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275 KV 200 MVA ON-LOAD TAP CHANGING AUTOTRANSFORMER WITH INDIRECT VOLTAGE REGULATION

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I. INTRODUCTION

Interconnection of 400 kV transmission line which will be adopted in Japan in near future with existing 275 kV or 220 kV transmission lines will surely be realized by autotransformers from economical points and they are generally believed to be of on-load tap changing, because of necessity for system operations. Therefore one of the most interesting subjects among the transformer makers in Japan is to manufacture on-load tap changing autotransformers for extra high voltage interconnection.

We have recently completed 200 MVA autotransformer for Himeji S.S. of the Kansai Electric Power Co., Inc., which interconnects 275 kV transmission line of the Kansai Electric Power Co., Inc. with 220 kV transmission line of the Chugoku Electric Power Co., Inc. This is the first on-load tap changing autotransformer with indirect voltage regulation for interconnection extra high voltage transmission systems in our country.

It is well known that autotransformers have many peculiar technical problems, which differ from those of the usual power transformers. In this autotransformer these problems are reasonably solved by our original technology; oscillation-free type cylindrical layer windings in the main autotransformer, double electrostatic shield construction in the series transformer, etc. Such a latest and original technology can, of course, be applied to 400 kV autotransformers, which are expected to issue in the near future in Japan. So this 275 kV 200 MVA autotransformer has a great and epochmaking significance in that view-point.

In the following an outline of this autotransformer is given.

II. SPECIFICATION AND DATA

Construction:	Outdoor use, 'Fahrbar' type, forced oil circulated, fan cooled, three phase core type, autoconnected, graded insulation, with nitrogen sealed oil conservator	
Frequency:	60 c/s	
Capacity:	Primary side,	200 MVA
	Secondary side,	200 MVA
	Tertiary side,	18.6 MVA
Voltage:	Primary side,	275 kV
	Secondary side,	255–252. 5–250–247.5–245–242.5–240–237. 5–235–232. 5–230–227. 5–225– 222. 5 –220^R–217.5–215^F kV
	Tertiary side,	15.4 kV
BIL:	Primary side,	1,050 kV
	Secondary side,	900 kV
	Neutral side,	400 kV
	Tertiary side,	200 kV
Impedance voltage:	4% between primary and secondary, at secondary voltage 235 kV, 200 MVA base	
Total weight:	Main autotransformer + series transformer	253 tons
	On-load voltage regulating transformer	49.8 tons
Dimensions:	Main autotransformer + series transfoamer width; 12.01 m, depth; 6.85 m, height; 9.45 m	
	On-load voltage regulating transformer width; 6 m, depth; 3.99 m, height; 5.32 m	

1. Main Autotransformer

Voltage:	Primary side,	275 kV
	Secondary side,	235 kV
	Tertiary side.	15.4 kV
Capacity:	Series winding,	29.1 MVA
	Parallel winding,	47.7 MVA
	Tertiary winding,	18.6 MVA
Cooling method:	Forced oil circulation fan cooled	

2. Series Transformer

Out put:	18.6 MVA	
Voltage:	Primary side,	23.16 kV (人)
	Secondary side,	20 kV (人)
BIL:	Primary side,	200 kV
	Secondary side,	900 kV
Cooling method:	Forced oil circulation fan cooled	

3. On-load Voltage Regulating Transformer (separated)

Output: 18.6 MVA

Voltage: Primary side, 15.4 kV (△)
Secondary side, ±(23. 16–20. 265–17.37–14.475–11.58–8.685–5. 79–2.895) kV (人)

BIL: Primary side, 200 kV
Secondary side, 200 kV

Cooling method: Oil immersed self cooled

In *Fig. 1* this 275 kV 200 MVA on-load tap changing autotransformer with indirect voltage regulation at site is shown.

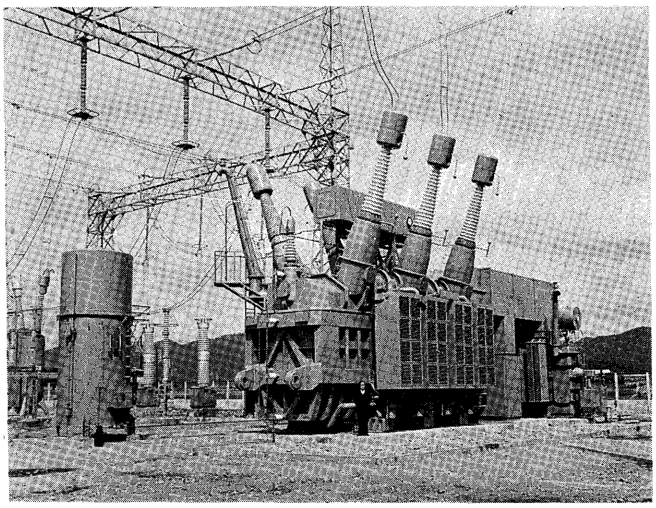


Fig. 1 275 kV/235 kV±8.5% on-load tap changing autotransformer with indirect voltage regulation

III. CONNECTION

Fig. 2 illustrates the connection of this autotransformer.

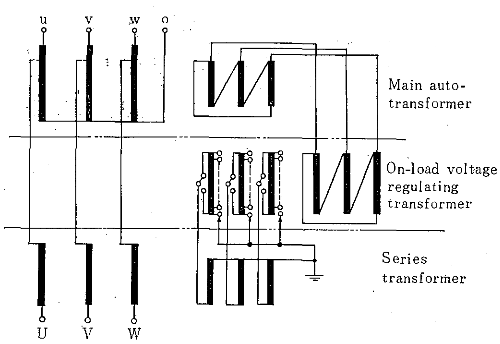
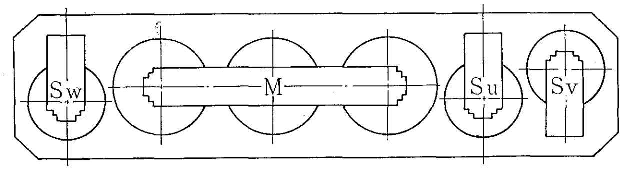


Fig. 2 Connection diagram of autotransformer

IV. CONSTRUCTION

This autotransformer consists of main autotransformer, series transformer and on-load voltage regulating transformer. In order to utilize inner space of the tank effectively and consequently to reduce dimensions of the autotransformer, the series transformer is divided into three single phase units and they are housed in a common tank with the main autotransformer, as shown in *Fig. 3*. The on-load voltage regulating transformer is installed separately. Connections of the separate regulating transformer with the main autotransformer and the series transformer are respectively made by isolated-phase buses.



M: Main autotransformer
Su, Sv, Sw: Series transformer

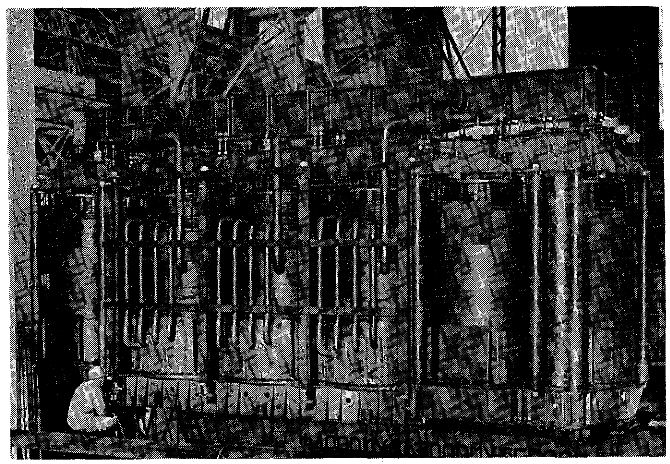


Fig. 3 Interior view of main autotransformer and series transformer

For iron cores of each transformer cold-rolled grain oriented electrical steel G_{11} are used. Each iron core of three single phase units of the series transformer has especially a single phase two-legs construction. And only one of the two legs has windings because of a convenience for their arrangement in the tank. As stresses are induced into electrical steel sheets whenever they are punched or sheared, stress-relieving anneal is carried out carefully in order to relieve these stresses and restore the original magnetic properties. Mechanical stresses are also induced by the electro-magnetic forces on the short-circuit, so a special winding clamping method to prevent iron cores from these forces are adopted.

Fig. 4 shows the arrangement of windings on a core of the main autotransformer. Disc coils are used for tertiary winding, the oscillation-free type

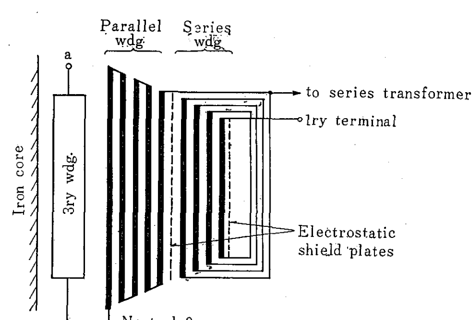


Fig. 4 Arrangement of windings of main autotransformer

cylindrical layer winding with so-called U form connections, i.e. top-top, bottom-bottom connections between adjacent layers, are used for the parallel winding and that with so called N form connections, which are made from the top of one layer to the bottom of the adjacent layer, are adopted for the series winding, as shown in *Fig. 4*. The oscillation-free type cylindrical layer winding has many features as follows;

1) The voltage distribution in the winding is practically linear and free from voltage oscillations when an impulse voltage are impressed.
2) Therefore the winding can be arranged in a form of trapezoid by utilizing effectively the graded insulation effect and raises the winding space factor in core window.
3) High reliability of insulations can be gained, since a uniform safety can be kept in every part of winding.
4) It is easier to control the fringe fields by insulating paper parallel to the surfaces of equal electric potential and to avoid local field concentrations at the edges of winding copper.
5) Insulation space can be shortened by both adoption of solid insulation between high and low tension windings and innermost neutral layer. Therefore the outer diameter of windings can be made smaller and this is advantageous for transportation in an assembled unit.
6) Inner cooling is excellent because of the clear and unrestricted oil flow through vertical ducts between layers.
7) Mechanical strength is high because of small axial forces which occur on the short-circuit.

Fig. 5 illustrates the arrangement of windings on a core of the series transformer. Disc coils are adopted for primary winnding and cylindrical block winding for secondary winding. Secondary winding leads directly to 220 kV line, so ring-form electrostatic shield plates are placed on its end faces and two sheets of shield plate surround its peripheral surface, which are respectively connected with its top end and bottom end, as shown by dotted lines in *Fig. 5*. We call this a double electrostatic shield construction and this construction is one of the most remarkable design features of this autotransformer.

Owing to this shield construction of the series transformer and the cylindrical layer windings of the main autotransformer, an excellent impulse voltage characteristic could be obtained, that is, any abnormal voltage did not appear, indeed, in any points of the autotransformer, as described later.

The parallel wound cylindrical layer tap winding are adopted for the tap winding of the regulating transformer. Therefore the impulse voltage distribution is always linear and no abnormal voltage do not appear across taps. Furthermore, no-current section in some tap position is distributed along the whole height of the tap winding. So the unbalanced leakage ampere-turn becomes quite small in the radial direction between primary and secondary winding and the appreciable axial electromagnetic force on the short-circuit does not occur. *Fig. 6* shows an interior view of the regulating transformer.

DS type Yansen switches of built-in construction are used as diverter switches, which have an established reputation of their reliability. Detailed explanations as to these diverter switches are omitted here, as they have been often introduced by us. The exchanging device of diverter switch case oil under operating condition belongs to them, by which oil in the diverter switch case can be always kept clean.

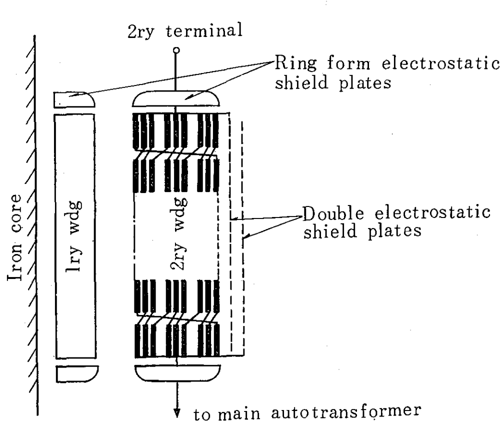


Fig. 5 **Arrangement of windings of series transformer**

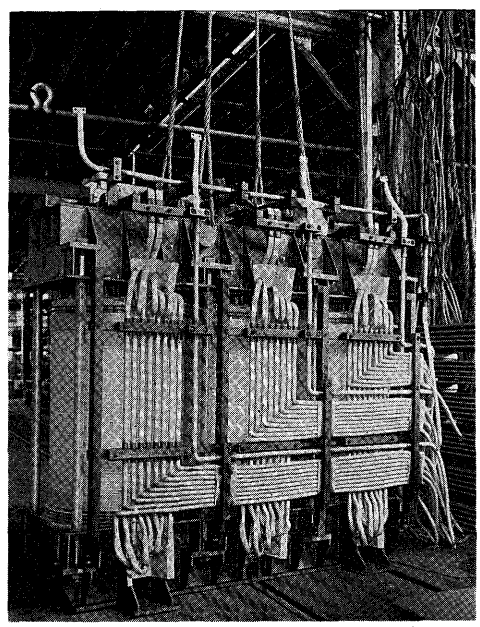


Fig. 6 **Interior view of on-load voltage regulating transformer**

V. VOLTAGE REGULATING METHODS

Representative possibilities for the voltage regulating method are considered as shown in *Fig. 7*. According to CIGRE Rep. No. 140, 1960, *Fig. 7* $(a)\sim(c)$ are direct methods and *Fig. 7* (d), (e) are indirect methods. Now brief comparisons of these methods are described in the following.

In case of *Fig. 7* (*a*) it occurs that core flux density varies largely with tappings depending on co-ratio and range of voltage regulation and large tap winding part to be necessary. So the autotransformer becomes uneconomical. But this method keeps still an advantage in the point of insulation of tap-changing equipments. From *Fig. 8* the ratio a between maximum and minimum core flux density and the percentage b of the tap winding part are given by the following equations,

$$a=\frac{V_{H\ \max}-V_{L\ \min}}{V_{H\ \min}-V_{L\ \max}} \qquad \cdots\cdots(1)$$

$$\left.\begin{array}{l} b_L=\dfrac{n_T}{n_L}\times 100=\left(a\cdot\dfrac{V_{L\ \max}}{V_{L\ \min}}-1\right)\times 100\ (\%) \\ \text{or} \\ b_H=\dfrac{n_T}{n_H}\times 100=\left(a\cdot\dfrac{V_{H\ \min}}{V_{H\ \max}}-1\right)\times 100(\%) \end{array}\right\}\cdots(2)$$

The ratio a of this autotransformer is

$$a=\frac{275-215}{275-255}=3$$

which is a very big value. In addition, the range of voltage regulation is relatively large, 235 kV ± 8.5%. So the adoption of this voltage regulating method is quite out of considerations.

In case of *Fig. 7* (*b*) and (*c*) such a variation of core flux density does not occur. Since only an iron core is provided, these methods are fundamentally more economical than any other methods. But a careful consideration must be concentrated to the insulation of the tap-changing equipments, arrangement of tapping leads, etc., because of their very high potential.

Last two methods *Fig. 7* (*d*) and (*e*) have common advantages that not only longitudinal voltage control is possible, but also radial and oblique control and by housing series and main transformer in two separate tanks it is possible to make their transport easier in case of large capacity. Furthermore (*d*) method is attractive, because no switching is required on high tension side. The reason why this connection has only rarely been used in the past would be the fact that the autotransformer, like a directly regulated

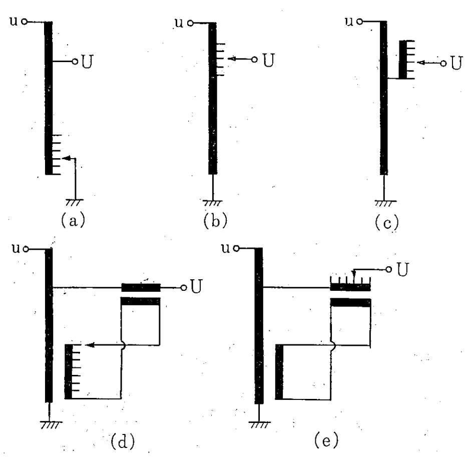


Fig. 7 **Voltage regulating methods**

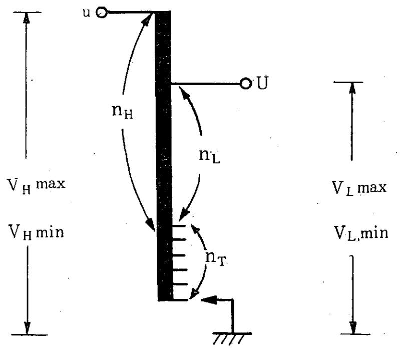


Fig. 8 **Voltage regulation at neutral point**

unit, contains a tap winding as well as a tap changing equipment and larger currents have to be switched. (*e*) is the method which has been used for many autotransformers, for example, 380 kV autotransformers of RWE, Germany, manufactured by SSW, BBC and AEG in 1957. Here we have a very simple autotransformer. But special considerations must be taken for the insulations, as in (*b*) and (*c*). These problems of insulations, however, can be controlled by now-a-days advanced technology.

The autotransformer, we recently completed, has a connection which differs from *Fig. 7* (*a*)~(*e*), as shown in *Fig. 9*. The main reason of its adoption

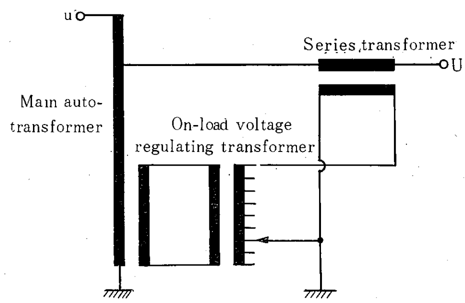


Fig. 9 **On-load tap changing autotransformer with indirect voltage regulation**

is the reliability on tap-changing equipments.

We have supplied a greatest number of on-load tap changing transformers in Japan and have no doubt whatever about the reliability on Yansen type tap changing equipments. But it would be unavoidable that customers will feel uneasy about their reliability especially in case of this first 275 kV autotransformer of largest capacity in Japan for interconnection of trunk power systems, taking account of statistically the most fault experiences of tap-changing equipments in originally rare faults of transformers in Japan. Therefore in compliance with customer's requirements that even if a fault occures on a tap-changing equipment the fault shall not extend over the autotransformer itself, the damaged equipment can be easily separated and power supply can be resumed with a minimum of down time, the voltage regulating method of *Fig. 9* is adopted. In case of *Fig. 9* the regulating transformer can soon be separated at emergency and thereafter the autotransformer can be put into service under fixed secondary voltage of 235 kV. This method has another appreciable advantages that tap-changing equipment is possible to take earth potential and a optimum selection of switching current in relation to step voltage is possible.

VI. IMPEDANCE VOLTAGE

1. Decision of Impedance Voltage

At the decision of impedance voltage following factors must be taken into account.

(1) Breaking capacity of the circuit breakers
(2) Necessary transmission capacity for the system
(3) Economization of the autotransformer
(4) Mechanical strength of the autotransformer

As these factors contradict each other, the value of impedance voltage must be decided with careful considerations.

In case of this autotransformer, it was said that impedance voltage more than 3% was enough for breaking capacity and impedance voltage of 3% to 6% was suitable for transmission capacity. But 3% was put out of considerations because of disadvantage in economization and mechanical strength of the autotransformer. Finally comparison was made between 4% and 6% in the earlier stage of the projection. *Table 1* gives the results of weight comparison. It can be seen from this table that there is no appreciable difference between 4% and 6% in total weight.

Then, the mechanical strength is compared in the following.

Electromagnetic force on the short-circuit is given by the equation (3)

$$F=K_1\cdot(NI)^2\cdot U_m \qquad \cdots\cdots(3)$$

***Table 1* Comparison between 4% and 6% impedance**

Impedance	4%	6%
Weight of core	1.14	1
Weight of winding	0.83	1
Quantity of oil	1.06	1
Total weight	1.01	1

where K_1 is constant, N is number of turns, I is short-circuit current and U_m is mean circumferential length of winding.

On the other hand, impedance Z_T of the transformer is given by

$$Z_T=K_2\cdot N^2\cdot U_m \qquad \cdots\cdots(4)$$

where K_2 is also constant.

And when line voltage is E and line impedance is Z_L, short-circuit current is determined by

$$I=\frac{E}{Z_T+Z_L} \qquad \cdots\cdots(5)$$

Therefore the electromagnetic force can be written as equation (6)

$$F=K_3\cdot Z_T\left(\frac{E}{Z_T+Z_L}\right)^2 \qquad \cdots\cdots(6)$$

where K_3 is constant.

By comparing the force at 4% with that at 6%, equation (7) is obtained,

$$\frac{F(4\%)}{F(6\%)}=\frac{K_3(4\%)}{K_3(6\%)}\cdot 1.2 \qquad \cdots\cdots(7)$$

Constant K_3 of above equation (7) is determined by the winding height and length and the width of main leakage kanal between windings. By actual calculations K_3 is given by

$$\frac{K_3(4\%)}{K_3(6\%)}\fallingdotseq\frac{1}{1.1} \qquad \cdots\cdots(8)$$

After all, the electromagnetic force in case of 4% is larger than that in case of 6% only by about 10%.

It should be remembered that the mechanical strength of a transformer depends not only on the magnitude of the electromagnetic force on the short-circuit, but also on the pre-pressing of winding, drying treatment of insulations and the strength of winding itself and of clamping device of winding. In order to compensate the slackness of winding, which will be caused by its shrinkage during service, each winding is individually pre-pressed by the optimum pressure, determined by the proportion of insulations in winding, insulation spaces to yokes, area of winding to be pressed and magnitude of the electromagnetic force on the short-circuit. And perfect drying treatment is carried out under high vacuum heating with conditions; temperature 110°C to 115°C and vacuum lower than 1 mm Hg. Therefore we can say as to above two points that there is no differences between 4% and 6%. But as to the strength of the clamping device, circumstances are somewhat different, because it is affected by dimensions of iron core and winding. As a result of our comparative discussions by taking account of those factors and, in addition, eddy current losses in windings and other constructive elements caused by leakage flux, we decided that impedance voltage of 4% has an advantage over 6% and consequently adopted the former.

2. Variation of Impedance Voltage with Tapping

In the autotransformer not only stray field but also internal rating vary more or less with tapping, therefore the variation of impedance voltage is unavoidable. It is one of the peculiar problems of the autotransformer and attentions must be paid for this problem.

% impedance voltage of this autotransformer $(\%Z)_L$, based on line capacity $(\mathrm{kVA})_L$, is determined by equation (9).

$$(\%Z)_L=\frac{(\mathrm{kVA})_M}{(\mathrm{kVA})_L}\cdot(\%Z)_M+\left(\frac{V_{2\,\min}}{V_2}\right)^2\cdot\frac{(\mathrm{kVA})_S}{(\mathrm{kVA})_L}(\%Z)_S+\left(\frac{V_{2\,\min}}{V_2}\right)^2\cdot\frac{(\mathrm{kVA})_R}{(\mathrm{kVA})_L}\cdot(\%Z)_R \qquad \cdots\cdots(9)$$

where

$(\mathrm{kVA})_M$: Winding capacity of the main autotransformer

$(\% Z)_M$: % impedance voltage based on $(\mathrm{kVA})_M$

$(\mathrm{kVA})_S$: Winding capacity of the series transformer

$(\% Z)_S$: % impedance voltage based on $(\mathrm{kVA})_S$

$(\mathrm{kVA})_R$: Maximum regulating capacity of the regulating transformer

$(\% Z)_R$: % impedance voltage based on $(\mathrm{kVA})_R$

$V_{2\,\min}$: Minimum secondary voltage

V_2 : Secondary voltage at voluntary tap position.

Fig. 10 shows how the variations of the leakage flux distribution and the winding capacity with tapping in the main autotransformer are. *Table 2*

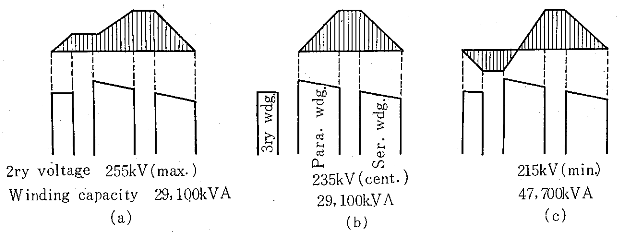


Fig. 10 Distribution of leakage flux

Table 2 **Variation of impedance voltage**

Item	Tap position	Max.	Cent.	Min.
I	Impedance voltage of main autotrans.	134	100	100
II	Impedance voltage of series trans.	85	100	120

Note: in percentage of the value at center tap position

item I gives the variation of the impedance voltage of the main autotransformer in percentage of the value at center tap position. That the value at minimum tap position is equal to that at center, is caused by both reduction of the leakage reactance and contrary enlargement of the winding capacity.

The second term of equation (9) indicates that the impedance voltage of the series transformer increases as the the secondary voltage becomes lower. *Table*

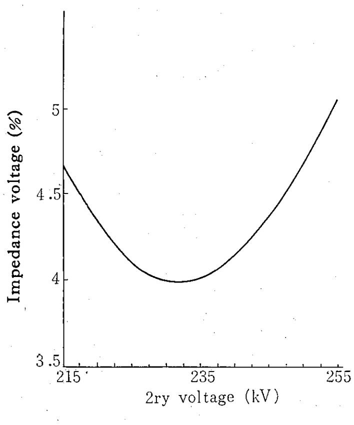


Fig. 11 Impedance characteristic

2 item II gives it numerically.

The impedance voltage of the regulating transformer disappears at center tap position, from where it increases with tapping. As the third term of equation (9) indicates, its value at minimum tap is larger than the value at maximum tap.

Therefore the total impedance voltage of this autoformer shows only an insignificant variation, as shown in *Fig. 11*.

VII. IMPULSE VOLTAGE CHARACTERISTICS

About three years ago we ascertained with electromagnetic model that the excellent impulse voltage characteristics could be obtained by the adoption of the oscillation-free type cylindrical layer winding for the autotransformer and reported it in an earlier paper. Its contents can be, of course, applied to the present main autotransformer but conditions of this autotransformer are somewhat different and more complicated because of presence of the series transformer and the regulating transformer. So exhaustive discussions are required.

1. Theoretical Analysis

1) When 220 kV Terminal U earthed and impressed to 275 kV Terminal u.

Equivalent circuit at the instant of impact of impulse voltage can be expressed by *Fig. 12*, since the main autotransformer is given by the concentrated elements because of its oscillation-free type cylindrical layer

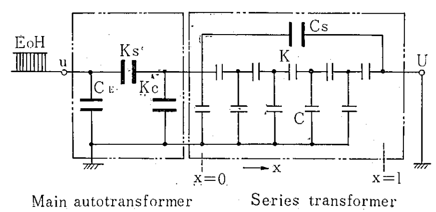


Fig. 12 Equivalent circuit for initial voltage distribution

winding. The initial voltage distribution along the secondary winding of the series transformer is determined by equation (10),

$$e=\frac{\sinh\alpha\left(1-\frac{x}{l}\right)}{\sinh\alpha}\cdot E \qquad \cdots\cdots(10)$$

where

$$\alpha=\sqrt{\frac{C}{K}}$$

$$E=E_{OH}\frac{K_S}{K_S+K_C+\sqrt{C\cdot K}+C_S}$$

E_{OH} : Impressed impulse voltage, assumed to be a square wave

K_S : Total series capacitance of the series winding of the main autotransformer

K_C : Total series capacitance of the parallel winding of the main autotransformer

K: Total series capacitance of the secondary winding of the series transformer

C: Total parallel capacitance of the secondary winding of the series transformer

C_S: Capacitance between the double electrostatic shield plates of the series transformer

In *Table 3* item I the voltage stresses of the secondary winding of the series transformer with double electrostatic shield plates are compared with the voltage stresses without them as a result of calculations by equation (10).

2) When 275 kV Terminal u earthed and impressed to 220 kV Terminal U

Since the initial equivalent circuit of this case can similarly be drawn as shown in *Fig. 13*, the initial voltage distribution along the secondary winding of the series transformer is given by equation (11),

$$e=E_{OL}\left(\gamma-\frac{C_S'}{C_S'+C}\right)\frac{\sinh\alpha\frac{x}{l}}{\sinh\alpha}+E_{OL}\frac{C}{C_S'+C}\cdot\frac{\sinh\alpha\left(1-\frac{x}{l}\right)}{\sinh\alpha}+E_{OL}\frac{C_S'}{C_S'+C}\cdots(11)$$

where

$$\alpha=\sqrt{\frac{C_S'+C}{K}}$$

$$\gamma=\frac{C_S-\alpha\cdot K\frac{C_S'}{C_S'+C}}{C_S+K_S+K_C+\alpha\cdot K}$$

E_{OL}: Impressed impulse voltage with a square wave form

C_S': Capacitance added by one of the double electrostatic shield plates of the secondary winding of the series transformer

C: Total capacitance between primary winding and secondary of the series transformer.

Results of calculations by equation (11) are shown in *Table 3* item II in comparison between two cases, with and without double electrostatic shield plates, as to the stresses on the secondary winding, interturn stresses in the secondary winding of the series transformer and potential to earth of the connecting point between main autotransformer and series transformer.

Table 3 **Valtage stresses on 2ry winding of series transformer**

Item	Double electrostatic shieled plates	With	Without
I	Max. stress between terminals	0.54	1
	Max. interturn stress	0.91	1
II	Max. stress between terminals	0.42	1
	Max. interturn stress	0.87	1
	Max. potential of connecting point	0.6	1

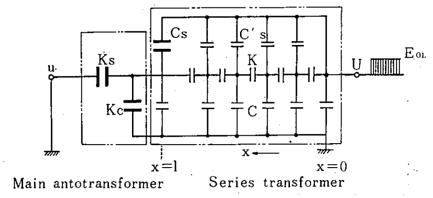


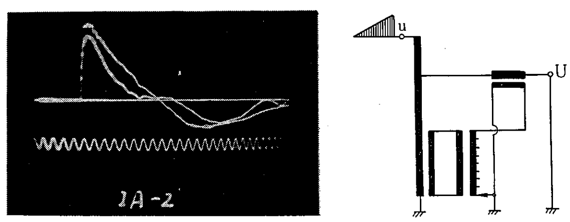
Fig. 13 **Equivalent circuit for initial voltage distribution**

By observing *Table 3*, it proves theoretically that the double electrostatic shield construction of the series transformer improves effectively and remarkably the impulse voltage characteristics of this autotransformer.

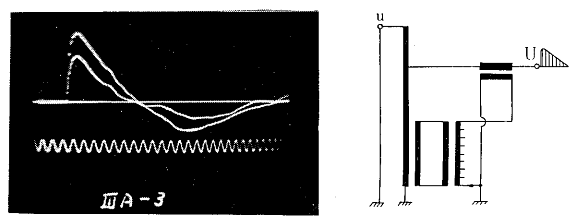
2. Measured Results

1) Stresses on the Series Winding of the Main Autotransformer

Fig. 14 shows two examples of these stresses. When an impulse voltage is applied to 275 kV terminal the series winding is subjected to 82.5% of the applied voltage, that is, $1050\times0.825=866$ kV. On the other hand, when applied to 220 kV terminal it is subjected to 66.5% of the applied voltage, that is, $900\times0.665=600$ kV. These values are practically independent of the tap position of the regulating transformer.



(a) When impressed to 275 kV terminal



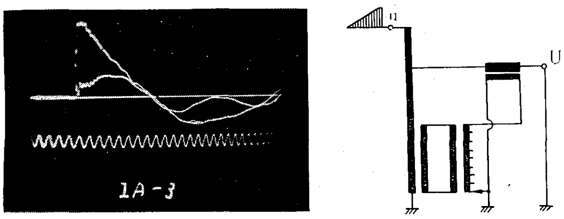
(b) When impressed to 220 kV terminal

Fig. 14 **Voltage stresses on series winding of main autotransformer**

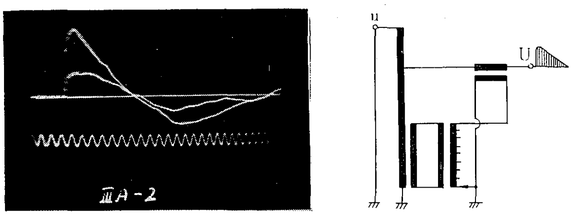
We were required to carry out impulse voltage tests under such conditions that unimpressed terminals were directly earthed in accordance with the draft of JEC 110 (Japanese standard) to be revised. Therefore the series winding is designed for impulse withstand voltage of 1,050 kV applied to the 275 kV terminal and above impulse stresses are quite out of question.

2) Stresses on the Secondary Winding of the Series Transformer

Fig. 15 shows two examples of these stresses. From these wave forms it can be seen that only a little voltage oscillations appear when impressed from either 275 kV terminal or 220 kV terminal and therefore inner capacitance control by double electrostatic shield plates of the series transformer is nearly in optimum. Magnitudes of the stresses vary slightly with tap position and they become maximum at both extreme tap positions, minimum at center tap position.



(a) When impressed to 275 kV terminal



(b) When impressed to 220 kV terminal

Fig. 15 Voltage stresses on 2ry winding of series transformer

3) Potential to Earth of the Connecting Point between Main Autotransformer and Series Transformer

Fig. 14 (b) shows impulse stress on the series winding of the main autotransformer as well as the impulse potential to earth of the connecting point when impressed to 220 kV terminal. *Fig. 15 (a)* shows also impulse stress on the secondary winding of the series transformer as well as impulse potential to earth of the connecting point when impressed to 275 kV terminal. Since this connecting point is designed for impulse withstand level of 900 kV, no fear is necessary for its insulation against above potentials at all.

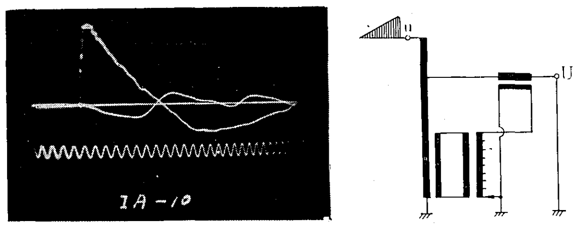
4) Transfer Voltages to the Tap Winding of the Regulating Transformer

Transfer voltages to the tap winding of the regulating transformer are mainly composed of two components, which are

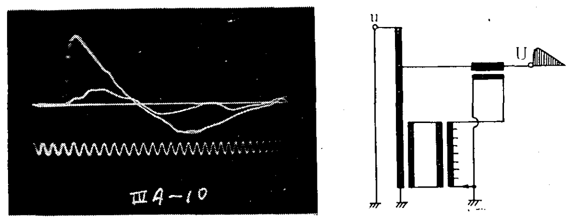
(1) Component due to the electromagnetic transfer of the stresses on the secondary winding of the series transformer

(2) Component due to the electromagnetic transfer of the transfer voltages to the tertiary winding of the main autotransformer.

Therefore the magnitude of the transfer voltage varies largely, depending on the tap position and it becomes unappreciable at some tap positions, as shown in *Fig. 16* and *17*. *Fig. 18* shows the crest values of the transfer voltages as a function of the tap position. It is due to the phase condition between two components that the transfer voltage at 255 kV tap is higher than that at 215 kV tap.

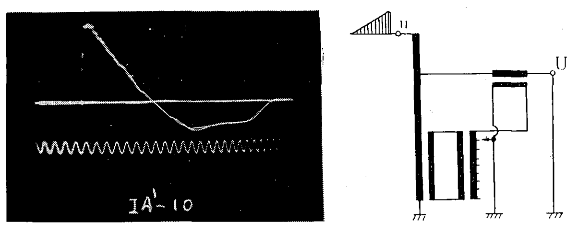


(a) When impressed to 275 kV terminal

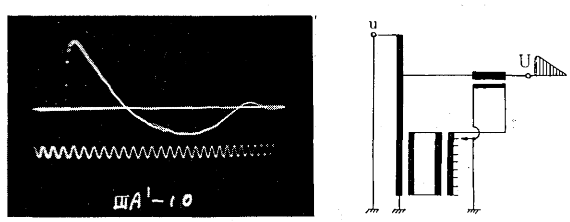


(b) When impressed to 220 kV terminal

Fig. 16 Transfer voltages to tap winding of regulating transformer (No. 1)



(a) When impressed to 275 kV terminal



(b) When impressed to 220 kV terminal

Fig. 17 Transfer voltages to tap winding of regulating transformer (No. 2)

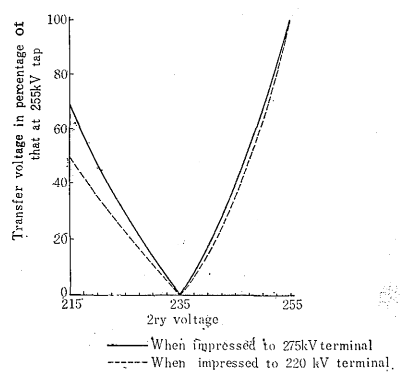
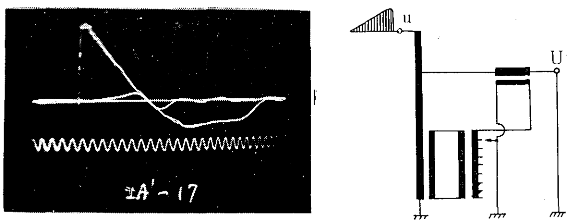
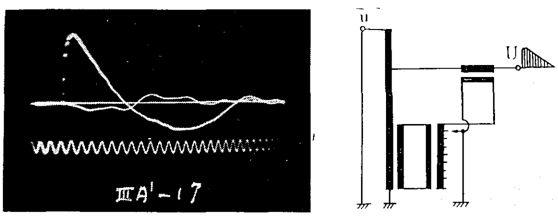


Fig. 18 Transfer voltages to tap winding of regulating transformer (No. 3)

Fig. 19 illustrates the voltages at the end terminal of the no-current section in the tap winding which occurs by tapping. In case of tap position of *Fig. 19* voltages transferred from the series transformer are approximately zero, therefore it may be considered that the wave forms of *Fig. 19* indicate those of the voltages transferred from the tertiary winding of the main autotransformer.



(a) When impressed to 275 kV terminal



(b) When impressed to 220 kV terminal

Fig. 19 Transfer voltages to tap winding of regulating transformer (No. 4)

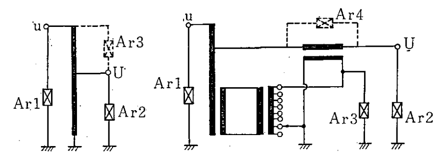
From above observations it proves that the transfer voltage to the regulating transformer is maximum at the tap position of 255 kV. This conclusion gives the base of the selection of the tap position at the impulse voltage tests, as described later.

Impulse voltage distribution along the tap winding is practically linear as understood by *Fig. 20 (a)* to *(d)* and any abnormal stresses can not be seen in any parts of tap winding. This result has been expected as a matter of course because of adoption of the parallel wound cylindrical layer tap winding.

VIII. SURGE PROTECTION

By only providing with arresters Ar_1 and Ar_2 to the line terminals, as shown in *Fig. 21 (a)*, the usual autotransformers, except those of lower co-ratio, can be enough protected and the series winding can be insulated with high reliability without by-pass arrester Ar_3.

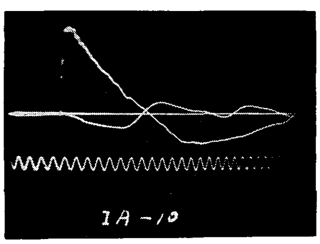
But in case of this autotransformer with indirect voltage regulation [*Fig. 21 (b)*], even if primary and secondary line terminals are respectively provided with arresters Ar_1 and Ar_2, violent voltage oscillations will occur on the connecting point, if the main autotransformer and the series transformer are connected carelessly. It is impossible consequently not only to expect high reliability on insulations, but also to make the autotransformer more economical.



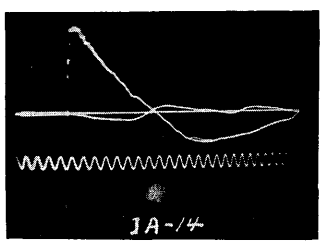
(a) (b)

Fig. 21 Surge protection of autotransformer

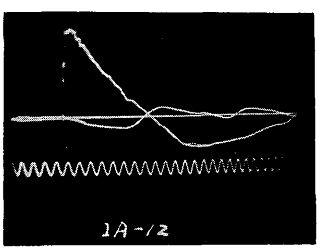
According to the results of our trial calculations for such case, insulation level above 1,050 kV to earth was necessary for the connecting point and above 900 kV between terminals for the secondary winding of the series transformer. Taking into account that the secondary winding of the series transformer has a few number of turns for regulating voltage of 20 kV, it would be understood easily how difficult it is to insulate the secondary winding reasonably and economically so as to withstand above mentioned abnormal stress. For that reason the use of the by-pass arrester Ar_4 has been a general practice, as shown by dotted line in *Fig. 21 (b)*. Although the insulation level of the secondary winding of the series transformer can be sucessfully reduced by this by-pass arrester certainly, we can not think that such a



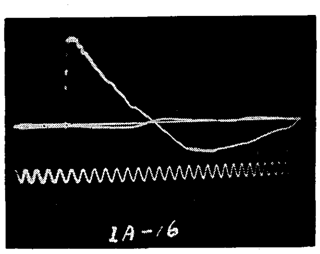
(a)



(c)



(b)



(d)

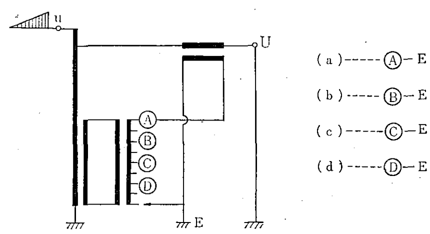


Fig. 20 Transfer voltages to tap winding of regulating transformer (No. 5)

method is the best one.

In order to solve this problem reasonably and economically, inner capacitances are satisfactory controlled by the double electrostatic shield plates of the secondary winding of the series transformer, as described above. Namely, by our method the initial voltage distribution, which depends on inner capacitances, can be made perfectly equal to the quasi-stationary voltage distribution, which depends on leakage inductances. In fact, inner voltage oscillations could be made minimum, abnormal potential to earth did not appear on the connecting point and the secondary winding of the series transformer was only subjected to the smallest stresses. Therefore in case of this autotransformer by-pass arrester Ar_4 becomes unnecessary and nevertheless a high reliability on insulations are kept only by arresters Ar_1 and Ar_2.

Besides, in this autotransformer the primary winding of the series transformer is provided with arresters Ar_3 of 30 kV class against transfer voltages from a prudential consideration.

IX. PROVING OF DIELECTRIC STRENGTH

1. Induced Overvoltage Tests

The induced overvoltage tests at our Factory were made under such conditions that 220 kV terminals *V* and *W* were directly earthed instead of 275 kV terminals *v* and *w* and the tertiary winding of the main autotransformer was excited by a single phase source, so that the test voltage of 460 kV was induced on the 275 kV terminal *U*, as shown in *Fig. 22*. It was unavoidable because of the turn-ratio of the main autotransformer that the voltage of 413 kV was simultaneously induced on the 220 kV terminal *U* which was about 6% higher than the test voltage of 390 kV. The test voltages were applied to the individual phases in succession.

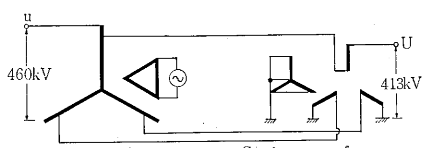


Fig. 22 Connection diagram at induced test

2. Impulse Voltage Tests

Impulse voltage tests were carried out in accordance with the draft of JEC 110 to be revised under such conditions that the unimpressed terminals were directly earthed, that is, when impressed to 275 kV terminal, 220 kV terminal was earthed directly or vice versa.

For the low voltage circuit, which consists of the tertiary winding of the main autotransformer, the regulating transformer and the primary winding of the series transformer, it is unnecessary to consider the direct impact of the surges constructively. Therefore no impulse voltage tests were carried out for the windings in this circuit, but the tap position of the regulating transformer was merely left maximum in order to make the transfer voltages to this circuit maximum during the impulse tests of the main circuit of extra high voltages.

X. TRANSPORTATION

The main transformer, which consists of the main autotransformer and the series transformer in a common tank, was transported by our " Schnabel " wagon of type SHIKI 280 with carrying capacity of 165 tons as shown in *Fig. 23*. This main transformer

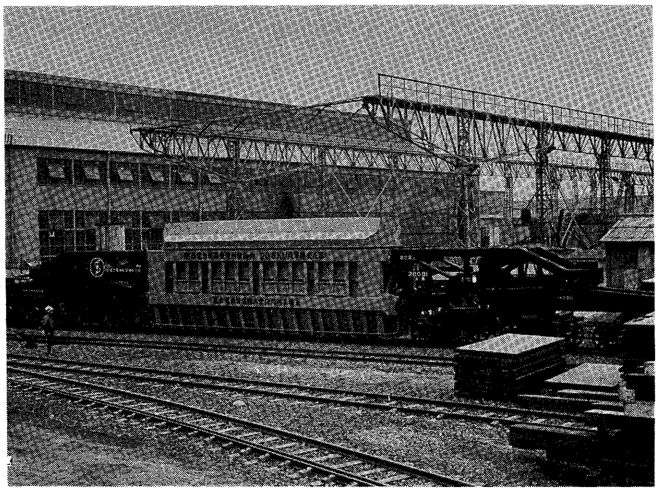


Fig. 23 Transportation style of autotransformer

has a shipping weight of 145 tons. The on-load voltage regulating transformer, having a shipping weight of 45 tons, was transported with built-in tap-changing equipments by our wagon with flat deck of type SHIKI 40 with carrying capacity of 30 tons.

XI. CONCLUSION

275 kV 200 MVA on-load tap changing autotransformer with indirect voltage regulation, which has recently been manufactured by us and is now in satisfactory service at Himeji S. S. of the Kansai Electric Power Co., Inc., is characterized by the oscillation-free type cylindrical layer windings of the main autotransformer and the double electrostatic shield construction of the series transformer. This newest and original technology of ours has remarkably improved the impulse voltage characteristics of this autotransformer and successfully solved one of the most difficult problems peculiar to the autotransformers.

Such a newest and original technology of ours will surely be used as one of the most effective means to solve the technical problems of 400 kV autotransformers. From such a viewpoint this autotransformer has an extremely important significance.