Recent Power Transformer Technology

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1. Introduction

Power transformers are essential components of substation equipment for the efficient and stable operation of electric power systems. There is demand for transformers with lower price and higher reliability. In addition, depending upon the onsite conditions, such as narrow roads, mountainous areas or highly congested urban areas, harmony with the surrounding environment is required throughout shipping, installation and operation. Contribution to the global environment throughout the transformer life cycle is also required.

As topics of recent interest, we have been promoting the application of the technology of UHV level equipment to general power transformers, and focussing on the Hanshin-Awaji great earthquake disaster, the reinvestigation of disaster prevention and safety.

In response to diverse requirements, Fuji Electric has always developed and applied new and reliable technology. This paper describes recent features of power transformer technology.

2. Oil-Immersed Large Power Transformers

2.1 Structuring technology for the core and windings

The core and windings are important components determining basic performance and reliability that should always be maintained and improved. However, the core and windings are also a source of energy loss, causing problems in the energy environment. To conserve resources, it is necessary to downsize these components and lighten the materials used. Moreover, these components occupy a large percentage of the cost. It is also necessary to develop fast- and easy-to-make structures because Japanese labor, at present, is among the most expensive in the world. Fuji Electric has been promoting technological development with total evaluation and measures to overcome these contradictory problems, and the coordinated and harmonized marketing of products.

2.1.1 The core

We have utilized high-grade grain-oriented silicon-steel sheets in the core, selecting material with thin sheets, coating-processed sheets, or high magnetic flux density (B8), corresponding to the requirements for low no-load loss or low sound level.

To reduce the man-hours required for assembly and work lead-time, we have standardized the types of materials and components used in the core. The manufacturing process automates a series of operations; the automatic press line cooperates with the Fuji Electric's original automatic core stacking facility to make the cutting of silicon steel sheets and stacking work of the lower yoke and legs in a sequence. The facility stacks the cut core sheets on the core erection equipment and stands them upright as a core. Glass-fiber bands are commonly used to bind the core into a single unit. This process helps stabilize the performance quality of the core.

For three-phase large power transformers, if it is desirable to reduce the weight of the upper yoke for a transformer with rated power of 600MVA or more, or if there is a limitation in height for transportation, we utilize a five-legged core instead of a three-legged construction.

2.1.2 The winding

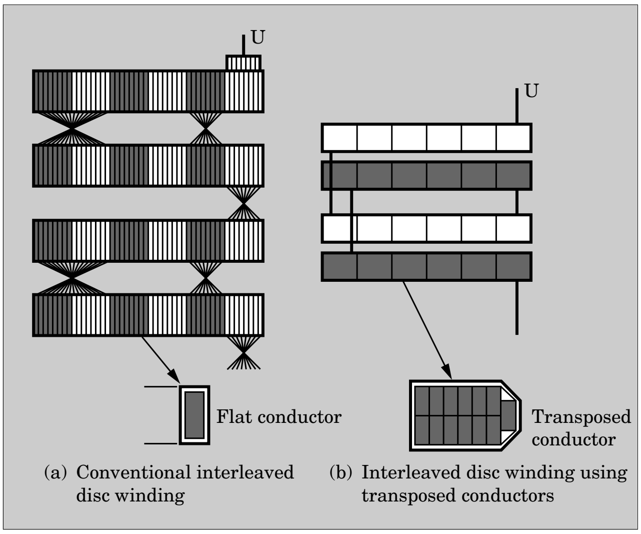
Fuji Electric has aggressively expanded the use of transposed conductors for windings. Transposed conductors make the continuous winding work reasonably easy and shorten the required man-hours and work lead-time, they are also useful to decrease the eddy current losses in the winding.

(1) Interleaved disc winding using the transposed conductors

Conventional high voltage windings use from two to ten or more flat conductors with normal or common insulation paper to construct the interleaved disc winding. In this case, a high series capacitance can be obtained from the capacitance between conductors that are repeatedly wound in the radial direction of the coil.

Interleaved disc winding using transposed conductors is introduced to increase series capacitance by creating a disc coil with one or two transposed conductors in such a way that the conductor of the first coil extends over to the third coil and then returns back to the second coil. In this manner, a high series capacitance can be obtained from the capacitance

Fig.1 Coil configuration of interleaved disc winding



between coils that are axially arranged. Figure 1 compares coil compositions and conductor connections of the interleaved windings.

The conventional continuous disc winding has been widely utilized in transformers, including extra-high-voltage class transformers, to increase the efficiency of winding manufacturing and decrease the eddy current losses in the winding. In addition, the aforementioned interleaved disc winding demonstrates excellent lightning impulse voltage withstand characteristics, and contributes to reduced equipment size when applied to the extra-high-voltage class. The winding work and insulation performance was verified using the actual-scale winding model shown in Fig. 2.

(2) Self-bonded transposed conductors

Short-circuit current flows into the winding when the system connected with the transformer is short-circuited, and then an electromechanical force is generated in the winding. Conductor strength must be improved so that the transformer can withstand this electromechanical force that increases with transformer rated power. The use of stiff material such as semi-hard copper increases the lead-time for winding work on the winding form.

The self-bonded transposed conductor consists of element wires enameled with heat-stiffened resin. After forming the winding, the element wires are heated to dry, and during this time they are integrated en bloc. This improves the strength of the conductors and the winding. After the winding is completed, direct current is supplied and the conductor is heated to securely integrate the element wires into a single unit and stiffen the winding itself.

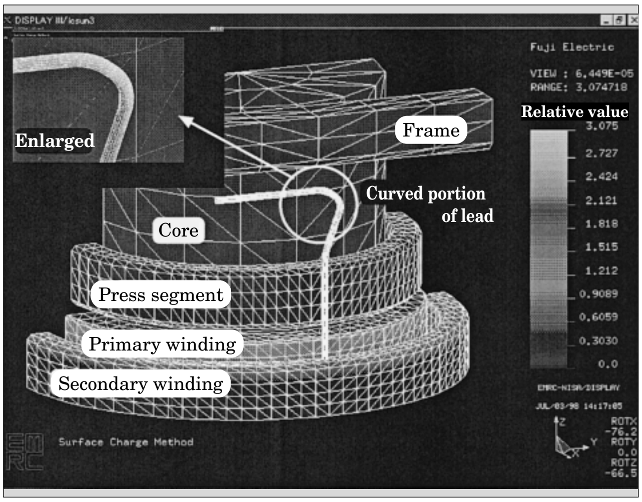
2.2 Insulation technology

2.2.1 Review of insulation structure

The insulation of the oil-immersed transformer is basically a composite insulation structure consisting of insulation oil and oil-impregnated paper. Depending

Fig.2 Actual-scale model of interleaved disc winding using transposed conductors

Fig.3 Three-dimensional electric field analysis for terminal lead outlet

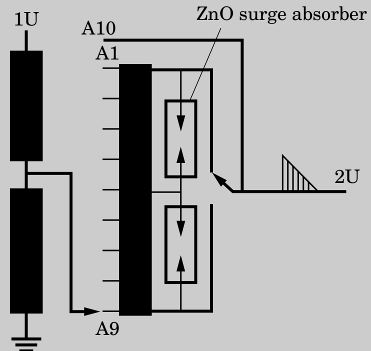


upon the shape of the conductor and its coating insulation, the oil may be separated into multiple layers by molded barriers.

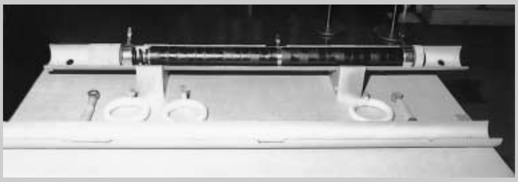
Depending upon the insulation structure, analysis is performed using the finite element method (FEMT), finite difference method (FDMT) or the surface charge method, and work is performed to simplify and make efficient the structure while maintaining the reliability of the insulation.

Figure 3 shows an example of three-dimensional analysis by the surface charge method. This example analyzes the electric field distribution around the high-voltage lead conductor extracted from the upper part of a winding. The computational accuracy of conventional two dimensional electric field analysis is limited because the curved portion of the lead and the shape of

Fig.4 ZnO surge absorber



(a) Connection to tap winding



(b) External view

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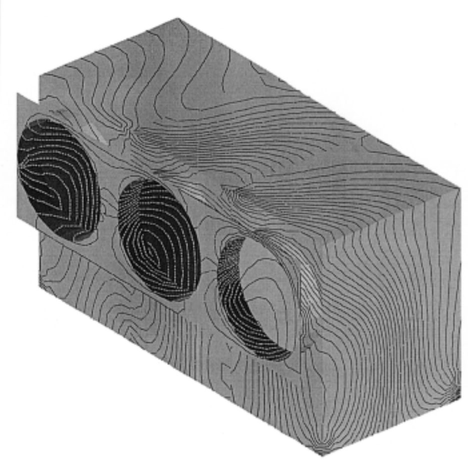
Fig.5 Three-dimensional current distribution analysis of the connection box



grounded peripheral parts are influenced by the electric field. However, it is possible to understand the electric field distribution in detail with such three-dimensional analyses and to find a reasonable insulation structure.

Moreover, to improve the reliability of the insulation structure, we have carefully observed the detailed mechanism at the start of partial discharge. We implement precise measures to control the withstand voltage tolerance, utilize insulating materials with low dielectric constants, and arrange the shield on the grounded side.

2.2.2 ZnO surge absorber

In an extra-high-voltage transformer, when the lightening impulse voltage impinges on the winding terminal, a voltage oscillation occurs within the winding and across the tap coils. This voltage oscillation occasionally becomes a problem depending upon the winding arrangement, connecting conditions, and the tap positions of the winding, and therefore, requires enlargement of the insulation distance or reinforcement of the insulation structure. To avoid this potential problem, we use a ZnO surge absorber with a nonlinear voltage characteristic connected to the corresponding winding part and to suppress excessive oscillatory voltage. Installing these elements in the transformer tank simplifies the associated insulation structure and makes the entire equipment more compact. Figure 4 shows the external view and the application example of the ZnO absorber. A long-term excessive voltage test has verified the reliability of the ZnO absorber with no deterioration.

2.3 Technology for reducing eddy-current and stray load losses

On the load losses of the transformer, it is possible to exactly calculate the resistance and eddy-current losses in the winding. However, the source of stray load loss cannot be determined since only the difference of measured load losses and the aforementioned calculated losses are obtained as collective values. At Fuji Electric, stray load loss is being closely studied to locate the source of the stray load loss, and to decrease the amount of loss.

2.3.1 Three-dimensional magnetic field analysis

Because the amount of magnetic flux that overflows from the winding or is generated around the large current lead increases with the transformer rated power, the study of magnetic flux is indispensable in the evaluation of eddy currents, stray load loss of adjacent structures, and in the implementation of measures against local overheating.

To implement a reasonable design specific to the structures and the materials, Fuji Electric performs three-dimensional magnetic field analysis and precisely computes the current distribution in the structural paths, the eddy current distribution and the associated losses. In addition to the losses, we also evaluate the temperature distribution in the structures based on the above calculation results.

Figure 5 shows an analysis of the current distribution in the connection box, where large currents flow from the transformer primary side to phase-isolated buses connected with the generator in a power plant. This example shows that it is possible to construct a common connection box for all three phases instead of independent connection boxes for each phase as has been done in the past. This figure shows neither an abnormal current concentration nor cause for local overheating, as seen from the currents displayed as line bunch flows on the box.

Fig.6 Analysis and measurement of unbalanced currents between conductors with the helical coil windings

1	2	3	4	5	6	7	8	9	10	11	12
24	23	22	21	20	19	18	17	16	15	14	13

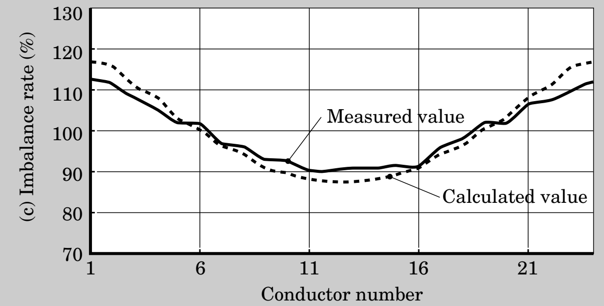
⇩

24	1	2	3	4	5	6	7	8	9	10	11
23	22	21	20	19	18	17	16	15	14	13	12

⇩

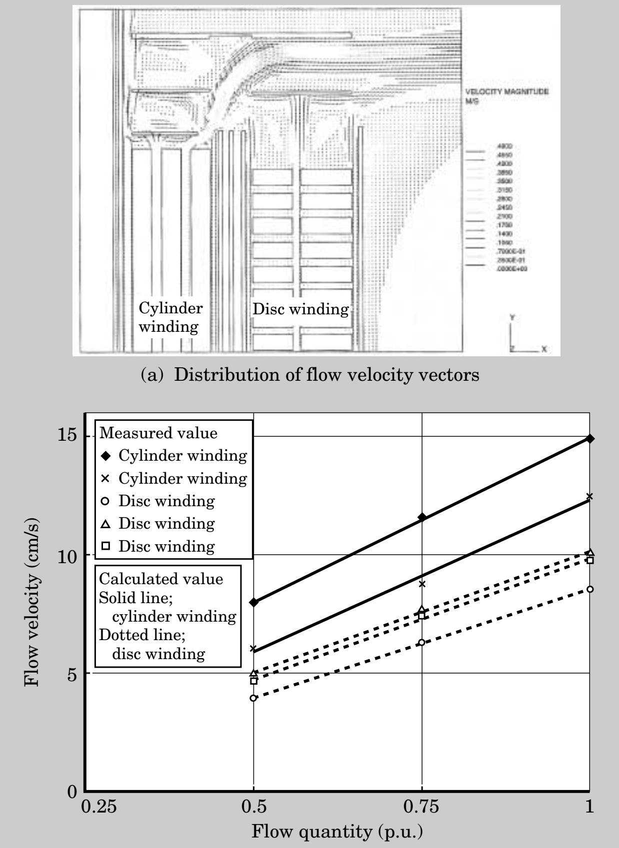
23	24	1	2	3	4	5	6	7	8	9	10
22	21	20	19	18	17	16	15	14	13	12	11

(a) Arrangement and transposition of helical coils



(b) Current distribution of helical coil conductors

Fig.7 Oil-flow velocity distribution inside and outside the windings



(b) Flow velocity distribution at the outlet of the windings

2.3.2 Measures against eddy-current and stray load losses in the winding

In windings that carry extremely large currents, we use many conductors connected parallel. The linkage of each conductor with the leakage flux slightly differs, and therefore, causes an imbalance in the currents among the parallel conductors and increases the load loss. This load loss adds to the eddy current loss that is usually calculated on the assumption of balanced currents. We can decrease the imbalance of these currents by selecting the optimal way of transposition of each conductor.

Fuji Electric has developed simulation software for these unbalanced currents to choose the best transposition method. Figure 6 shows an example of the current imbalance rate between conductors in helical windings.

2.4 Cooling technology

2.4.1 Oil-flow velocity distribution inside and outside the winding

To optimize the cooling structure inside and outside the winding, it is necessary to understand the oil-flow distribution in detail.

For this purpose, we used a three-dimensional supersonic wave Doppler flow velocity meter. This meter is capable of detecting echoes of supersonic wave pulses that are reflected from a tracer particle moving in oil, and measures the three-dimensional instantaneous flow velocity. A gas bubble was inserted into the oil as the target tracer. On the other hand, we used general-purpose heated fluid analysis software (finite volume method) to obtain the oil-flow velocity. The principal equation is the law of conservation of mass and momentum. The software performs a steady state analysis using a turbulent flow model.

Figure 7 shows an example of the analysis and the measurement of the oil-flow velocity distribution for the actual-scale model. The agreement of these results is comparatively good.

Because this technique can confirm whether the oil-flow velocity distribution meets the design objective, we can accumulate data and then apply it to practical designs.

2.4.2 Zigzag oil-flow

In directed oil-flow type transformers, we mainly use the zigzag oil-flow method instead of the conventional duct flow method. The zigzag oil-flow method improves heat transfer from the winding to oil, makes a balanced distribution of the winding temperature rise, and decreases the highest temperature of the transformer. As results, this method decreases the size of the cooling equipment and improves the reliability. Comparison of the modeled analysis and actual measurements using an actual-scale model has verified good agreement of the temperature distribution, and made it feasible to choose the best oil-passage structure, including the method of arranging the curving plates.

Fig.8 Shipping of the transformer with the steel plate dampers mounted

2.5 Noise reduction technology

The sound level of a transformer, i.e. the noise, is now a regulatory problem closely related to the city life environment in urban areas and the home life environment in residential areas. Low noise specifications for power transformers are universally spread throughout the domestic marketplace.

To decrease the transformer noise, it is important to use core sheets with small magnetostriction, to improve the corner jointing of core sheets, and to optimize the soundproofing equipment, including that of the coolers. With consideration of the noise specifications, Fuji Electric always tries to apply optimal anti-noise measures. We also try to devise an optimal shipping form as well as to simplify onsite construction work as much as possible.

On the other hand, to clearly find the relation between vibration and transformer noise, we are investigating with basic numerical analysis.

2.5.1 Step-lap jointing of the core corner

Changing the jointing method of the core corner sheets from the conventional bat-lap joint to the step-lap joint decreases the transformer noise approximately 4 to 6 dB(A). The exciting current and no-load loss can also be decreased. Fuji Electric utilizes the step-lap joint as a standard for low noise specifications.

2.5.2 Steel sheet dampers

Steel sheet dampers sandwich the resin between two thin steel plates and attenuate the vibration effected by the shear deformation of the resin. Steel sheet dampers have been used since the 1970’s and Fuji Electric recently attained a sound level of 60 dB(A) for a three-phase 450MVA transformer. Figure 8 shows an application example for the transformer.

2.5.3 Sound emission analysis

The boundary element method is applied to sound emission analysis in which the given vibration distribution of the transformer surface is used to compute the sound level distribution on a plane separated some distance from the transformer. By selecting a boundary surface through which the sound propagates, this method solves the wave propagation equations for this surface in terms of a boundary integration formula. We used laser light to measure the vibration distribution on the surface of a three-phase model core, and calculated the sound level distribution [dB(A)] in a plane 30cm from the core. Figure 9 compares example data for typical high harmonics of the vibration and noise.

3. SF_6 Gas-Immersed Transformer

As nonflammable substation equipment, SF_6 gas-immersed transformers attracted attention when the manufacture of transformers containing PCB (poly chloro biphenyl) synthetic oil was prohibited due to environmental pollution problems. Since the latter half of the 1980’s, SF_6 gas-immersed transformers have been widely used to improve disaster prevention, safety, and the environmental harmony of electric equipment. Recently, this trend has been accelerated especially in Japan and China, including Taiwan and Hong Kong. In Japan, the scope of application currently ranges from small distribution transformers of the 6kV class to extra-high-voltage large power transformers.

SF_6 gas-immersed transformers are best suited for the various performance requirements of urban substations. Because a conservator is unnecessary, the ceiling height can be reduced in rooms where this transformer is installed. This contributes to reduced building construction costs.

3.1 Details of development

Fuji Electric has extended the product series of the SF_6 gas-immersed transformers as follows.

(1) For the 6kV class, products from 50 to 2,000kVA have been standardized as a series.

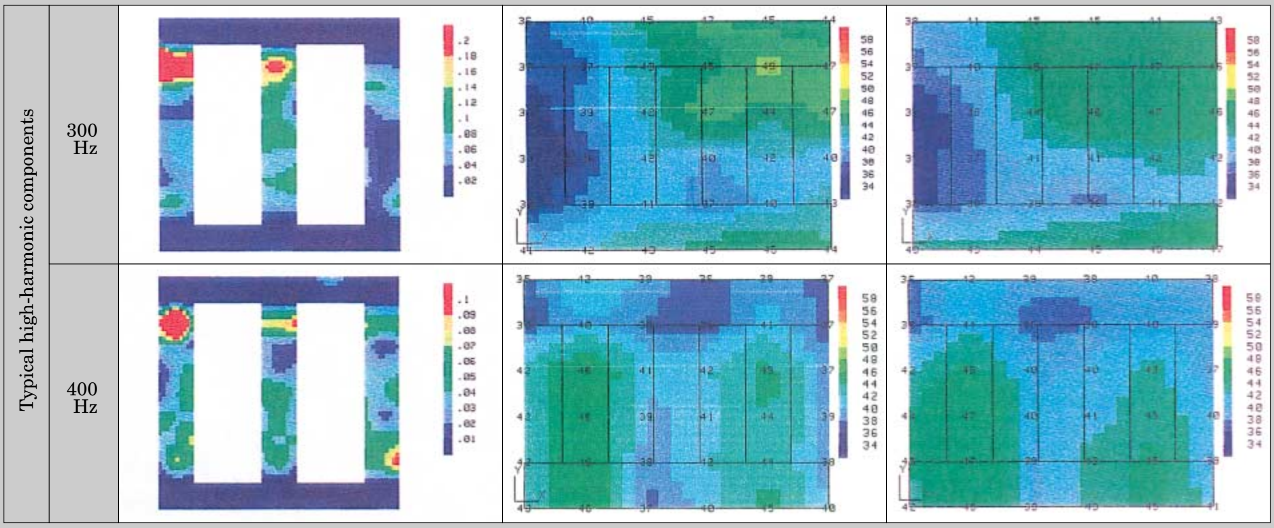
(2) For the 22 to 77kV class, products from 3,000 to 15,000kVA, for which most demand is expected, have evolved into a new series, the ALFOS Σ, with a new structure that uses windings of aluminum foil sheets.

(3) For high-voltage and the large power rated class, Fuji Electric has already delivered 3-phase 154kV/25MVA and 3-phase 110kV/40MVA units.

3.2 Prototype transformer for 66kV/60MVA

Advancing toward the production and marketing of large power rated 3-phase 66kV/60MVA gas-immersed transformers with SF_6 gas-directed forced-water cooling for intermediate substations, a prototype for one

Fig.9 Analysis and measurement of vibration and noise distribution for the three-phase core model



(a) Distribution of maximal vibration displacement (μm) (b) Calculated noise distribution dB(A) (c) Measured noise distribution dB(A)

Fig.10 SF_6 gas-immersed prototype transformer being tested for reliability (Single-phase, 60/3MVA)

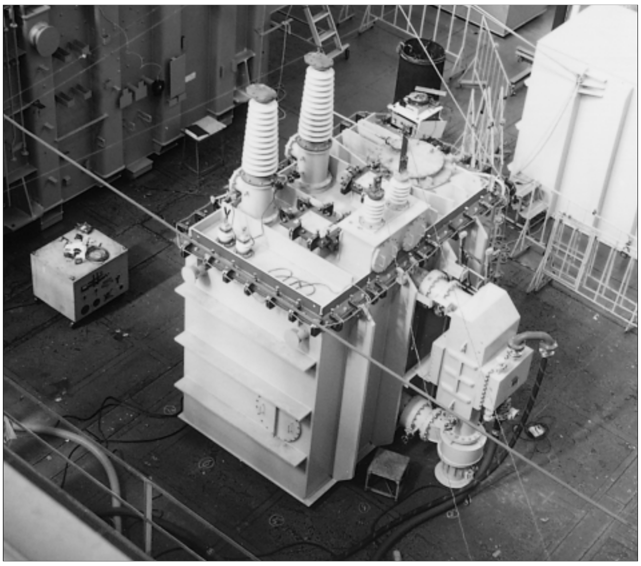


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Table 1 Specifications of the 66kV 60MVA SF_6 gas-immersed transformer prototype

Standard	JEC-2200-1995
Cooling method	Gas-directed and forced-water (GDWF)
Insulation system	E
Maximum winding temperature rise	49K
Number of phases	Single
Frequency	50Hz
Rated power	60/3MVA
Rated voltage	Primary : $66/\sqrt{3} \pm 6/\sqrt{3}$ kV (17 taps) Secondary : $22/\sqrt{3}$ kV
Rating	Continuous
Short-circuit impedance	16%
Withstand test voltage	Primary : LI 350kV AC 140kV Secondary : LI 150kV AC 50kV
SF_6 gas pressure	0.13MPa (gauge pressure at 20°C)

phase of this transformer was manufactured for trial and verification purposes.

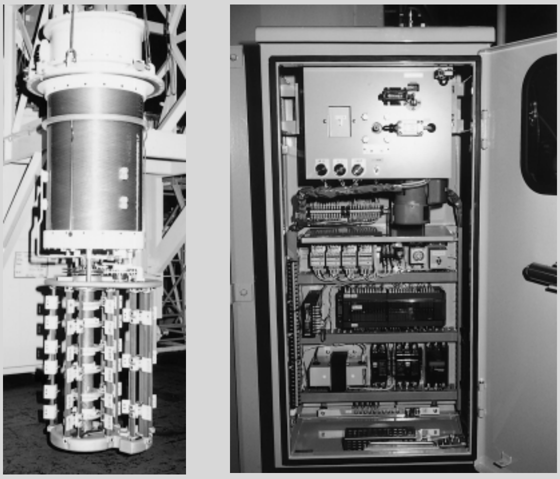
Figure 10 shows the transformer being tested, and Table 1 lists the specifications of the prototype transformer.

Before designing the prototype, Fuji Electric studied the component technology as part of the developmental work for this transformer, confirmed its performance using three-dimensional electric field analysis, gas flow analysis, model experiments, etc., and established insulation and cooling design technology as well as measures against short-circuit electromechanical forces.

The insulation system of the transformer is class E. However, the primary winding uses Nomex-insulated electric wires (class H) to provide sufficient tolerance for the short-time overload capacity. The primary winding uses a mixed interleaved disc winding for improved insulation reliability against lightening impulse voltage. The secondary winding uses heat-resistant self-bonded transposed conductors for improved mechanical strength. Consequently, a unit could be assembled with smaller size and lighter weight than before.

This prototype equipment passed all the tests prescribed in the JEC Transformer Standard and

Fig.11 Vacuum switch type on-load tap-changer



(a) Tap-changer (b) Operating mechanism

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demonstrated sufficient quality to enter production. The high degree of correspondence between the component technology and the performance of the prototype equipment confirmed that larger equipment could be manufactured without problems.

3.3 Vacuum switch type on-load tap-changer

The aforementioned SF_6 gas-immersed transformer is equipped with a 600A on-load tap-changer system consisting of two resistors and four vacuum switches with an electronically controlled operating mechanism shown in Fig. 11. The two models of 400A and 600A tap-changers can now be used with SF_6 gas-immersed transformers.

Advantages of this on-load tap-changer are listed below.

(1) The current is switched with vacuum switches, which are installed in a SF_6 gas-immersed chamber separate from the transformer tank.

(2) The switching mechanism of a two-resistor and four-vacuum-switch system assures high reliability. The vacuum switches are secured by a cassette structure that facilitates the inspection work.

(3) Since the roller contacts are used to connect the tap selector with the winding taps in the transformer tank, harmful metallic wear powders do not peel off.

(4) The operating mechanism has achieved high performance with electronic and digital control. This contactless method assures improved reliability and maintainability.

4. Conclusion

Fuji Electric will continue to aggressively introduce new materials, to develop components and processing methods to promote resource conservation and recycling, to further develop advanced technology in response to the requirements of society, and to implement useful proposals for reducing the total life-cycle cost, that is, to help optimize the investment of the customer side. In addition, we will also continue development of transformer peripherals, for example, active noise control.