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STEEL MELTING ARC FURNACE TRANSFORMER EQUIPMENT DIRECTLY CONNECTED TO 154 KV POWER SOURCE WITH TERTIARY LOAD SWITCHING SYSTEM

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I. INTRODUCTION

The ultra-high power techniques developed in the United States in recent years for steel making arc furnaces have resulted in remarkable improvements in mass production and production efficiency in Japan. The demand for scrap has increased considerably in accordance with very active market in steel products, especially automobiles and under such favorable conditions, steel makers have been expanding their arc furnace facilities very rapidly in the last few years.

However, there are many problems to solve when planning such facilities. Irregular voltage variations from the arc furnace load which influence the power supply system cause flicker in other general loads, particularly lighting and television lines, which are supplied electrically from the same bus lines. This results in a public hazard so that flicker suppression measures are often required.

There are three types of flicker suppression systems now in use : (1) minimizing load variations by means of a series reactor, (2) decreasing the influence of load variations which influence the power supply system by controlling reactive power using a synchronous phase modifier and (3) decreasing the apparent power supply reactance by inserting a series capacitor in the transmission line.

Of these methods, the first is limited in terms of the magnitude of the reactor because of suppression of the effective power input to the furnace. The second method is expensive in terms of equipment and the third can not be carried out in cases of general requirements because of relations with the power supply network.

The most simple method is one in which power for the arc furnace is received a plant where the supply capacity is as large as possible, i. e. from a site having a very small supply impedance. Therefore, it is necessary that the arc furnace be directly connected to a high voltage system of 60 to 154 kV. However, since there are frequent load switchings and short circuit interruptions in arc furnaces, a load switch for closing and interrupting has to be provided on the 60 to 154 kV side. Problems arise concerning the reliability of this switch and voltage disturbances in the supply network due to rush currents of transformer during closing.

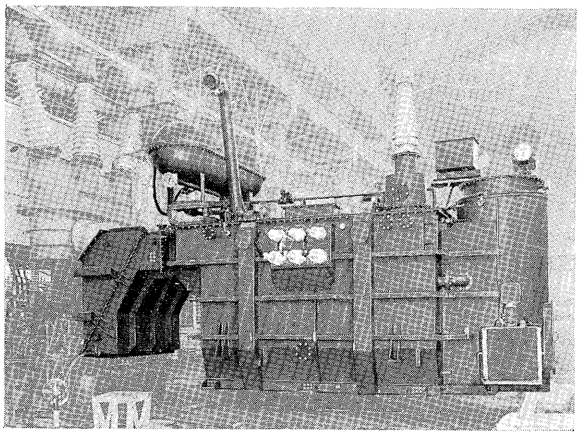


Fig. 1 Outer view of arc furnace transformer

To solve these problems, Fuji Electric has developed a method in which load switching is performed in the tertiary circuit rather than on the primary side. Since the first 15,000 kVA arc furnace transformer with a one-stage step down from 77 kV was delivered to the Nishinomiya Works of the Kawasaki Steel Corporation, several more units have been completed and all are now operating well. Based on this experience, techniques for the manufacture of extra-high voltage power transformers have been developed and Japan's first 18,000 kVA transformer directly connected to a 154 kV power source for a steel melting arc furnace has been delivered to the Ishinomaki Works of the Ito Steel Corporation. This is a first not only for arc furnaces but also for smelting and electrolytic furnaces and an outline is presented in this article.

II. RELIABILITY AND FEATURES OF SYSTEM DIRECTLY CONNECTED TO 154 kV

Since Fuji Electric manufactured its first arc furnace transformer for direct step down from 60 to 70 kV to the furnace voltage in 1929, more than 60 such units have been manufactured. By combing the recently developed tertiary load switching principle, a transformer which can withstand frequent load switches can be produced which is ideal for both ferro-alloy and arc furnaces.

Since the techniques used in the 154 kV direct step down system are basically the same as those used for 60 to 70 kV direct step down, the same high reliability as in the latter can be obtained. The reliability and features of the 154 kV system are as follows.

1. High Voltage Winding Reliability

The windings in the main transformer are arranged concentrically beginning with the innermost tertiary tap winding, followed by the tertiary fixed winding, the primary high voltage winding, and the secondary low voltage winding, the primary high voltage winding, and the secondary low voltage winding. The primary winding is of the high series capacitance disk type which is often used as a high voltage winding in power transformers because of its excellent impact voltage withstand characteristics. Since the effective static series capacitance of this type of winding is increased very much by the connections inserted between the winding, there is sufficient tolerance in respect to switching surges and other abnormal voltages.

The tertiary tap winding is of the multi-axial lap wound sheet type which has several conductor in the form of a single unit wound in a cylindrical shape and connected in series. Therefore, ampere turn unbalance is small in all positions so that there is sufficient suppression of mechanical force in the axial direction which arises during short circuits and increases in leakage flux.

2. Special High Current Low Voltage Winding

The enclosed type sheet coil is employed in this unit because of its structural convenience and suitability for use with large currents. This enclosed type sheet coil was specially developed by Fuji Electric and has been used successfully in almost all furnace transformers including those for smelting furnaces. The cooling effect is excellent and it is very strong mechanically.

3. Excellent Wire Lead-in

Since arc furnace transformers are usually installed in narrow indoor locations which are very dusty, it is essnetial to give careful consideration the insulation of high voltage parts. The danger from the viewpoints of both safety and protection increases particularly above 60 kV and special care is needed when leading cables directly into the high voltage side of the transformer. Thus, the elephant bushing method has been used in this arc furnace transformer to improve the reliability of the 60 to 150 kV cables.

4. Voltage Regulation

Large variations must be made in the secondary voltage in order to regulate the arc furnace closing voltage but in general such regulation must be conducted under on-load conditions due to the very wide regulation range of 30 to 100%. For this reason, an primary high voltage winding has excellent impact voltage withstand characteristics with no taps. Mechanical strength is high and all the taps are arranged in the gaps of the tertiary winding.

The on-load tap changer can be used for several decades even under conditions whereby it is required to change the taps 20 or 30 times a day. Other systems with excellent capabilities which are employed include the resistance changer, spring changer and long-life contacts.

5. Improvement of Power Factor

In the arc furnace, it is impossible reduce circuit reactance very much because at the need for stabilizing the arc and suppressing the flicker which arises due to arc disturbances. Therefore, it is necessary to consider separate means of improving the power factor.

When the incoming voltage is over 60 kV, it becomes very expensive to connect a phase advancing capacitor directly to the receiving terminal. A more economical method is to connect a capacitor in parallel to one or both terminals of the tertiary tap winding in the arc furnace transformer employing the above mentioned indirect voltage regulation method. In this way, there is no need for a special winding and the same winding can serve for both voltage regulation and power factor improvement. Therefore, an ordinary high voltage capacitor can be used and the method is very economical.

6. Load Switching

Since the arc furnace transformer for direct connection to a 60 to 154 kV high voltage system must perform highly stable and accurate load switching 50 or 100 times or more a day, this equipment uses Fuji Electric's original tertiary load switching system. The details of this system have already been reported in Fuji Electric Journal(1) and only the essentials will be given here.

In furnace transformer equipment employing the indirect voltage regulation system, the high voltage required by the arc furnace is divided equally between the main transformer and the series transformer, and a breaker is inserted on the tertiary side of the main transformer, i. e. the primary side of the series transformer. In this way, the arc current can be switched by the series transformer. In this way, the arc cnrrent can be switched by the breaker on the tertiary side and not the breaker on the primary side of the main transformer.

7. Suppression and protection of Transferred Voltage

Lightening and other surge voltages permeating

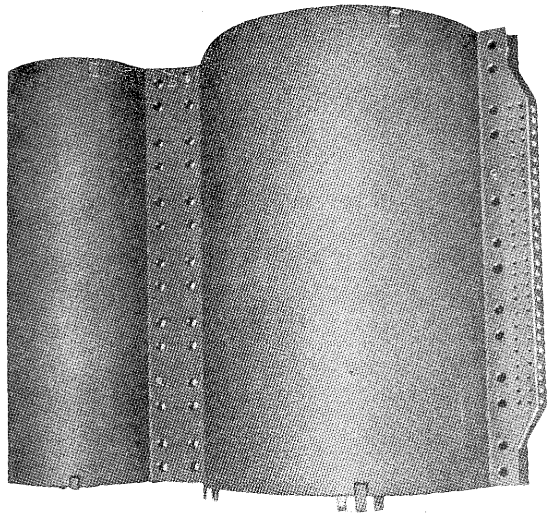


Fig. 2 Enclosed type sheet coil

the primary side of the transformer are transferred electrostatically and electromagnetically to the low voltage secondary side. Particular care is necessary in transformers where the winding ratio between the primary and secondary is especially high.

1) Electrostatic transferred voltage

Electrostatic transferred voltage is voltage which appears on the secondary side due to electrostatic voltage division. As can be seen in *Fig. 2,* the voltage V_2 transferred to the secondary side when a impact wave of peak value V_1 permeates from the primary side is as follows:

$$V_2 \doteqdot \frac{C_{12}}{C_{12}+C_{2E}} \cdot V_1$$

where C_{12}: Electrostatic capacitance between the high and low voltage windings

C_{2E}: Electrostatic capacitance between low voltage winding and ground

Three measures are employed collectively to reduce this electrostatic transferred voltage.

(1) A capacitor is inserted between the low voltage winding and ground. In the above equation, the denominator must be increased in order to reduce the transferred voltage. To achieve this, a capacitor is inserted between the low voltage winding and ground, and the value of C_{2E} is increased.

(2) A ground shield plate is inserted between the high voltage and low voltage windings. In large capacity equipment directly connected to 154 kV systems, an electrostatic shield plate (at ground potential) is inserted between the high and low voltage windings as shown in *Fig. 3* in addition to insertion of the abovementioned capacitor. In this case, $C_{12}=0$ and therefore $V_2=0$. This grounded shield plate prevents any contact between the primary and the secondary.

(3) A lightening arrester is inserted between the low voltage winding and ground. Because of the special load characteristics encountered in an arc furnace, a lightening arrester is connected between the low voltage winding and ground.

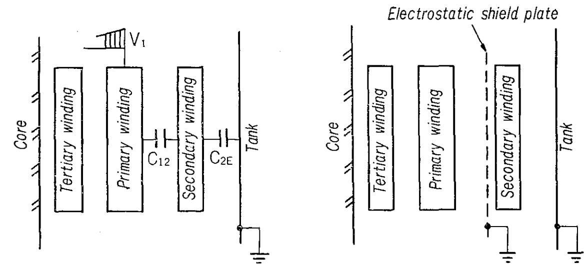


Fig. 3 Capacitance of transformer windings and suppression of electrostatic transferred voltage

2) Electromagnetic transferred voltage

The electromagnetic transferred voltage arises as a surge on the secondary side due to an electromagnetic conductor, following the same principle as the transformer itself. If the number of turns on the primary and secondary sides are N_1 and N_2 respectively, then;

$$V_2 = k\frac{N_2}{N_1} \cdot V_1$$

where k: Constant depending on the connections, winding construction and vibrations in the transferred voltage

A comparison can be made between direct step-down from 66 kV and from 154 kV with the same secondary voltage of 325 V. In the case of 66 kV, BIL is 350 kV and therefore;

$$V_2 = k \cdot \frac{N_2}{N_1} \cdot V_1 = k \times \frac{325}{66{,}000} \times 350 = 1.72k$$

In the case of 154 kV, BIL is 750 kV and therefore;

$$V_2 = k \cdot \frac{N_2}{N_1} \cdot V_1 = k \times \frac{325}{154{,}000} \times 750 = 1.58k$$

V_2 is thus smaller when the primary voltage is larger. Therefore, there is no need to worry about transferred voltage to the secondary side even in the 154 kV step-down system.

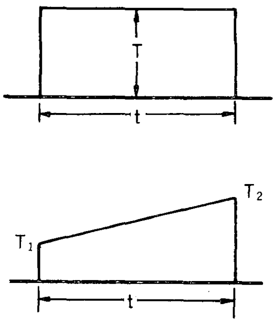
8. Overload Withstand

With the arc furnace transformer, there are large changes during the melting and refining periods, and it is necessary to plan for sufficient withstand against overloads. For example, in this equipment, the load withstand capacities for the three load cycles are as follows:

At maximum secondary tap:

Melting period 120% 90 minutes
Refining period 70% 30 minutes
Charging period 0% 20 minutes

The life of the transformer is generally determined according to decreases in the mechanical and electrical strength and deterioration of insulation due to ambient conditions during operation. This means that the life of the transformer is very closely related



$$A = te^{NT} \quad \cdots\cdots\cdots\cdots(1)$$

$$A = t\left[\frac{e^{NT_1} - e^{NT_2}}{N(T_1 - T_2)}\right] \cdots\cdots\cdots(2)$$

t: Time
T_1, T_2: Temperatures
N: Constant
A: Unit of deterioration

Fig. 4 Temperature curves

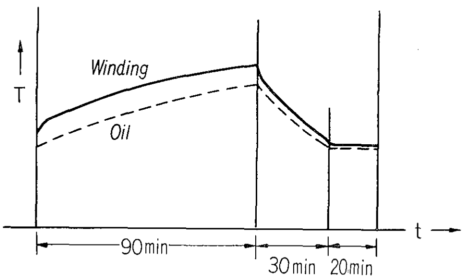


Fig. 5 Temperature curves of oil and winding

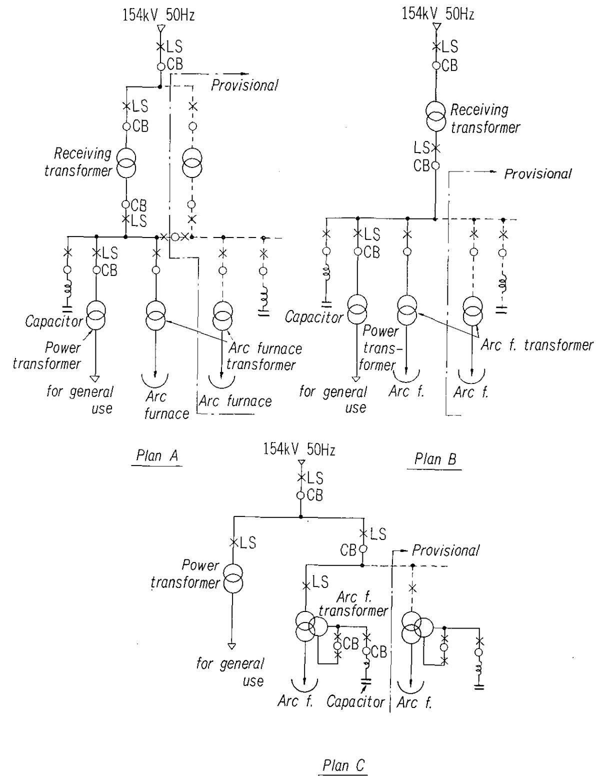


Fig. 6 Skeleton diagram of distribution plan

to maximum temperature rises in the insulation materials. If the temperature curves for a specific load are as shown in *Fig. 4,* the life losses of the transformer are as shown in equations (1) and (2). If the load cycle of the transformer is as mentioned above, the temperature curves are as shown in *Fig. 5,* the equations mentioned above are suitable for each part and the deterioration units are obtained. It has been confirmed that the standard life loss does not changed under continuous operation at 95°C.

III. OUTLINE OF EQUIPMENT

The electrical equipment recently delivered was combined with an arc furnace of the latest type for high power operation as developed by the Ishikawajima-Harima Heavy Industries Co., Ltd. The most up-to-date electrical techniqhes were incorporated in the equipment on the basis of close technical cooperation between Ishikawajima-Harima and Fuji Electric.

When the equipment was planned, three plans as shown in *Fig. 6* were considered for the distribution system with an incoming voltage of 154 kV. In the A plan, the overall equipment costs are high and the B plan is not convenient because of the high initial equipment costs since it is necessary to decide in the beginning on all future expansions and also because of limitations on the capacity in the case of future increases. In the case of the C plan, overall equipment costs are rather low, there are no limitations of any kind when future expansion is needed. In the latter case, the space occupied can be small and it is especially economic and convenient for use indoors. There are also few voltage oscillations inside the factory. Therefore, the C plan was judged to be the best and is used in this equipment.

The cooling system for this transformer is of an unusual type used in electric furnaces because the cooling water is taken from the mouth of the Kitakami River and contains a rather high level of organic compounds and also because there is an irregular alternation between brine and fresh water. These two factors mean that there is a danger of corrosion in the cooling water pipes. The system is a forced oil, forced air type with the forced air radiator arranged separately outside outdoors.

The automatic electrode regulating equipment which was developed in conjuuction with the Ishikawajima-Harima Heavy Industries Co., Ltd. employs a double winding squirrel cage induction motor. The equipment has a primary winding thyristor control system and details will be given later.

The arrangement of the electrical equipment is as shown in *Fig. 7.* Since an elephant construction is used for direct lead-in of the 154 kV cable to the furnace transformer, there are no parts charged with 154 kV exposed to the exterior and the equipment can be made more compact.

The arc funace transformer ratings are as follows:

Cooling system:	Forced air, forced oil system
Capacity:	3-phase 18,000 kVA 50 Hz
Overload withstahd:	120% at maximum tap voltage
Primary voltage:	154 kV
Secondary voltage:	F400 ~ R325 ~ 100 V (25 V steps, 13 taps)
Primary current:	67.5 A

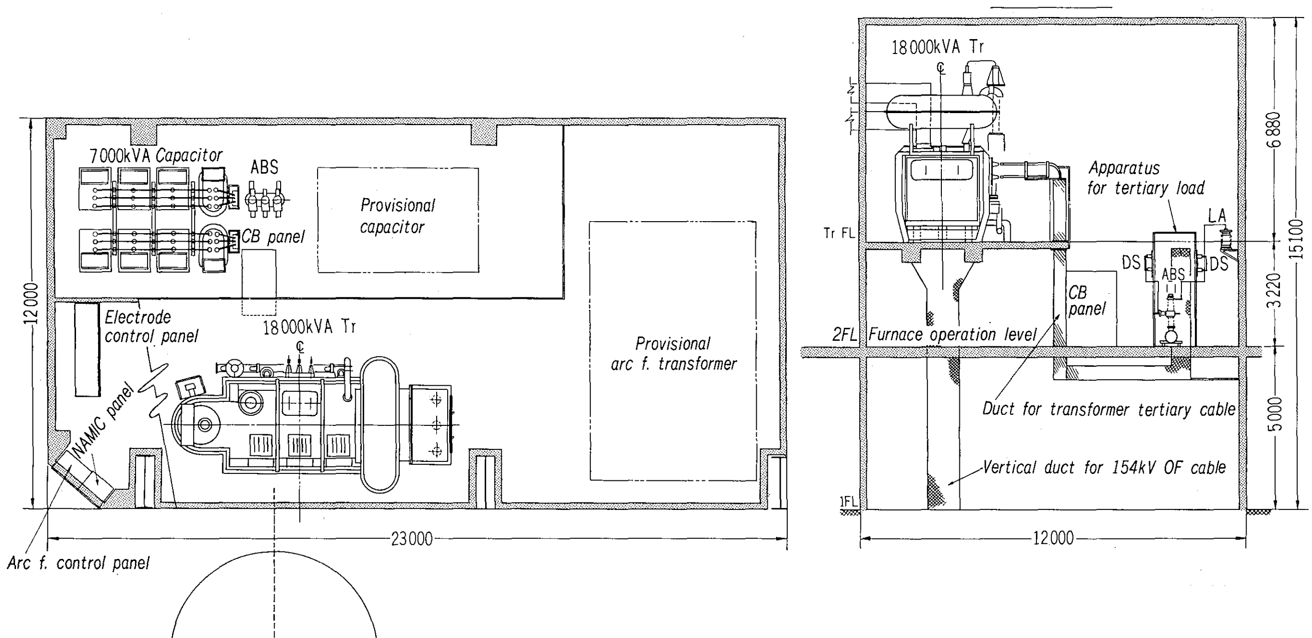
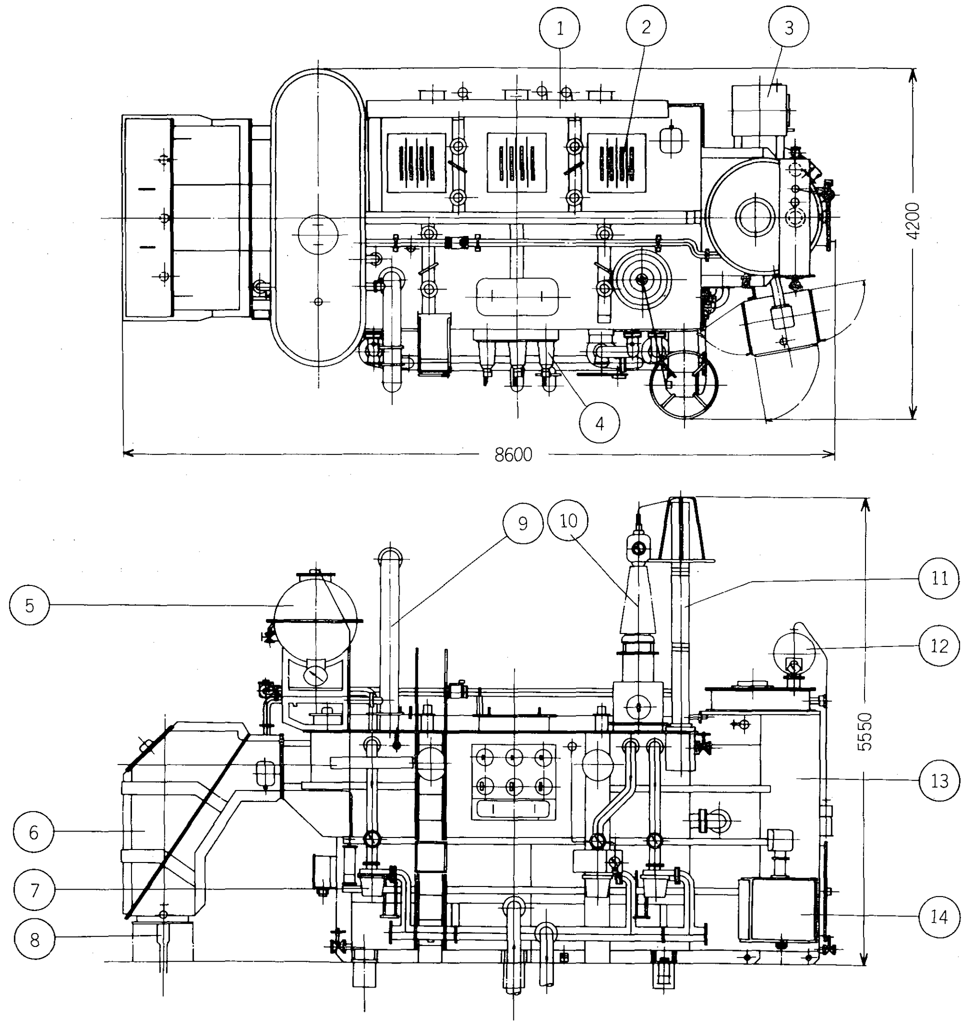


Fig. 7 **Arrangement of electric equipment**



① Secondary conductor support
② Secondary terminal
③ On-load oil filter
④ Tertiary terminal
⑤ Diaphragm type oil conservator
⑥ Primary elephant case
⑦ Oil pump
⑧ Primary OF cable head
⑨ Pressure outlet tube
⑩ Primary neutral terminal
⑪ Lightening arrester
⑫ Switch room conservator
⑬ On-load tap changer
⑭ Electromotive operating mechanism

Fig. 8 **Outline of arc furnace transformer**

Secondary current:	32,000 A
Connections	
primary:	Wye type (neutral point 120 kV with lightning arrester)
Secondary:	Open delta type
Bushing primary:	Elephant construction (Insulation class 140)
Secondary:	Self cooled flat type copper terminal (AC 4 kV insulation)
Tap changing:	Electrically operated on-load tap changer
Impedance voltage:	13% between primary and secondary (18,000 kVA base)

Fig. 8 shows an outline of the arc furnace transformer.

IV. CONNECTIONS

Fig. 9 is the connection diagram of the arc furnace transformer. The tertiary load switching system can be explained in accordance with the single phase connection diagram shown in *Fig. 10.* When the load switch is open and the series transformer looses its excitation power supply, a base current loop is formed and at the same time the secondary circuit is shorted by the secondary bypass switch. The secondary voltage of the main transformer is applied to the secondary winding of the series transformer, a reverse voltage occurs and the electrode voltage and current both become completely zero.

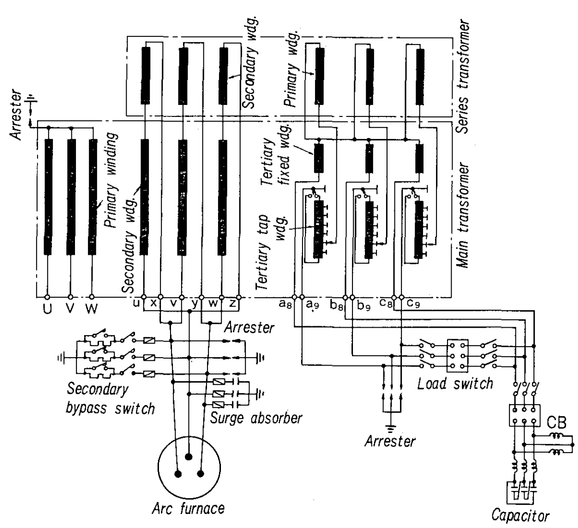


Fig. 9 Connection diagram of arc furnace transformer

In other words, in load switching, the required voltoge is 100 to 400 V and this voltage is divided between 200 V for the main transformer and 50 ± 150 V for the series transformer. The tertiary side consists of the tap winding and a fixed winding with no taps. Since the polarity is changed only in the tap winding, the secondary voltage can be regulated over a wide range. In addition, the tertiary fixed winding is connected in parallel with a 3 kV phase advancing capacitor, and the arc furnace load power factor can be improved economically.

V. CONSTRUCTION

1. Core

Both the main and series transformers employ a core-type 3-legged iron core with a band clamp system which uses no tightening bolts.

2. Windings

As is shown in *Fig. 10,* the windings of the main transformer are arranged concentrically beginning with the inner tertiary winding followed by the primary and secondary windings. The primary winding employs the high series capacitance disk winding which has a high resistance to abnormal voltage such as impact and surge voltage.

The secondary winding has low voltage and high current and employs the enclosed type sheet coil developed by Fuji Electric. This coil is now used in cases when the multi-axial lap wound sheet winding was used previously. The enclosed type sheet coil connects the main and series transformers and is wound continuously in the form of a *Fig. 8.* With this type of winding: 1) the winding space factor is improved and the winding unit is smaller, 2) the

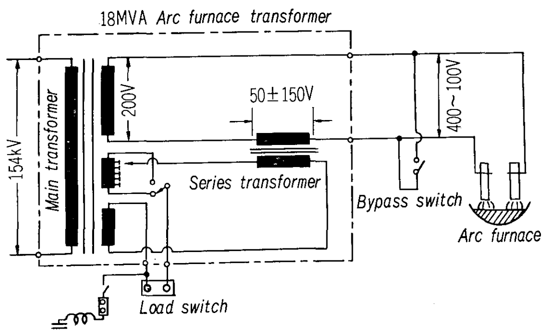


Fig. 10 Single phase connection diagram

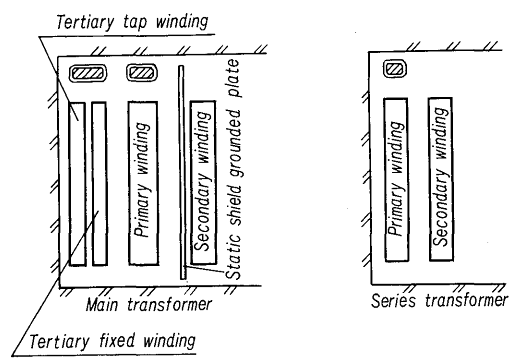


Fig. 11 Arrangement of windings

windings are very resistant to electromagnetic force during short circuits and 3) the coil construction is simple and leads can be easily connected. The lead is led upwards from the coil outlet and is adjacent to a lead in which a current of the same phase is flowing in the reverse direction. In this way, the leakage flux is reduced and reactance and stray load loss are minimized.

3. On-load Tap Changer

Since the taps are frequently changed, a phase regulating 3 DSCP on-load tap changer with a highly reliable resistance changing system, spring changing chamber contains an on-load oil filter which filters the oil by means of uninterrupted electricity.

4. Primary Terminal

Since the elephant type construction in which the capacitor type pass-through bushing is connected directly to the cable is used, there is no need to worry about dust or gas in the atmosphere surrounding the transformer. Because the transformer oil in the elephant case are completely separate, it is possible to connect the cables at the site without any transformer oil leaks.

5. Secondary Terminal

A self-cooled flat copper terminal is used.

VI. TEST RESULTS

Estimation of the impedance voltage and load loss becomes much more difficult in transformers with lower voltages and higher currents since they are influenced by the lead wire arrangements, dimensions, increases in stray load loss etc. However, with this transformer, detailed tests were conducted beforehand using a computer and the actually measured results were in close agreement with the planned values. It was also found that there were no abnormal places with local temperature rises etc. due to the large current.

To test the insulation, an AC voltage test was sufficient suppression and the insulation was maintained effectively.

VII. ELECTRODE REGULATING SYSTEM

In steel melting arc furnaces, the arc length changes as the scrap is melted down and there are also changes in the short circuit between the electrodes and the arc path. These changes give rise to sharp alterations in the impedance within the furnace. In addition, these phenomena occur independently at each electrode. The electrode regulating system must be able to raise or lower the electrodes rapidly in accordance with furnace conditions and even when there is an electrode raising or lowering due to a change of one phase, this must not cause any instability in electrodes of other phases. To achieve this, the so-called impedance regulating method in which the ratio of the voltage and current for each electrode is held constant is generally used for electrode regulation.

This equipment contains a new system developed in cooperation with the Ishikawajima-Harima Heavy Industries Co., Ltd. as an improvement on the previous electrode regulating system. It employs an AC squirrel cage induction motor to raise and lower the electrodes. The fixed winding of this motor is a double winding with 4 poles for raising and 8 poles for lowering. A thyristor is delta-connected to the connection part of each winding. The raising/lowering speed control and forward/reverse operation control are performed by regulating the primary voltage. In this system the following improvements have been made:

1) There are no short circuits during phase changes on the primary side which were the main problem in the AC thyristor system.

2) The total motor heat capacity is small and the response is good because the windings on the low capacity 8 poles side are used when lowering the electrodes. When the motor will not produce a raising torque, the electrodes are lowered naturally by means of their own weight and there is no need for a lowering torque. However, since the starting characteristics are adversely affected by the static friction torque of the reduction gear, the minimum required limit of the lowering torque is produced only during starting. In this way, the heat loss during starting and stopping is reduced and the starting characteristics are good because of the own-weight lowering system. When a trial melting was conducted with no lowering torque and lowering only by the electrodes own weight, it took 1.2 sec. to the maximum speed, but when a lowering torque was produced, this was reduced to 0.17 sec. and the response was 10 times better.

3) Maintenance and checking are simplified by the use of the squirrel cage induction motor.

4) Since a cooling fan is connected to the motor to provide effective cooling for both the stator and rotor windings, the electrode raising motor unit can be in the form of a single unit and regulation is facilitated.

5) The control panel is compact and occupies only a small area. The specifications of the electrode regulating motor are as follows:

Type:	Forced air ventilation squirrel cage induction motor
Output:	3-phase 22 kW 50 Hz
No. of poles:	4/8 poles (1,500/750 rpm)
Voltage:	400 V

The connections of the system are as shown in *Fig. 12.* This figure shows only one phase of the electrode regulating equipment. The system is connected to the electrode support and the electrodes

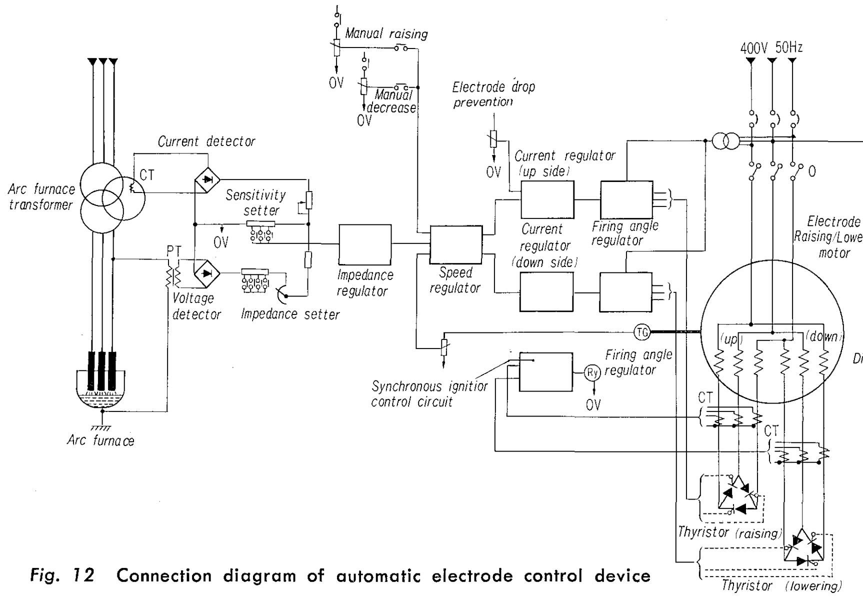


Fig. 12 **Connection diagram of automatic electrode control device**

are lowered by the 3-phase induction motor for lowering via the reduction gear. The 3-phase induction motor consists of a stator winding for forward operation and a stator winding for reverse operation. Both stator windings are supplied from a 3-phase AC power source via thyristor equipment for forward and reverse operation respectively. The thyristors obtain firing pulses from their respective gate circuits.

The electrode voltage element obtained via the potential transformer and the current element obtained via the current transformer are compared in a comparing circuit and difference is amplified in an amplifier and sent to the speed regulator as the standard speed value. This standard speed value is compared with the actual speed value from the tachometer generator connected to the rotor of the motor in the speed regulator. The motor speed in the forward or reverse directions is controlled in accordance with the polarity and magnitude of this deviation. While the electrode voltage and current are maintained in a relation corresponding to the predetermined impedance, the motor is stopped without rotation torque. If the electrode current overcomes the electrode voltage, the forward thyristor equipment is fired via the gate circuit and the motor is started to raise the electrodes. If the voltage overcomes the current, however, the reverse thyristor equipment is fired via the gate circuit and the motor starts to lower the electrodes. An oscillogram of running characteristics is shown in *Fig. 13*.

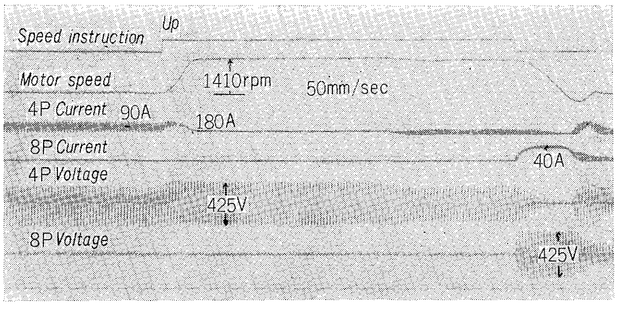


Fig. 13 **Oscillogram of running characteristics**

VIII. CONCLUSION

Recently, the input voltage of general users has risen from 60~70 kV to 154 kV and direct connection to 154 kV or over has become a necessity in steel making arc furnaces also due to the aforementioned flicker problem. Since steel melting arc furnace equipment for direct connection to 154 kV and with tertiary load switchihg has recently been completed, an outline is presented in this article. It is hoped that this information will be of some use in the development of the electric steel industry.

In conclusion, the authors wish to thank those persons in the Ito Steel Corporation and the Ishikawajima-Harima Heavy Industries Co., Ltd. for their guidance and help in the design and manufacture of this equipment.