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SITE MAINTENANCE OPERATIONS ON OIL-IMMERSED TRANSFORMERS AND THE STATE OF RENEWAL FOR LOW-COST OPERATIONS IN JAPAN

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1. Summary

Our living environment and social functions are becoming increasingly sophisticated and complex, calling for high reliability of electric power supply more strongly than ever before. Accordingly, the reliability of transformers which play a major role in the maintenance of stable supply of electric power is ever increasing in importance.

It is generally said that transformers have a service life of 30 years. In order to minimize the cost of operation of the transformer throughout its life, it is important to periodically check the internal conditions of the transformer carefully, diagnose the degree of its deterioration on the basis of its performance and operating condition, and carry out proper maintenance of the transformer taking its remaining life into account.

Some causes of transformer deterioration are thermal, electrical, mechanical, and environmental stresses. Under these stresses, the transformer insulators decline in performance and component materials become degraded, causing the transformer characteristics and performance to decline. Therefore, the maintenance of oil-immersed transformers is carried out based on accurate judgments on the influence of each of the above stresses on the deterioration of the transformer and its accessories and on the process of deterioration.

On the other hand, with the aim of reducing the total cost of electric power facilities through prolongation of their life, improvement of efficiency of transformer operation, etc., standards and techniques to evaluate transformers are being established. In particular, not only the renewal of the entire transformer but also the periodical replacement of its accessories and the renewal of its internal components (the windings, iron core, etc.) for prolongation of the transformer life have been positively proposed.

This paper describes the concepts of on-site maintenance and renewal of oil-immersed transformers in Japan. In addition, this paper introduces the techniques to replace the internal components of transformers efficiently, including the on-site quality control of transformers that applies the established technique of site assembly transformer, as part of the efforts to minimize the cost of transformer operation.

Keywords:
power transformer, transformer maintenance, mechanism and process of deterioration, on-site assembly transformer, optimum renewal cycle, life prolongation, economics.

2. Deterioration Mechanism and Maintenance of Oil-Immersed Transformers

2.1. Factors that cause transformer deterioration

Transformer deterioration is the phenomenon in which the transformer or any of its component parts undergoes a change in its chemical or physical properties under various stresses and environmental conditions and declines in its characteristics and performance. The factors that cause deterioration of oil-immersed transformers can be divided into the following four.

a) Thermal factors: The heat generated by the transformer in operation causes a decline in characteristics of component materials of the transformer and a structural deterioration of the transformer due to a stress induced by a temperature change.

a-1) Factors in thermal deterioration

(1) Steady-state operation (operation for long period of time)

Even when the temperature rise is within the specified limit, the insulating material deteriorates with the lapse of time. The deterioration of the coil insulator—the transformer part that becomes the hottest—governs the transformer life. According to some data, the effect of the insulating paper thermal deterioration on the decline in withstand voltage performance is 15% to 20% even after the transformer is operated for 30 years . However, due to thermal deterioration, the average degree of polymerization, which is the indicator of mechanical strength of the insulating paper, drops to about 50% in 30 years (see Figure 1&2), and the mechanical strength of the insulating paper declines accordingly. Thus, the transformer thermal deterioration in steady-state operation is governed by the mechanical strength of the insulating paper. [1]

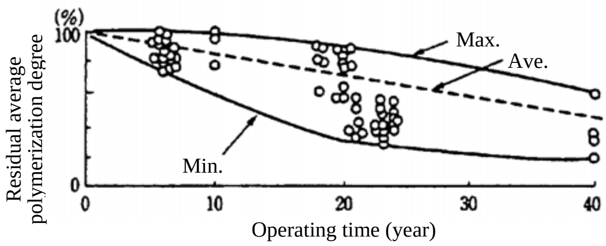
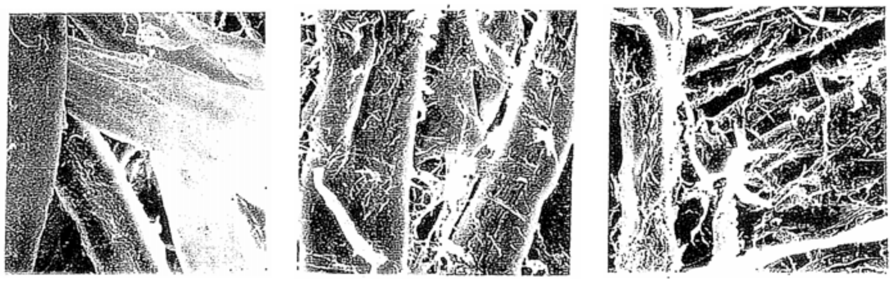


Fig. 1 Changes in average degree of polymerization of insulating paper of actual transformer with lapse of time

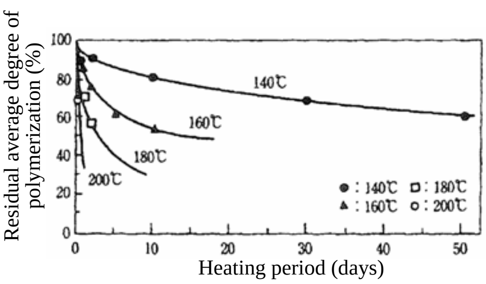


a) New product (DP1000) b) Deteriorated (DP=500) c) Deteriorated (DP=300)

Fig. 2 Insulating paper fibers viewed under electron microscope (1000 magnifications)

(2) Overload

It has been known that the higher the transformer temperature, the faster is the progress of deterioration (see Fig.3). Recently, a new concept of the allowable limit of overload has been proposed. According to this new concept, the allowable limit of overload operation should be the time when air bubbles begin to occur from the insulating paper as the result of a sharp temperature rise of the windings. In this connection, the results of an experiment are shown in Figure 4. The temperature at which air bubbles begin to occur varies according to the moisture content of insulating paper. The experimental results show that it is 160°C when the moisture content is 2wt% and 135°C when the moisture content is 4wt%. It has been known that when the moisture content of insulating paper is 0.5wt%, no air bubbles occur unless the transformer temperature rises to 180°C. There is a movement to review the allowable limit of overload operation on the basis of these results. [2]



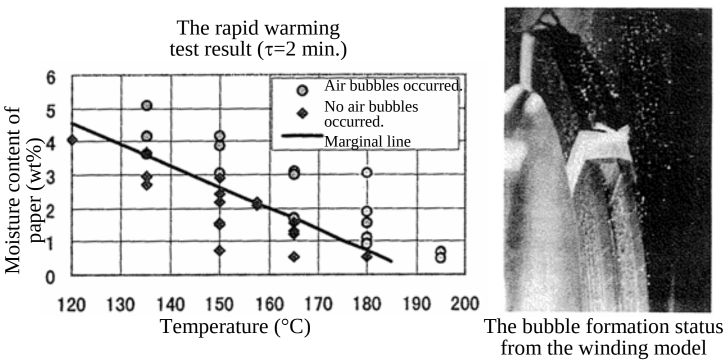


Fig. 3 Relationship between remaining average degree of polymerization and number of days of heating

Fig.4 Relation between moisture content of insulating paper and temperature at which air begin to occur, obtained by temperature test bubbles using model a-2) Method of estimating thermal deterioration (sensor technology)

The diagnosis of transformer life affected by thermal deterioration is done by analyzing furfural and CO_2 + CO dissolved in the insulating oil. The accuracy of diagnosis has improved appreciably. For on-site monitoring of gases dissolved in the insulating oil, a portable gas analyzer and an on-line gas detecto r(Figure 5) are used. The on-line gas analyzer is intended for constant monitoring of gases and applied to important devices. For monitoring gases dissolved in the insulating oil, various devices which detect specific types of gas and use a specific gas sampling method have been proposed.

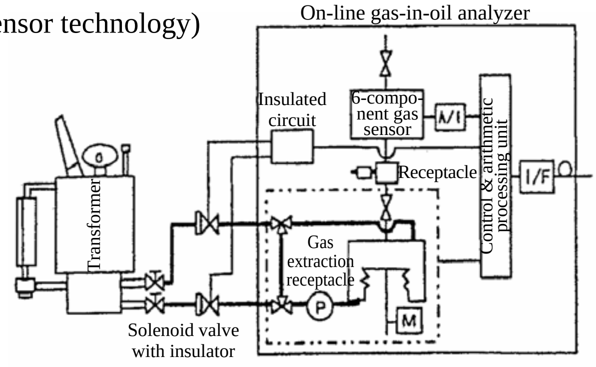


Fig. 5 On-line gas-in-oil analyzer

b) Electrical factor: This is the phenomenon in which an electric field or the concentration of an electric field causes transformer material to deteriorate. For example, an abnormal voltage which enters the transformer from the outside causes damage to the transformer material and thereby causes the insulating performance to decline.

b-1) Factors in electrical deterioration

(1) Surge voltage

According to a study report on statistical anti-lightning design, a lightning surge occurs two to three times/year.100 km. Concerning a switching surge, it is expected to occur 10 to 20 times in a year. If these surge voltages are applied to the transformer more times than estimated during its life, they can cause damage to the insulating material and thereby cause its dielectric strength to decline. The other factors are AC over-voltage etc.

(2) Electrostatic charge

When the insulating oil flows inside the transformer, electric charge separation occurs at the interface between the oil and the solid insulating material. Namely, negative electric charges are accumulated in the windings and solid insulating material of the oil passage, whereas positive electric charges are supplied to the insulating oil. If this electrostatic charge separation takes place violently, the DC electric potential in the insulating material due to the electrostatic charges increases, causing an electrostatic discharge inside the transformer. This in turn can cause a breakdown of the transformer.

The factors that strongly influence the flow-induced electric charge are the flow velocity (flow rate) and temperature of the insulating oil (see Fig.6). The flow velocity influences the electric charge separation and relieving, and the oil temperature influences the electric charge movement, separation, and relieving. It is necessary to take suitable measures to prevent the flow-induced electric discharge, such as restraining the occurrence of electric charges by properly controlling the oil characteristics and optimizing the structures of the oil passage and insulator to control the oil flow velocity, shorten the oil passage, and make the oil flow smooth and preventing the electric field produced by electric charges from concentrating in the oil gap.

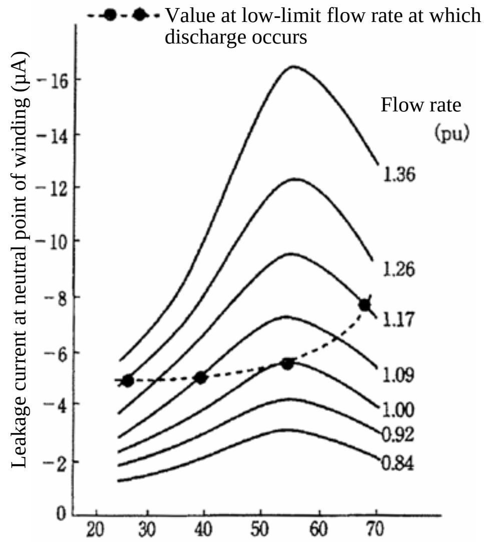


Fig. 6 Temperature characteristic of winding leakage current

b-2) Method of estimating electrical deterioration (sensor technology)

The phenomenon of partial discharge can be detected by a partial discharge sensor (AE sensor, etc.). When an partial discharge occurs inside the transformer, an electrical pulse is generated and at the same time, a sound wave of wide frequency band is produced. By detecting this electrical pulse or the sound wave which propagates through the insulating oil, it is possible to confirm whether or not a partial discharge has occurred. There are three detection methods which are commonly used: the method in which a discharge current flowing through the ground wire is detected by a high-frequency CT to determine on the presence or absence of a partial discharge; the method in which a discharge sound is detected by an ultrasonic microphone installed on the transformer tank; and the method that combines the above two methods as shown in Fig.7.

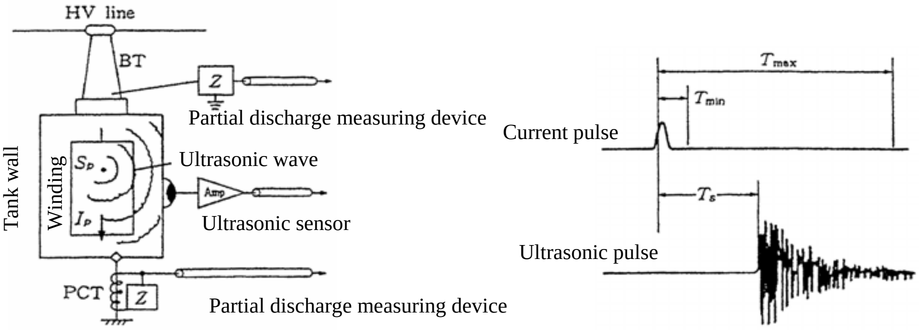


Fig. 7 Partial discharge monitoring system

c) Mechanical factors: When a mechanical stress due to an external fault, frequent switching operation , over-excitation, or overload is applied to the winding, iron core, or structural component, it can cause the component parts to become loose, thereby causing the transformer vibration and noise to increase to such a degree that the transformer breaks down.

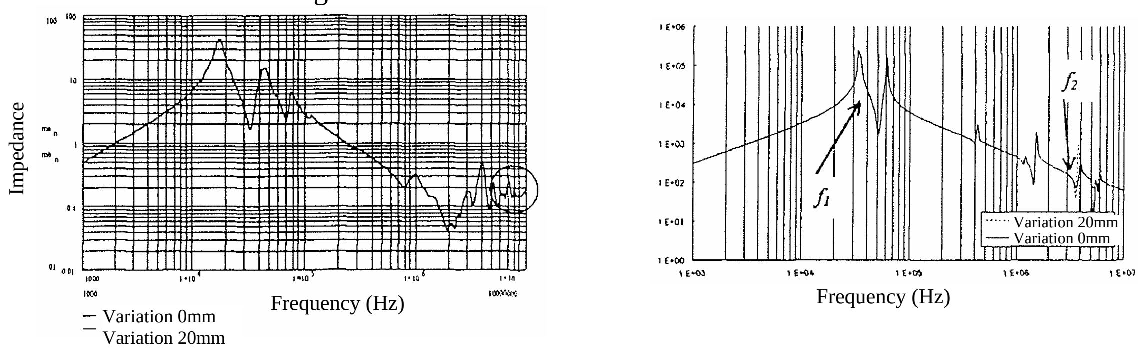
c-1) Factors in mechanical deterioration

(1) External fault current

Although the transformer is so designed that it can withstand short circuit electromagnetic forces, if the coil insulating paper has declined in mechanical strength (DP = 450 or less), the possibility of an insulating paper rupture becomes strong. Besides, if an external fault current occurs frequently ,for example, frequent switching operation (exciting in-rush current), the repeated impact force causes the vibration and noise to increase as the clearance between the coil and the insulator/clamping structure widens.

c-2) Method of estimating mechanical deterioration (sensor technology)

In addition to the conventional method of measuring time-serial changes in vibration and noise, frequency response analysis (FRA) appropriate to transformers is being positively applied. This is an effective method of diagnosis since it permits detecting even slight changes of the windings. TF is measured by varying the coil clamping force and thereby changing the dimension in the axial direction of winding. FRA was applied to measure the transfer function (TF) of one phase of a 750MVA, 345/18.5kV transformer. The results of measurement and analysis are shown in Figure 11. It can be seen that the measured and calculated values agree well. The change in TF due to a dimensional change is several MHz.



a) Results of measurement b) Results of analysis

Fig. 8 Change in TF when winding dimension is varied

d) Environmental factors:

These include rain (acid rain), sunshine (ultraviolet rays), corrosive gases , particles of sea salt, etc. Since the transformer interior is immersed in controlled insulating oil, it is not directly affected by those environmental factors. It is the tank and accessories that are affected by those factors.

Normally, the presence or absence of an abnormal condition is judged by the presence or absence of oil leak, the indication of oil gauge, etc. For totally-enclosed power transformers the method in which the concentration of nitrogen in the insulating oil is measured to check for the entry of air into the transformer has been proposed.

2.2. Processes of transformer deterioration and measures against deterioration

Due to the factors that have been described above, the transformer deteriorates in various manners as shown in Figure 9. The measures against transformer deterioration include: (1) coil replacement or transformer renewal, (2) internal repair (coil re-clamping, etc.), (3) insulating oil treatment or replacement, and (4) tank repair.

Concerning deteriorated internal components (the windings and iron core) of the transformer, it was common practice to renew the entire transformer because of the difficulty involved in partial renewal and the low cost effectiveness of partial renewal. Recently, however, with the development of disassembly & transportation technology which allows for on-site disassembly and reassembly of the internal components, it has become possible to renew only deteriorated internal components.

a) Processes of transformer deterioration

In each of the deterioration processes as shown in Fig.9 , when the ultimate phase of deterioration is observed, it is necessary to take suitable measures against the deterioration. If the dielectric strength has declined so much that the prescribed short-circuit strength cannot be guaranteed, it is necessary to replace the coil or renew the transformer.

The actual conditions of transformer deterioration are extremely complicated, and transformers which have been in operation for nearly 30 years are very likely to break down because their deterioration must have progressed markedly due to various factors. Therefore, from the standpoint of preventive maintenance too, it is necessary to periodically measure the degree of deterioration of each individual transformer taking into consideration the above deterioration processes and the actual condition of use of the transformer, determine parts to be repaired and parts to be renewed, and carry out the repairs and renewals as required.

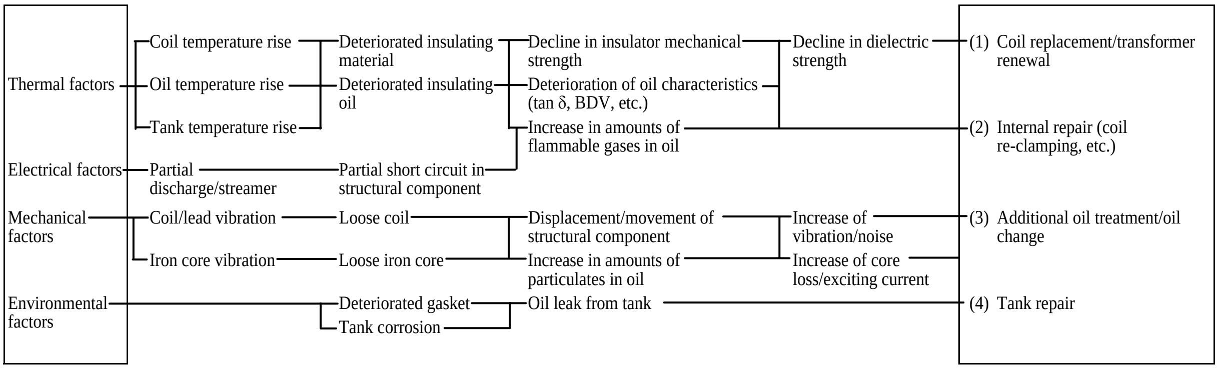


Fig. 9 Transformer deterioration processes, aspects of defects, and measures against deterioration

b) Example of on-site winding replacement procedure

Formerly, the transformer internal components were considered difficult to renew due in part to the low cost effectiveness. Recently, however, with the development of transformers which can be disassembled, transported, and reassembled at site, the technology for disassembling and reassembling the transformer internal components has advanced to such an extent that renewing only the internal components is possible. There are three types of renewal of the transformer internal components: replacement of only the windings; replacement of all internal components, including the iron core; and replacement of the transformer, including the tank. All these can be carried out on site or at the factory. Table 1 summarizes the effects (includes the cost effectiveness) and characteristics of the individual types of renewal.

Table 1 Comparison of methods of transformer renewal (effects and characteristics)

Part renewed	Place of replacement	Effect	Characteristic
Winding only	On-site repair	・ When the transportation capacity is large, on-site repair is more economical than factory repair since it does not require transportation cost. ・ On-site repair can be finished faster than factory repair.	・ Preventing dust and moisture absorption is required (tent house or some other suitable facility is required). ・ Cutting oil off iron core takes considerable time.

Part renewed	Place of replacement	Effect	Characteristic
	Factory	· Dust and moisture absorption can be completely controlled. · Verification by factory testing is possible.	· When the transformer capacity is large, factory repair is costlier than on-site repair because transportation cost is not negligible. · Factory repair takes more time than on-site repair.
Internal components of transformer, including iron core	On-site repair	· When internal components can be transported as one unit, work period becomes shorter than when only windings are replaced. · Power loss can be reduced (improved efficiency) · Noise can be reduced to some extent.	· Dust and moisture absorption need to be controlled (tent house or some other suitable facility is required).
	Factory	· same as winding only (factory) · Power loss can be reduced (improved efficiency) · Noise can be reduced to some extent.	· same as winding only (factory)
Transformer proper, including tank	–	· Quality of internal components is not affected at all. ·Replacement is easy. · Work period is short.· Transformer can be made compact. · Power loss can be reduced (efficiency can be improved). ·Noise can be reduced appreciably.	· Total cost is very likely to increase because additional replacement materials are required.

A typical procedure for on-site transformer winding replacement is shown in Figure 9.
On-site replacement of the windings requires a tent house or some other suitable facility to keep them from dust and moisture. Secure a suitable place of installation at the site, transport factory-tested replacement windings in a tank filled with dry air to the site, and keep them until the time of replacement.
The structure of a dustproof house erected at site is shown in Figure 10. The house must always be ventilated with dry air and kept under positive pressure. Generally speaking, it is to be desired that the inside humidity should be 50% or less during assembling the internal components.

3. Deterioration and maintenance of transformer accessories

3.1. Deterioration and maintenance of accessories

The service life of a transformer depends more or less on the life of its accessories. Here, the present practice of maintenance of the on-load tap changer—the accessory that fails more often than the other accessories—shall be introduced.

(1) On-load tap changer (OLTC)

As the deterioration of OLTC due to electrical and mechanical factors, the deterioration of the contacts caused by an electric arc which occurs each time the tap is changed is a problem. In this case, a tap-to-tap short circuit can result. The maintenance of OLTC consists mainly of periodical inspection and renewal after a prescribed number of times of OLTC operation. There are cases in which on-line monitoring of OLTC based on the motor current and driveshaft torque is applied to early detect abnormal conditions and prevent accidents before they happen (Figures 11).

In this method, a torque control value is previously set for each of the OLTC operation patterns, and the shaft torque and operation pattern are detected by a torque sensor fitted to the OLTC driveshaft to check for any anomaly based on the detected torque and pattern. The point of any anomaly is determined from the torque wave form. In addition, it is possible to detect an abnormal condition by comparing the motor current during tap changeover, detected by a current transformer (CT) installed in the OLTC motor-driven mechanism, with the normal current.

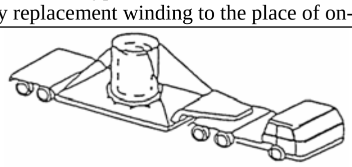
Securing place of on-site work

Make arrangements for the place of on-site work by prior consultation with the customer.

(1) When a transformer plant in the neighborhood of the customer can be used
(2) When the customer's plant (building, etc.) can be used
(3) When there is no useful facility in the neighborhood of the customer
- Rent a wrecker.
- Take measures to prevent moisture absorption and dust.

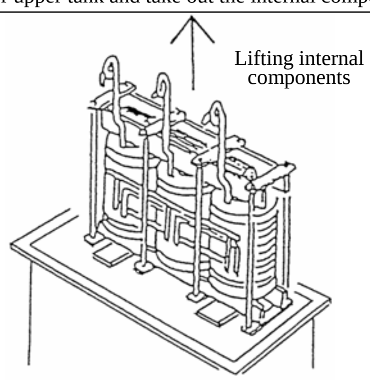
Use a bellows-type tent house.

(4) Carry replacement winding to the place of on-site work.



Taking out transformer internal components

First drain the insulating oil, and then remove the transformer upper tank and take out the internal components.



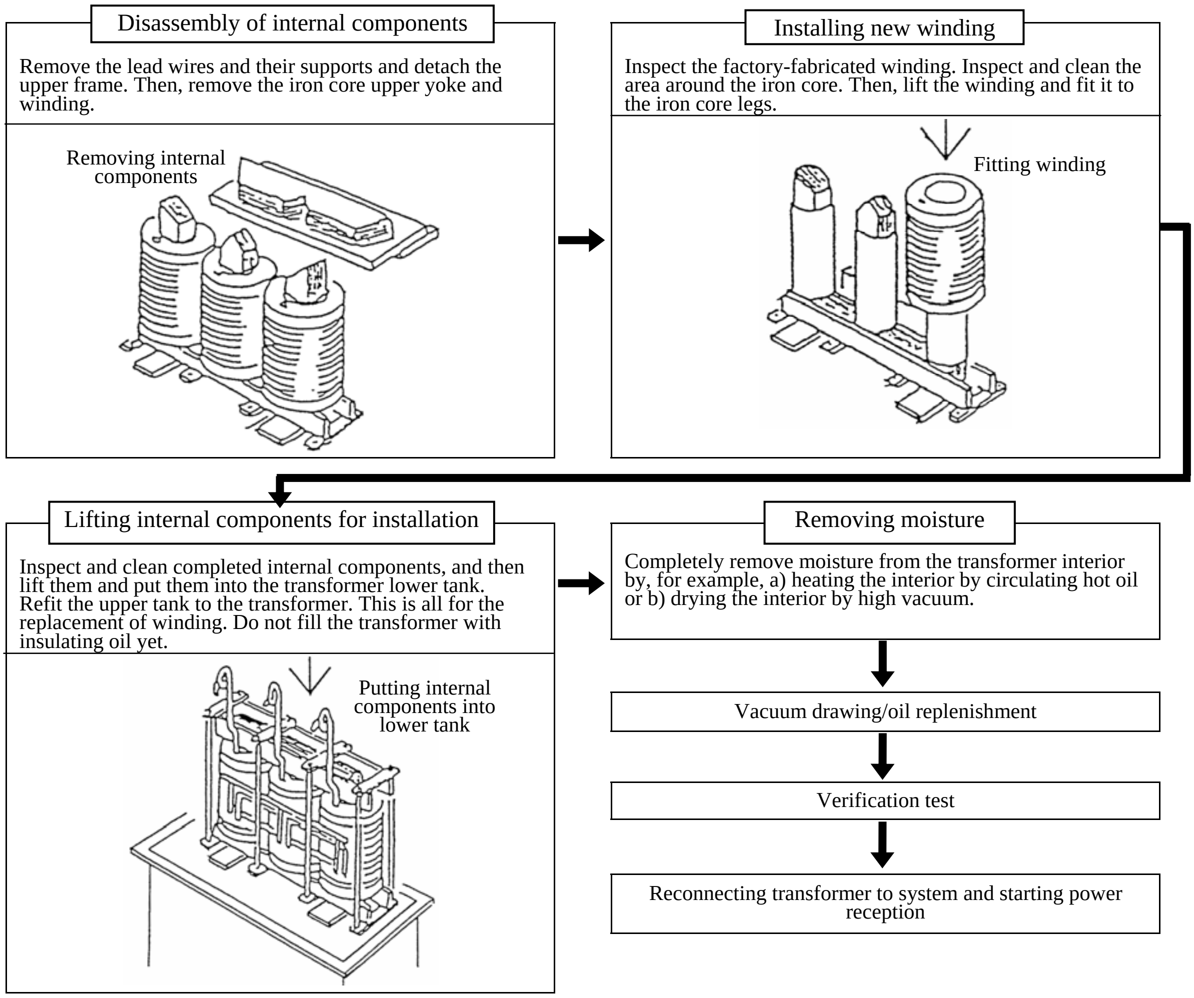


Fig. 9 Procedure for on-site replacement of windings

Fig. 10 Coils being reassembled in dustproof, low-humidity house

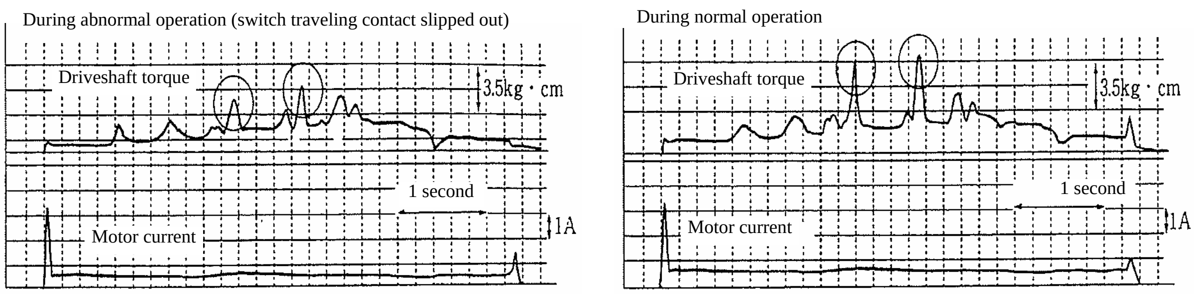


Fig. 11 Examples of measured values of OLTC driving torque

4. Proposal on optimum renewal cycle for prolongation of transformer life

Judging from what has been discussed so far, it is necessary to build a transformer maintenance system not only for the internal components but also for the tank and accessories from the standpoint of prolonging the transformer life and minimizing the total cost of the transformer as one of the most important components of a power supply system. The recommended renewal cycles for the transformer proper and its accessories are shown in Figure 12. When a transformer is to be used for 40 to 50 years, its accessories (the OLTC, etc.) should be subjected to planned inspection/renewal and so controlled that they do not become critical parts in the judgment of transformer life. On the other hand, the internal components, including the windings and iron core, need to be renewed at the optimum timing (the transformer life is assumed to be 30 years). By implementing periodical renewal of the transformer proper and its accessories in accordance with the recommendations, it becomes possible to minimize the unscheduled transformer shutdown and prevent the propagation of accidents and the malfunction of accessories and thereby improve the transformer reliability.

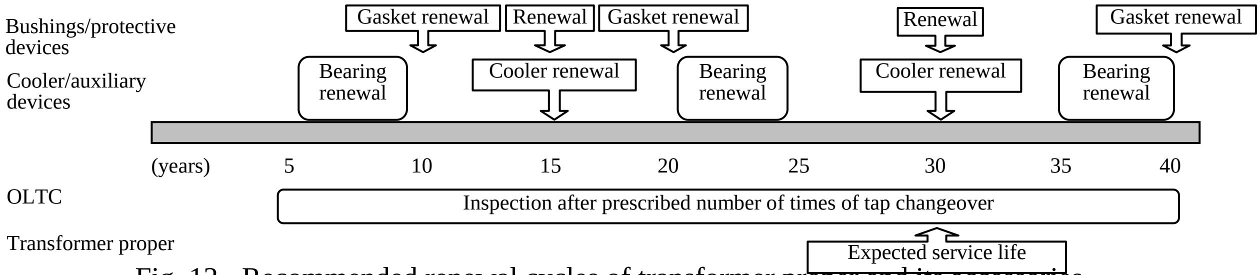


Fig. 12 Recommended renewal cycles of transformer proper and its accessories

a) Effects of renewal/refreshment in saving of energy and conservation of the environment
   The estimated effects of renewal of the internal components of a 30-year-old transformer in the saving of energy and the conservation of the environment are described below. The estimation was made with a 275kV, 300MVA transformer made in 1967. It was found that the load loss and no-load loss could be reduced to about 80% and about 50%, respectively, and the overall loss became about 70-80%. This translates into significant savings of electric energy. Concerning the effect on the environmental conservation, it was found that the level of transformer noise could be reduced by about 10 dB through improvement of the iron core material, development of new joint technology, etc. The estimated reduction of CO_2 emissions.

b) Example of cost estimation of transformer which is disassembled, transported, and reassembled at site. When it comes to renewing the internal components of a transformer, it is recommended that on-site renewal be carried out taking into account the site conditions and transformer reliability, together with the cost effectiveness.
   It is generally said that when the above technology is applied to a 500 kV transformer, the cost can be cut by some 5% to 10% for the ordinary single phase x 3 unit system, although it depends much on the substation location and installation conditions. By applying this technology to on-site replacement of the internal components , it should be possible to significantly cut the cost of transportation and reduce the number of replacement parts.
   Using a transformer whose 30-year service life had expired, we compared the cost between two cases in which only the internal components were renewed by different methods. Case 1 is an example of estimation when the transformer proper was transported from the site to the factory, where the internal components were replaced with new ones. In this case, the transformer that was transported from the site to the factory was subjected to disassembly, replacement of internal components, reassembly, and testing before it was transported back to the site and re-installed. Case 2 is another example of estimation when the transformer was disassembled in a clean house at the site, the internal components were replaced with new ones which had been fabricated and tested at the factory and which had been carried to the site, and the transformer was reassembled at the site. It was estimated that the cost in Case 2 would be about 30% lower than in Case 1 and that the work period in Case 2 would be some 20% shorter than in Case 1.

5. Conclusion

The phenomenon of transformer deterioration develops as various factors are interrelated in a complicated manner. It is, therefore, important to quantitatively measure the decline in transformer reliability due to deterioration and implement inspection and renewal of the transformer properly. The guidelines given in this paper should help minimize the total cost of a transformer on the basis of its operating condition.

References

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