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A PROTOTYPE FOR 500-KV CLASS TRANSFORMERS

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I. INTRODUCTION

The power transformers of Fuji Electric have been making constant progress under the technical cooperation with the Siemens & Halske A. G. of Germany over a long period of 40 years, thus maintaining top rank in the product's manufacturing field.

Upon announcement of this prototype for 500 kv class transformers, Fuji Electric is proud to mention the past history of outstanding development of the products in recent years, as follows:

1951 Manufacture of a perfectly shielded oscillation-free cylindrical layer winding transformer, the first product of its kind in Japan.
1953 First success in Japan in transportation of a completely constructed product by means of "Fahrbar" (transportable) type tank and "Schnabel wagon" (suspension truck).
〃 Completion of 275 kv transformer No. 1.
1959 Manufacture of the first elephant transformer in Japan.
1961 Manufacture of ultra low noise transformer with concrete enclosure.
〃 Completion of extra-high voltage interconnecting autotransformer attached with regulating transformer.
1963 Manufacture of completely fitted all aluminum transportable transformer.
〃 Commencement of optimum design using a digital computer.
1964 Completion of "Fahrbar" type 275 kv, 345 Mva three winding transformer (refer to *Fig. 1*).
〃 Manufacture of a prototype for 500 kv transformers.
1965 Completion of 275 kv 345 Mva on-load tap changing transformer

The Japanese 275 kv power transmission, which was put into operation in 1952, is now in a period of transition into further development, due to the unprecedented demands for power increase along with the rapid growth of the postwar economy and the presently existing small areas for transmission routes near the cities. Tokyo Electric Power Co., Inc. has started construction of a 500 kv class transmission line around Tokyo, while Extra-High Voltage Laboratory is now proceeding steadily with the test facility project for 500 kv class power transmission equipment.

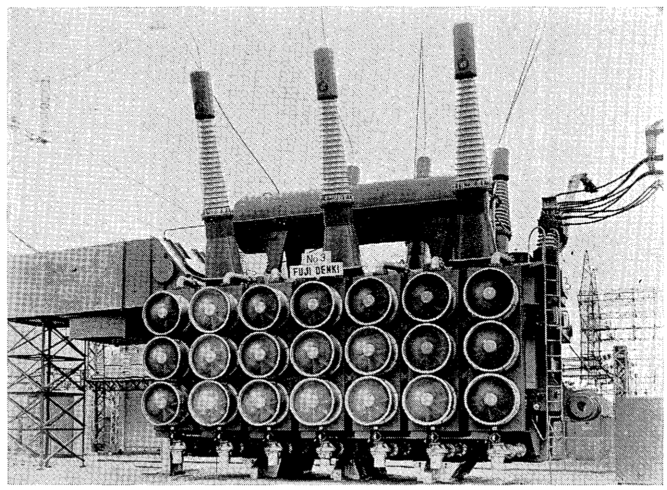


Fig. 1 External view of 275 kv 345 Mva transformer

Actual manufacture since 1953 of Fuji Electric extra-high voltage transformers having cylindrical oscillation-free layer windings now exceeds 60 units, with total capacity reaching 7000 Mva. All are now in service and show satisfactory results. The largest Japanese extra-high voltage interconnecting 200 Mva autotransformer, and the three winding 300/300/90 Mva transformer for substation use are included among them. For transportation of large capacity units in a fully assembled state over the narrow railroad gauge in Japan, the most advanced techniques in related fields are indispensable. Facing the realization of 500 kv class power transmission, Fuji Electric reviewed existing techniques and completed an ultra extra-high voltage prototype transformer with the objective of developing new insulation arrangement and winding construction. Further research covered prevention of internal corona, protection from surging, and on load tap changing. The following provides detailed information regarding the product, together with features.

II. 500-KV CLASS TRANSFORMER

Before entering a discussion of the project for new

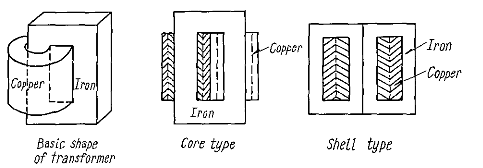
500 kv class transformers, it is important to consider the most suitable type and the possibility of special difficulty as compared with conventional types.

1. Which is Better, the Core or Shell Type?

Standard construction employed by both Siemens and Fuji Electric is based on what is generally termed the core type, with a three-leg core for three-phase usage and a two-leg core for single-phase usage. Both companies also make use of single-phase center-leg cores, three phase five-leg cores, and other cores with special construction. The single-phase center-leg or three phase five-leg core may be not included in the core type category according to definition, but are conveniently classified as the core type if there is close resemblance. *Table 1* gives a comparison of core and shell type features.

There is at present no confirmation of the superiority of either the core or the shell type for 500 kv class transformers. However, it is certainly a fact that the shell type winding must be divided into groups, resulting in the necessity of extra insulation space and complicated lead connections. This deteriorates the utilization factor of the core window space. To cover this disadvantage, a number of solid insulators are used at present between the winding and the core of the shell type transformer, with so-called "Form-fit" tank aranged arround the core.

Table 1 Comparison of Core Type and Shell Type

	Core Type	Shell Type
Definition	Each phase is provided with a core of a single magnetic circuit, together with winding applied around it	More than two shells of magnetic circuit surround the windings
Essential Difference	As seen from the following diagrams, the shell type has larger % impedance than the core type, this being taken to mean that the core cross-sectional area must be made larger for the same % impedance, and that the winding must be divided into groups, resulting in increase of iron quantity 	
Difference in Characteristics	In the case of three-phase unit there is no passage of zero-phase magnetic flux	In the case of three-phase unit there is passage of zero-phase magnetic flux
Usual Differences	Cross-section is circular (More types of iron sheets The winding is round) Core is upright. In case of concentric arrangement, the winding is not divided into many groups	Cross-section is square (Fewer types of iron sheets The winding is square) The core is laid flat. The winding is divided into a number of groups. The average winding length does not vary (advantageous point) Insulation arrangement becomes complicated in construction

For the core type transformer, solid insulation can be used between the periphery of the conventional winding and the tank, with the tank following this shape. This allows for the possibility of smaller and lighter units in the future. For this reason Fuji Electric decided to consider employment of conventional core construction, due to long experience and the fact that this type has been used for the majority of transformers in the world.

2. Should the Winding be Cylindrical Layer or Disc Type?

The long-used disc type winding does not permit better potential distribution with respect to impulse voltage. Thus even more complicated shielding or interacted connection is necessary and graded insulation to the neutral point cannot be utilized effectively. On the other hand, a cylindrical layer winding has an intrinsically good potential distribution inside the winding and provides oscillation-free characteristics with respect to impulse voltage. Features of the oscillation-free cylindrical layer winding entirely adopted for the Fuji Electric extra-high voltage transformer are shown in *Table 2*.

Selection between the cylindrical winding and the disc type winding depends not only on voltage or capacity of the transformer, but also on whether it is two windings or multi-windings, whether it has independent each winding or auto-winding connection, as well as the insulation class specified to the neutral point and the line end of each winding. An oversimplified discussion of which is better should be avoided.

However, the fact that the oscillation-free winding made its appearance only after voltages became higher, and that it is widely used, may be considered as evidence of its excellent features in respect to insulation performance. Fuji Electric has decided to employ the cylindrical layer winding for 500 kv class transformers.

3. On Load Tap Changing Method

A rapid increase in employment of on-load tap changing transformer has become apparent in recent years in Japan.

Principles are based on the standard method of direct switching by means of built-in type on-load tap changer at the neutral point of the high-voltage side, which Fuji Electric developed and popularized before other companies. Since the device is located in the high voltage side, small currents of the diverter switch, tap selector and tap leads are sufficient for normal operation; since it is on the neutral point, large grounding insulation is not required under ordinary conditions. Another advantage is the ease

Table 2 **Excellent Characteristics of Cylindrical Layer Winding (Oscillation Free winding)**

(1) The initial voltage distribution along the winding when an impulse voltage impressed is practically linear, so that it is quite free from internal voltage oscillations. High and uniform reliability can be achieved at every part of the winding.
(2) The trapezoidal from of the winding is a rational construction for the graded insulation and enables space utilization in the core windows to be more effective.
(3) For the insulation between layers oil-impregnated papers are always arranged orthogonal to the electric lines of force to avoid break down caused by surface discharge. Local field concentrations at the ends of the layers are much reduced by adopting a partially round cross-section for the conductors.
(4) Inner cooling is very excellent because of the distinct and unrestricted oil flow through vertical ducts fletween layers.
(5) Since the neutral side, which has lower insulation level, of the high voltage winding faces the low voltage winding, the main insulation distance between high and low voltage windings can be reduced. This results in low impedance. If equal impedance is assumed, the core and the weight of transformer will become smaller compared to those of the conventional disc type winding transformers.
(6) Electrostatic surge transfer to the low voltage winding also becomes comparatively small.
(7) For the tap coil, the parallel wound cylindrical layer type is usually adopted. This tapping arragement has the important merits that no dangerous impulse voltage stress and extremely slight axial electromagnetic force appear.
(8) In order to withstand electromagnetic forces in case of short-circuit accidents, besides the methods which make the short-circuit forces smaller, the mechanical strength of the windings themselves and the supporting devices for the windings must be kept strong. We take full consideration for these points. These will be illustrated in another paper.

of insulation between phases for the on-load tap changer. Actual delivery by Fuji Electric of the transformers equipped with the resistance type on-load tap changer now exceeds 300 units, including the record of 275 kv 300/300/45 Mva.

The interconnecting transformer for 500 kv to 275 kv will be mostly auto-connected one, often rendering neutral point adjustment impossible. One reason for this is shown by *Fig. 2,* where, for instance, the voltage on the high voltage side is held constant and by selecting the tap for changing the voltage in the low voltage side, the tertiary voltage must be varied accordingly. Another reason is that an extremely large tap winding is necessary in case of wide range regulation.

Constant voltage at high voltage side E_1

Variation voltage at low voltage side $E_2\ (1+a)$

a is a number representing the tap range (either plus or minus). Thus the tap winding percentage with respect to the shunt winding is:

$$\frac{n}{N_2}=\frac{a}{1-(1+a)\ (1-r)} \quad \cdots\cdots\cdots\cdots (1)$$

where

$$r=\frac{E_1-E_2}{E_1}=\frac{N_1-N_2}{N_1}$$

This is, co-ratio when $a=0$

For coupling of 500 kv and 275 kv classes in the case of +10% adjustment of the 275 kv side;

$$r=\frac{500-275}{275}=0.45 \qquad a=0.1$$

where

$$\frac{n}{N_2}=0.254$$

That is a tap winding of 25.4% of the shunt winding is required. In a similar way, the constant voltage of the low voltage side can be calculated.

Accordingly, methods shown in *Fig. 3* may be considered as ordinary connections of 500 kv on-load tap changing autotransformers. There is also a method available by which the main transformer is not tapped, and a separate regulating transformer is attached. This form is easier to manufacture but is uneconomical. Since the prototype is aimed at the top class, the examination of this two-core prototype was omitted.

Each of the connections given in *Fig. 3* has its own special feature, and may be selected depending on specifications of the 500 kv autotransformer.

4. Reduction of Stray Load Loss

Magnetic flux leakage of a transformer increases roughly in proportion to the square root of the capa-

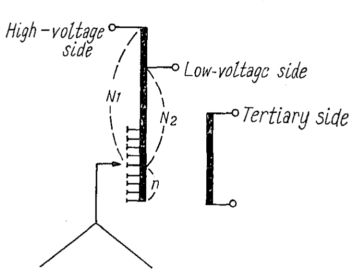
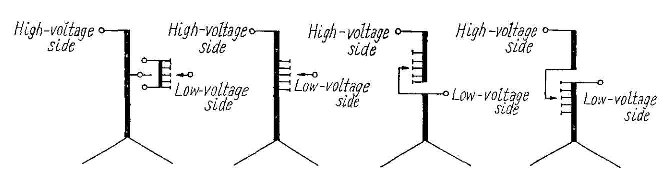


Fig. 2 On-load tap changing at neutral side of autotransformers



(a) Constant voltage in the high-voltage side, suitable for variation voltage in the low-voltage side

(b) Same as at left

(c) Constant voltage in the low-voltage side, suitable for variation voltage in the high-voltage side

(d) Same as at left

Fig. 3 Principal connections for direct on-load tap changing autotransformers city, resulting in an increase of eddy current loss in the winding and stray loss in metal-constructed material. Particularly in case of autotransformer the relation shown in the following exists:

$(\% Z_s) = (\% Z_L)/r$ ....(2)

$(\% Z_s)$: % impedance of self capacity base

$(\% Z_L)$: % impedance of line capacity base

r: Co-ratio, (refer to (1)) usually below 1

Accordingly, for a given line capacity base, a high impedance results for the self capacity base, with a large amount of leakage flux. Careful consideration should be directed to reduction of stray load loss. For reduction of eddy current loss in the winding, a common insulated conductor is used and construction around the winding employs non-magnetic substances. For the tank, the most massive metal unit, silicon steel lamination is used for complete shielding against leakage flux, thus reducing almost to zero the occurrence of stray load loss. This construction has already been utilized in various types of large unit, and should display splendid effects in the 500 kv class transformers.

5. Bushings

Bushings currently used for extra-high voltage may be classified into various types, including the oil-filled, dry condenser, and wet condenser types.

In case of the 500 kv class, the oil filled type has a large flange diameter due to necessity of oil insulation between the center conductor and the mounting flange, and is less frequently used. Both dry and wet condenser types are employed abroad. The former is used by Micafil, Hafely, and others, mainly in Continental Europe while the latter appears to be used mainly in England and the United States.

The dry type features the possibility of a smaller transformer tank because the part under oil is short, while the wet type features good salt resistivity due to the smaller porcelain shell at the upper part. Along with the trend toward larger bushing size, there exists no particular difficulty in manufacture of the condenser core, and large porcelain shell of sufficient size at the upper part is available. *Fig. 4* is the external appearance of a 500 kv class standard bushing.

As serious salt damage due to typhoons and seasonal winds occurs every year to the external insulation of extra-high voltage equipment, research is active in Japan concerning this problem. With the standard bushing, the impulse test voltage determines the flashover length (effective length) in air. In case of contamination, this is determined by an ac test voltage which corresponds to the accumulation of salt. When the porcelain shell at the upper part has a length of eight meters and the maximum surface leakage distance is approximately 22 meters, permissible salt accumulation is approximately 0.08 mg/sq. cm. if 375 kv is taken as the normal phase voltage under a single line-to-ground fault (500 kv working voltage) and if the relationship shown by *Fig. 6* for ac flashover characteristics of the large porcelain shell is used. Thus usage at points greater than ten or twenty kilometers from the coast becomes possible. There are many problems to be solved regarding counter measures against salt contamination. However, extremely substantial investigations have been carried out. An example of a salt resistant bushing is shown in *Fig. 5.*

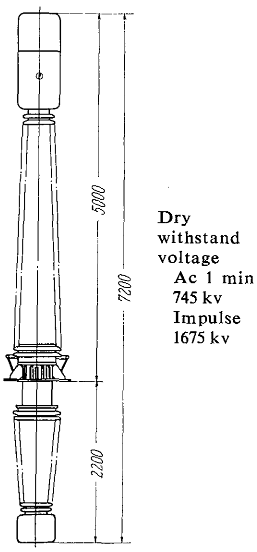


Fig. 4 Standard wet condenser bushing

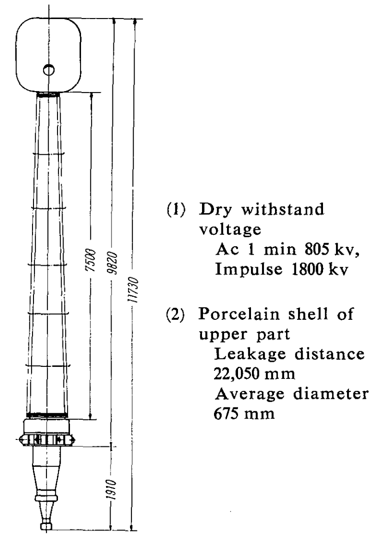


Fig. 5 Salt proof dry condenser bushing

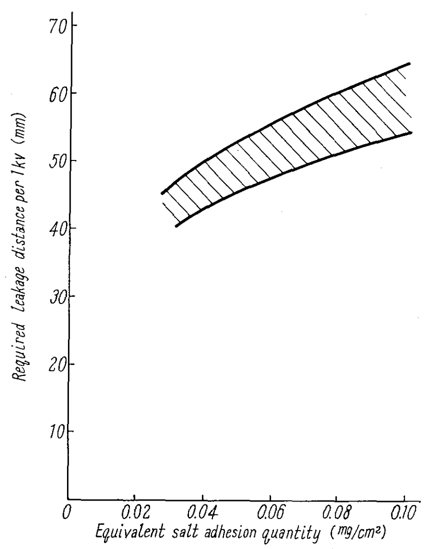


Fig. 6 Leakage distance of salt proof long porcelain shells

6. Transportation

In 1953, just 13 years ago, a 100 kv class 50 Mva transformer with a somewhat unusual shape was completed. It is provided with a tank of low height, narrow width, and sturdy construction, as shown in

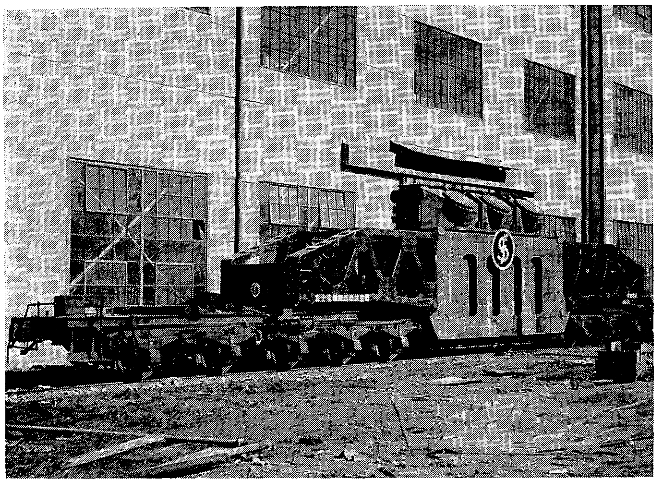


Fig. 7 Transportation of "Fahrbar" transformer

Fig. 7. It was of a shape never before seen in Japan. This transformer was transported by rail with such components as bushings, conservator, explosion vent and cooling equipment removed, and the oil drained, however the interior parts were intact. The tank was suspended at both ends by specially designed suspension truck ("Schnabel wagon"). Transportation of this completely assembled transformer by means of a car type tank ("Fahrbar tank") with full utilization of the techniques developed by Siemens permitted maintaining of insulation in a condition established on completion of manufacture, thus greatly contributing to reliability of the transformer as well as reducing facilities and work days required for installation on site. For this reason, this type of transformer was soon extensively applied. The total number of transformers transported in completely constructed condition inner parts by four suspension cars of Fuji Electric now exceeds 100 units, including the 275 kv 345 Mva unit.

Size limit rather than weight is a problem in transportation of large capacity 500 kv class autotransformer in completely constructed condition over narrow railroads in Japan. As a result of research about this prototype, solid insulation will be used between the periphery of the winding and the tank, with a newly developed construction used for the bottom section of the tank; this will enable a great increase in the capacity limit.

For sea transportation, a 300-ton gin pole has been installed at the factory wharf permitting approach of an ocean vessel in the 10,000-ton class. There should be no difficulty in shipping 500 kv class transformers.

III. CONCEPTION OF PROTOTYPE TRANSFORMER

It is a very difficult problem to determine the insulation level in a 500 kv class transformer (the basic impulse insulation level BIL, commercial frequency test voltage). This should not be simply determined. A plan was made for the maximum BIL of 1925 kv and commercial frequency test voltage of 860 kv then under study in Japan. This plan means an actual increase of approximately 1.85 times over the present 1050 kv and 460 kv of the 275 kv class. The main purpose of manufacturing a prototype was the study of insulation strength for the 500 kv class transformer.

Special research has been conducted in relation to high-voltage insulation, and recent concepts have resulted in solid insulation. The conventional idea that oil serves to insulate and cool the winding is no longer considered applicable to the 500 kv class. Oil should be used only for cooling, the insulation being accomplished by oil impregnated paper. Solid insulation is bound to contain voids in either the liquid or gaseous state, emphasizing the corona problem. Before or during manufacture of the prototype, tests were made on various electrode shapes and insulating material arrangement regarding relationship between the corona starting voltage and the one-minute breakdown voltage at the commercial frequency, between the impulse corona and impulse breakdown voltage, and among the commercial frequency, impulse, and intermediate frequency breakdown voltage, in order to accumulate data. From the theoretical standpoint, calculation of complex field concentration and distribution voltage or field mapping was carried out, obtaining a considerable amount of data which confirms experimental results.

Practically, the following experimental formula may be applied under certain conditions with respect to a given insulation arrangement in the respective range of t.

$$V = at^n \quad \text{..................(3)}$$

Where:

- V: Breakdown voltage (kv)
- t: Insulating distance (mm)
- a: Number to be determined according to type and quality of insulating material.
- n: Number to be determined according to electrode and insulating arrangement.

n approaches 1 in the ideal case of insulation breakdown of a uniform field, and is ordinarily approximately 0.7 at maximum. In the case of surface discharge due to an extremely poor condition at the electrde end, it may be less than 0.1. It may be considered that a is determined according to the type and quality of the insulating material, as well as the degree of combination of the two. It is, for instance, around 25 for the one-minute breakdown voltage of oil impregnated pressed board.

This knowledge in respect to insulation indicates that the utility may diminish unless the prototype transformer has electrode and insulation arrangements similar to those of the actual unit. This is where importance of prototype transformer manufacture lies, differing from simple insulation tests of the material concerned. In actual cases, 500 kv to 275 kv interconnecting autotransformer with the following specifications were considered, and discussions were held on how to decrease size while fully retaining original capabilities.

The specifications of single-phase 50 cps on-load tap changing antotransformer.

Primary side

$500/\sqrt{3}$	(=289) kv	200 Mva

Secondary side

$302.5/\sqrt{3}$	(=174.65) kv	........+10%
$275/\sqrt{3}$	(=158.77) kv	200 Mva
$247.5/\sqrt{3}$	(=142.89) kv	........−10%
$3.4375/\sqrt{3}$	(=1.98) kv	±8 steps 17 taps

Tertiary side 66 kv 60 Mva

The side where taps are provided, the tap range, and the number of taps will be determined in respect to system conditions. Even when these vary, no difficulties arise if the research results of the prototype are fully applicable.

Primary and secondary voltages of the prototype are completely identical to those of the actual unit, while the tertiary voltage was made 15 kv for the insulation test power supply. (Since the autotransformer connection is used for the primary and secondary and the neutral point is directly grounded, an ordinary voltage test could not be applied. Thus the power supply for performance of the insulation test of the line end of the high voltage side must be made from the tertiary.)

It is important to include the winding end in the study of the insulation, as shown in *Fig. 8*. The part of the uniform field at the center of the winding is not quite such a problem. Winding of the prototype is considerably reduced axially as compared to the actual transformer, while the radial size is nearly identical, as it otherwise affects insulation of the winding end and that between the layers.

The number of layers of the cylindrical winding as well as the voltages between the layers are also

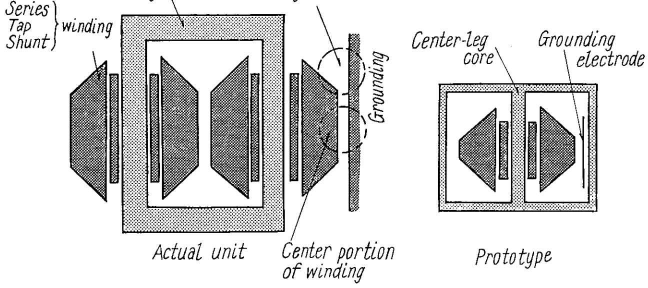


Fig. 8 Prototype and actual unit

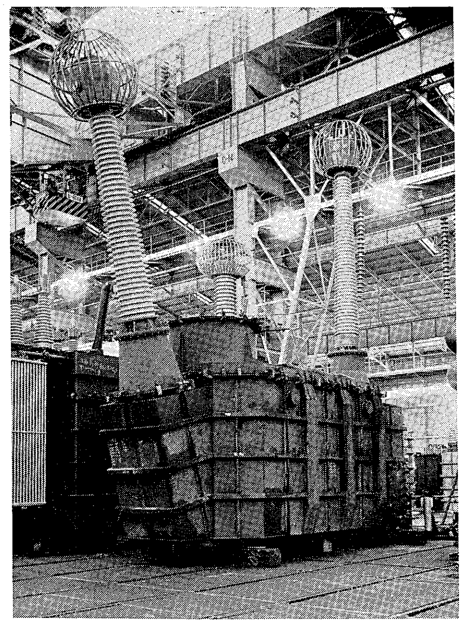


Fig. 9 Outer view of prototype

identical to those of the actual unit. In order to reduce size of the core, the voltage per turn should be reduced. Since the voltage is the same, the number of turns must be increased. The axial size of the copper conductor is shortened as much as possible so as to permit as small an axial size of the winding as possible, in spite of an increase in the number of turns.

In order to secure the staging of the trapezoidal form, which is important for insulation, the size of conductor is changed for adjustment. Since the purpose of research is satisfied if one leg is made, the center-leg core construction is adopted for the prototype, as shown in *Fig. 8,* while the two-leg core is used in the original transformer.

Size and weight of the prototype are determined according to the above mentioned concept. If the result is expressed in electrical capacity, the prototype may be said to be approximately 20 Mva. (It is often meaningless to state the capacity, but is mentioned here merely to indicate the size.) *Fig. 9* is a photograph of the prototype, and *Fig. 10* is a line drawing which shows dimensions.

IV. FEATURES OF THE PROTOTYPE

The prototype is purely for experiment and research, not for confirmation of temporary or partial insulation strength of a transformer for practical use. It is intended for insulation test up to the breakdown, repairing it for repeated testing, thus permitting comprehensive and continuous research.

Provision of an on-load tap changer is another feature of the prototype. This is used to determine how the tap winding should be arranged for a

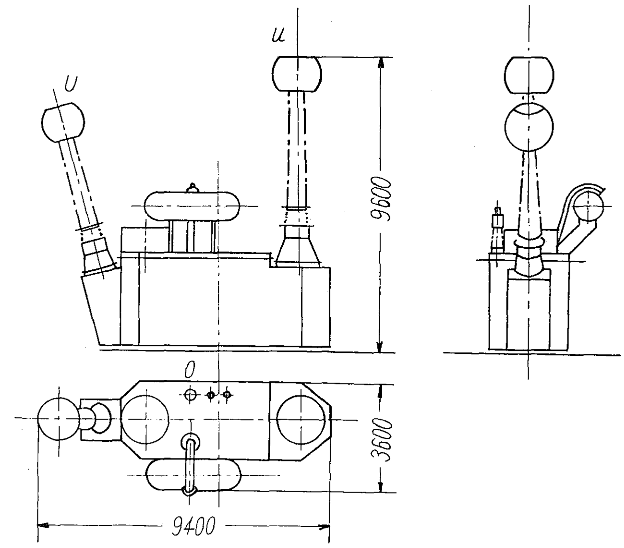


Fig. 10 Outline of prototype

wide range tapping and extraction of tap leads, in addition to development of the on-load tap changer. Behind prototype manufacture was the concept of handling overall and difficult problems as much as possible, leaving partial and simple problems to be resolved in the future.

The final goal of prototype manufacture is to increase the transportable capacity limit of the 500 kv class transformers. The largest possible capacity of a transformer which can be manufactured within size and weight limits imposed by rail transportation is also a guiding principle for engineering related to transformer design and manufacture. The connection and arrangement of prototype windings are shown in *Fig. 11*. A number of newly developed construction methods is adopted for the purpose of research and study of the possibility of increasing the capacity limit. Details are given in the following.

1. Internal N Connected Oscillation-free Winding

The oscillation-free winding of the cylindrical layer permits the internal potential distribution to be linear with respect to the impulse voltage and does

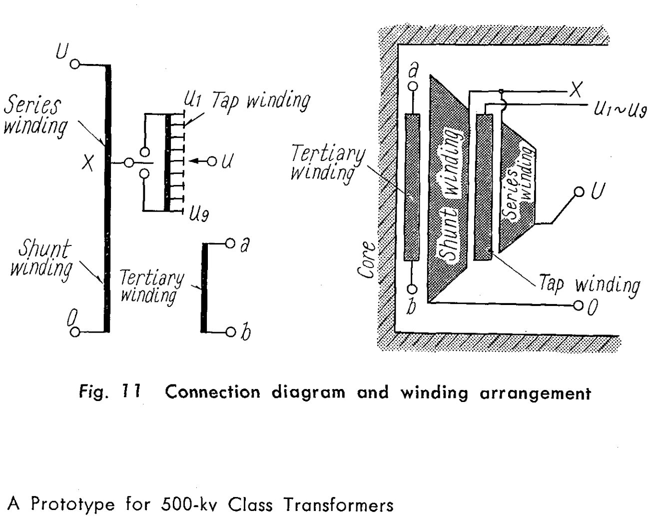
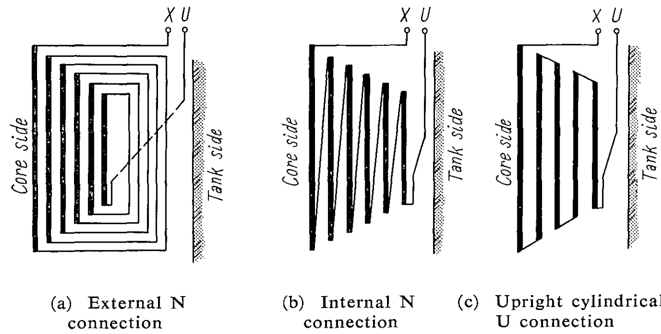


Fig. 11 Connection diagram and winding arrangement



(a) External N connection (b) Internal N connection (c) Upright cylindrical U connection

Fig. 12 Connection method between layers

not produce voltage oscillation in the winding. It is a popular winding construction highly suitable for extra-high voltage and displays full performance when voltage in the line side is high.

In the conventional type of this transformer the connections between layers are made outside the winding, as shown in *Fig. 12*. However, in this prototype, these connections are made inside the winding. Development of this method eliminates the layer-to-layer connecting lead which has to pass outside of the winding, considerably reducing distance from outside of the winding to the tank. This enables a larger winding capacity within a limited space, thus greatly contributing to increases in the transportable capacity limit.

Consideration has long been given to the internal N connection. However, full-scale research at this time resulted in the prospect of future practicability. Regarding the insulation strength of the internal N connected lead which passes between the high voltage layers, a total of 44 models differing only in axial length were prepared in cooperation with the Insulation Research Department of the Central Laboratory. Corona starting voltage or breakdown voltage was studied with respect to the commercial frequency and impulse voltage. During the experiment a new technique was discovered for measurement of impulse corona, and a detailed account was made in an article appearing in the Journal of the Japanese Institute of Electric Engineers. With this prototype detailed investigations for design and manufacture of the internal N connection were completed, thus providing engineers concerned with much confidence in application for practical use. Further efforts will be made in relation to this construction and possible resultant features will be given in detail upon employment in large capacity transformers.

2. U Connected Inclined Cylindrical Winding

Available for cylindrical winding are U and N connection as shown in *Fig. 12*. The U connection features connecting leads which do not protrude from the winding. However, an insulation strength of as much as 2 layers is necessary at the winding end of

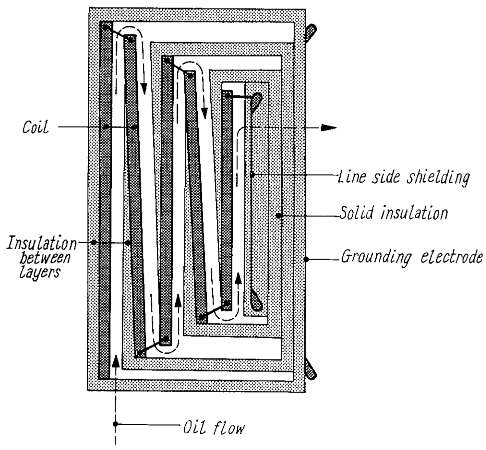


Fig. 13 **U connected cylindrical layer winding with slanting insulation**

one side. In an attempt to reduce the insulation space, an inclined cylindrical winding is employed for each layer instead of the existing upright cylinder, and the radial dimension to which voltage is not applied is decreased. This is motivated by the desire to increase space for the purpose of increasing winding capacity. This U connected inclined cylindrical layer winding is used for the shunt winding of the prototype. Fuji Electric is now in the process of developing another internally cooled type, as shown in *Fig. 13*. The present plan calls for breakdown tests which confirm the mechanical strength limit after insulation tests have been completed.

3. New Method of Parallel Wound Cylindrical Tap Winding

In the case of wide tap ranges, a tap winding is provided, separate from the main winding. This prevent large electrical and mechanical stresses in the winding, and is the present practice. Fuji Electric has employed unique parallel wound cylindrical tap winding to solve the problem. For this winding, the existing method allows the leads to be extracted both from the upper and lower side of the winding, connected outside the winding to the tap changer. However, in this prototype, a new method has been devised for tap winding connection, in which each tap coil is connected inside the winding. The tap lead is extracted only from the upper side. This method permits simplification of insulation between the winding and the tank even in on-load tap changing transformer. Thus solid insulation structure over the outer surface of the winding has appeared, as stated below.

4. Solid Insulation Structure Over Outer Surface of Winding

Solid insulation structure of main insulation of the winding between high and low voltage sides was first realized in 1953 by the Fuji Electric staff, and outstanding results have since been obtained with respect to manufacture of extra-high voltage transformers. The prototype has insulating paper wound around the

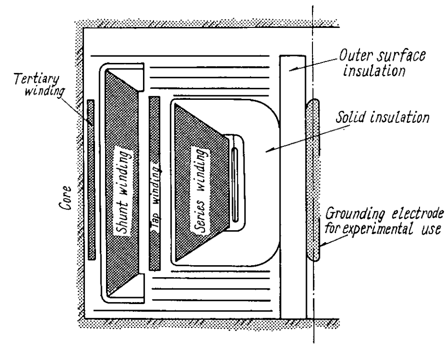


Fig. 14 **Solid insulation structure over winding outer surface**

outer surface of the winding at the super extra-high voltage line end, combining it with layer-to-layer insulation (as shown in *Fig. 14*) together with provision of outer pressed board insulation. This serves for insulation from the tank. This method permits reduction by 1/3 to 1/2 of the present insulation distance between the outer surface of the winding and the tank, enabling a large increase in winding capacity for the same tank size. As stated above, partial grounding electrodes are provided on outer surface insulation of the winding for experimental purposes. The relevant tests were repeated for studying the breakdown phenomena at ultra extra-high voltages.

5. Trial Use of Non-metallic Construction Material

In the range where f, μ, and a are large and p is small, eddy current loss p per unit volume in constant magnetic flux density B is:

$$p \propto f^{\frac{1}{2}} \mu^{-\frac{3}{2}} a^{-1} \rho^{\frac{1}{2}} B^2 \quad \ldots\ldots\ldots\ldots (4)$$

In the range where f, μ, and a are small and p is large, it is:

$$p \propto f^2 a^2 \rho^{-1} B^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

f: Frequency — μ: Magnetic permeability

ρ: Specific resistance — a: Size perpendicular to magnetic flux

Generally, loss is determined with formulas (4) and (5), requiring very difficult calculation. When a nonmetal of extremely high specific resistance is used for the construction material, eddy current loss approaches 0, as shown in *Fig.* (5); it also has the another advantage that it may be arranged to combine the function of an insulating material. For the prototype transformer, glass laminated board bonded with epoxy resin instead of metal is used in various portions. Actual performance of this epoxide glass lamination was studied for future reference.

6. On-Load Tap Changer

The on-load tap changer, to be equipped at the 275 kv side, is the most reasonable built-in type for insulation purposes. For the diverter switch, a two-resistor Yansen type is used. The diverter switch is single phase, rated at 1800 amp. The changer comprises, as shown in *Fig. 15,* the diverter switch

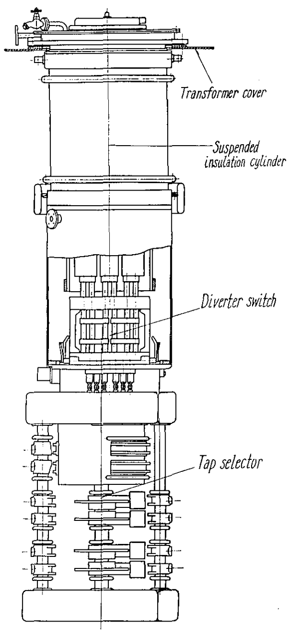


Fig. 15 On-load tap changer

chamber under the suspended insulation cylinder and the tap selector located beneath it. The diverter switch is separated from the clean oil of the mainpart of the transformer because of its possible contamination due to arcing. Oil is connected outside by means of an insulated pipe. Through this pipe oil is filtered by circulation and gas decomposed upon changing is discharged.

Unlike the typical one-shaft selector switch in which the current carrying moving contact and the non-current carrying moving contact slide simultaneously over the separate fixed contacts when changing the tap, this selector is the two-shaft type, with the shafts of two moving contacts separated so that only the non-current carrying moving contact moves when the tap is changed. This reduced contact wear. The changer size is that actually used. With respect to special insulation problems between contacts and contacts to the ground, sufficient studies utilizing prototype are now in progress.

7. Bushings Used for Prototype

Bushings used for the prototype are of the wet condenser type manufactured by Furukawa Denko, and are well known for excellent performance as extra high-voltage bushings. Working voltage of the bushings was limited by size of the porcelain shell of the upper part available at that time.

Table 3 shows characteristics of the bushings:

Table 3 **Characteristics of Bushings**

	High Voltage Side	Low Voltage Side
Ac Dry Withstand Voltage, One Minute (kv)	900	770
Impulse Dry Withstand Voltage Three Times (kV)	2010	1610
Visual Corona Starting Voltage	775	Not appeared at 770
Tan δ (at 300 kv)	0.43	0.44
Overall Length (mm)	8450	7150
Length of Upper Insulator (mm)	5700	4850
Effective Length of Upper Insulator (mm)	3900	3400
Length under Oil (mm)	2750	2700
Effective Length under Oil (mm)	1900	1600
Weight (kg)	3200	2800

V. CHARACTERISTICS AND TEST RESULTS

The prototype is aimed mainly at insulation research, but is also useful in studies of % impedance characteristics and abnormal surge voltages appearing in the tap winding since the autotransformer has a wide tap range.

1. % Impedance Characteristics

Impedances across each winding and the degree of impedance variation due to tap position are determined by division and arrangement of windings inside the core window, and may be freely selected to a certain extent. This is limited, however, by insulation construction requirements, for both core and shell type transformers.

In this prototype, the tap winding is arranged between the series winding and the shunt winding. Changing of the tap winding position gives different impedance characteristics. Impedance of a transformer with this complicated winding arrangement may be accurately calculated by means of circuit theory using the impedance between the two windings or by obtaining the total energy of the magnetic field of each part at the relevant kva. For instance, the % impedance at each of the taps between the primary and secondary of the prototype is expressed by the following formula; it was then confirmed that calculated results and actually measured values exactly coincide.

$$(\%Z)=\frac{N_S N_C}{N_L^2}(\%Z_{S-C})\pm\frac{N_S N_T}{N_L^2}(\%Z_{S-T})\mp\frac{N_C N_T}{N_L^2}(\%Z_{C-T}) \quad \cdots\cdots\cdots (6)$$

(For compositon, the upper is taken in plus adjustment and the lower in minus adjustment)

N_L: Line capacity
N_S: Series winding capacity
N_C: Shunt winding capacity
N_T: Tap winding capacity
Z_{S-C}: % impedance between series winding and shunt winding
Z_{S-T}: % impedance between series winding and tap winding
Z_{C-T}: % impedance between shunt winding and tap winding

For the above values, the values corresponding to respective taps are taken.

2. Abnormal Voltage

Since this prototype is not an electromagnetic model, the problem of voltage oscillation in the winding cannot be investigated rigorously. However, regarding the impulse voltage behaviour of the autotransformer of the oscillation-free cylindrical winding, research has already been made. Consequently, particular attention was fixed to the tap winding in rigorous analyzer testing of the voltage of each part by means of a direct observation device for transient phenomena, fitting or removing the shielding. *Fig. 16* shows one example of the test results, which indicates that no large voltage appeares in the tap winding if a reasonable amount of shielding is applied.

3. Insulation Test

As a preliminary test, insulation strength of the tertiary winding and the neutral side of the auto-connected winding were checked. Then the neutral side was grounded, and full wave impulse voltages up to 1425 kv were applied to the high voltage terminal. Commercial frequency test voltage up to 630 kv was induced at the high voltage terminal, with the neutral point properly raised. Corona tests were also conducted, before entering main testing. Main testing was divided into two stages, the ground insulation test and layer insulation test. The ground insulation test of the line end was conducted in the following combinations:

	Full wave impulse	Commercial frequency
(1)	1550 kv	680 kv
(2)	1675 kv	745 kv
(3)	1800 kv	800 kv
(4)	1925 kv	860 kv

As stated, the breakdown test was carried out under different conditions, with the insulation distance varied by moving the grounding electrodes. In some cases, a streamer as long as one meter started from the extracting outlet for high voltage lead, and passed horizontally around the outer surface of the winding, rising vertically along the insulation surface of the grounding electrode before dropping into the uncovered metal portion. Such a realistic view of insulation breakdown phenomena in ultra extra-high voltage class equipment, was a reminding of true difficulty involved in solving the problem.

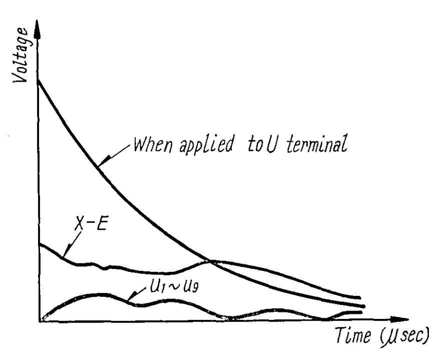


Fig. 16 Analyzer test of the voltage between taps

The layer test in the winding will be carried out after all planned tests with respect to grounding have been completed. For the commercial frequency, a long-period inducted voltage test will be carried out. Afterward, for the series winding, the low voltage terminal will be grounded and the above mentioned full wave impulse will be applied to the high voltage terminal. For the shunt windıng, the neutral terminal is grounded for application of an impulse wave of greater than 1050 kv to the low voltage terminal, in order to obtain the breakdown strength.

VI. CONCLUSION

After three years of experiments and research at high expense, the 500 kv class transformer has now been completed. This transformer is based on unprecedented winding construction and insulation arrangement providing unmatched insulation strength including insulation against an impulse voltage of 1925 kv and a commercial frequency voltage of 860 kv. A number of preliminary tests and partial experiments were conducted in the three year period and results are now fully utilized in the design and manufacture of various kinds of transformer. Also manufactured for delivery to Furukawa Denko was a 12 Mva testing transformer with a commercial frequency test voltage of 845 kv 10 min (which is considered to be the highest of the world, if converted into one-minute test voltage as a practical unit with in sulation strength corresponding to ultra extra-high voltage).

The world's first 400 kv class power transmission system was placed in operation in Sweden in 1952. This system has extensively spread throughout Europe. A number of 400 kv class power stations as well as substations have also been installed. According to actual records, unit capacity of associated transformers at the sending and receiving ends is approximately from 300 to 600 Mva. In the case of a 500 kv class power transmission system, it is said that for reasons of economy, unit capacity may be more but never less.

The prototype was first aimed at the maximum insulation level, as already mentioned. In recent days, BIL of the 500 kv class in Japan is reported as 1675 kv or 1550 kv. Reduction of the insulation level specifications may be considered to permit transportation of the 500 kv class transformer with a bank capacity in 900 Mva class over the narrow gauge railroad, in a completely assembled condition, along with development of a new winding construction and insulation arrangement. As stated, transformers using the core type core and oscillation-free layer winding display their advantages at valtages which are especially high. Fuji Electric is continuing efforts to develop transformers for future damands.