A Guide for Analyzing Fault Causes of Pole Transformers

Jong-Wook Jung, Byung-Sung Lee, Il-Keun Song and Hee-Ro Kwak

Abstract - This paper describes the symptoms with the fault causes of pole transformers analyzed by Korea Electric Power Corporation(KEPCO) branch offices' request in 2001, and ultimately aims to devise proper countermeasures against the faults. The fault causes are generally divided into problems in manufacturing, mounting and operating. The pole transformers encounter the fault with unique aging mechanisms. To verify the mechanisms with the faults and to devise proper countermeasures, a flowchart for analyzing the fault causes is proposed, by which the fault causes of the pole transformers can be analyzed more exactly.
Keywords - symptoms, fault causes, pole transformers, countermeasures, aging mechanisms, flowchart

1. Introduction

As of December 2000, the number of pole transformers mounted and operated in South Korea was about 1.3 million and many of the transformers has been replaced every year because of the damage due to various causes[1]. It is, however very difficult for the workers with a KEPCO branch to find out the exact fault causes. There are several reasons: insufficient data or information applicable to practical analysis, compared with power transformers ; non-systematization of analytical techniques and lack of understanding of an expert system constructed by experts' know-how. Therefore, this paper ultimately aims at the preparation of countermeasures against the recurrence of pole transformer faults, based on the authors' experience, case studies carried out abroad, and studies by researchers and officials concerned with KEPCO, KEPRI and several companies. The results acquired will be useful in operating, designing and manufacturing pole transformers.

2. Fault of Pole Transformer

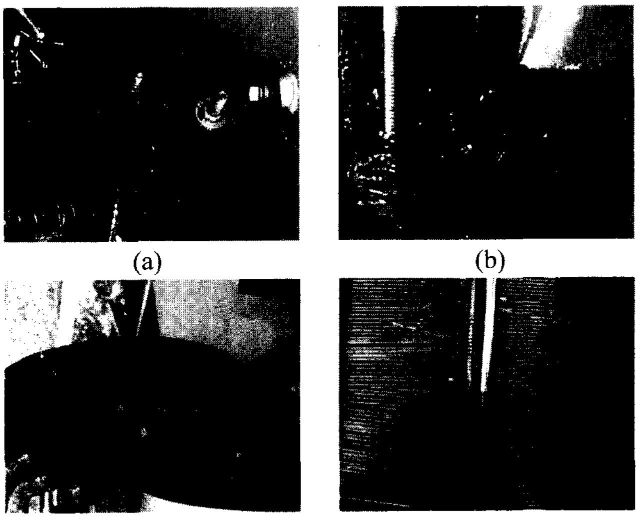
2.1 Factors affecting pole transformer fault

2.1.1 Problems in manufacturing

a. Poor impregnation with varnish

Unexpectedly, the faults due to poor impregnation with varnish frequently occur, and the causes are as follows ;

- voids or impurities created in the impregnating process under vacuum
- imperfect hardening due to impregnation with insulating oil before complete drying of varnish
- imperfect filling up with varnish between coils due to the use of varnish which is too strong



(a) (b) (c) (d)

Photo. 1 Faults due to poor impregnation with varnish ; (a), (b) imperfect hardening due to impregnation with insulating oil before complete dry of varnish (c) closing up the oil ducts to interrupt the circulation of insulating oil (d) imperfect filling up with varnish between coils due to varnish which is too strong

Because of the above causes, voids are created between coils and varnish, which concentrates the electric field around the voids, therefore they act as a factor causing partial discharges and electrical breakdown in the high voltage winding. In addition, the varnish flows down and hardens in a drying process, which closes up the oil ducts to interrupt the circulation of the insulating oil. The process gives the pole transformers the hottest spot to reduce the insulating performance of main insulations.

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b. Poor winding

The deformation of the windings is more severe when the winding is poor, and the main factors causing the faults are as follows;

- space between turns
- misalignment of winding centers and ends
- double windings on a turn

When space exists between turns of the conductors wound on insulating paper between layers, the conductors move with the frequency twice the system frequency because of electromagnetic forces. If the movement is continued, mechanical fatigue is accumulated on the insulation to cause the fault.

c. Elbowed coil due to solid strips in oil duct

In a winding process, solid strips or corrugated boards are inserted every 3 or 4 layers to improve the cooling efficiency by forming oil ducts. An elbowed coil is caused by a structural problem when solid strips are employed, and the bending angle of the elbowed coil is sharpened by :

- winding with excessive force on solid strips
- winding not taking curvature at 4 corners into account

Photo. 2 Fault of elbowed coil due to solid strips

When the coils are wound as above, an elbowed coil can be formed on the solid strips, which ultimately causes partial discharges or breakdown since electrical stress increases at the triple junction at which different materials meet.

d. Poor sealing

For perfect sealing, proper force must be applied lest the gaps between the high voltage terminal and the top surface of the high voltage bushing should exist. The causes below drive the pole transformers to fault.

- poor material of gasket or O-ring
- imperfect sealing not using cementing or bonding materials
- cracks of bushing due to excessive tightening force

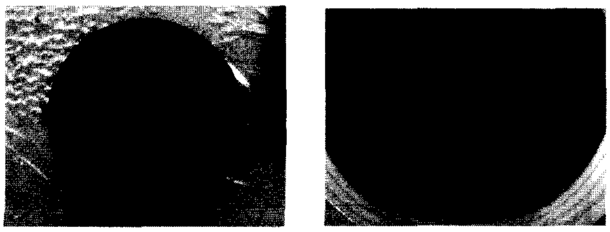


Photo. 3 Cracks of gasket material(NBR) and water content in tank

As shown in Photo. 3, the cracks due to poor gasket material causes the permeation of water content into the pole transformers.

e. Poor welding

Poor welding mainly leads to the permeation of water and the leakage of insulating oil.

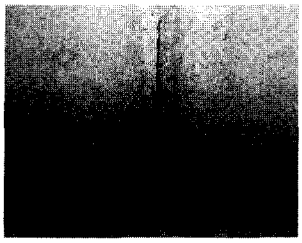


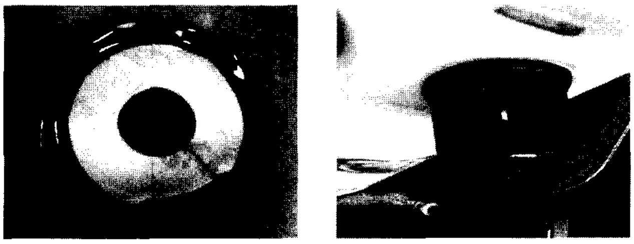
Photo. 4 Pin-hole on tank due to poor welding

2.1.2 Problems in mounting

a. Breakage of high/low voltage bushings

The cracks of the high/low voltage bushings are due to :

- damage or cracks due to external impact or careless handling
- reduction in hardness due to poor ceramic stuff



(a) (b)

Photo. 5 Breakage of bushings : (a) crack of high voltage bushing (b) crack of low voltage bushing

The causes mentioned above also result in the permeation of water or the leakage of insulating oil.

b. Poor relief valve

The relief valve is designed to automatically work and release the internal pressure when its rise reaches 0.7 ± 0.14[kg/cm2], and reaches the fault because of the following causes:

- pull ring axis bending due to careless handling
- loose bolt due to poor assembly in manufacturing

The poor relief valve often causes the permeation of water or the leakage of insulating oil.

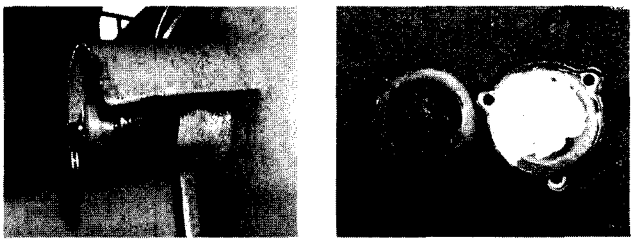


Photo. 6 Insulating oil leakage due to poor relief valve and abnormal handhole covered with rust

c. Bad restoration to original state after voltage regulation

Unless the handhole is not completely sealed after adjusting the tap changer to compensate the voltage drop at the distribution line end, the permeation of the water content and the leakage of insulating oil are expected.

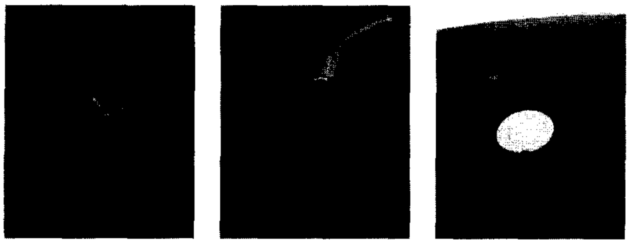
2.1.3 Problems in operating

a. Operation under overload

When the pole transformers are operated for long under overload condition, the internal insulations are aged by the temperature rise and the leakage current, etc. Since the insulations are carbonized and the leakage current increases, the aging is accelerated and the insulating performance is getting worse to be short circuit fault due to internal arc. The energy generated at arc decomposes the insulating oil into combustible gases[2]. The internal pressure rapidly increases because of the generated gases, which has the insulating oil blown off or the pole transformers can be exploded[3].

b. High voltage side/low voltage side surges

The high voltage side surge results in the breakage of the high voltage bushing, the arc between the cover and the high voltage bushing terminal and the breaking down of the high voltage conductors in the outer layer, while the low voltage side surge causes the breaking of the high voltage coils in the inner/medium layer and low voltage coils and carbonization of the adjacent insulations[4].



(a) (b) (c)

Photo. 9 Faults due to high voltage side and low voltage side surges ; (a) broken high voltage coils (b) broken low voltage coils (c) dark pitmarks on the interior walls around low voltage bushings

c. Secular aging

The life of the pole transformer is generally known to be about 30 years, but it is actually used for more than 20 years in Korea. The secular aging of the pole transformers can be distinguished by the discoloration degree, the dissipation factor and the spectrophotometry of insulating oil.

2.2 Developing mechanisms by fault causes

The fault causes of the pole transformers are typically divided into; thermal aging due to overload and high temperature operation, reduction in dielectric strength due to the permeation of water content, short time aging due to internal or external surge, aging due to discharge and mechanical damage or aging, etc. The increase of the combustible gases and leakage current and accumulated fatigue due to aging finally lead the pole transformers to breakdown[3].

2.2.1 Thermal aging

Thermal aging is divided into thermal depolymerization and thermal oxidation.

a. Thermal depolymerization

The molecular chains of insulations are cut by heat, and the cutting is the main sources of thermal aging known as pyrolysis, thermal dissociation and depolymerization. Combustible gases are generated by the source generating local heat in insulating oil. The gases exponentially increase with temperature. Hydrogen(H2) and acetylene (C2H2) are mainly generated at over 1,000[℃], and propyiene (C3H3), ethylene(C2H4) and methane(CH4) below 1,000[℃]. By using the characteristics, the temperature of hot spots and the amount of the generated gases can be determined[8].

b. Thermal oxidation(oxidative aging)

The molecular chains are separated by the reaction of insulations on the ambient oxygen, that is, thermal oxidation. In thermal depolymerization, molecular chains are cut by the reaction on the environmental materials, while, in thermal oxidation, molecular chains need oxygen to be cut. Thermal oxidation can progress by automatic oxidation below 0[℃], as well as at a high temperature. The basic consumption of oxygen increases the reaction speed of thermal oxidation. Since the reaction is exponentially governed by temperature, ambient moisture and metal, the life of the insulations exponentially decreases according to the Arrhenius equation.

2.2.2 Reduction of dielectric strength due to water permeation

The water globules existing in pole transformers cause the fault with another mechanism, and the mechanism is shown in Fig. 1.

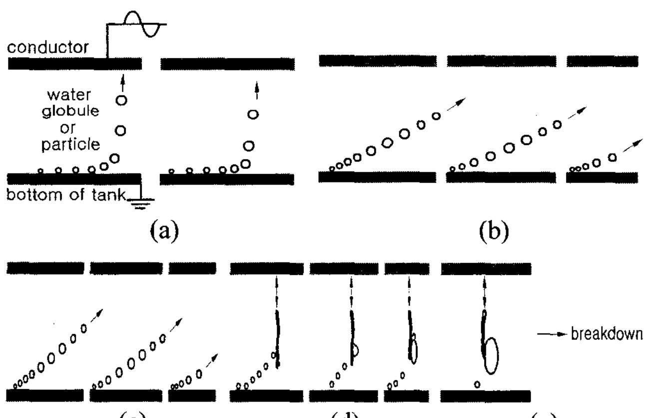


Fig. 1 Fault mechanism due to water globule on tank bottom

As shown in Fig. 1, as the field strength increases, the water globules on the tank bottom are arranged in the direction of the field to ultimately make a bridge between the conductor and the tank[7].

2.2.3 Thermal aging within short time due to internal or external surge

Surges generated by internal or external causes of pole transformers gives rise to a short time fault, and the surge is mainly due to: lightning or switching impulse voltages via high voltage side or low voltage side of the pole transformers; internal short circuit current due to the breakdown of insulations; external short circuit current on load side. Out of the causes, as the last is explained in many references, the fault mechanisms due to former 2 causes are illustrated in this paper. To explain the first case, surface flashover paths when impulse voltage was superimposed on ac are shown in Fig. 2.

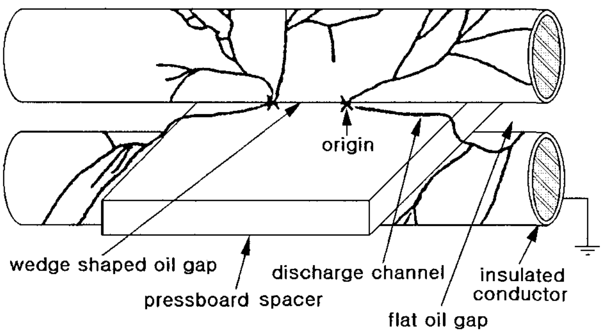


Fig. 2 Surface flashover paths due to surge

As shown in Fig. 2, according to the experiment simulating the transformer conductors subjected to the surge, the discharge mostly appears to be surface flashover[6], and the discharge channels are originated from a small oil wedge. Similar to most surface flashovers, however, the breakdown due to the discharge channels does not inflict damage on the insulations. Generally, the follow current flowing through the channels formed by the surge causes larger faults.

Fig. 3 shows the schematic for the short circuit analysis of pole transformer windings.

As shown in Fig. 3(a), the faulted high voltage winding can be divided into two parts: the faulted turns(k turns) and the remaining turns(m turns) and analyzed as a two winding transformer. The unfaulted turns will be energized at the system voltage and act as a "secondary" winding with a turns ratio of m/k. The voltage induced in the shorted turns will be k/m times the source voltage and the current in the shorted turns will be m/k times the high voltage side current(ignoring the magnetizing current). The fault current on the high voltage side is limited by the leakage reactance between the faulted and unfaulted windings(not the same as the short circuit reactance) and the effective high voltage side resistance.

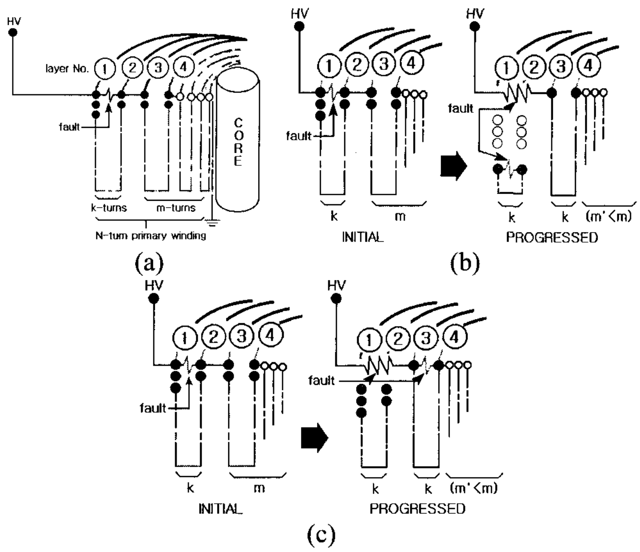


Fig. 3 Short circuit analysis of winding; (a) faulted high voltage winding (b) progressed to short circuit between turns (c) progressed to short circuit between layers

Fig. 3(b) schematically describes the progression of a fault within initially faulted layer 1 and 2. The fault involving k shorted turns burns into layers 1 and 2 bypassing some of the turns and reducing the number of shorted turns to k'/k.

Fig. 3(c) schematically describes the progression of a layer 1 to 2 fault to an adjacent layer-to-layer fault(layers 3 to 4). The involvement of the 3rd and 4th layer can occur without the original layers because the turns are simply burned off by the fault current. This type of progression is observed during transformer tear-down[5].

2.2.4 Aging due to discharge

Aging due to discharges is divided into aging due to arc with high temperature and aging due to partial discharges with chemical reactions. The heat generation due to the arc is very high to be in the thermal depolymerization process, but in some cases, gases are produced at oxidative aging as each atom and molecule generated by dissociation reacts with ambient oxygen. In partial discharge aging, it is oxidative aging in principle, but the oxidative aging is a chemical reaction due to heat and ultraviolet light, while the partial discharge aging is governed by the direct collision of electrons with positive/negative ions, electrons, atomic typed oxygen and activated oxygen.

2.3 Methods for fault cause analysis

2.3.1 Macrography

This is to inspect the apparent defects by eyes, and it is a very important item over all processes of fault cause analysis of pole transformers. Carbonization or discoloration of pole transformer components, melting due to arc, leakage of insulating oil, permeation of water and apparent deformation are observed.

2.3.2 Mechanical tests

a. Hygroscopic tests

This test is to examine the defect of ceramic stuff such as bushings. After crushing the bushings of interest, several splinters of the bushing is impregnated in fuchsine solution under high pressure. In a specified time, the bushing is taken out from the solution and crushed again to a smaller size to inspect the permeation of the fuchsine solution into the ceramic stuffs.

b. High pressure test

This test is to judge the sealing condition of the tank. For the test, the leakage of the oil is distinguished after the pole transformer is hung upside down for a specified time, or the leakage of compressed gas is observed after several [atm] of the compressed gas is injected through the relief valve.

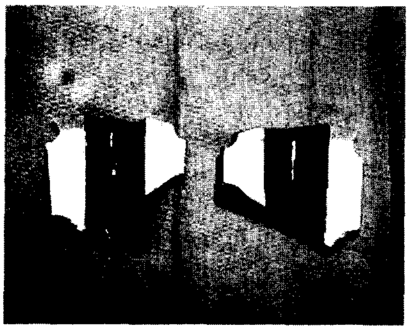


Photo. 10 Permeation of fuchsine solution into ceramic due to poor material

2.3.3 Electrical tests

a. Measurement of winding resistance

This is to understand whether the high voltage and low voltage conductors are broken or not. In normal cases, the resistance lies 10～30[Ω] between a high voltage terminal and grounding terminal, and less than 1[Ω] between low voltage terminals, but in abnormal cases, it becomes very high. In addition, the contact between the high voltage windings and low voltage windings can be determined by measuring the resistance between high voltage terminal and low voltage terminals.

b. Measurement of turn ratio

As needed, the turn ratio of pole transformers can be taken by using a turn ratio meter or by directly measuring the voltages of the high voltage side and low voltage side.

c. Other tests

Other tests except the measurement of the resistance and turn ratio of windings - dielectric strength, relative permittivity, dissipation factor and specific resistance, etc. - are based on KS C 2105(Testing Methods for Electric Strength of Solid Insulating Materials) and KS C 2313(Testing methods of electrical insulating papers, pressboard and presspaper) in the case of solid dielectric, and KS C 2101(Testing methods of electrical insulating oils) and KS C 2301(Electrical insulating oils) in the case of liquid dielectric.

3. Flow for fault cause analysis of pole transformer

The fault factors mentioned above cause the secular aging or shot time fault of pole transformers, with their unique mechanisms. A general understanding of the flow to the fault is indispensable for analyzing the fault causes and devising proper countermeasures. Therefore, the flow of fault analysis is proposed.

The fault cause analysis flow is basically for one transformer with a fault and electrical and physical analysis is carried out from taking it over to complete disassembly.

A flowchart constructed under the assumption above is shown in Table 1.

4. Conclusions

This paper sets forth guidelines for both the officials with KEPCO and pole transformer manufacturers, by analyzing the fault causes of pole transformers requested by KEPRI and verifying the mechanisms at the faults. A study on the pole transformers has often been neglected despite the fact that only exact analysis of the fault can prevent utilities from encountering a similar fault again. In fact, the pole transformers are installed often in distribution systems; it is, however, not easy to find out the references dealing with exact analysis and proper countermeasures of pole transformers. The pole transformers are mounted closest to the customers, which gives direct damage when they fail. Therefore, the reliability of the power sully depends on the stable operation of the pole transformers. As various kinds of pole transformers manufactured by many domestic companies are installed in the distribution lines, as many fault aspects as possible must be enumerated, but there are some restraints. The flowchart for fault cause analysis was constructed based on only the phenomena commonly observed in the failed pole transformers. The purpose of this paper was to originally prevent the pole transformers from encountering faults, but it is very difficult. The fault aspects of pole transformers are far different from those of power transformers in some points, therefore continuous studies must be performed.

Table 1 Flowchart for fault cause analysis

[illegible] checking leakage of sealing test

Stage	macrography	electrical test	mechanical test
before opening cover	· identifying which end of winding is connected to ground · leakage of insulating oil at; - high/low voltage bushings - handhole - relief valve - tank · breakage/deformation/displacement - high/low voltage bushings - relief valve - radiator · high voltage bushing/terminal - checking for high voltage lead bolt condition after opening high voltage bushing terminal - sealing(NBR or cork)	· winding condition - resistance of winding · turn ratio · partial discharge	· examination of exterior of transformer for evidence of damaged or defective sealing of tank, cover and bushings - injection of compressed gas · hygroscopic tests for ceramic stuff
after opening cover before taking coil and core assembly out	· insulating oil; - discoloration degree and smell - minimum liquid level · tap changer; - position and contact condition - examination for signs of burning or arcing · top of core clamps - checking for evidence of water - impurities/sludge/soft varnish dregs	· tests for insulating oil - dielectric strength - permittivity - dissipation factor - specific resistance - moisture content measurement - spectrophotometry	
after taking coil and core assembly out	· varnish; - varnish conditions(hardness, impregnation, etc.) - closing up of oil duct · examination for signs of burning or arcing on exposed area; - carbonized spots · deformation/displacement of conductors - inspection of assembly for axial shifting due to short circuit forces · tank bottom - water globules - impurities or sludge/rust		
after disassembling core and removing coils	· high voltage winding; - examination for signs of burning or arcing between layers - winding condition/space between turns - signs of arcing on tap lead connecting parts and connecting condition · insulating paper condition; - carbonized or punctured spots · solid strips - elbow-shaped bend on solid split bars	· tests for insulating paper - dielectric strength - relative permittivity - dissipation factor - specific resistance	

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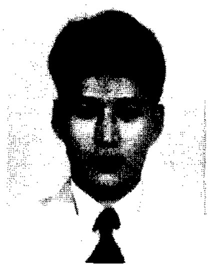

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