angle δ.

The D. C. reactor having specially large inductance is employed to reduce fluctuation during faults and transient together with quick automatic grid control to be described later.

1–Static condenser, outdoor use, oil-immersed, self-cooled, with series reactor, having the following ratings.

Rated Capacity	250 kVA
Rated Voltage	3,300 V 3 phase △ connectoin
Rating	Continuous
Rated Frequency	140 cycles
Total Capacity	2,500 kVA

In response to required reactive power of inverter, i.e., to the load, 10 steps of change-over is automatically made, and entire static condensers are cut off upon stopping the operation of converters. The total capacity is fairly large because it is also provided for the power factor of load together with. The total capacity is adjustable by means of tapped transformer.

(3) Grid Control Device

A grid control device of new system is a combination of phase shifter consisting of phase reactor X_S and balancing resistance R and peak wave generating apparatus L_S, C_e, R, C_f, its performance being as illustrated in Fig. 14. A choke coil L_S is made up of right angle special iron core of B-H characteristics and, being a kind of switch to be saturated in the neighbourhood of maximum value of impressed voltage e, it will charge or discharge the series condenser C_e. This current is made use of obtaining voltage e_p having peak wave form as a voltage drop. The specific feature of this apparatus is to extend the phase shifting range to 180° from the ordinary range of 60°, and is suitable for driving a magnetic amplifier and

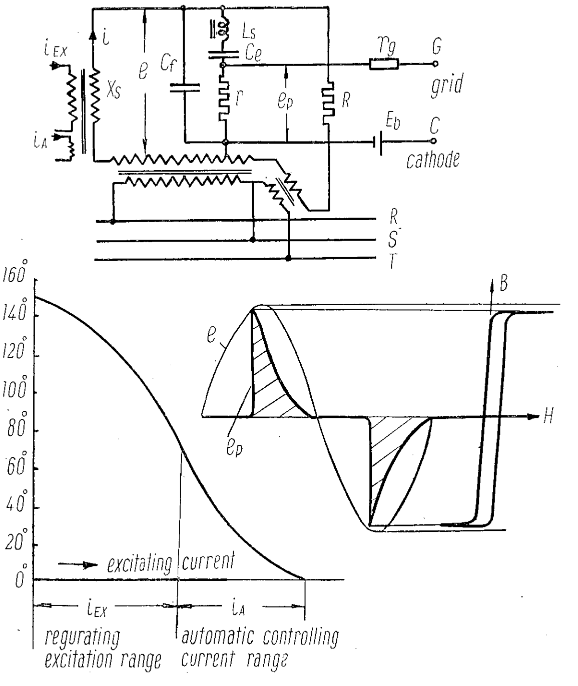

Fig. 14. Performance of grid control device

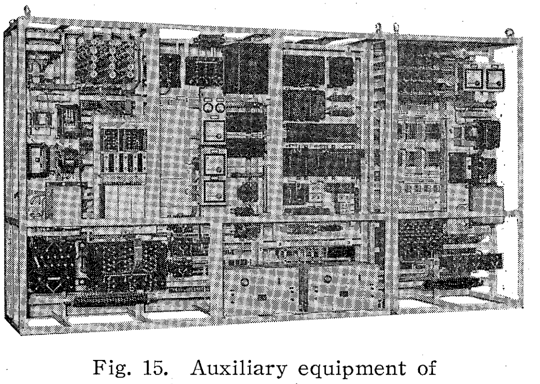

Fig. 15. Auxiliary equipment of frequency changer

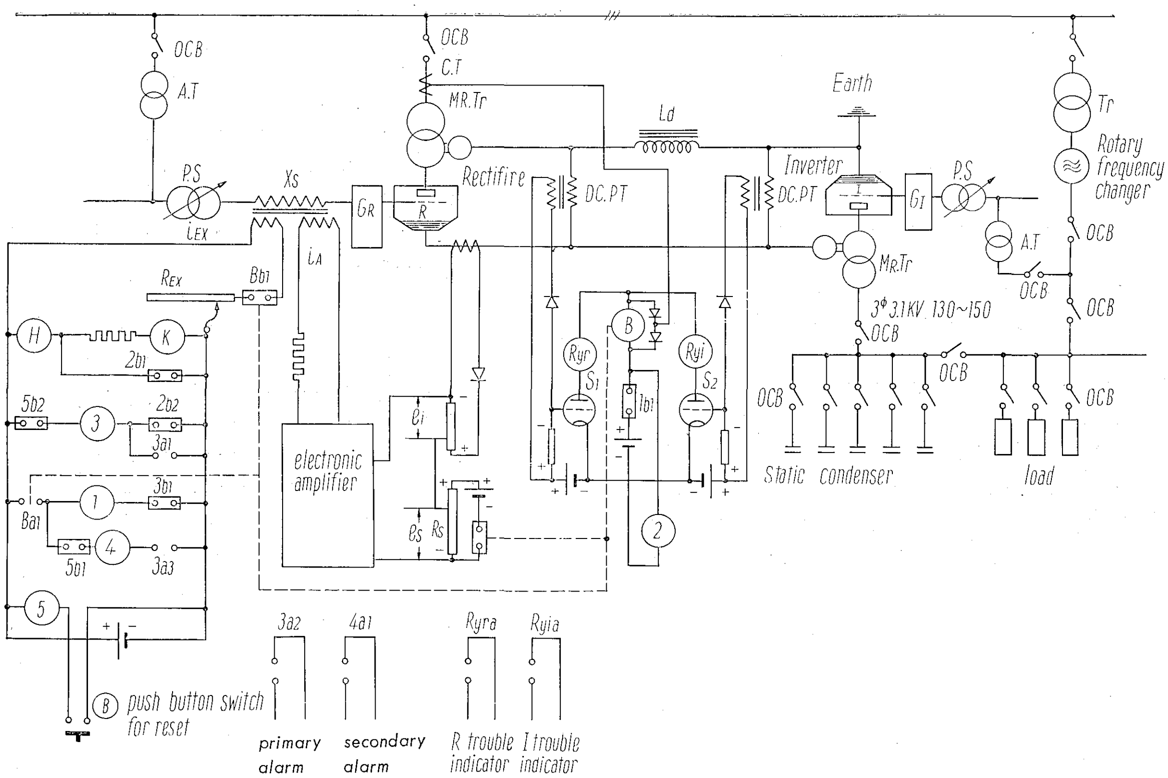

Fig. 16. Automatic restarting equipment by constant current control

electronic amplifier in case of automatic control. Its controlling speed of phase shifting is very quick and is to the extent of 5°/ms. A part shown in the left in Fig. 15 is the new type control device.

(4) **Constant Current Automatic Control** Restarting Equipment (Refer to Fig. 16)

After making preparation of operation in the order of inverter and rectifier, drive resister R_{EX} by means of master controlling handle to increase provisional excitation I_{EX} of phase shifting reactor. It will, then, reduce angle α retard of the rectifier grid to raise D.C. output voltage, which overcomes the reverse electromotive force of inverter to start flowing rectified D.C. current. In this case the angle γ of advance of inverter grid is set to a pre-determined definite value beforehand. Next, difference between voltage e_i, proportional to rectified D.C. current by means of D.C. current transformer and reference voltage e_S is amplified and impressed on the phase shifting reactor. Since constant current automatic control is thus made, setting of rectified D.C. current is determined from reference voltage e_S with the master controller handle. There are opening and closing contacts interlocked with it to throw in static condensers of proper number according to the load.

In case of internal fault of converting equipments of fault in both A.C. systems, ordinary practise is to interrupt the fault current by grid arc quenching and restart it after a certain time. This method, however, has a demerit of time for grid arc quenching becoming long when inductance of D.C. reactor takes a large value. Hence, the new equipment does not employ the method of grid arc quenching. It adopts a new system of quickly shifting the grid phase angle α of retard to the region of inverter. As a result, inductance of D.C. reactor is made to increase considerably, which reduce the disturbance to the system in case of faults or during the transient. In a certain definite interval, the grid angle α of retard returns to the region of rectifier automatically, entering into a regular operation. In such a case the first alarm signal is despatched and an indication for the fault is made. If a push button switch for resetting is pressed after restarting, the original condition is resumed entirely. If the restarting is tried after a certain time when the fault still remains, the circuit breaker is interrupted with the second alarm, stopping the operation. Fig. 17 shows oscillograms of the case when the commutation was made to fail on purpose and automatic restarting was tried.

In Fig. 18 are seen a Thyratron on the left and electronic amplifier on the right.

(5) Load Tests and Other Remarks

Fig. 18 is an oscillogram of the operation under

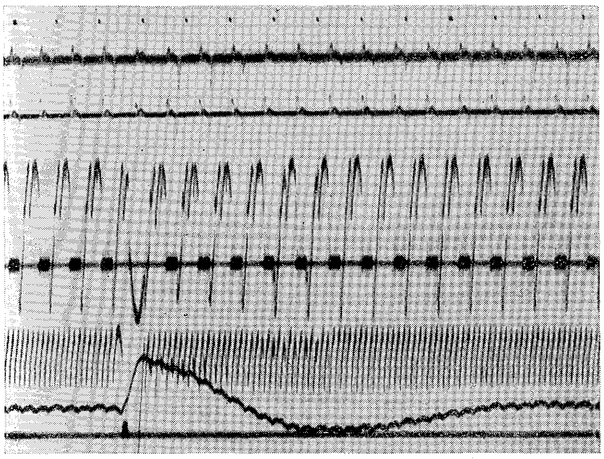

Fig. 17. Oscillogram of automatic restarting

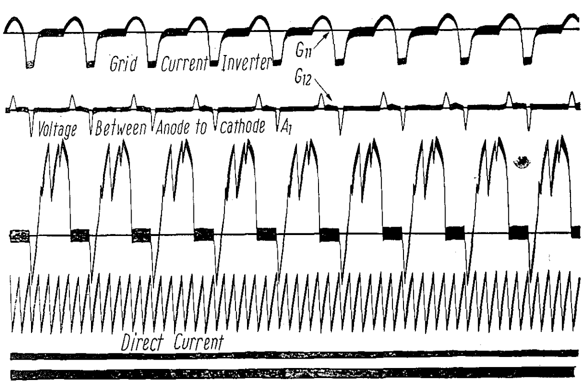

Fig. 19. Load test oscillogram

load. Efficiencies are 91.9, 92.5 and 92.9% for frequencies of 130, 140 and 150 cycles respectively. In conducting the tests, special effect on pot motors due to higher harmonics in the A.C. output side was taken into account, but test results have revealed that the increase of losses is only 1~2%. Noise or higher harmonic torque gives no problems in vibration tests, the maximum amplitude being

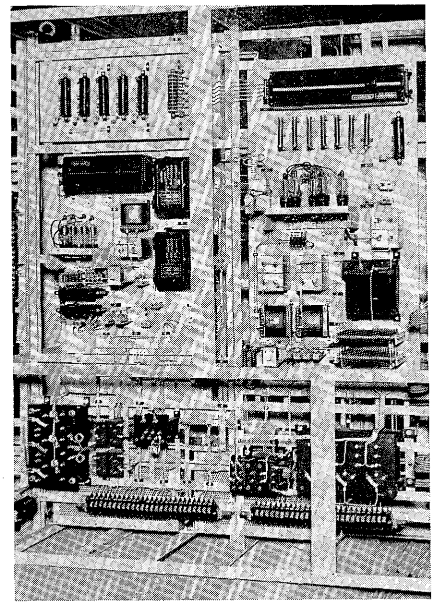

Fig. 18. Automatic restarting equipment by constant current control

0.7 mm in the case of 10 gr unbalance. Induction disturbance to the telephone lines at Nobeoka Works was kept in mind but it has been attested that no problems arise for 6 phase connection system in the degree of 1,500 kW.

The static frequency changer mentioned above is of separate excitation having parallel rating frequency changers in A.C. output system side, but what is called a self excitation system is sometimes desirable for the rayon industry, when the A.C. output system has no equipment of supplying required reactive power. It is theoretically so in the case of rayon industry because of almost stable load by switching on and off static condensers which are splitted and connected on A.C. output system side in response to throw-in and cutting-off the load. Static frequency changers of self excitation have two types of series and parallel systems, each having its demerit. It is, then, necessary to make a study on an automatic controlling system capable of supplying stable converted power, combining the advantages of two system together.