Comparing Equation (7)′ and Equation (8)′,

$$\sigma' \doteqdot (m^2+3n^2+3mn)\sigma_2 \cdots\cdots\cdots\cdots\cdots\cdots (9)'$$

It coincides with Equation (9) in the body of this article. m and n are the capacity ratio of the secondary and tertiary windings when the capacity of the primary is assumed to be 1.

Next, σ in Fig. 2 of Item 4 in the body of the article is equal to that available from Equation (3)′ by assuming $B_1 = B_2 = k\left(\frac{AT_2}{m}\right)$ for one conductor.

Therefore, for total of the secondary winding

$$\sigma = \frac{w^2 b a^3 m_0}{360\rho} k^2\, 15\left(\frac{AT_2}{m}\right)^2 \cdots\cdots\cdots (10)'$$

Comparing Equation (8)′ with Equation (10)′

$$\sigma \doteqdot 3\,\tau_2 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (11)'$$

This Equation (11)′ coincides with Equation (4) in the body of this article.

AMPLITRANS TYPE AUTOMATIC VOLTAGE AND POWER-FACTOR REGULATING DEVICE

By

Yoshio Nakajima

(Switch-board Div., Engineering Department)

I. INTRODUCTION

Usually the synchronous machine of large capacity is provided with main and sub-exciters and is controlled for its excitation by the automatic voltage regulator or automatic power factor regulator, the over-load limiting device, and automatic voltage balancing device for synchronizing operation. Consequently, the controlling system of the excitation becomes considerably complex to set side by side the above-mentioned devices which are independent apparatus each having unique principle of operation. Also, these devices are in many cases of very sensitive regulating relay systems having contacts or moving parts of very delicate constructions which operate off and on very frequently. They require fine adjustments and difficult maintenances, which are apt to be the causes of the failures. Automatic regulators using electronic tubes are also static type devices and good performances can be obtained by manufacturing. However, as a economically practical device, it is inferior in the point of reliability owing to its limited output and possibility of degrading the life and performance.

Rotary amplifiers are sometime used, but magnetic amplifiers are perfectly static type. Therefore, it is mechanically substantial and has semi-permanent life without any troubles for maintenance. Not only linear characteristics but also any non-linear characteristics can be easily obtained from it and also very superior characteristics can be obtained by selecting the superior materials. Consequently, it is best fitted for these devices at the present stage. Fuji Denki is manufacturing the iron core material of highest characteristics which can be obtained in our country, and by using this material we are getting various kinds of magnetic amplifiers inclusive of D.C. amplification of such small energy as EMF of thermo-couple. We call this magnetic amplifier as "Amplitrans", which is adopted as our standard for the various automatic controlling devices. The present device, which is described here, is the collective automatic regulating device which can control automatically and smoothly the series of excitation control such as AVR (Automatic Voltage Regulation), APFR (Automatic Power Factor Regulation), kVA limiting, and automatic voltage balancing at the time of synchronizing, and yet it is a perfect static type device, of which each part consisting of "Amplitrans". Further, magnetic amplifiers having the considerable large capacity can be manufactured economically, and this device dispenses with the sub-exciter because its out-put enough to excite the main-exciter directly. Therefore, it can be said to serves as a sub-exciter. This device has already many actural results of operation with very excellent performances.

II. FEATURES OF THIS DEVICE

Main points of the features of this automatic regulating device are as follows:

(1) The regulation of excitation of large capacity synchronous machine is feasible automatically with accuracy and safety from its starting to its normal operation. Namely, if the machine is started, it builds up the voltage to the value to coincide with the line voltage for the synchronizing operation. After setting the machine into parallel operation, either AVR or APFR can be performed at any desired selection. For sudden voltage drop caused by the failure of short circuit of the line, the quick excitation is made to keep the stability, but, for the continuous over-load, it limits the out-put up to the allowable kVA. Even in case that APFR is selected, at the light or no load operation the characteristics of AVR becomes more effective automatically to maintain the stability of the excitation.

(2) Except some relays are in use changing over the simple line, regulating parts are of fully static type using the " Amplitrans ", so that the performances are very excellent and free from the maintenance troubles. There is no contact and setting spring in main part of it, and all setting operation can be executed by the mean of adjustable rheostat.

(3) The installation can be made at any place because constant supervisions and maintenances are not necessary, so that the device is usually set as a cubicle type in a cornor of the synchronous machine room. The resistor, necessary for regulating the setting values are to be driven by the motors controlled from the main switchboard.

(4) The electric source of the device is taken from the A.C. generator coupled directly to the synchronous machine or from the motor-generator connected to the terminal of the synchronous machine, so that the stable operation is available independently of A.C. or D.C. sources of station service. If the frequency of the source is made high, the degree of amplification of the magnetic amplifier increases and simultaneously its time constant is decreased. Hence, high frequency of 400 Cy/sec is usually adopted to make the device small and the degree of response high.

(5) The direct excitation of main exciter is made by the last stage magnetic amplifier and the subexciter is omitted. Also, the main-exciter is provided with a shunt-field windings besides the positive and negative field coils energized by the magnetic amplifier. First, the rapid regulation is executed by the latter coils and then is

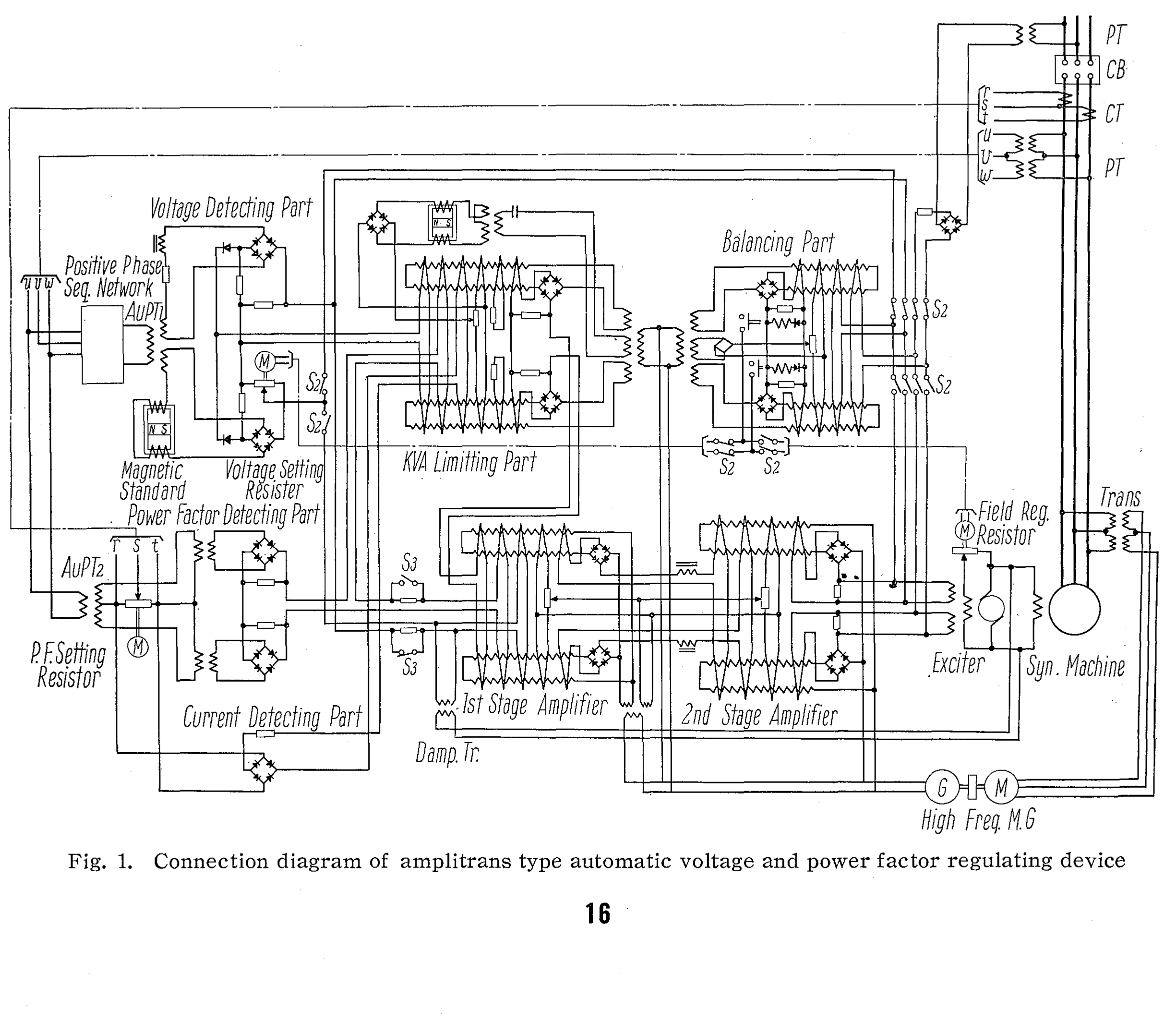

Fig. 1. Connection diagram of amplitrans type automatic voltage and power factor regulating device

gradually shifted to the former windings, so that the latter to be kept nearly at its zero out-put in the ordinary state to keep always an ample margin for the quick excitation.

III. PRINCIPLE OF OPERATION

Fig. 1 shows the brief connection of this device. Firstly there is a main-exciter having the shunt windings and two pieces of independent field coils. Then, there are a synchronous machine excited by this exciter, a circuit breaker on its A.C. side, potential transformers to obtain 3 phase voltage and current transformer to obtain two phase current, placed on the side of the synchronous machine from the circuit breaker. And there is a *PT* to obtain single phase voltage on the side of line from the breaker. As a power source, there is a high frequency generator either coupled directly to the synchronous machine or drived by a motor, as shown in the illustration, connected to the A.C. side of the synchronous machine through transformer. In the present device, there are 1st stage and 2nd stage push-pull type magnetic amplifiers.

With their out-put the positive or negative excitation is given to the main-exciter in addition to its shunt-field. As it is not necessary to select the degree of amplification so large in this device, a degree about 10^5 is employed to be used for tens of thousand kVA synchronous machines, though there is some changes depending on their capacity.

3 sets of coils namely, for voltage regulation, for power-factor regulation and for kVA limiting, are provided on the in-put side of 1st stage amplifier. For them, there are voltage detecting parts and power-factor detecting parts. The rheostats, which determine the setting values of voltage and power-factor, are of motor driven type to be remotely controlled at will from the main switchboards or distant controlling stations. In addition, there are kVA limiting parts and balancing parts, consisting of push-pull type magnetic amplifiers. The former possesses non-linear characteristics and, adjusting the degree of amplification of the abovementioned main amplifier part properly by its out-put, limit the over-load beyond the allowable capacity of synchronous machine. The latter has two kinds of missions. Namely, at the starting of synchronous machine, it controls automatically the voltage setting rheostats to make the voltage of synchronous machine to coincide with the line voltage to satisfy the necessary conditions of synchronizing throw-in. Then, during the operation, it shifts the out-put of the amplifier gradually to the shunt-field of the main-exciter in order to keep the device always at very slight load so that it is always ready for quick adjustments for the sudden variations. Further, for the purpose of stabilization of the automatic regulating circuits, the damping transformers are used, by which, only the transient part of D.C. voltage of the exciter is taken out for feeding back it negatively to the in-put of the amplifier part to prevent hunting.

IV. AUTOMATIC VOLTAGE REGULATION

Connecting the positive phase sequence network to the secondary side of potential transformers connected between the synchronous machine and the circuit breaker for getting 3 phase voltage, the positive phase sequence voltage of its out-put is led to the voltage detecting part. Voltage detecting part, as shown in Fig. 2, is divided by auxiliary *PT* (*Au PT.*) into two circuits, one is a proportional current circuit and the other is a constant current circuit. The former is rectified to full-wave as it is to gain such a current as shown by the curve 2 in Fig. 3, while the latter is rectified to full-wave through a constant current device to gain current as shown by the curve in Fig. 3. For the constant current device, the so-called " Magnetic Standard " is used,

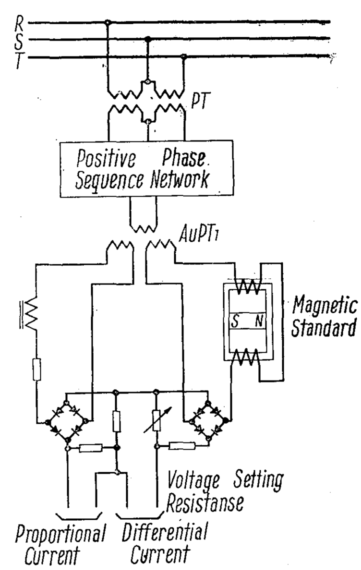

Fig. 2. Principle diagram of voltage detecting part

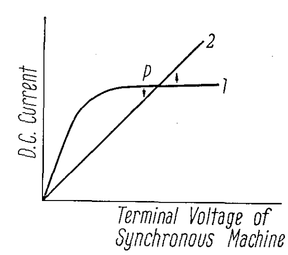

Fig. 3. Characteristic of voltage detecting part

as shown in Fig. 2, instead of the controlling D.C. windings of a saturable reactor, flowing the controlled curent through the A.C. coil, the constant flux of a permanent magnet being used, thus the current at a constant value in a wide range of variations of A.C. voltage, being maintained. Hence the out-put current can be kept in a constant value with a very high accuracy for a wide range. Accordingly, if the differential out-put current between the proportional current circuit and the constant current circuit is taken by connecting them as shown in Fig. 2, D.C. currents of opposite directions upward and downward of the clossing point P of curves 1 and 2 in Fig. 3 are obtainable. Leading this differential current into the in-put coil of amplifier and giving positive or negative excitations to the exciter, it regulates the terminal voltage of the synchronous machine so as to kept it at point *P*. The out-put resistor R_1 of the constant current circuit is a motor driven rheostat. By operating it the curve 1 can be shifted upward or downward, and the terminal voltage of the synchronous machine can be set at a definite value. The excitation of the exciter at the ordinary state is born by its shunt field, while 2 sets of field windings of out-put of the magnetic amplifier supply only the varied portions of voltage or power-factor at the time of fluctuation, so that automatic regulation is operated. Although this regulating operation is of the static control, the degree of amplification is very high and the deviation of regulating value is within 0.5%. Therefore, it is the same as the astatic control, and further, there is no unresponsive zone at all as in the case of astatic control, being of very superior characteristics. Loop gain is about 800, and the error can be suppressed within 0.5% even for the rapid variations. As it is static control, it is very stable. Since high frequency is used as an electric source, the time-lag to take out the out-put variation of 100 V 25 A is only 0.01 seconds, and then the time-constant can be considered only that of the exciter and the synchronous machine. This device, even in its operation as AVR, the effect of power-factor regulation, to be described later, is added in its state of a little lowered sensibility. Accordingly, it is regulated in such a manner that power-factor does not vary too much from its predeterminal value and the circulating current between the each machines in parallel operation is limited. The magnitude of this effect can be adjusted freely according to the operating conditions.

V. AUTOMATIC POWER FACTOR REGULATION

The connection of power-factor detecting part is as shown in Fig. 4. Divide the one phase portion

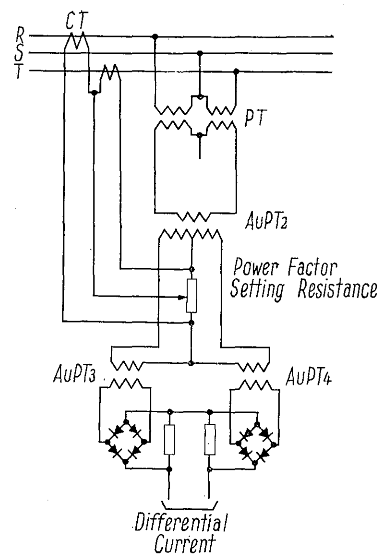

Fig. 4. Principle diagram of power factor detecting part

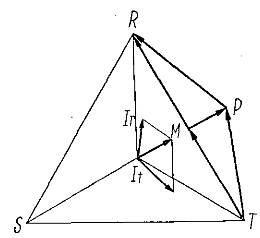

Fig. 5. Vector diagram of power factor detecting part

of the terminal voltage of the synchronous machine into two parts by the auxiliary transformer and lead the main circuit current to this middle point of this voltage through the *CT* and add its voltage drop perpendicular to this voltage. Namely, in Fig. 5 two voltages *RP* and *TP* are available by adding voltage drop *MP*, produced by the current perpendicular to *RT*, to the middle point *M*, *MP* can be obtained by the vector-sum of *R* phase and *T* phase currents, but *MP* is to be determined in such a manner as the vector-sum becomes perpendicular to voltage *RT* by adjusting the resistance values of resistors, through which the both phase currents flow respectively at a certain power-factor to be maintained. When the synchronous machine is kept at a certain predetermined power-factor, the magnitudes of voltage *RP* and *TP* are equal. However, if power-factor changes, both voltages become different in magnitude. Namely, the positive or negative D.C. current are available at the time of variation from the predetermined power-factor if these two voltages are given full-wave rectification to get the differential current between them. Giving this D.C. current thus obtained to the amplifier part, the excitation is regulated to predetermined power-factor. The setting of the power-factor value can be made freely from the main switch-board or remote controlling station by operating the motor driven rheostats which produce the voltage drop by the current.

The changing over of AVR and APFR can be made very simply, but, AVR is also effective in such a state that its sensibility is lowered to a certain degree even in the operation of APFR, and that in case APFR loses its stability by the decrease of current at light or no load of the synchronous machine, it operates as AVR automatically thus very smooth and stable operations being expected.

VI. KVA LIMITING DEVICE

The limitation of the active power while the synchoronous machine is operating as a generator or a motor is outside of the duty of this device. As this is a device of controlling the excitation, it is necessary to provide a kVA limiting device to limit the load in case the synchronous machine out-put exceeds its allowable overload capacity. However, as it is practically unnecessary to use the synchronous machine up to its allowable limit of insulation and temperature, and also as it is sufficient to limit it safely in case of stepping out of the normal operation, a simple device which can be used for both purposes is adopted. The kVA limiting part shown in Fig. 1 is constituted of differential type magnetic amplifier, and there are 4

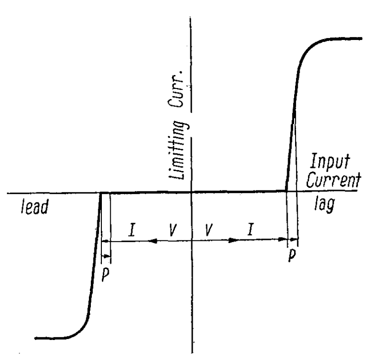

Fig. 6. Characteristic of kVA limitting part

sets of controlling coils, which are respectively fed by D.C. current proportional to the main circuit current, D.C. current proportional to the main circuit voltage, D.C. current which varies in response to the power-factor and changes its polarity according to its leading and lagging, and constant bias D.C. current. Bias current is kept at a constant value by " Magnetic Standard " and also this value is selected large to the push-pull type magnetic amplifier, so that the characteristics of this amplifier become non-linear as shown in Fig. 6. If the performance is adjusted in such a manner as to be in a range of coinciding with the horizontal axis of this characteristics in case of unity power factor within the allowable voltage and the allowable current of the main circuit, the limiting operation will not be executed at all in this range. If the current in main circuit becomes too large over the allowable value, it exceeds this range, but the current corresponding to the power-factor is to change its polarity depending on wheather leading or lagging, so that the sum of the controlling current becomes not identical at the left or the right, producing the positive or negative out-put current which gives such an effect to the amplifier part as to increase or to decrease the excitation and limiting the kVA.

VII. BALANCING DEVICE

As shown in Fig. 1, balancing device also consists of the push-pull type magnetic amplifier, and in its out-put circuit, there is respectively one set of relay which is to be operated on current of positive or negative polarity, and according to the operation of either one of this relays, the motor driven type rheostat is driven in one or the other direction to adjust the resistance value.

The balancing device is given two kinds of missions in order to increase the utilization factor of the device. Namely, in starting the synchronous machine, relay-contacts of the out-put side of the balancing device are connected to the driving motor of the voltage setting resistor, and to each of 2 controlling coils of the in-put side, D.C. current proportional to the terminal voltage of the synchronous machine obtained from the voltage detecting part and the line voltage available from line-side *PT*, are led in respectively. If the synchronous machine starts, the above-mentioned circuits are made, and as the line-voltage is already established and the voltage of the synchronous machine is null, the voltage setting resistors decrease its resistance value with relative slowness from its maximum value and the voltage of the synchronous machine increases gradually and stops at a point where it coincides with the line voltage. In this state, the other automatic speed adjusting device and the automatic synchronizing device operate to perform the parallel operation. This balancing device is cut off from the above-mentioned circuit by the close of the circuit-breaker and, if necessary, the voltage setting resistor is controlled to a certain setting value by the operation from the main switch-board or the remote controlling room operating as the AVR, or as the APFR if it is changed over. After the closing of the circuit breaker, with respect to this ballancing device its relay-contacts of the out-put side are connected to the driving motor of the field rheostat for the shunt-field circuit of the exciter and 2 sets of in-put side controlling coils are connected to the positive and negative excitation circuit which are on the out-put side of the amplifier. Accordingly, if the difference is occured between currents flowing 2 circuits of the amplifier out-put upon the operations of the AVR or APFR, the balancing device operates the field-rheostat with relative slowness to shift the amplifier out-put to the shunt-field, bringing the amplifier out-put to zero. Thus, this balancing device can be maintained in such a state that it can be always ready to response even to large and rapid variations of the voltage or the power-factor.

VIII. ACTUAL RESULTS OF THIS DEVICE

There has been such examples of using the magnetic amplifiers as AVR for the generators of small capacity since long ago. However, such examples that the magnetic amplifiers were used for the synchronous machines of large capacity by adopting the systems of considerable higher class and the fully static type are rare. Moreover, this device is not only the simple AVR but also it operates reasonably and smoothly for every stages from startings to operations of the synchronous machine, so that this is believed to be the epoch-making synthetic automatic regulating device.

Our company has several years experience since the commencement of the actual operation of the first set of this device, and is enjoying good reputations because of its superior performances but also because of its high reliability and its simple handling of adjustments and maintenances. At present, 10 sets of these devices, inclusive of 2 sets for use of 24,000 kVA of Sudagai P.P. of Tokyo Denryoku K.K., are being operated very smoothly, and now, 9 sets, inclusive of 1 set for use of 41,000 kVA of Akiba No. 2 P.P. of Dengenkaihatsu K. K. and 2 sets for use of 30,000 kVA of Akiba No. 1 P.P. of the same company are under manufacture.

The accuracy required for AVR in Japan is 1%, but our company guarantee 0.8% for this device and even 0.5% is possible. The voltage rise at the time of full-load rupturing of the ordinary hydro-turbine generator can be suppressed less than about 20 to 26% within 0.3 to 0.5 seconds, and there is such a record that it was only 14%.

Also, it can suppress the voltage difference between both circuits less than 1% if it operates as the automatic voltage balancing device after starting. By using this device, the sub-exciter is omitted and this device, as shown in Fig. 7, is to be installed at any corner of the machine room. The ordinary setting of this device is to be made from the main switch-board or the remote controlling room, and simple adjustments and tests of this device proper can be carried out from the outside of the cubicle, and the fine adjustments and the partial tests can be done simply by opening the door. Fig. 8 shows the back view the door is opened.

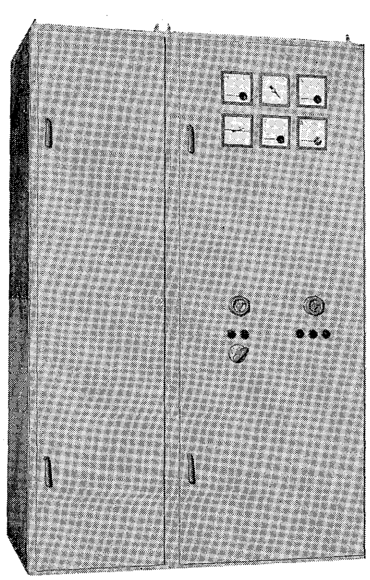

Fig. 7. Front view of amplitrans type automatic voltage and power factor regulating device

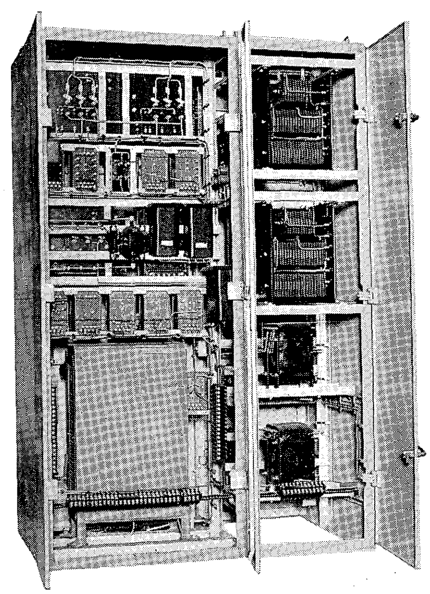

Fig. 8. Backside view of amplitrans type automatic voltage and power factor regulating device (door opened)

IX. CONCLUSION

AVR or APFR, which are necessary for the operation of the synchronous machine, are generally very troublesome in their maintenances, and there was even such an example that these devices are being not used at all in spite of the actual installations. Also there was such an undesirable example that the other resistance is inserted in the excitation circuit because the existing device can not suppress the voltage-rise enough in case of full-load rupturing. Owing to the fact that APFR can not perform the stable regulating operation at light or no load, there was such an example which had to install the other AVR additionally. Further, the automatic voltage balancing device, over-current limitting device, over-voltage limitting device, etc. needed so that the whole set become very complicated and consequently, the large space was required in the switch-board room, this device is fully static type and no problem arises of its life and maintenance. Also it is using commonly the amplifier which can be substituted for the sub-exciter, and the other parts are constructed in a very small sizes. Further, the installation can be made at a corner of the synchronous machine room. Consequently, these troublesome problems as mentioned above are perfectly solved away and it becoms very simple and highly reliable.

The actual applications of this device are all such that manufactured and delivered along with the Fuji Denki synchronous machine of large capacity. However, it is quite possible to apply this device by some reconstructions to be existing synchronous machine. At present, the further investigations are being carried out and it is expected that in the near future, the more excellent performances will be available.

Introduction of Products

154 kV 81,000 kVA PERFECTLY SHIELDED OSCILLATION-FREE TYPE "FAHRBAR" TRANSFORMERS

By

Sadao Maekawa

(Transformer Dev., Engineering Department)

One of the transformer engineer's visions—to save the time of drying the unit again or of assembling it at the site and simplify the crane facilities has come true by the birth of "Fahrbar" transformers, with which it has become feasible to maintain high insulation strength attained by means of thorough drying at the factory.

These "Fahrbar" transformers were first developed in Europe. It is reported that the Siemens Schuckert Works has built a unit of this design having a capacity of 245 kV 200 MVA recently. Unlike Europe, transportation facilities in Japan is confronted with various unfavorable conditions, which have hampered the growth of building large sized units. Our company, since 1945, however, pioneered in the effort of taking up "Fahrbar" design of large capacity transformers and has been successful in producing 187 kV 78 MVA units, 161 kV 78 MVA units, 66 kV 81 MVA units, etc.

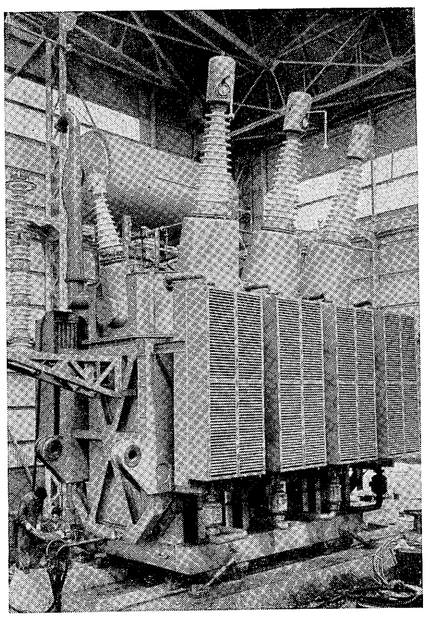

Fig. 1. 154 kV 81,000 kVA Perfectly shielded oscillation-free type "Fahrbar" transformer

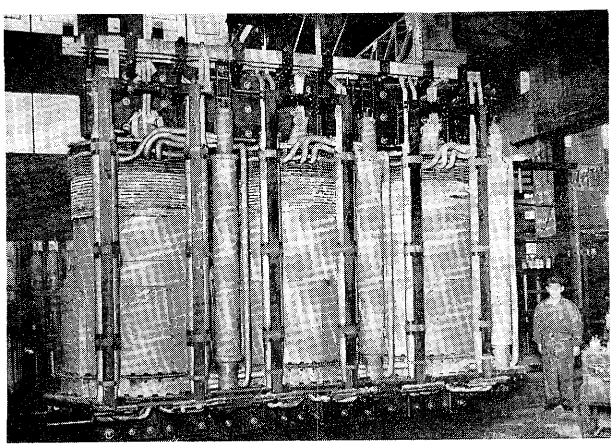

Fig. 2. Interior view of 154 kV 81,000 kVA transformer

The 154 kV 81 MVA "Fahrbar" transformer delivered to the Tokyo Electric Power Company and introduced herein is a record transformer in voltage and capacity transported on a narrow gauge track. Furthermore, as far as the design of perfectly shielded and non-oscillation design is concerned, it may well be called a record product in the world.