Life Assessment of Aluminium and Copper Winding Distribution Transformers Using Loss of Life Analysis

Zainal Arifin
PT. PLN (Persero)
Institut Teknologi PLN
Jakarta, Indonesia
zainal.arifin22@pln.co.id

Nugroho Adi
Corporate Planning Division
PT. PLN (Persero)
Jakarta, Indonesia
nugroho.adi.t@pln.co.id

M. Herdy Ardiansah
Institut Teknologi PLN
Jakarta, Indonesia
herdy.elektro@gmail.com

Haztuti Aziz
Electrical Enginering Depatment
Institut Teknologi PLN
Jakarta, Indonesia
hastuti@itpln.ac.id

***Abstract*—In general, the life of distribution transformers is very dependent on the conditions of oil insulation and windings. Some disturbance conditions and the transformer overloading capacity can cause a high-temperature rise and accelerate the decrease in insulation level so that the loss of life of the transformer can be even greater. While the recent population of distribution transformers mostly consist of Copper (Cu) and Aluminum (Al) windings. Based on that, this study determines the life time of distribution transformers for both technologies. Life assessment is executed using loss of life analysis due to the disturbance phenomenon called cold load pick up (CLPU) and loading conditions. Using 79 units Cu-Cu and 105 units Al-Al distribution transformers installed at PLN UP3 Cengkareng Jakarta, the loss of life is conducted using CLPU algorithm and IEC 60354 and 60076-7 calculation. The result of study found that the life time of copper winding is longer than aluminium winding transformers. In additions the total owning cost of transformer aluminium is higher 9% than the copper one.**

***Index Terms*—Loss of life, aluminium winding, copper winding, distribution transformers, CLPU.**

I. Introduction

Due to a large number of the transformers world population is approaching its expected end-of-life, some research focusing on transformer life evaluation and monitoring has emerged over the last decade [1]. On the other hand, most utilities try to predict the transformers lifetime and use them until the end of their life. Indeed it needs some effective methods to see whether the transformers are still fit for use or need to be retrofitted or replaced. One of the highly utilized methods is “loss of life” analysis. The loss of life of a transformer is means the loss of life of its insulation. Life consumption of insulation in transformers is governed by several factors primarily are load and the ambient temperature. To assess the life consumed in an interval due to the loading and ambient conditions that have to investigate the all related phenomena during operation of transformers [1].

There is a phenomenon that occurs quite often during a power outage, when the network is re-energized after recovery interruptions, the loads entering the network are often greater than before the outage occurred. These loads include thermostatic loads such as heating or air conditioning equipment, lighting loads, motors and capacitive loads, etc. This phenomenon is called Cold Load Pick Up (CLPU) because the power supply is not available for a certain period of time so that the load has reached a ”cold” condition before being re-energized [2].

The current in CLPU conditions is a combination of the non-variable cycle load current, continuous operating load current, transformer magnetization current, capacitor inrush current, etc. This combination can produce a significantly higher current level than the normal peak load level [2]. The CLPU current can be high enough to cause a momentary over current and cause an increase in oil temperature and distribution transformer windings.

Analysis of the loss of life of the distribution transformer can be done by the method of calculating the rise in hot spot temperature of the oil and transformer winding caused by the factor of the transformer loading and CLPU phenomenon. Calculations in this study were carried out on aluminium and copper winding distribution transformer samples installed at PLN UP3 Cengkareng. Totally 184 units of transformers (79 Cu-Cu and 105 Al-Al winding) is investigated and observed to determine their loss of life.

Additionally the loss of life calculation is also conducted due to loading condition based on IEC 60354 and 60076-7 to observe the loss of life for the similar samples transformers operated at PLN UP3 Cengkareng.

II. Aluminium and Copper Winding

Copper (Cu) and aluminium (Al) are the two most commonly used materials for conductors and transformer wind-

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ings. The first transformers were built with copper conductors, since copper was more accessible at that time. During the Second World War, some industries began to manufacture transformers with aluminium because copper became scarce. It continues to increase in the 1960s when the demand for copper caused a large increase in its price [1]. Al – Al windings have been successful especially in distribution transformers. While Cu – Cu design is more common for large power transformers. Each has positive and negative characteristics that affect their use in various applications. To select the right material, the designer has to take into consideration several factors such as weight, maximum size, transformer total cost, availability and cost of the material [3]. The transformers takes a crucial role on utility company performance like PLN, Indonesia.

Table I shows some important physical properties of copper and aluminium. While the resistivity of copper is lower than aluminium, the mass density of copper is much higher than the mass density of aluminium. The expansion coefficient of copper is lower than aluminium, but the thermal conductivity is higher in copper than in aluminium.

TABLE I
PHYSICAL PROPERTIES OF CU AND AL

Physical properties	Unit	Copper	Aluminium
Resistivity	$\mho - mm^2/m$	0.016642	0.03
Mass density	kg/dm3	8.89	2.7
Expansion coefficient	µm/(m ^oC)	16.7	23.86
Thermal conductivity	W/(m K)	398	210
Tensile strength	Mpa	124	46.5
Melting point	^oC	1084.88	660.2
Specific heat	J/(kg K)	384.6	904

In addition, some studies conclude some interesting finding as follows [3]:

- The length of an aluminium winding is on average 15% larger than the length of a copper winding for same power.
- An aluminium transformer requires on average 20% more core weight;
- The weight of the aluminium windings is on average 25% less than the weight of copper windings.
- An aluminium transformer requires 45% more oil than a copper transformer.

III. ALGORITHMS

At the CLPU condition, it can be addressed that during period of time after the network is re-energized, the load may increase few times than the normal condition. Based on the experiences of some developing countries, the load during time is about 1.5 to 2.5 times than the normal load [4]. In this study, the estimated values of the load after CLPU condition is 1.5 times than the normal condition in 30 minutes duration of time.

For the data provided in this study, the algorithms proposed by Gupta et al. (2007) have been used to calculate the loss of

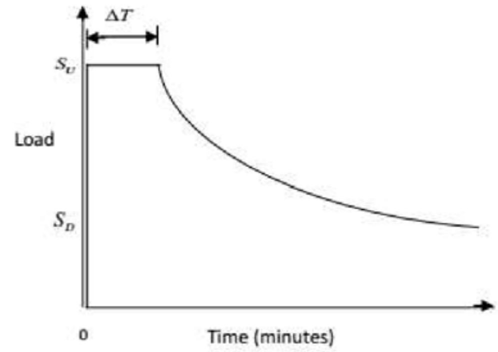

Fig. 1. Load During CLPU [2]

life of either the copper and aluminium winding distribution transformer due to CLPU problem. The detail algorithms are described as below: The computation of Factor of Load Loss (k) is given by:

$$(k) = \left(\frac{Load\ on\ the\ Transformer\ \Delta\top}{Rated\ Load\ on\ the\ Transformer}\right)^2 \quad (1)$$

Then the total loss either at rated load and during T when the CLPU is happened is given by:

$$W_{LR} = No\ Load\ Loss + Load\ Loss \quad (2)$$

$$W_{LDelta\tau} = (K \times\ Load\ Loss) + No\ Load\ Loss \quad (3)$$

After that, we defined a constant as a comparison between WLR and W $_{\mathrm{LT}}$,

$$L\,(Constant) = \left(\frac{W_{L\Delta\tau}}{W_{LR}}\right) \quad (4)$$

The winding temperature rise at end of T minutes after switch on is described by :

$$\Theta\tau = \left(1 - e^{-\frac{\Delta t}{tW}}\right) \times \Theta_W \times L \quad (5)$$

The calculation of the total winding temperature can be obtained by:

$$\Theta_{WT} = \Theta_W + \Theta_{amb} \quad (6)$$

The calculation of Hot Spot Temperature at time T is as below:

$$\Theta'_{HOT} = 1.2 \times \Theta_\tau + \Theta_{amb} \quad (7)$$

The calculation of Hot Spot Temperature at rated load can be described as below:

$$\Theta'_{HOT} = 1.2 \times \Theta_W + \Theta_{amb} \quad (8)$$

The calculation of Loss of Life (LoL) at Θ'_{HOT},

Where α = 0.0865, t0 = 24 x 60 minutes The observation of the effects from hot spot temperature rise to the transformers loss of life is further analyzed in normal operating conditions with the guidance of IEC 60076-7 :2005 and IEC 60354: 1991 methods within the algorithm to calculate the hot spot temperature rise and the loss of life as follow,

$$\Theta_{HOT} = \Theta_{amb} + \Delta\Theta_{0\Gamma}\left[\frac{1+RK^2}{1+R}\right]^X + H_{gr}K^y \qquad (9)$$

Where Θ_{amb} is an Ambient temperature, 30○C; R is Loss Ratio, for distribution transformer is 5; K is a Load Factor, described by Load Rating/Capacity Rating; then H is Hot-spot factor, for distribution transformer is 1.1; X is an Oil exponent, for distribution transformer is 0.8; Hgr is Hot-spot to top-oil gradient, for distribution transformer is 23°K / C and y is winding exponent, for distribution transformer is 1,6.

The loss of life calculation based on IEC 60076-7 is as below:

$$L = \sum_{n=1}^{N} V_n \times t_n \qquad (10)$$

Where $V_n = 2^{\frac{\Theta_{HOT}-98}{6}}$, the relative ageing rate and tn is the nth interval.

IV. SAMPLES

Two different aluminium and copper winding DT with the same rated capacity in substation DK31 was observed to analyze the impacts of CLPU and loading to its performance in terms of loss of life. The aluminium DT was installed in 2017 and the copper one has operated since 1987.

TABLE II
NAMEPLATE RATING

No Trafo	**Transformer Winding**	**Rated Capacity (kVA)**	**Trafo Load (kVA)**	Total Rated Loss (W)
DK31	Cu-Cu	630	579,51	10.025
DK31	Al-Al	630	601,25	7.800

The outage data from 2018 was taken to analyze the loss of life of the DTs regarding CLPU phenomenon. For the calculation loss of life due to loading conditions, online load measurement was conducted for a week to get more convincing data.

TABLE III
OUTAGE DATA 2018

DAY	**DATE**	**FEEDER**	START TIME	END TIME	OUTAGE TIME (MINUTES)
SUNDAY	2018-02-04	TILAK	11:18	17:40	382

Fig. 2 shows the typical daily load curves from both DTs.

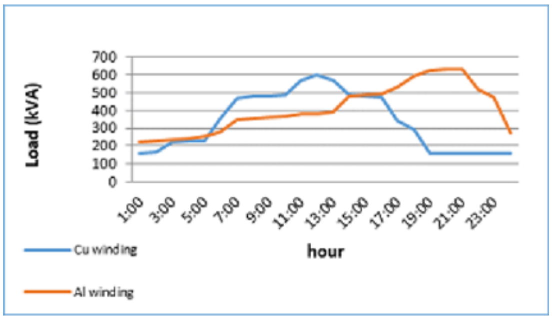

Fig. 2. Daily Load Curve DK 31 Transformer

A. CLPU

The calculation in this study is conducted with the assumption that the increasing load after CLPU has occurred in 30 minutes duration of times . The average winding temperature rise for copper winding is 45.8 ○C based on the laboratory test data, and so for the aluminium winding is 43.3○C. The ambient temperature is set at 30°C. The thermal winding time constant is 14 minutes based on laboratory test.

TABLE IV
LOSS OF LIFE CALCULATION DUE TO CLPU

DK31	ΔT **(min)**	**Load Trafo** ΔT **(kVA)**	**Total loss (W)**	**Loss at** ΔT **After CLPU**	ΘHot ΔT **After CLPU**	**Loss of Life at** ΘHot ΔT **After CLPU**
Al-Al	30	901,874	7800	14620,64	117,52	0,45130
Cu-Cu	30	865,265	10025	17978,52	117,00	0,33291

From the results above, it can be seen that the loss of life in the aluminium winding distribution transformer is 0.4513 %, slightly higher than the copper ones, which is 0.33291 %. It can be explained because of the loading capacity of the aluminium winding transformer is higher than the copper ones. When it meets to the same loading rating capacity, based on the design at Table IV, the loss of life of aluminium winding might be lower than the copper ones, so there is another factor to be considered that is the no-load and load loss design of the transformer, where the copper ones has a higher losses design because it was an old transformer that had been operated since 1987. So it must be taken into consideration with the future design of copper winding transformers losses.

B. Loading Condition

The observation of substation DK31 is conducted in a site measurement during a week online data capturing from the transformer, starting from May 20th until 26th, 2019.

With the relation of loading and the hot spot temperature rise as we found by the previous calculation (CLPU), the value of the hot spot temperature rise in substation DK 31 is also increase following the load increment. From the load curve (fig.2), we can see that the aluminium winding transformer serving a high load longer than the copper ones. It also has a longer peak time with a higher load (600 kVA in 3 hours) while the peak load from the copper winding transformer, 600 kVA, happening is just in an hour. This led to a higher hot spot temperature rise in the aluminium winding transformer, reached over 100 $^oCin4hoursdurationoftime.$

Fig. 3. DK31 Hot Spot temperature Rise

From the calculation, it can be seen that the loss of life per hour is dynamics following the change of the load and the highest loss of life has happened at the peak load time. The results in Fig. 4 describe the movement of loss of life in average hourly for a week.

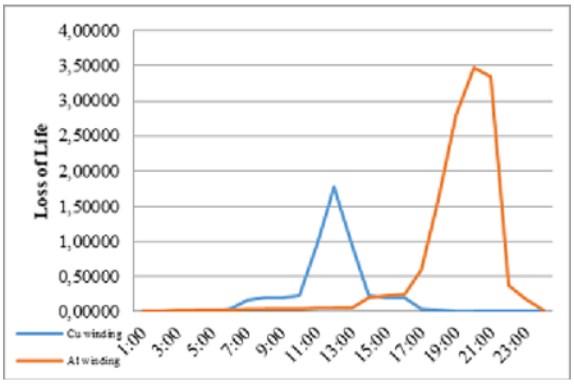

Fig. 4. DK 31 Loss of Life Calculation

The loss of life that has been considered is a cumulative of a day, as it represents the actual value of loading. The average cumulative loss of life per day is given in Table IV.

TABLE V
AVERAGE CUMULATIVE LOSS OF LIFE DK 31

No Trafo	Transformer Winding	Rated Capacity (kVA)	Trafo Load (kVA)	Loss of Life (%)
DK31	Cu-Cu	630	579,51	5,17117
DK31	Al-Al	630	601,25	13,38338

In this observation, we found that the loss of life in the aluminium winding transformer is greater than the copper winding. The aluminium winding transformer has a loss of life 13.38% with recent loading conditions, while the value for the copper ones is 5.17%. Loading condition and the duration of peak load is the major causes in the differences in the loss of life between these two types of transformers. If the load is getting higher in the future, it will lead to the life reduction of the transformer because the value of the loss of life will be greater.

V. LOSS OF LIFE AND COST ANALYSIS

Regarding the development of distribution asset management in PLN which is just starting and not established yet, it is not easy for gathering data related to the distribution equipment such as transformers, re-closer, MCB, electric meter etc. Not only basic information such as technical specification, year of manufacturing and technology type, but also historical data such as outage report, maintenance cost, modification record and so on. Due to “poor” data available related to distribution transformers in PLN then such cost analysis cannot be conducted.

To do cost analysis within limited data, the levelized cost of electricity (LCOE) is one of method which is able to need the minimum data requirement. LCOE is a way to measure holistically the costs, including the timeline of those expenditures, that go into the production of a kilowatt-hour. It is levelized over the lifetime of the plant. This measure is a useful, if imperfect, metric for electricity cost which incorporates the time value of money as well as variable profit and costs during the lifetime of a plant.

An easier calculation, very similar to the LCOE, is the approximate cost of electricity, which neglects this year-by-year assessment. The LCOE equation that must be calculated during each period, n are as follows.

$$\sum_{t=1}^{n} = \frac{I_t + M_\Gamma + F_\Gamma}{(1+\Gamma)^t} \sum_{t=1}^{n} = \frac{E_t}{(1+\Gamma)^t} \tag{11}$$

Where, It is an investment expenditures in year t (including financing), Mt described as operations and maintenance expenditures in year t, Ft is fuel expenditures in year t, Et is electricity generation in year t, r is discount rate and n is life of the system.

For this study, to analyze the financial of distribution transformers who have loss of life during its operation period, the simplified of LCOE can be used. Its formulation as follows;

Simplified LCOE = I + ((O + M) variable x kWh delivered) + (O+M) fixed Where: I is capital (investment) cost, O + M variable is operation and maintenance variable cost, O + M fixed is an Operation and Maintenance Fixed Cost, kWh delivered is KWh electricity delivered by transformers during its lifetime.

Referring to the result of study as previous chapter, there are two transformers’ losses of life calculation. First thing is loss of life based on CLPU (Cold Load Pick Up) method showing that transformer copper winding is 0.3329116%. Another is transformer aluminium winding who has 0.4512987% loss of life. The second calculation is the IEC 60354 and IEC 60076-7 result showing that the loss life of copper winding transformer is 5.17117% and the aluminium one is 13.38338%. Considering the optimum operation of distribution transformer at the grid system, then the IEC method is mostly represent the real operation of transformer. Therefore, the IEC result is more appropriate to be used for the cost analysis of this study.

To compare the distribution transformer copper winding with the aluminium one within the same performance, the simplified of LCOE of both should be equal. Then simplified LCOE Cu = LCOE Al, thus:

I Cu + ((O + M) variable x kWh delivered) Cu + (O+M) Cu fixed = I Al + ((O + M) variable x kWh delivered) Al + (O+M) Al fixed

Assuming that design lifetime of both transformers is 30 years (IEEE and IEC standard), then the actual lifetime of transformer is equal to the design lifetime reduced by its loss of life. Then:

The actual lifetime of transformer copper = 30 x (1 - 5.17117%) = 28.45 years The actual lifetime of transformer aluminium = 30 x (1 - 13.38338%) = 25.98 years It means the actual lifetime of transformer aluminium is shorter 2.46 years than the copper one. Referring to the best practice of distribution system equipment operation, the variable O M cost and fixed O M cost for both technologies is relatively same then it can be neglected, thus:

I Cu x (1 − 0.0517117) = I Al x (1 − 0.1338388) 0.94829 I Cu = 0.86612 I Al Hence: I Cu = 0.9134 I Al

VI. CONCLUSION

Loss of life due to a loading condition is higher because of the duration of the occurrence is long and continuous. The effects of CLPU are instantaneous but it has a higher inrush current. Frequently CLPU occurrence will increase the probability of distribution transformer failure. Furthermore, the combination of overloading transformers and CLPU conditions may give a serious problem in transformers, both from loss of life and direct failure of the transformer.

Based on the calculation, the life time of copper winding distribution transformer is 2.45 years longer than aluminium one. Additionally in order to achieve the equal LCOE within its loss of life, the difference life cycle cost or total owning cost of distribution transformer aluminium should be similar or higher 9% than the copper one.

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