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550 KV, 300 MVA ON-LOAD TAP-CHANGING AUTOTRANSFORMER FOR BONNEVILLE POWER ADMINISTRATION, U.S. DEPARTMENT OF THE INTERIOR

By Hiromu Kawashima

Shigeaki Kunieda

Yoshiaki Ikeda

Chiba Factory

I. INTRODUCTION

Fuji Electric completed three units of very large autotransformer which were ordered by Bonneville Power Administration, U.S. Department of the Interior (BPA) in April 1967. The units were rated at $\frac{525}{\sqrt{3}}$kv/$\frac{241.5}{\sqrt{3}}$kv/34.5 kv, single-phase 300/300/25 Mva and destined for the Allston Substation in Oregon. The most outstanding technical features of the units were—

(1) Corona discharge measurements were performed in conjunction with the long-duration, low frequency test.

(2) The on-load tap-changer is directly connected to the 241.5 kv line side of the series winding. That is, it is applied to a high operating voltage.

The units are the result of our development work, which included the design, construction, and testing of propotypes. The completion of the autotransformers will be an important step in the manufacture of 500 kv transformers for export and the com ing domestic market.

II. TECHNICAL SPECIFICATIONS

The main specifications of the autotransformer are as follows.

Standards — ASA C57, 12–1950 and BPA Specifications

Type — Outdoor use, oil-immersed, forced cooled, autotransformer, single-phase, 60 Hz with ratio control under load

Rated kva — Primary (H-) Winding kva 300,000
Secondary (X-) Winding kva 300,000
Tertiary (Y-) Winding kva 25,000

Each transformer winding has a supplementary rating of 112%, based on an average temperature rise not in excess of 65°C

Voltage — H-Winding with full capacity taps...... F550/$\sqrt{3}$∼R525/$\sqrt{3}$∼F500/$\sqrt{3}$ kv
step voltage: $\frac{6.25}{\sqrt{3}}$kv, number of taps: 9
Connection ......grounded wye
X-Winding ....241.5/$\sqrt{3}$ kv
Connection ......grounded wye
Y-Winding ....34.5 kv
Connection ......delta or open-circuit with one terminal grounded

Impedance — H to X Winding.................10%
X to Y Winding.................27%
H to Y Winding.................40%
Base kva 300,000

Low-frequency tests, kv, rms
H-Line end 630
X-Line end 275
Neutral end 34
Y-Line end 70

Impulse voltage tests, crest voltage, kv

	Full wave	Chopped wave	Front of wave
H-Line end	1425	1640	—
X-Line end	650	750	960
Neutral end	110	—	—
Y-Line end	200	230	345

Switching surge withstand crest voltage, kv
H-Line end............................1180
X-Line end............................ 540

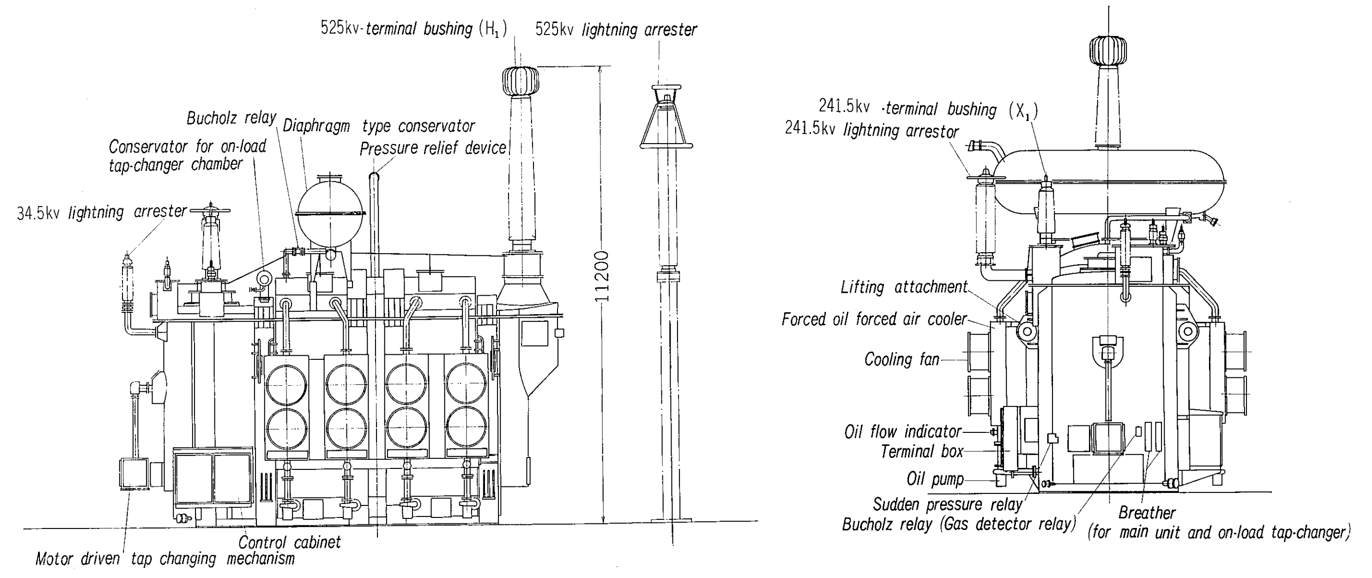
Specific data for the transformer are
Total weight ....320 t (706,000 lb)
Oil quantity ....121 kl (32,000 gal)
Shipping weight......185 t (406,000 lb)

Fig. 1 shows an outline of the transformer.

III. CONSTRUCTION

1. Core

To facilitate processing of the windings and allow for reduction of electromagnetic forces during short-circuits, a two-leg construction was used instead of a three-leg construction with the windings on the center leg which is generally used in single-phase cores. The core consisted of oriented silicon steel



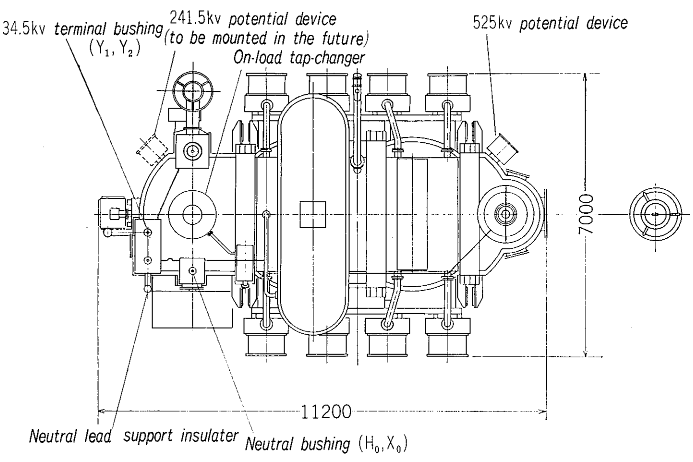


Fig. 1 Outline of the transformer

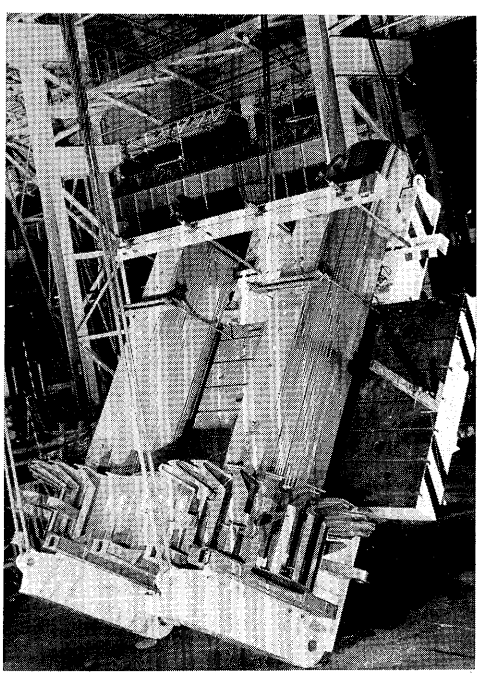


Fig. 2 Election of iron core

laminations with very high permeability and low losses (G9 Core). Core lamination assembly and clamping were characterized by the use of center-bolts and glass-fiber bands. The center bolts were arranged through a cooling duct between two layers of core sheets, and clamp the core via leg-clamping plates. Therefore, all bolt holes in the active core section were eliminated.

The glass-fiber bands are made of epoxy-resin-impregnated glass-fiber tape rendered extremely strong by curing. The bands proved highly satisfactory in tightening the core and preventing the outer edges of core laminations from expanding.

To avoid deterioration of excitation characteristics which can occur even in very high quality laminations because of stress and strain during punching, handling and assembly, a new "core cradle" as shown in *Fig. 2* was added to the manufacturing facilities.

This new equipment is used to raise cores of very large dimensions and weights to the upright position after assembly, without distortion or loosening of the legs.

2. Windings

The windings were wound in parallel on two legs with half of the winding on each leg. The N-connected oscillation-free multi-layer winding, parallel-wound cylindrical tap winding, U-connected oscillation-free multi-layer common-winding, and special disc tertiary winding were arranged concentrically in the above sequence beginning outermost.

The connection diagram and a sectional view of the autotransformer windings are shown in *Fig. 3* and *Fig. 4* respectively.

Continuously transposed conductors with thermally upgraded paper insulation were used in the series, tap and common windings. In this type of conductor, each strand was insulated with a thin film

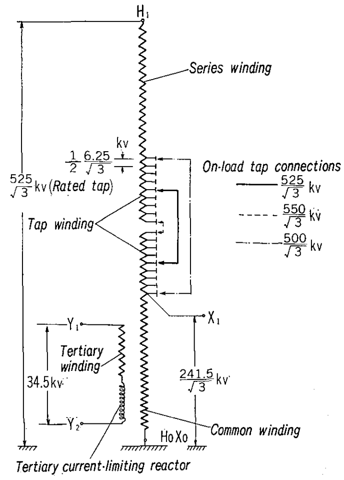


Fig. 3 Connection diagram of autotransformer

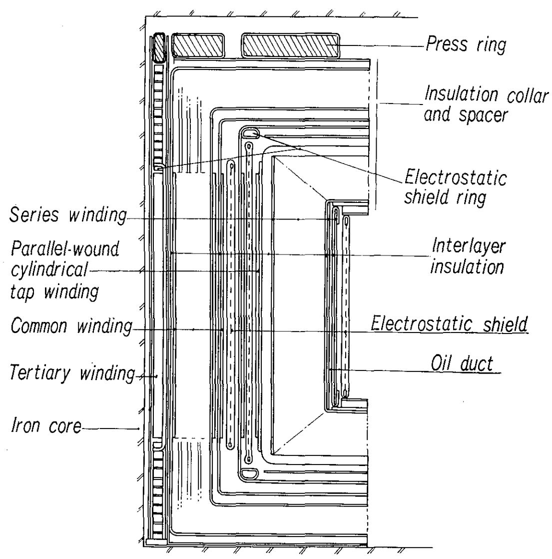


Fig. 4 Section of windings

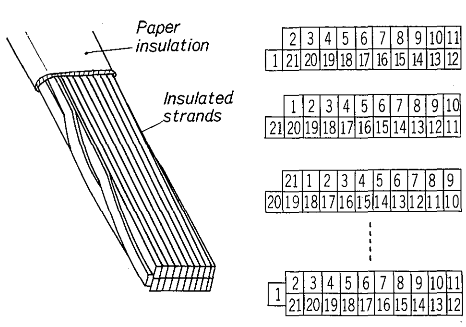


Fig. 5 Transposed conductors

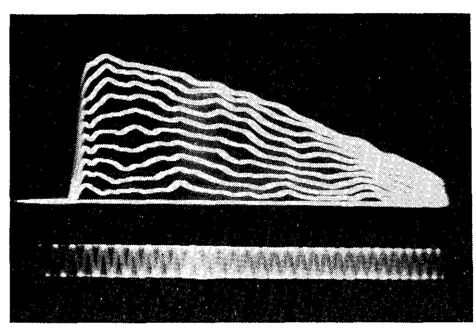
of synthetic enamel. The strands were arranged together in two groups side by side as shown in *Fig. 5*, with frequent changes in relative position. Paper lapping was used for overall insulation. By employing this multiplicity of small-size conductors, which are continuously transposed, eddy- and cross-current losses in the windings were reduced considerably. The elimination of manual transposition also enabled a continuously wound layer winding of high reliability and workability.

The oscillation-free multi-layer winding with its rationalized arrangement allowed for excellent space utilization in the transformer. The reason for this is that the insulation distance between the tap winding and series winding as well as the common winding is nearly equal to the width of the interlayer insulation in the multi-layer winding, and the trapezoid-shaped series winding is suitable for graded insulation.

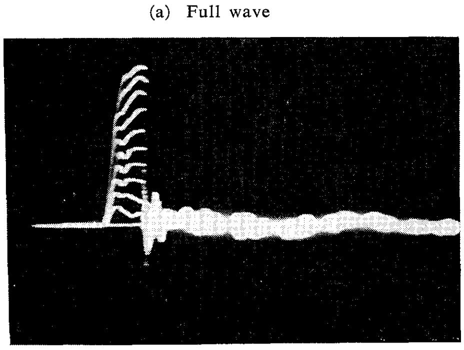
The X- and Y-winding terminals were subjected to " front-of-wave " tests, in which transient voltages injurious to winding end turns are likely to occur due to sudden chopping of the steep wave front. In this multi-layer winding, the path of electrostatic charging current is distinct, because of a higher series capacitance between layers, and coincidence of electrostatic and electromagnetic voltage distribution is achieved intrinsically, which eliminates transient voltage oscillation.

Impulse voltage to ground in each layer of the series winding measured by a transient analyzer is shown in *Fig. 6* as an example of oscillation-free characteristics of the winding.

The tap winding was connected to the end of the series winding for $\pm 5\%$ voltage regulation at the 525 kv side. The winding consists of two layers, each consisting of multi-parallel-wound turns corresponding to half of one step voltage. The turns in respective layers are connected in series to obtain one step regulation. An electrostatic shield is placed between the layer to surpress transient voltage oscillations caused by impulse voltage impinged from the X-line end.



(a) Full wave



(b) Chopped wave

Fig. 6 Potential distribution in series winding

Reduction of stray load losses, which appear in the conductive or magnetic material in the structure as well as in the windings, is one of the most important points in the design of large units. Stray load losses were estimated in individual parts, by calculating leakage flux density with an electronic computer, since it was necessary to insure against local over-heating.

Practical methods employed are as follows.

The electrostatic shield was composed of thin aligned strips of high-resistance alloy and the electrostatic shield ring was made of synthetic resin with very thin strips of aluminium wound around it.

Press-rings to clamp the windings were made of a non-metallic material of epoxy-impregnated glass fibers.

To insure that there would not be overheating, a series of experiments were carried out before design using sectional models placed in a high density magnetic field.

The frame structure was arranged as far from the windings as possible. The silicon steel sheets were bonded together and bolted to the tank wall, to form parallel return paths for leakage flux and to reduce flux density in the tank wall, as well as reduce flux losses.

As the specified impedance between the *X* and *Y* winding, or the *H* and *Y* winding was large, a current limiting reactor was connected in series to the *Y* winding. The reactor was arranged in a corner of the transformer tank. This reactor was divided in parallel circuits because of dimensional requirements and reduction of electromagnetic forces on short circuits, and was enclosed with the magnetic steel-sheet shielding.

The techniques mentioned above have been applied to many of our large power transformers, and results have been very successful.

3. Bushings and Lightning Arresters

Bushings manufactured by the LAPP Insulator Company, Inc. and lightning arresters of the OHIO BRASS Company, both made in U.S.A., were used in the autotransformer.

Main specifications of the bushings and lightning arresters of 525 kv-terminal are shown in *Table 1.*

Bushings were all oil-impregnated-paper condenser types provided with capacitance taps and arrangements for mounting potential devices.

An outline of the 525 kv-terminal bushing is shown in *Fig. 7.*

The potential device of the 525 kv-terminal bushing was mounted on the transformer tank. The lightning arrester of 525 kv-terminal was installed separately from the transformer, but those of X- and Y-line terminals were mounted on the transformer with brackets.

4. Tank and Accessories

Because of the large size of the transformer, an arc-shaped tank wall was employed. Since these subdivided arced wall sections ensured proper stress distribution against internal and external pressure, this type of tank construction allowed for a higher steel utilization factor, oil economy since the tank wall was suitable for core and winding assembly, and also a reduction of vibration of tank walls during operation, when compared with plane-shaped tank walls.

A diaphragm type conservator was employed as the oil preservation system. This was accepted by the BPA, although they first expressed preference for an inert-gas-pressure system. In the diaphragm type conservator, the oil is completely isolated from the air by a thin diaphragm of nylon film coated with nitrile rubber, which directly contacts with the oil surface and moves upwards or downwards in proportion to the change of oil volume. The conservator case, therefore, requires very little space in comparison with other types of conservators and routine maintenance work is quite simple. This air sealing diaphragm ensures long life even in an

Table 1 **Specifications of 525 kv bushing and lightning arrester**

(a) 525 kv-terminal bushing

Dry withstand, 60-Hz, 1-minute, kv, rms	630
Wet withstand, 60-Hz, 10-second, kv, rms	630
Wet withstand, 60-Hz, 15-minute, kv, rms	535
Impulse withstand, 1.5×40 microsec, kv, crest	1425
Impulse withstand, chopped wave, kv, crest	1830
Wet switching surge withstand, 100×300 microsec, kv	1180
Minimum creep distance, inches	290
Visible corona discharge, kv, rms	340

(b) 525 kv-terminal lightning arrester

Arrester rating, kv, rms	396
Maximum IR discharge, kv, crest at 10,000 amp	1100
Maximum switching surge sparkover, kv, crest	936

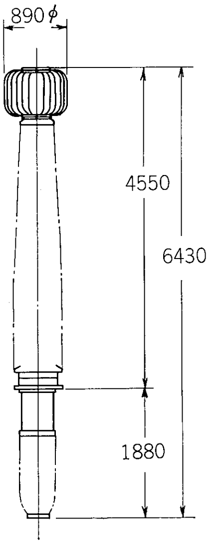


Fig. 7 **Outline of 525 kv bushing**

ambient temperature of −30°C, as specified in the cold-weather life test performed previously. Thus this system is the most effective means of preventing insulation oil deterioration.

5. On-Load Tap-Changer

An on-load tap-changer is connected to the tap winding at the end of the series winding, and mounted in the tank close to the X-line terminal. As can be easily seen from *Fig. 3*, the maximum operating voltage of the on-load tap-changer is $291.5/\sqrt{3}$ kv. Since on-load tap-changers have not been used with such high operating voltages in Japan (although they have been used in 400∼500 kv transformers abroad), great care was taken in the design including insulation for corona and impulse voltage and a series of type tests was performed to ensure reliability.

Because of the high rated step voltage of $6250/\sqrt{3} = 3600$ v, two diverter switches with rated step voltage 1900 v were connected in series for simultaneous operation. *Fig. 8* shows a photograph of the on-load tap-changer.

Two diverter switches (type DSD1) with step voltage rating of 1900 v, and through-current of 1200 amp, which already passed type tests (including a service duty test of 200,000 electrical operations and 800,000 mechanical operations) were combined in one chamber. (type 2DSD1).

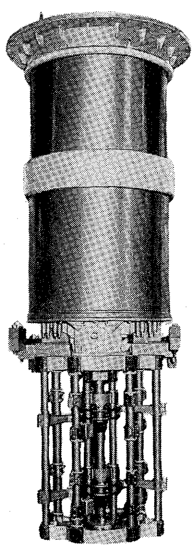


Fig. 8 2DSD1 type on-load tap-changer

Since the operating voltage to earth of the diverter switch is $266.5/\sqrt{3}$ kv maximum, electrostatic shields were attached to the active parts to reduce electric field intensity and a guide to remove gaseous foams generated during tap changing was arranged in the diverter switch chamber to assure the insulating strength. The tap selector selected among nine (9) tapping positions without a changeover selector.

The tap selector was composed of insulation tubes circumferentially arranged with their upper and lower ends fixed by metallic frames and contacts which were fixed to the insulation tubes and were divided in two groups each making odd or even-numbered tapping positions respectively.

Two rotary insulation shafts arranged coaxially in the center, were provided with moving contacts and each shaft was rotated alternately through an angle corresponding to a unit step by a driving mechanism.

The insulation tubes were made of synthetic resin with high creep withstand voltage. To surppress corona discharge from the blank contacts or electrodes, shield rings with paper lappings were attached to them and special consideration was given to the proper arrangements of tap leads connected to the tap selector.

A service duty test was performed as a type test with $365/\sqrt{3}$ kv (corresponding to 135% of operating voltage) imposed between the diverter switch and the grounded part. During the test, the tap-changer was subject to 50,000 continuous operations carrying 112% of the rated current and diverting the rated step voltage without inspection or maintenance. The test results showed that the on-load tap-changer was quite capable of meeting the specifications.

After the service duty test, a dielectric test was carried out with the on-load tap-changer having the same proportion of insulation to ground as the autotransformer.

The on-load tap-changer passed the low frequency test of 400 kv, rms, for 1 minute which represented 120% of the voltage imposed on the on-load tap-changer during the low-frequency test of the autotransformer. It also underwent 300 kv, rms, for 2 hours with no trace of corona and an impulse voltage test at full 900 kv showed favorable results.

6. Transportation

The autotransformers were loaded directly onto a freighter from the wharf of Fuji Electric's Chiba Factory (*Fig. 9*), taken to Oregon via the north Pacific and unloaded on the bank of the Columbia River. From there they were transported by trailer

Fig. 9 Shipping of the autotransformers

truck to the Allston Substation. Special consideration was paid to fixing the transformer main unit and internal components firmly to withstand vibrations caused by rolling, etc. during sea transport. Although the main unit is nitrogen sealed for transport, a moisture absorption detector is installed in the tank to provide a means of detection in the rare event that moisture penetrates into the tank.

IV. PREVENTION OF INTERNAL COLONA

1. Prevention of Internal Corona

Since a severer corona test was required for this transformer than in previous cases, special consideration was given to the prevention of internal corona. Generally, the main factors in the generation of internal corona are as given below.

(1) Strong electric field

(2) Residual air bubbles (void)

In connection with item (1) (strong electric field) the potential gradient of each internal component in relation to the transformer test voltage was maintained below the value at which corona commences in such a construction. For this purpose, a two dimensional calculation of the electric field was carried out by means of an electronic computer in this transformer. In addition the electric field condition was examined by a large number of field mappings and further confirmation was obtained from experiments conducted on a sectional model. Item(2), (residual air bubbles), arises from the fact that if the internal parts are immersed in oil, air bubbles will remain somewhere in the system and corona in void will arise in these bubbles. Therefore, in order to solve this problem, the internal components must be constructed so that no residual air bubbles arise and great care is necessary during the oil immersion process as will be described later. Naturally there are many matters which can be considered, but one very effective means of preventing corona is to maintain maximum material purity by intensifying quality control at the work shop through such means as cleaning the premises and materials with a vacuum cleaner, manufacturing the components in dustproof enclosures, etc. Careful consideration was given to all of the above points in an effort to prevent internal corona.

2. Drying and Oil-Impregnation Procedure

Since the transformer size increased so much, it became necessary to devise various means for drying. For example, temperature distribution in internal components of large transformers was disproportionate due to the disparity of the distance from the heat source, to the drying furnace. In order to solve this problem, a new drying method was used which depended mainly on a combination of hot blast drying and vacuum drying.

In order to achieve perfect oil impregnation, drying was divided into 2 steps. At the first drying, the internal components only were dried under high temperature and high vacuum, and then immersed in oil. At the second drying, the internal components were put inside the tank, and drying was performed once more with the own tank in the drying furnace at a temperature slightly lower than during preliminary drying and oil impregnation was carried out. After the second drying, bushings, etc. were installed on condition that the windings do not contact with air. Extremely careful oil impregnation was then carried out with no further disturbances of the oil.

Applying all of the countermeasures mentioned above, it was possible to obtain very excellent results in the corona discharge test as described in section **V**. From now on there will be an increasing tendency to perform the corona test for EHV transformers and therefore, in order to improve and rationalize transformer quality, maximum attention should be paid to each of the abovementioned procedures during production.

V. TESTS

Largely because of improved operating reliability of the lightning arresters and the necessity of maintaining dimensions and weights of transformers within economical limits, the insulation level of EHV transformers becomes generally much lower. Dielectric tests, however, now include some special tests which recent developments in transformer testing technology have made feasible. The special tests used with this autotransformer were the switching surge test and long-period, low-frequency test with corona discharge measurements, which will be described in the following paragraphs.

1. Switching Surge Test

The wave shapes and magnitudes required by the BPA's specifications were a time to crest of at least 100 microseconds, a total duration above zero of at least 1000 microseconds, and a duration above 90% of crest in excess of 200 microseconds. The test voltage was to be approximately 83% of the winding BIL. The much slower switching surge is distributed inductively in the winding almost from the beginning and causes no subsequent oscillation voltages which often occur with impulse voltages. Therefore, despite of the longer duration, which imposes more severe conditions than with impulse voltages, the internal insulation capacity of oil-immersed transformers may be considered to be not less than 85% of the impulse withstand level. Another facet of switching surge is the longer gap withstand level in air. As shown in *Fig. 10*, 50% sparkover voltage through an air gap does not increase so much as with impulse voltage. This fact was fully considered in designing the outer

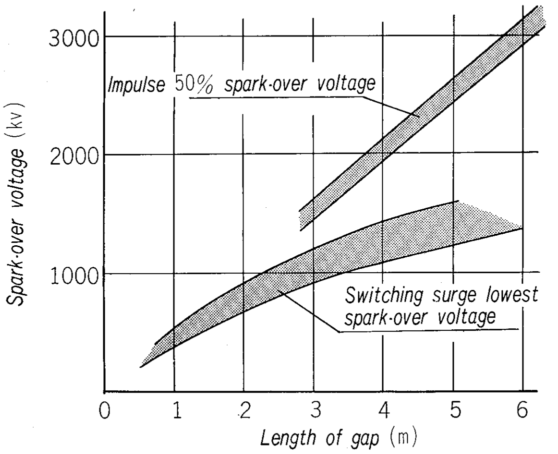
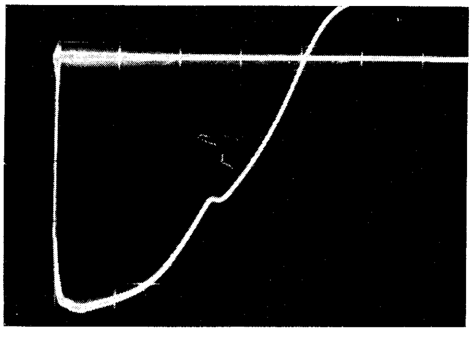


Fig. 10 **Examples of spark-over characteristics of long air gaps**



Crest valve : 1227 kv
Total duration above zero : 2250 μs
Wave front length : 140 μs
Duration time above zero : 911 μs

Fig. 11 **Wave-form of switching surge voltage**

insulation of the transformer.

Methods for applying switching surge to trans formers are either to apply the voltage directly to the high-voltage terminal of the transformer or to discharge the impulse generator into one of the low-voltage terminals of the transformer and to induce the specified test voltage in the high-voltage winding.

The latter method was used for the autotransformer. As a decrease in winding inductance was likely to cause the wave tail to overshoot toward the opposite polarity, overshoot of the wave tail was controlled to a minimum by adjusting the wave-shaping circuit-parameters. *Fig. 11* shows an oscillogram of the test voltage wave.

The switching surge test consisted of applying two full voltage transients as specified above prior to the impulse test.

An examination of the oscillogram of each induced voltage transients proved that the test was passed successfully.

2. Corona Discharge Test

Corona discharge measurements of the autotransformer were made in conjunction with the induced potential test. Measurements were taken at the 475 kv level on voltage rise, at the full rated test voltage of 630 kv for one minute, and again at the 475 kv level, as the voltage was reduced. The

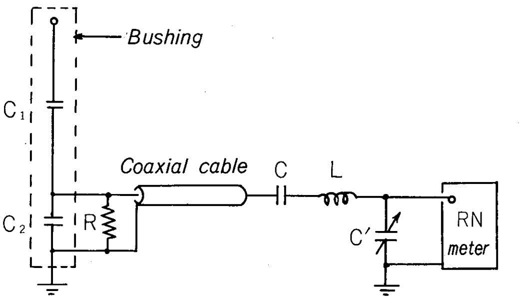


Fig. 12 **Connection diagram for measuring corona discharge**

second 475 kv level, which corresponded to 1.5 times the operating voltage, was held for two hours.

Acceptance criteria in these measurements given by the BPA were as follows :

There shall be no evidence of any internal corona discharge at any 475 kv measurement level. The apparent background noise shall not exceed 25 microvolts at either 475 kv voltage level. Careful investigation shall be made to insure that any corona discharge measurement in excess of background is external to the transformer. Any variation in corona intensity between the measurement taken on rising voltage and measurement taken and held for two hours after performance of the full rated induced potential test shall be explained to the satisfaction of the contracting officer. The corona discharge measured at the full rated induced potential 630 kv shall not exceed 825 microvolts.

This corona discharge test was performed in accordance with NEMA Publication 107, Methods of Measurement of Radio Interference Voltage (RIV) of High Voltage Apparatus, 1964. The RIV was measured by a radio noise (RN) meter coupled to the H-line terminal through the capacitance tap of the bushing as shown in *Fig. 12*.

Meter readings taken during the above described test are shown in *Table 2*.

Table 2 **Results of corona discharge test**

Induced Potential (kv, rms)		RIV (μv)
0		8.5
475	On voltage rise	9.5
630	Full rated voltage	168
475	Beginning of two hours	10
	End of two hours	19
0		7

In addition, the corona discharge test was supplemented by sonic and corona pulse measurements selected by Fuji Electric, which also indicated a corona-free condition inside the transformer.

3. Some Opinions Concerning Corona Discharge Test Criteria

The authors have taken a positive attitude in research concerning corona (partial discharge) phenomena, and corona detection techniques in transformers. The reason is that " corona " inside a transformer cannot be considered safe, and a "corona-free" condition insures greater reliability in transformers.

There is no general agreement in Japan as to the method, voltage, and duration of the corona discharge test and criteria for the " corona-free " condition but foreign customers in the U.S.A. and Canada give specific requirements of their own choosing.

According to IEEE Committee Report " Tests for Damaging Corona for Oil-Insulated Power Transformers," it is reported that there has been a tentative agreement that radio interference voltage (RIV) measurements are sufficiently sensitive to provide reasonable insurance against progressive corona damage. The actual values of RIV have not been agreed upon, nor has even the detailed procedure concerning the test voltages at which readings should be obtained. There is some agreement that a relatively small RIV number should not be exceeded at 125 or 150 percent of the normal operating voltage, but this is still being discussed by the IEEE Working Group.

Therefore, corona discharge tests of transformers still pose controvertial questions in the U. S. A. and elsewhere.

The corona discharge test specified by the BPA for the 525 kv autotransformer, as described above, was

(a) During induced low frequency test,
(two hours at 150% operating voltage),
the transformer shall be corona free

(b) During full induced potential test,
(one minute at 200% operating voltage)
the RIV shall be less than 825 μv

Actually, these criteria were the severest in Fuji Electric's experience and called for greater consideration than the winding BIL. These criteria essentially determined insulation design, i.e., the size and weight of the autotransformer.

The authors agree that in order to obtain improved operating reliability by specifying tests which might be more compatible with service requirements, low-frequency test voltages are reduced and their duration is increased with corona-free requirements.

The key point is, in the authors opinion, that revision of dielectric tests for EHV power transformers should be associated with a knowledge of the power system characteristics which the transformer will be exposed to during its operating life.

4. Selection of Corona Discharge Test Methods

The corona discharge test methods now in general use can be divided into two broad classifications: the NEMA method and Corona pulse method. The former is used mainly in the United States and Canada. Its detection principle is based on the numerical value of the RIV measured with a radio noisemeter. The measuring principle of the latter corona pulse method is based on its waveform, charge and frequency of occurrence etc. In Europe, conferences concerning transformer corona discharge tests are now on the increase. These conferences are mainly investigating the corona pluse method rather than the NEMA method.

Fuji Electric has conducted detailed research into both the NEMA and corona pulse methods to find out which would provide perfect precision. Since the two methods are not opposed but actually complementary and each possess characteristic advantages,it is hoped that when a standard corona test is established, it will not be based on the test only, but will incorporate the advantages of both methods. As was described previously, the corona discharge test proves whether the tested equipment can be operated in practice for long periods with no damage to insulation. Therefore, especially when more than one method exists for deciding exactly whether damaging corona are present or not inside the transformer, the best means would be to select one method for actual use and employ another method to support the results of the first one.

VI CONCLUSION

This article contains a detailed description of the construction and main features considered during manufacture of the recently completed 550 kv 300 Mva transformer with special emphasis on the ac long-duration induced test and the corona discharge test, as well as the direct-type on-load tap changing system for the high voltage parts. The authors wish to express their sincere thanks for guidance and cooperation from Japan and abroad concerning the manufacture of this transformer. To repay this kindness, they will endeavor to achieve further progress with previous experience and results as a basis.