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154 kV 390 MVA ON-LOAD TAP-CHANGING POWER TRANSFORMER DELIVERED TO AKITA THERMAL POWER STATION, TOHOKU ELECTRIC PORWER CO., INC.

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I. INTRODUCTION

The 390 MVA on-load tap-changing transformer described in this article has been delivered to Akita Thermal Power Station of Tohoku Electric Power Co., Inc. in northern Japan.

It is used for voltage step-up in this new high capacity thermal power plant. All of the large capacity power transformers for thermal power plants manufactured by Fuji Electric are listed in *Table 1*. This transformer, however, is the first one to exceed 280 MVA in capacity. The transformer employs a direct type on-load tap-changing system in which Fuji Electric's DSF1 on-load tap changers are attached to the neutral side of the high voltage windings in each phase. Other features include special winding

Table 1 **Supply list of large power transformer for thermal power station (above 200 MVA)**

Delivery date	No. of units	No. of phases	Frequency (Hz)	Capacity (MVA)	Voltage (kV)	Cooling system	Tap changing
1965	1	3	50	210	11.7 / 150.5-147-143.5 R-140	OFA	No voltage tap-changing
1965	1	3	50	210	11.4 / 69-67.5 R-66	OFA	No voltage tap-changing
1967	1	3	50	280	13.5 / 150.5-147 R-143.5	OFA	No voltage tap-changing
1967	1	3	60	265	12.3 / 115-110 R-105	OFA	No voltage tap-changing
1967	1	3	50	210	11.7 / 150.5-147-143.5 R-140	OFA	No voltage tap-changing
1968	1	3	60	265	19 / 287.5～250 R～237.5	OFA	On-load tap-changing
1968	1	3	60	265	19 / 287.5～250 R～237.5	OFA	On-load tap-changing
1969	1	3	50	280	13.5 / 150.5-147 R-143.5	OFA	No voltage tap-changing
1969	1	3	50	270	15 / 161-157.5 R-154-150.5	OFA	No voltage tap-changing
1970	1	3	50	390	19.4 / 168～154 R～140 F	OFA	On-load tap-changing
1970	1	3	50	267	14.8 / 195.5-191.25-187 R	OFA	No voltage tap-changing
1970	1	3	60	210	16.6 / 69-67.5-66 R-64.5	OFA	No voltage tap-changing
1971	1	3	50	267*	14.8 / 195.5-191.25-187 R	OFA	No voltage tap-changing
1971	1	3	50	280*	15.1 / 168～154R～140	OFA	On-load tap-changing
1971	1	3	50	390*	19.4 / 161-157.5-154R-150.5	OFA	No-voltage tap-changing

Note: * is under construction

construction and methods for reduction of stray load losses. An outline of the transformer is given in the following paragraphs.

II. SPECIFICATIONS

The main specifications of this transformer are as follows:

Type:	3-phase on-load tap-changing transformer for outdoor use with forced-oil forced-air cooling
Frequency:	50 Hz
Rated capacity:	390,000 kVA
Voltage:	Primary 19.4 kV Secondary 154(R) ± 8 × 1.75 kV (17 taps)
Connection:	Primary delta (△) Secondary wye (Y)
Insulation class:	Primary BIL 150 kV Secondary BIL 750 kV Secondary neutral BIL 550 kV
Impedance voltage:	15% (390 MVA base)
Total weight:	414 t
Transport weight:	274 t
Total oil capacity:	107 *kl*

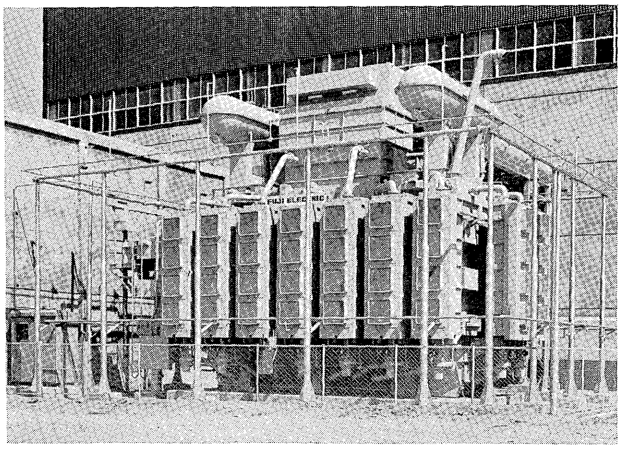


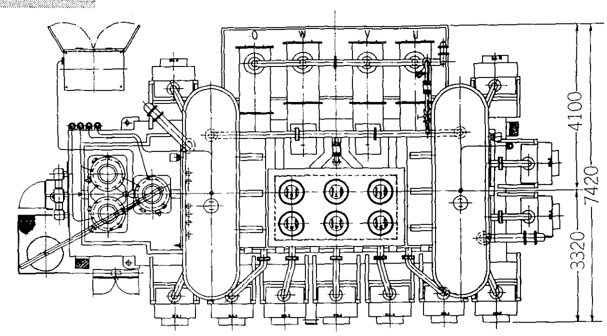
Fig. 1 Outer view of transformer

Fig. 1 shows an outer view of the transformer at the site and *Fig. 2* is an outline of the same equipment.

III. FEATURES OF THE CONSTRUCTION

1. Iron Core

Since the equipment was transported by sea, there were no limitations concerning dimensions. A light-weight, high-efficiency three-legged iron core was used. This core is clamped by means of bolts passing through the cooling duct in the center of the core. In addition, a band clamp system is employed with epoxy-resin impregnated glass-fiber bands around the core in order to bind the steel sheet sides tightly to the core. With these two systems, not only is the efficiency increased, but there is also little vibration or low noise. The silicon steel sheets used for the core are of type G9. In order to maintain a high level of exciting characteristics, special care is



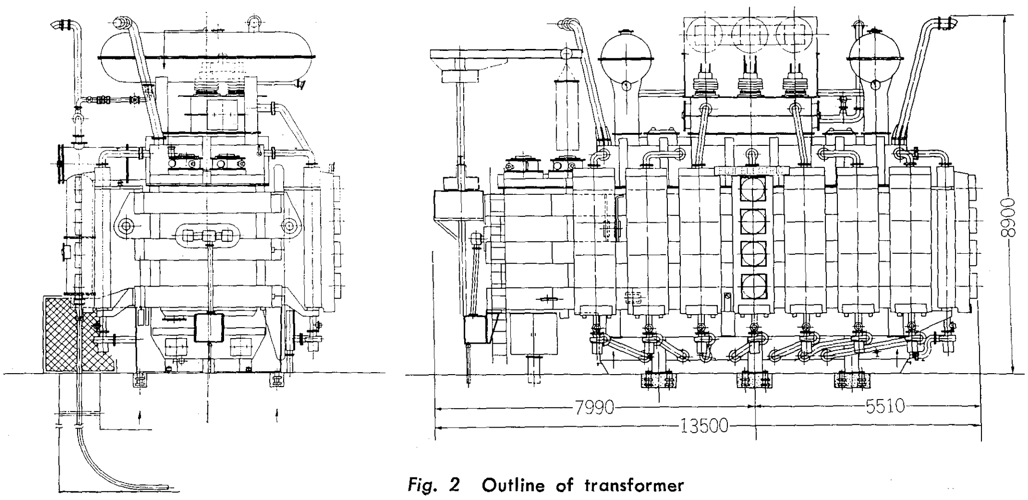


Fig. 2 Outline of transformer

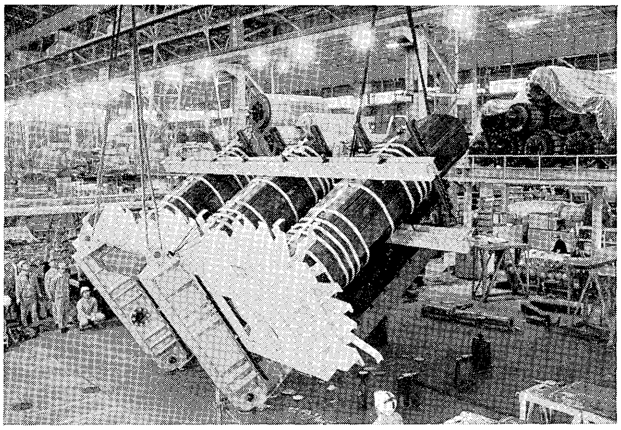


Fig. 3 Erection of iron core

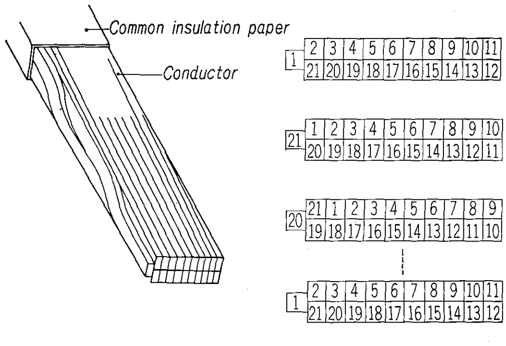


Fig. 5 Transposed conductors

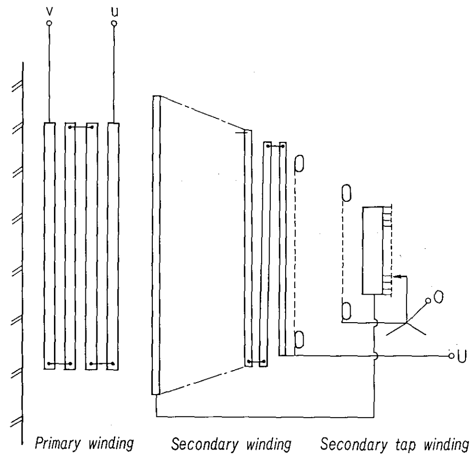


Fig. 6 Arrangement of windings

paid to mechanical stresses during processing, assembly and transport. The iron core erecting device used with this equipment is shown in *Fig. 3.* When such a large iron core is erected, precautions are taken so that no stress is applied to the silicon steel sheets.

After cutting, the silicon steel sheets were subjected to stress relief annealing in a continuous annealing furnace. This continuous annealing furnace is especially effective as a method of reducing transformer noise level. The noise level achieved including that of the forced-oil forced-air cooler was 78 dB which is very low compared with the JEM standard level.

2. Windings

The high voltage windings (secondary windings) are oscillation-free cylindrical layer windings which are standard in Fuji extra-high voltage transformers. The layers of these windings can be connected by two methods: U-connection or N-connection.

This transformer employs U-connection since it is best for eliminating exterior connection leads. The oscillation-free cylindrical layer windings have excellent impulse-voltage characteristics, insulation reliability, cooling performance and mechanical strength. As will be described subsequently, there are three parallel conductors for each phase in order to make the current distribution in the parallel circuits of the on-load tap changer uniform. The tap winding is arranged at the outside of the high voltage winding. It is divided into three blocks since there are three parallel circuits for each three phases. Each of these three parallel circuits is connected to one of the three high voltage main windings as shown in *Fig. 4.*

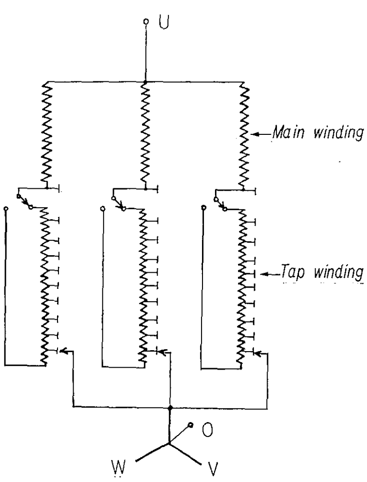


Fig. 4 Connection diagram of secondary winding

The low voltage windings are multi-cylindrical layer windings which are best suited to low voltage and large currents. Since both of the terminal leads are at the top in this winding, the positive and negative of the large current ampere turns are cancelled due to the fact that the terminal leads are very close together. So, the leakage flux due to the large current ampere turns is minimized and the leads are led to the primary bushings. Transposed conductors are used to reduce eddy current loss in all the windings. The transposed conductors are arranged in two levels, each with a large number of conductor wires annealed to a polyvinyl polymer cover. These conductors are transposed at a constant pitch and covered with common insulation paper. These conductors can be wound continuously so that reliability is high and workability is excellent, both of which are indispensable for conductors of large capacity transformers.

Fig. 6 shows the arrangement of the windings.

3. External Construction

Since the transformer tank is comparatively large, the side plates and main and auxiliary stiffeners are all arranged in straight lines so that the welding can be automated. Special measures were taken to suppress vibrations in the side plates during operation. There are two oil-conservators of the diaphragm type. There are two pressure relief devices arranged in opposite corners of the tank in order to release abnormal pressure rises within the tank to the exterior. The cooler is the standard forced-oil forced-air cooler which employs a corrosion-proof aluminum fin-tube.

4. On-load Tap Changer

The tap-changing equipment for this transformer employs three (one for each phase) DSF1 models for 1,800 A, and tap changing is performed on the neutral side of the 154 kV winding. The DSF1 model has a rated current of 1,800 A (single phase) and a rated step voltage (phase voltage) of 1,900 V. It can be used with 275 kV extra-high voltage transformers of up to 800 MVA. The DSF1 is of the same construction as the DSF3 which is used for three phase use. The latter model has a rated current of 600 A and a rated step voltage (phase voltage) of 1,900 V.

The DSF3 has already been employed for many years with good results. This is Fuji's main on-load tap-changer. In this transformer, three DSF1 models are used, one for each phase. They are operated by one motor-driven operating mechanism. The arrangement is shown in *Fig. 7* and the construction is shown in *Fig. 8*.

The contacts of each tap changer are divided into three groups of parallel circuits and they are connected to each group of the tap winding which is also divided to three groups in order to balance the current in these parallel groups of contacts.

The contacts of the diverter switches of each group are also arranged in several parallel groups, but the current is balanced during switching by either a current balancing reactor, or a current limiting resistor.

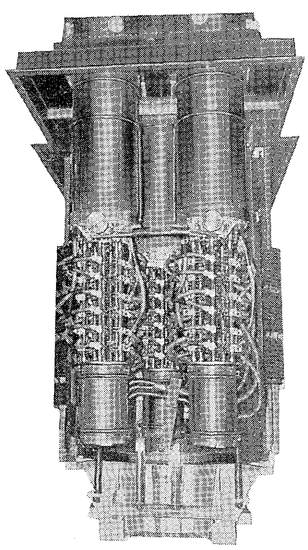


Fig. 7 Arrangement of three DSF1 type on-load tap changers

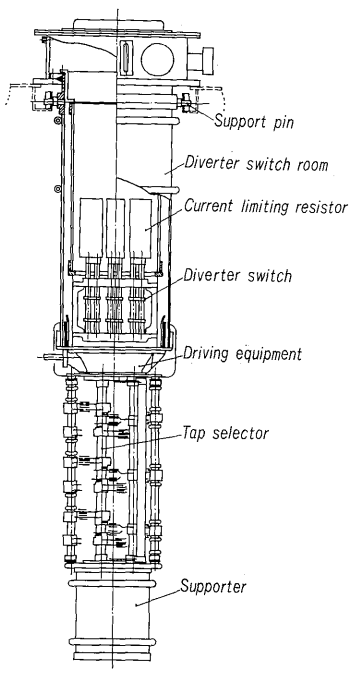


Fig. 8 Section of DSF1 type on-load tap changer

The oil in the diverter switch chamber is purified simultaneously in all three phases by one large oil filter with a filtering capacity of 100 *l*/min. Special care is taken in arranging the oil pipes so that pure oil will be circulated uniformly in each phase. A pressure equalizing pipe is also arranged between each phase in the diverter switch chamber. It was shown from the results of tests conducted after manufacturing was completed that the circulation of pure oil in each phase was satisfactory.

Type tests were conducted for all three phases in common. Life tests were conducted for 800,000 operations mechanically and 200,000 operations electrically. Tests were also performed on the operating mechanism including the motor-driven device using actual equipment and an equivalent torque load. The power supply was an unbalanced three phase transformer with its windings divided in parallel in the same way as the actual equipment. The switching load used for the test was the same as that in actual conditions.

Generally in the case of 3-phase diverter switch, the switching current for each phase flows through zero points with phase differences of 120°, and the arcs are extinguished in sequence. When the same switch is used for single phase diverter switch and the current value phase is tripled, it is considered theoretically that there is some hardship in respect to the braking capacity even if complete current balance between the groups of parallel contacts is achieved. However, the results of the life tests indicated that the consumption was equal on all of the diverter switch contacts which were divided into several units and the necessary electrical life was confirmed. It was therefore decided that the previously mentioned matter would cause no problem in practice. After the life test, an overcurrent switching test using twice the rated through current was performed.

The oscillogram obtained from this test revealed that the arc was extinguished and the switching current of the parallel contacts was simultaneously balanced within the required time. For the overcurrent test, the test specifications of the Denkyoken stipulate that the test shall be conducted employing dirty oil at 1.5 times the rated through current after the life test. In IEC publication 214, " On-load tap changer ", states that the test shall be conducted at twice the through current employing a new diverter switch. Comparing these two, the above-mentioned overcurrent switching test is one level greater in respect to duty.

From the results of these electrical life tests and overcurrent switching tests, it is evident once again that the goals in using the large number of parallel contacts by means of the block system construction in Fuji diverter switches have been achieved.

This Fuji block system is based on a construction in which all the parallel contacts are arranged in a straight line by means of a four link mechanism. It has been proven that simultaneous operation of all the parallel contacts is easier to achieve with this switch when compared with other types of diverter switches.

Other tests were also performed including a short circuit current test at 10 times the rated through current. Results were as anticipated in every case.

IV. REDUCTION OF STRAY LOAD LOSSES

Stray load losses can be classified as (1) eddy current losses generated in the winding conductors by leakage flux, and (2) stray losses generated in the components other than the windings. Generally, the leakage flux of the transformer ϕ_l is as follows:

$$\phi_l \propto Z \cdot \phi_m \propto Z \cdot (\mathrm{kVA})^{1/2}$$

where Z is the transformer % impedance and ϕ_m is the main flux within the transformer core. In other words, it is evident that the leakage flux is proportional to the product of the transformer core flux and the % impedance and also that it increases with the capacity. This leakage flux leads to an increase in the stray load losses and causes local overheating. Therefore, in large transformers, considerable emphasis must be placed on measures against this leakage flux.

A very accurate calculation of the leakage flux distribution in the transformer can be obtained with a computer. Calculation formulae for various actual examples have also been established on the basis of Fuji Electric's wide range of experience and test results. When planning this transformer, the leakage flux distribution and the generated loss were obtained.

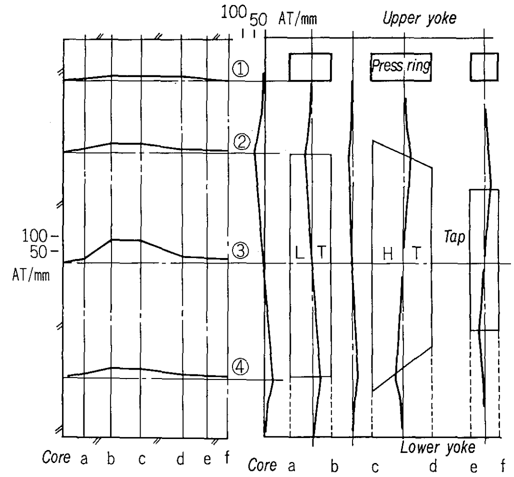


Fig. 9 Distribution of leakage flux

Construction was planned and materials were selected so as to reduce this loss. The temperature rise in parts where there was generated loss was also obtained and measures were taken to prevent local overheating in all parts. The main measures included in the transformer are as follows. *Fig. 9* shows leakage flux distribution in the main parts of this transformer.

The winding conductors are all transposed conductors in the primary, secondary and secondary tap windings, and the eddy current loss is minimized. The press rings used to clamp the windings are made of non-metallic materials based mainly on glass fibers. The shield rings for field dampening in the winding corners are made of non-metalic materials and aluminum foil.

The core clamping plates are such that the materials of the plates opposite the upper and lower ends of the windings are carefully considered and non-metallic materials are used. The surface of the top and bottom frames which support the windings are separated sufficiently from the windings and the stray loss is reduced by carefully dividing the interlinked surface of the leakage flux. The terminal leads from the winding terminal parts are arranged optimum for the leakage flux.

In contrast to the stray loss arising within the windings, the stray loss in the tank walls presents the biggest problem in respect to magnitude. In order to reduce this loss, the tank walls are covered with silicon steel sheets which have a high magnetic permeability and low loss.

With the above stray loss reduction measures concerning construction matters such as the winding conductor dimensions, arrangement, tank, frame and press rings show that all expectations have been achieved. On this basis, Fuji Electric has built up a great deal of confidence for the planning of trans formers of the 700 to 1,000 MVA class.

V. CORONA TEST AND QUALITY CONTROL

The aim of the transformer corona test is to confirm the insulation reliability under normal operating conditions, i.e. to determine whether or not the insulation in the high voltage parts is suitable and to check if there has been sufficient quality control during the manufacturing process. In this respect, all Fuji Electric transformers, BIL 750 kV and over, in capacity 50 MVA and over, undergo corona test in the factory and insulation reliability is checked.

For the purpose of preventing the generation of corona, common methods include making round at each electrode to suppress the concentration of field intensity in the high voltage parts and to keep the potential gradient low.

In addition, however, quality control during the manufacturing process is very important. Concerning the former, two dimensional field calculations are performed by a computer, the field condition is investigated in all parts by field mapping and the most suitable construction is selected. Concerning the latter problem of quality control, a high degree of cleanliness is maintained in the products by using dust-proof manufacturing areas, cleaning the factory and products with vacuum cleaners and carefully washing with oil.

Considerable care is taken with drying and oil impregnation in order to prevent residual moisture and air bubbles during assembly. This transformer is the biggest one for Fuji Electric products and so the corona prevention measures are assuredly conducted. As a result, there is no need to warry about corona occurring.

VI. TRANSPORT

Since this transformer was transported by ship, there were no limitations as to transport dimensions, but precautions were necessary in fixing the core and windings so that they could withstand the rolling acceleration occurring due to rolling of the ship in the winter of the Japan Sea. Fuji has had considerable experiences in shipping transformers by sea including a 345 MVA transformer in Japan and the 500 kV 300 MVA transformer shipped to the Bonneville Power Authority in the United States. There has been considerable opportunities to measure rolling acceleration in all parts during shipment and sufficient strength can be insured on the basis of these measurements. As was described previously, the on-load tap changer is inserted inside the unit and covered during shipment. Therefore, the transformer is not exposed to the air at the site and a very high degree of reliability is possible. *Fig. 10* shows the transformer being loaded on the ship.

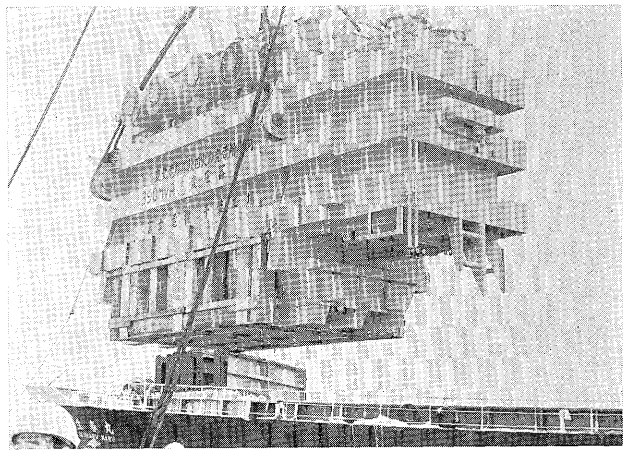


Fig. 10 Loading for shipment

VII. CONCLUSION

The Fuji Electric 390 MVA on-load tap-changing transformer has been completed very successfully. It was carefully planned to insure reliability, manufactured with great care and the most stable quality control, and tested with precision under rigorous conditions.

As a result, the overall facilities have been strengthened and greater confidence has been gained for the development of transformers of the 700 to 1,000 MVA class in the future.