UDC 621. 365. 2 : 621. 314. 22

JAPAN'S FIRST LARGE CAPACITY STEEL MELTING ARC FURNACE TRANSFORMER EQUIPMENT DIRECTLY CONNECTED TO 77-KV POWER SOURCE

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I. INTRODUCTION

With the recent rapid developments in the electric steel making industry, the capacities of arc furnaces for steel making are gradually being increased in order to improve productivity. As a result, problems concerning electrical installation etc. have arisen which require investigation.

In general, arc furnaces for steel making utilize scrap iron as raw material. Heat for melting this scrap iron is provided by means of a three-phase large current arc produced between the three carbon electrodes installed in the furnace and the scrap iron. During the melting process, the melting iron sometimes causes shorts in the electrodes which results in violent shocks to the power source. Changes in arc current caused by instability of the arc result in cyclic voltage fluctuations. For this reason, a "flicker" phenomenon is frequently observed in other loads like a TV, lamps etc. which happen to be connected to the same line. This flicker phenomenon becomes more serious as the capacity of the power source decreases in comparison with the arc furnace capacity. Therefore it is desirable for furnace power to be supplied from a source with as large a capacity as possible, that is from a source with a small impedance. It is common for large capacity arc furnaces to be connected directly to 60 kv, 70 kv or higher voltage sources.

In this case, two methods for obtaining power from the source are possible. The first one is to install a receiving transformer by means of which the voltage is first lowered to 10～20 kv before final connections are made to the arc furnace transformer. The second consists of entirely eliminating the receiving transformer and connecting the furnace transformer directly to the higher power source. The latter system features a lower energy loss in respect to the equipment, and economy, both in monetary and spatial considerations. For example: with 15,000 kva equipment, power loss is 65% and floor space is 70% of that necessary with the first method. Although smelting furnaces like carbide or ferro-alloy furnaces were quick to employ direct connections to 60 kv and 70 kv sources, steel making arc furnaces even now usually employ a receiving transformer for primary step down to an intermediate voltage of 10 to 20 kv prior to making connections to the arc furnace transformer, although this has proven uneconomical. The principal reasons for using this uneconomical method can be attributed to the fact that the power source had to be constantly cut off due to the frequent electrode shorting caused by molten iron getting between the electrodes during the melting process, and the need for constant replenishment of the scrap iron and additional ingredients. These operations usually had to be carried out about 50 times or more a day. Repetitive load making and breaking had to be performed by a circuit breaker on the primary of the transformer, so that for a furnace transformer with a primary voltage of 60 kv, 70 kv or over, either no circuit breaker was available which could withstand such highly repetitive operating requirements or maintenance of circuit breakers which could perform these duties became rather complicated at high voltages and presented more serious side effects in case of accidents. Faced with these disadvantages, the primary voltage of the furnace transformer had to be stepped down to 10 to 20 kv. One method of rationalizing this is to employ an indirect voltage regulating system for the arc furnace transformer and conduct repetitive load making or breaking operations by means of a small circuit breaker connected to the transformer tertiary circuit, instead of utilizing a circuit breaker on the primary circuit.

The first equipment using this method was delivered in 1961 to Kobe Steel Works Ltd., Kochi Plant for a silicon-manganese furnace. This method was also applied in the 6000 kva ferro-manganese furnace built for Mizushima Ferroalloy Co., Ltd. as well as in the 6800 kw silicon rectifier equipment built for Toyo Soda Company, although for different purposes than those described above. Recently, a 15,000 kva furnace transformer for direct connection to a 77 kv power source (the first of its kind in Japan) was delivered to Kawasaki Steel Corporation Nishinomiya Plant, for use on their steel making arc furnace. An outline of this equipment will be given below.

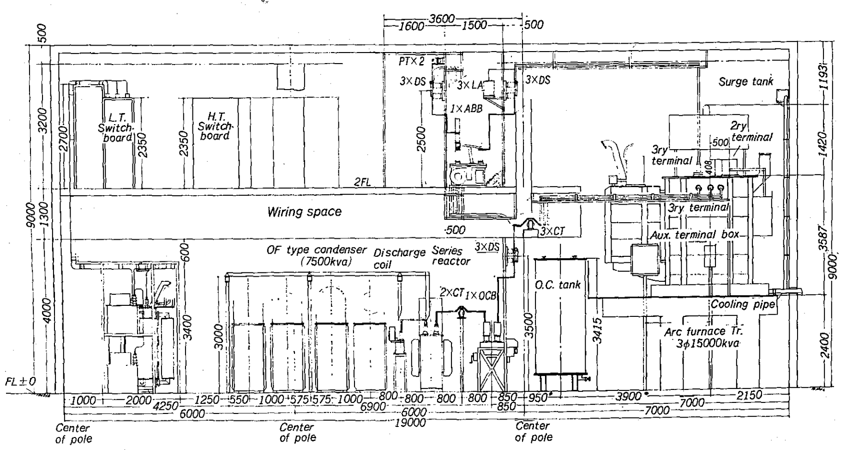


Fig. 1 Arrangement of electrical equipment

II. OUTLINE OF THE EQUIPMENT

The electrical equipment delivered by Fuji Electric was connected to the arc furnace built by Ishikawajima Harima Heavy Industries.

Fig. 1 shows the arrangement of Fuji Electric equipment. An elephant bushing was employed for connecting the 70 kv power cable to the arc furnace transformer allowing for compact construction without bare 70 kv charged portions. Ratings of the arc furnace transformer are as follows:

Cooling system:	Forced-oil water, cooled
Output:	3 phase, 15,000 kva, 60 cps
Ability to withstand overload:	120% maximum tap voltage for 2 hours
Primary voltage:	77,000 v
Secondary voltage:	350∼320 (R)∼110 v, provided with 17 taps in 15 v steps
Primary current:	112.5 amp
Secondary current:	27,100 amp
Connections:	
Primary:	Delta connection
Secondary:	Open delta connection
Tertiary:	Wye connection
Bushing:	
Primary:	Elephant type (♯70 insulation)
Secondary:	Dry flat-bar type terminals (♯1 insulation)
Tap changing method:	On-load, motor driven tap changing method
Impedance voltage:	10.66% (15,000 kva base)

Because the requirements of power transformers differ widely depending on their applications, the following points were carefully considered with regards to design and construction.

(1) Adequate precautions were taken with regards to stray losses and reactance drop due to low voltage/large current (350–110 v, 27,100 amp) on the transformer secondary. In this equipment, special efforts were made to improve winding methods and lead distribution in order to minimize stray losses produced in the windings and frame work as well as to reduce a reactance drop.

(2) The secondary voltage is adjustable over a wide range. The most suitable, economical system was used: i.e., indirect voltage regulating and load interrupting system on the tertiary circuit were employed to withstand repetitive load switching. Since on-load secondary voltage adjustments become extremely frequent due to automatic adjustment of the load power, a highly reliable new type of on-load tap changer has been employed.

(3) Load fluctuates considerably in steel making arc furnaces aside from the fact that the electrodes are frequently shorted due to molten scrap or unstable arcing. This equipment is however, of rugged construction, both mechanically and electrically, so as to be able to withstand mechanical stresses resulting from load fluctuations, temporary overloads and shorts.

(4) With regard to the installation area, precautions were taken to minimize the amount of dust present. An elephant type bushing has been installed on the 77 kv terminal for absolute safety.

(5) The main equipment has been made lighter and more compact. Particular considerations have been given to the distribution and installation of accessories and fittings so that all the equipment can be installed in an extremely small floor space.

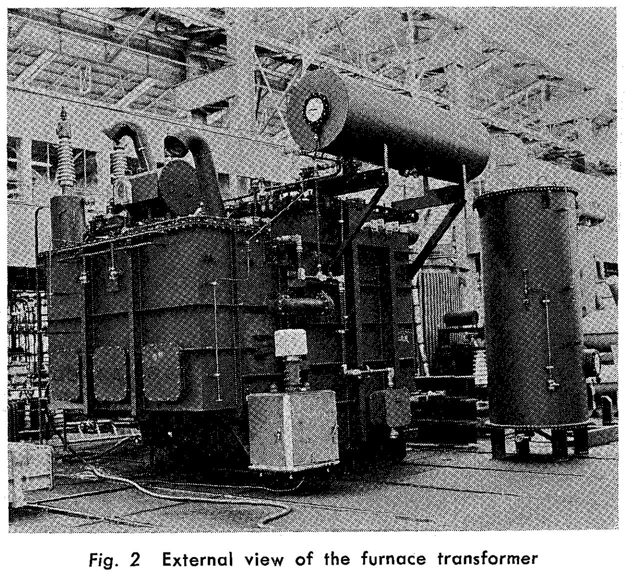
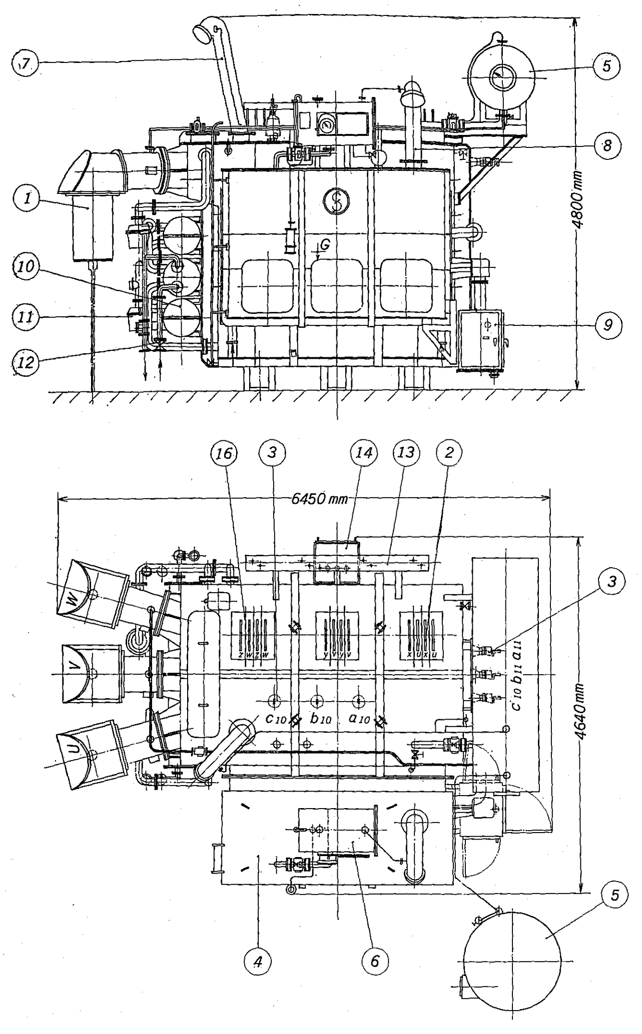


Fig. 2 External view of the furnace transformer



① 1ry side elephant case
② 2ry side flat-bar type terminal
③ 3ry bushing
④ Tap switch case
⑤ Oil conservator for main tank
⑥ Oil conservator for switch case
⑦ Pressure-relief device for main tank
⑧ Pressure-relief device for switch case
⑨ Motor driven tap changing mechanism
⑩ Water cooled oil cooler
⑪ Oil pump
⑫ Outlet of cooling water
⑬ Fixed plate for L.V. connecting lead
⑭ Magnet contactor box
⑮ Separate-type nitrogen gas sealing equipment
⑯ Interphase insulating barrier for 2ry terminal

Fig. 3 **Construction diagram of the furnace transformer**

Finally, matters particular to the furnaces themselves were taken into consideration with regards to the cooling equipment and construction of the secondary terminals.

III. CONNECTIONS

The complete connection diagram for this equipment is given in *Fig. 4*. In order to satisfy the requirements imposed by adjustments of the secondary voltage over a wide range as well as repetitive load switching, indirect voltage regulating and load interrupting system on a tertiary circuit; special devices manufactured by Fuji Electric were employed. A general description of these devices follows:

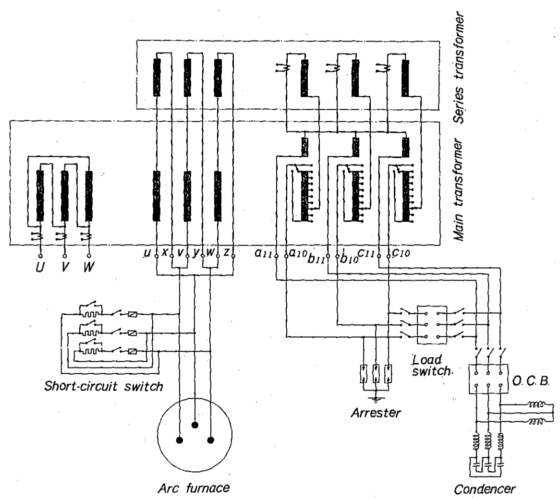


Fig. 4 **Connection diagram of arc furnace transformer**

Arc furnace transformer employing indirect voltage regulating system.

(1) The maximum required secondary voltage is equally divided between the main transformer and the series transformer.

(2) A circuit breaker is installed on the tertiary circuit of the main transformer, that is on the primary circuit of the series transformer. A switch has also been provided for shorting out the arc furnace electrodes.

Since the arc furnace current is interrupted by means of the circuit breaker on the tertiary circuit and not by the circuit breaker on the primary side, the voltage between the electrodes can be reduced to zero. (Patent No. 271066). Operation can be seen with the aid of the single phase connection diagram in *Fig. 5*. When the load switch is open, the series transformer is disconnected from its energizing power source and is converted into a choking coil. Secondary voltage on the main transformer is applied to the series transformer secondary winding through the load.

Only the exciting current which results when the

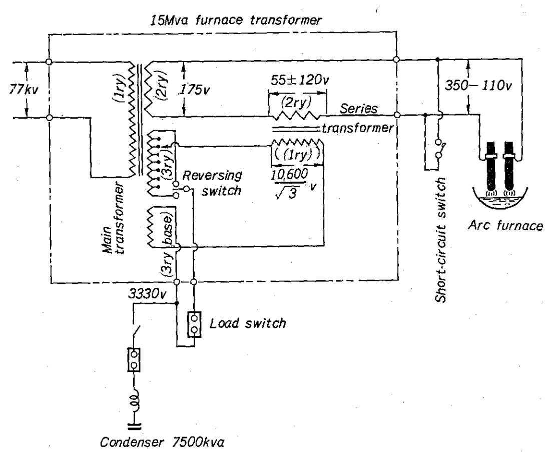


Fig. 5 **Single phase connection diagram**

series transformer is excited on the secondary side flows through the load circuit, (less than 1% of the rated current), so that load can be considered as practically cut off. When scrap must be replenished or when molten steel taken out, closing the secondary shorting switch will cause the exciting current previously mentioned to transfer to the shorting switch, making the electrode voltage and current exactly zero.

Since the required secondary voltage for this transformer is 350 to 110 v, secondary voltages are distributed on the main transformer (175 v) and the series transformer (55 ± 120 v). The tertiary side is made up of an untapped base winding as well as a tapped winding so that the secondary voltage can be adjusted over a wide range merely by changing the polarities on the tap winding. The load power factor of the furnace has been improved by the connection of a capacitor parallel to the tertiary base winding. (Patent No. 257038).

This transformer, with its indirect voltage regulating system, not only provides wide adjustments of secondary voltage and load switching on a tertiary circuit but also connecting of a phase-leading capacitor, and series reactor in a tertiary circuit when they become necessary in the future, thereby economizing on equipment cost while still allowing for the usual power load from the tertiary winding.

IV. CONSTRUCTION OF THE ARC FURNACE TRANSFORMER

1. Core and Windings

Standard three-legged cores were employed for both the main and series transformers in accordance with their capacity. Sufficiently annealed highest grade oriented silicon steel core sheets were utilized as core material. 45 degree angle joints were also used in the construction of the core, since they do not differ in any way from cores of highly reliable and well constructed power transformers presently on the market.

Windings of the main transformer are distributed concentrically in the following order starting from the innermost winding as shown in *Fig. 6*: tertiary tapped winding, tertiary base winding, primary high voltage winding, secondary low voltage winding. The reasons for placing the secondary low voltage winding in the outermost position in contrast to the usual practice with power transformers, are ease in connecting parallel conductors where large currents are involved, improvement in lead arrangements and reliability in construction, all of which may be thought of as general features of large current transformers for rectifier and arc furnace applications.

Since the 77 kv high voltage winding is sandwiched between the secondary winding and the tertiary winding, protection against surge voltages is decreased due to the stray capacitance between this winding

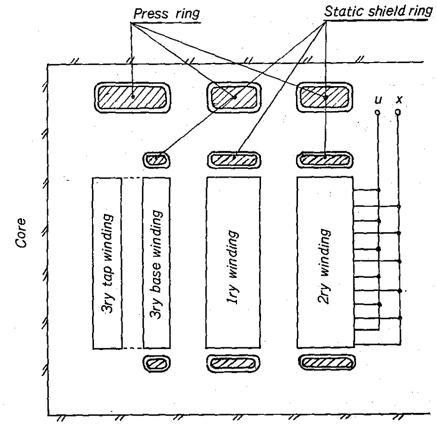


Fig. 6 Arrangement of main transformer windings

and the ground. After considering this point, a high series capacitance winding possessing excellent surge voltage characteristics (the type employed in the high voltage windings of power transformers) was used as the primary high voltage winding. Along with appropriate insulation this system provides sufficient capacity to withstand switching surge voltages and other irregular voltages as well as allowing for a decrease in winding dimensions and insulation space resulting in a lighter and more compact transformer.

Multi-parallel disc windings were employed for the secondary low voltage coil. Each parallel conductor was suitably transfered, resulting in uniform current distribution between conductors and minimizing stray load losses. Windings have also been constructed so that local overheating does not occur. Coil ends are connected to several flat-bar terminals ganged together and connected to the low voltage output terminals on the upper portion. Since very large currents flow through the low voltage leads, and the ampere-turn equivalent of the leads are subjected to rather large current values, it is necessary to construct them in such a way as to minimize the amount of leakage flux produced. For this reason, low voltage leads with similar phases but opposite current directions have been positioned together as close as possible starting from the coil ends up to the low voltage output terminals which causes mutual cancellation of ampere turns and minimizes the total leakage flux as well as preventing stray load losses resulting from neighbouring portions and reducing a reactance drop. Because of the excellent techniques used in the design of the windings and arrangement of the low voltage leads, very satisfactory results have been obtained from tests made on the transformer and extremely small load losses have resulted in spite of the large currents.

Cylindrical block windings with excellent cooling properties and spatial factors were employed for the tertiary base winding. Since the current of the capacitor connected to the tertiary terminals to improve the power factor flows through the coil, it

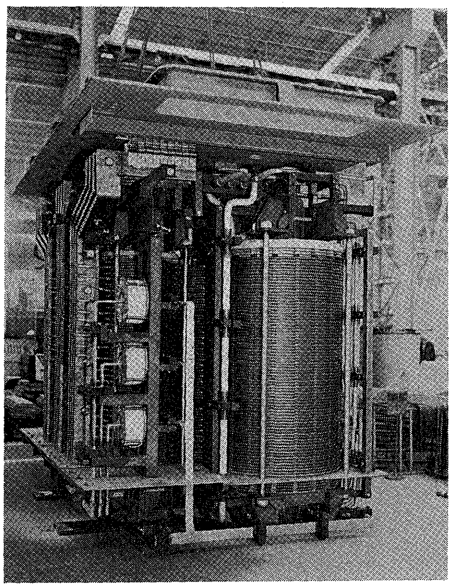


Fig. 7 Interior of the furnace transformer

is well suited to relatively large currents. Multi-parallel cylindrical tapped windings consisting of two layers were used for the tertiary tapped windings. In constructing the coil, conductors were arranged mutually so that ampere-turn distribution does not vary with tap positions, thereby minimizing leakage flux and suppressing the mechanical axial stresses produced during shorting.

In contrast to the usual power transformers, the chances of shorting the furnace electrodes are high so that special emphasis has been given to the mechanical strength of windings, winding supports and mountings, lead supports etc., in order to insure absolute safety. A mechanically durable phenol resin laminated plate has been inserted on the inner side of the tertiary winding to provide extra mechanical strength needed to withstand the mechanical stresses caused by shorting. *Fig. 7* illustrates the interior of the furnace transformer.

2. Elephant Bushing on the High Voltage Side

In order to prevent dust or gas from getting into the equipment as well as to satisfy the safety precautions required when dealing with extremely high voltages, an elephant type bushing was utilized on the 77 kv high voltage side. The direct system used in the elephant bushing where the cable head case is separated from the main transformer by a through-type insulation (one material is inserted through another) is a speciality of Fuji Electric. This through-type insulation serves to isolate the elephant case completely from the transformer during assembly or inspections. Based on numerous past results, this has been found to be the most appropriate type developed so far. This type presents advantages in respect to safety and compact design particularly for the installation of the equipment. The oil in the elephant case need not be drained even when

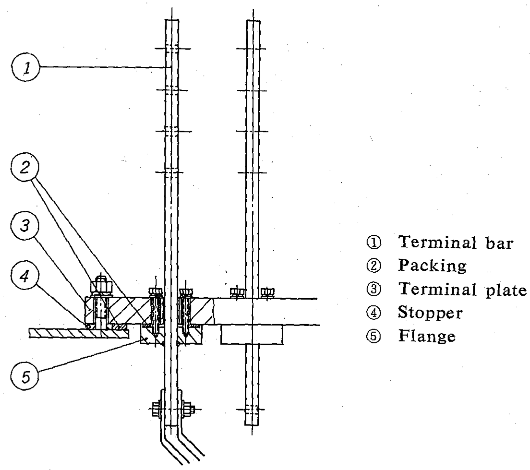


Fig. 8 Construction of the flat-bar type terminals

the OF cable must be connected during installation, since this oil and the main transformer oil are supplied separately. Therefore the same conditions present during the factory tests are preserved and official tests can be performed in conjunction with the results of factory tests.

3. Flat-Bar Type Low Voltage Terminals

Flat-bar type terminals, most suitable for low voltage/large current applications were employed as bushings on the tank outlet portion of the low voltage side. *Fig. 8* shows the construction of these terminals. Phenol resin laminations have been utilized as the terminal insulating plates on the outlet portion. Due to certain factors involved in connecting this equipment to the arc furnace terminals and problems with regard to transport, two plates each (+, −) were used for the one phase, making a total of four.

4. On-Load Tap Changer

As has been described earlier, load adjustments in the furnace transformer have to be conducted through the secondary tap voltages. When transformers like these are to be used for furnace operations, the on-load tap changer has to operate more frequently because of severe load fluctuations imposed by the service conditions. They cannot therefore be compared with the usual power transformers. For this reason, sufficient consideration must be given when selecting the equipment to the construction of contact points and the operating mechanism as well as high reliability with respect switching. Combining the results of past experience with the most recently developed techniques, the DSC-1 totally enclosed on-load tap changer has been utilized. This tap changer has already exhibited excellent results during more than ten years of use. It incorporates the 2-resistor switching method, double-four-node link mechanism and long life contactors, the superb capabilities of which have long been acknowledged. Certified results of type tests conducted jointly by various electric power companies with regard to durability, switching capability and other operating capabilities indicate sufficient ability to withstand severe switching requirements.

5. Forced-oil Water Cooled Oil Cooler

Since this transformer was to be installed near the arc furnace, a horizontal type water-cooled oil cooler was employed which was as compact as possible. Deoxidized copper pipes were utilized as the cooling pipes, ensuring durability in respect to the undesirable effects of hardness, chlorine ions and evaporation residues in the cooling water. For convenience in equipment lay-out, the horizontal cooler has been positioned below the high voltage elephant case, thereby contributing to the compactness of the entire transformer.

6. Transport

Assembled transportation, that is the transporting of pre-assembled equipment for direct installation so as to preserve the same factory conditions, has become usual practice nowadays. This transformer is a typical example of this manner of transport. Although weight and size restrictions are imposed by cargo vehicles, transformer of this capacity can be transported comparatively easily using railway cars within the secondary transportation limits for railways by merely detaching the oil conservator. However, the switch case had to be transported separately because of the limited floor space and also because it had to be located beside the main tank. As a result of the specially constructed terminals for connecting the main tank to the outlet portions on the switch case, assembly time has been shortened and the time required for conducting periodic inspections has been decreased.

V. POWER FACTOR IMPROVEMENT

In general, the circuit reactance is increased due to large current/low voltage on the electric furnace, resulting in a very poor power factor (around 80% to 90%). Although the power factor may be improved to a certain extent by proper electrode positioning and arrangement of connecting leads, it is not advisable to make the reactance too small because of problems which will arise concerning arc stabilization as well as the suppression of the "flicker" phenomenon caused by arc fluctuations. Therefore, to economize on power costs, separate equipment for power factor improvement has been provided.

Costs become prohibitive when the phase leading capacitor is installed on the 70 kv side and the switching requirements on the circuit breaker become more severe when the capacitance is to be increased or decreased in accordance with the furnace load. To overcome these problems, the capacitor is connected in parallel with the tertiary winding used for voltage adjustment (shown in *Fig. 5*) of the furnace transformer, thus employing an indirect voltage regulating system. That is, since the load current and capacitor current are superimposed on the tertiary winding, the phase of the main transformer primary current leads, and the power factor is improved.

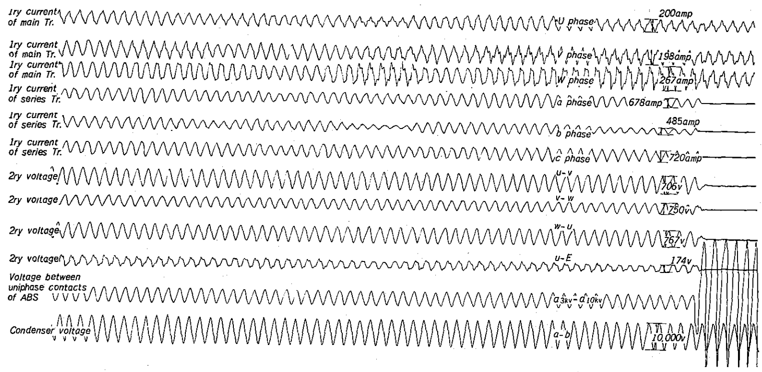
With this method, both voltage adjustment and power factor improvement are effected by the tertiary regulating coil without a separate winding for connecting the capacitor. Transformer size is therefore not increased. Since current with a leading phase compared to load current flows through the primary winding, the input capacity decreases, making it possible to minimize the copper loss. Since any ordinary high voltage capacitor can be employed, equipment cost is decreased considerably, compared to when the capacitor is connected on the 77 kv side. The leading phase capacitance should usually be selected in respect to power factor improvement not only for the furnace load but also for all other power loads in the factory. However, since, electric power is supplied from power companies through 77 kv power lines for exclusive use with the furnace, it is sufficient to consider only the arc furnace load when dealing with power factor problems.

The average power factor for one charge of furnace load has been estimated at about 82 to 83% and 78 to 80% during the melting period. A constant power factor of 100% is of course ideal, but when a 100% arc furnace load power factor is attempted, the power consumed during one charge fluctuates considerably, becoming more severe for the melting period where the power consumed is much larger. It then becomes practically impossible to adjust the capacitance properly. Since the magnitude of the capacitance for this equipment has been determined on the basis of the high input/low power factor during the melting period, the power factor may increase slightly during the refining process. The capacitor consists of eight 938 kva units connected in parallel forming one 7500 kva bank (it is possible to decrease the number of units).

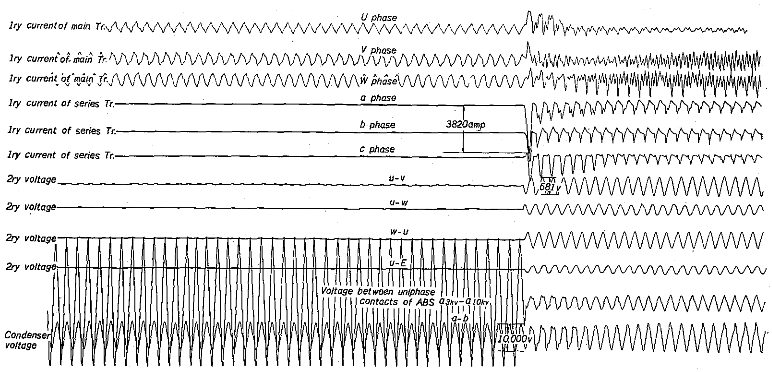
VI. OPERATING TEST

During on-load operating tests, numerous oscillograms of the tertiary load breaking characteristics were recorded. A typical result is shown in *Fig. 9* with the testing circuit used depicted in *Fig. 10*.

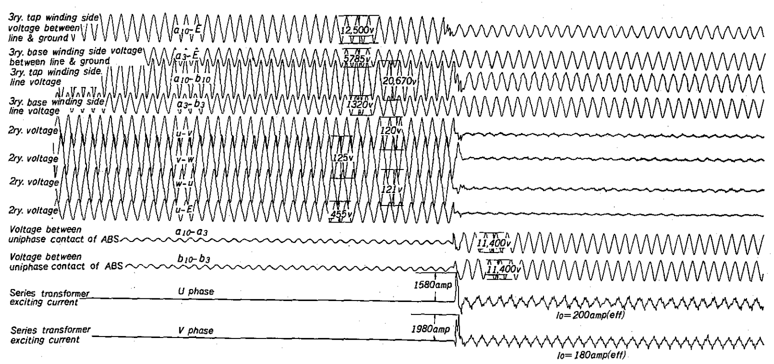
Fig. 9 (*a*) shows the transient responses of the primary current and secondary voltage observed during breaking the load switch on the tertiary side, (abbreviated as ABS) under load conditions of 11 Mw, using tap no. 6. Starting from the top, the oscillograms represent primary current (3 phase), series transformer primary current (3 phase), secondary terminal voltage (1 phase), ABS voltages between uniphase contacts (1 phase), and tertiary base voltage



(a) Breaking of 3ry ABS at load 11 Mw, tap No. 6



(b) Making of 3ry ABS at load 11 Mw, tap No. 6



(c) Closing of 2ry short-circuit switch

Fig. 9 **Oscillograms showing tertiary circuit load making and breaking characteristics**

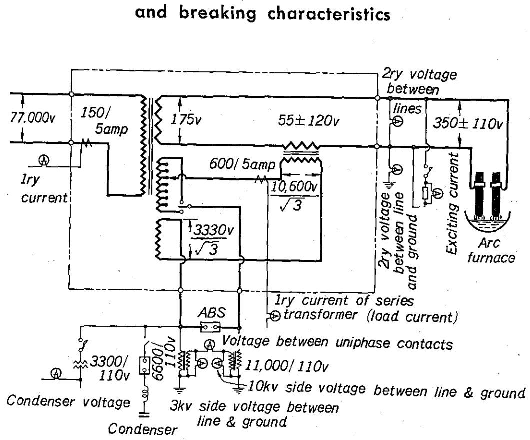


Fig. 10 **Testing circuit for tertiary circuit load making and breaking**

(1 phase). After breaking the ABS, current corresponding to the 7500 kva capacitor connected in parallel with the tertiary base winding flows through the primary winding. There is therefore no other method of determining whether the load has been cut off after the ABS is switched off except to observe the secondary voltage waveforms. Assuming that the secondary current drops to zero after the ABS has been shut off and the load is completely cut off, the secondary voltage should indicate 175 v of the main transformer secondary, but the oscillograms show a voltage drop of only $20\sim30$ v. This is because even after the load current is interrupted by means of the ABS, the load is not completely cut off but is short-circuited by means of a low-resistance. Excitation current (about 200 amp) on the series transformer secondary winding may be assumed to flow through this resistance, thereby accounting for the voltage drop.

Although oscillations are observed before the switch opens because of the difference in winding ratios of the PT inserted before and after the ABS for measuring purposes (see the testing circuit diagram illustrated in *Fig. 10*), the ABS open terminal voltage is actually zero. After the ABS opens, the voltage which appears between terminals of the same phase is the sum of the tertiary voltage and the eries transformer primary voltage. This resultant voltage is also indicated on the oscillograms. This value will not exceed a maximum of $2/\sqrt{3}=1.15$ times the line voltage since the tertiary connections are of the star type with connections to a neutral point.

Fig. 9 (*b*) shows the transient responses when the ABS is closed using the same measuring circuit employed in (*a*) of the same figure.

As can be observed from the oscillograms of (*a*), a low resistance short circuits the load after the ABS is opened and hence, when the ABS is switched on, surge current many times larger than the rated current is observed.

Oscillograms observed when the secondary shorting switch is closed are shown in *Fig. 9* (*c*). These help to ascertain how much exciting current flows when the secondary shorting switch is closed. The exciting current is measured by measuring the voltage drop over a limiting current resistor (60 mΩ) inserted in series with the secondary shorting switch. Oscillograms shown are as follows, starting from the top: 10 kv tertiary side voltage to ground (1 phase), 3 kv tertiary side voltage to ground (1 phase), 10 kv tertiary side line voltage (1 phase), 3 kv tertiary side line voltage (1 phase), secondary line voltage (3 phases) as well as voltage to ground (1 phase), ABS open terminal voltage (2 phases) and exciting current (2 phases). Exciting current flows on the secondary side due to the opening of the ABS so that when the shorting switch is closed at this stage, only the first half wave of the transfer current assumes a high value (in the order of 1500∼2000 amp). After this it is immediately attenuated and presents no problem to the transformer. However, since the shorting switch could be closed while the secondary is still open, a limiting current resistor is inserted into the shorting circuit to ensure absolute safety. The residual voltage resulting from the insertion of the limiting resistor serves to short-circuit the resistor by means of a timing relay, thereby rendering the output voltage exactly zero.

The tertiary voltage and ABS terminal voltage vary before and after closing the secondary shorting switch because the total resistance on the load side decreases due to the closing of the secondary shorting switch, resulting in an increased voltage load on the series transformer.

Although the above is based on only one typical example, oscillograms of other equipment did not show any abnormalities when load switching was performed on the tertiary circuit.

VII. CONCLUSION

The above has been a general outline of the steel melting arc furnace transformer equipment to be directly connected to a 77 kv power source. This is the first of its kind in Japan to be in actual operation. It would indeed be fortunate if this material should be in some way helpful to the rapidly developing electric steel making industry.