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Analysis of Winding Temperature and Design of Distribution Transformer for Improving Short Circuit Withstand Capability under Renewable Generations Mixed Environment

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Abstract: Under renewable generations mixed in today's modern grid system, many of renewable generation resources tend to increase the fault level to an existing power system. Rules and regulation for power equipment and devices need to be revised and updated, of course, no exception for the distribution transformers. This article, therefore, presents the evaluation and analysis of the winding temperature on both loading and short circuit conditions of an oil-immersed distribution transformer and propose the novel transformer design method for improving short circuit withstand capability. In the study, the methodologies of measuring and estimating the winding temperature of the transformer during short circuited are presented and implemented. In the study, various winding parameters are analysed including: the winding temperature, the hottest temperature of the winding after a short circuit, the short circuit current, short circuit force and short circuit duration. The tested and analysed result are benefit for the newly proposed distribution transformer design of a 400 kVA 3 phases 50 Hz 22 kV-400/230 V, Dyn11. The new design approaches will enable designers to find a weak spot and proper selection of raw materials, such as winding size, insulation thickness and properties of the silicon steel for a better quality of distribution transformer. Moreover, the new design can offer lower winding temperature rise of transformer while loading or experiencing with short circuit conditions meaning that it can prolong transformer insulation and extend transformer lifetime.

Keywords: Hottest spot temperature, Temperature rise, Short circuit current, Short circuit force.

1. Introduction

Distribution transformer (DT) is an important device in electrical power system. It is not just only the front end equipment to deliver electricity to end consumers but also plays an important role as a system healthy monitoring and indicator. At the present time, under the new environment of renewable generation mixed in smart grid system, an integration of renewable generation resources tend to increase the fault level and cause severe operation issues to an existing power system [1]. The variety of new converter technology in generations and load complexity can also cause power quality issues to a conventional power system. Therefore, the new safety design rules and regulations need to be revised and updated to power equipment, apparatus and devices including both power transformers and distribution transformers. Many articles have been studied about the hot-spot inside distribution transformer and its windings because this is an important factor indicate transformer efficiency, performance and lifetime. In 2008, methodologies of finding transformer winding hot spot while loading was proposed and implemented by [2], and [3] has investigated and compare the algorithm of the hot-spot temperature calculation to an experimental test of power transformer in 2015. While [4] used support vector regression to analyse and compared three of transformer top oil temperature modelling, [5] has analysed and compare the hot-spot thermal models of HV/LV prefabricated Oil-Immersed

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transformers by using top-oil temperature rise models. In addition, [6] described the application of finite element methods for determining the distribution of losses over windings and determining the value of the hot-spot factor and hot-spot temperature. Researchers in [7] and [8] revealed that external short circuit can produce high current in transformer winding and create high internal forces which are the major cause of damaging transformer. Moreover, [9] has found the impact of transformer's losses from harmonics which can deteriorate transformer lifetime. Hence, it can be seen that many researches aimed focus to transformer's lifetime analysis and study. Researchers in [10] have proposed an assessment on aging model of IEEE/IEC standards for Oil-Immersed transformer by using thermal model to analyse the behaviour transient thermal performance while [11] has defined the smart meter functions required to accurately assess the aging of distribution transformer according to IEEE Std. C57.91 and C57.110. Although many articles have been studied and focus on distribution transformer hot-spot temperature and lifetime, however, no one has been considering the design of DT which includes features to withstand the loading and short circuit conditions among the integration of various renewable generations mixed.

Therefore, this research is not only present new design methods of distribution transformer but also implement the testing, evaluating, and analysing the winding temperature on various loading and short circuit conditions of an oil-immersed distribution transformer. Then, based on analysis results, this research proposes new techniques for improvement and development of distribution transformers design for power system security enhancement and extend transformer's lifetime.

2. Method of analysis

Typically, the winding insulation aging depends on the thermal inside the transformer and operating time. The degraded insulation usually occurs at the hottest spot temperature. Therefore, in this study, main focuses aimed to these followings:

2.1 Specific parameter from a transformer temperature rise test

In Thailand, the Provincial Electricity Authority of Thailand (PEA) [12], who responses for almost 90% of distribution system in the country, has issued the regulation and limitation of distribution transformer parameters within specific range. Details of each parameter are shown in following equations:

2.1.1. Average winding temperature rise [13-15]

$$\Theta_{wr} = \Theta_{w2} - \Theta_a \tag{1}$$

$$\Theta_{w2} = \frac{Rt2}{Rt1}\left(k + \Theta_{w1}\right) - k \tag{2}$$

Where;

Θ_{wr} is average winding rise, °C

Θ_a is ambient temperature, °C

Θ_{w1} is initial average winding resistance, °C

Θ_{w2} is average winding resistance at shutdown, °C

R_{t1} is winding resistance at ambient temperature, Ω

R_{t2} is winding resistance after switch off (graphical extrapolation), Ω

k = 234.5 for copper, 224.5 for aluminum

2.1.2. Top oil temperature rise at rated load

$$\Theta_{or} = \Theta_o - \Theta_a \tag{3}$$

Where;

Θ_{or} is top oil temperature rise at rated load, °C

Θ_o is top oil temperature at rated load, °C

2.2 Parameter from transformer short-circuit

During short circuit condition, following critical parameter need to be calculated [16]

$$t = \frac{1250}{I^2} t \tag{4}$$

Where;

t is short-circuit current duration, in second

$I = I_{sc}/I_R$ is symmetrical short-circuit current, in multiples of normal base current

Remark: less than 500 kVA. However, for the larger transformer, the duration of the short circuit should not exceed 2 seconds by default.

2.2.1. Short-circuit current calculation [13, 16]

The short circuit current calculation can be calculated as following equations.

1. Symmetrical current can be found from the equation.

$$I_{SC} = \frac{I_R}{Z_T + Z_S} \tag{5}$$

Where;
I_R is rated current, in rms amperes
Z_T is transformer impedance, in per unit
Z_S is impedance of the system, in per unit

Remark: This research addresses short circuit current at the terminals of the transformer without change on impedance of the system. (Therefore, Short circuit current is the maximum)

2. Asymmetrical current can be found from the equation.

$$I_{SC(pkasym)} = KI_{SC} \tag{6}$$

Where;

$$K=[1+(e^{-(\theta+\pi/2)r/x})\sin\theta]\sqrt{2}$$

and
e is base of natural logarithm
θ is arctan x/r , in radian
x/r is ratio of effective alternating-current reactance to resistance, both in ohms

3. Calculation of winding temperature during a short circuit

Typically, final winding temperature value (T_f) at the end of short circuit duration can be calculated from Eq. (7).

$$T_f=(T_k+T_S)\times m(1+E+0.6m)+T_S \tag{7}$$

Where;

$$m=\frac{(w_S)t}{C(T_k+T_S)}$$

In Eq. (7), the recommend value of m should be restricted to m = 0.6 or less. However, for if value of m excesses than 0.6, T_f can be found from Eq. (8).

$$T_f=(T_k+T_s)[\sqrt{e^{2m}+E(e^{2m}-1)}-1]+T_s \tag{8}$$

Where;
T_k is 234.5 for copper, 224.5 for aluminum.
T_S is Initial temperature. It is equal to following conditions:

(1) 30 °C ambient temperature plus the average winding rise plus the manufacturer’s recommended hottest spot allowance; or

(2) 30 °C ambient temperature plus the limiting winding hottest spot temperature rise specified for the appropriate type of transformer.

Where;
e is base of natural logarithm ≈ 2.718
E is per unit eddy current loss, based on resistance loss (W_S), at starting temperature

$$E=E_r\left[\frac{T_k+T_r}{T_k+T_s}\right]^2 \tag{9}$$

Where;
E_r is per-unit eddy current loss at reference temperature
T_r is reference temperature: 20°C ambient temperature plus rated average winding rise
W_S is short-circuit resistance loss of winding at the starting temperature, in watts per pound of conductor

$$W_s=\frac{W_rN^2}{M}\times\left(\frac{T_k+T_s}{T_k+T_r}\right) \tag{10}$$

Where;
W_r is resistance loss of winding at rated current and reference temperature, in watt
N is symmetrical short circuit magnitude, in times normal rated current
M is weight of winding conductor, in pounds
C is average thermal capacitance per pound of conductor and its associated turn insulation, in watt-seconds per degree Celsius. It shall be determined by iteration from either of the following empirical equation:

For copper

$$C=174+0.0225(T_S+T_f)+110\left(\frac{Ai}{Ac}\right) \tag{11}$$

For aluminum

$$C=405+0.1(T_S+T_f)+360\left(\frac{Ai}{Ac}\right) \tag{12}$$

Where;
Ai is cross-sectional area of turn insulation
Ac is cross-sectional area of conductor

2.3 Short-circuit force calculation according to IEC 76-5 standard [17]

2.3.1. Asymmetrical short circuit current

The asymmetrical short circuit current will be calculated as follows:

$$I_{SC} = \sqrt{2}\times[1+e^{(\frac{-\pi R}{X})}]\times(\frac{Iph}{Ez}) \qquad (13)$$

Where;
Iph is Rated phase current
R is % Resistance
X is % Reactance
Ez is Per unit impedance

2.3.2. Calculation of radial forces

Axial leakage flux interacts with coil current generating radial force (F_{rad}). Radial flux component interacts with coil current generating axial force (F_{ax}). Both forces directly damage transformer coils. In normal operation, the forces are minimal, but if the transformer experiences short circuit conditions, current and magnetic force will become very high. Thus, short circuit current must be considered when designing a transformer. The radial force can be obtained from Eq. (14)

$$F_{rad}=0.628\times[\frac{(N\times I)^2}{H_w}]\times\pi\times D_m\times r^2\times\left(k\sqrt{2}\right)^2\times10^{-6} \qquad (14)$$

Where;
D_m is mean diameter of the pair of windings, mm.
H_w is geometrical average length of windings, mm.
N is number of winding electrical turns, mm.
I is rms value of winding current, A
$r = 1/EZ$ is overcurrent factor
$k=[1+e^{(\frac{-\pi R}{X})}]$ is peak amplitude factor

2.3.3. Calculation of axial forces

The value of axial force at short circuit withstand test can be calculated by Eq. (15)

$$F_{ax}=0.628\times[\frac{(N\times I^2)}{H^2W}]\times\pi\times D_m\times[d+\frac{a_1+a_2}{3}] \times(2K-1)\times r^2\times(k\sqrt{2})^2+10^{-6} \qquad (15)$$

Where;
d is width of the main duct
a_1, a_2 are radial width of winding

The value of hoop stress at short circuit withstand test can be calculated by Eq. (16)

$$\sigma_t=0.314\times[\frac{N\times I}{H_w}]\times D_m\times J\times r^2\times(k\sqrt{2})^2\times10^{-6} \qquad (16)$$

Table 1. Maximum permissible values of average temperature of the winding after short circuit (θ_1)

Transformer Type	Insulation system temperature (°C)	Maximum values of θ_1	
		Copper	Aluminum
Oil-immersed	105 (A)	250 °C	200 °C

Remark: Refer to [14, 17, 19]

Where;
σ_t is hoop stress, N/mm^2

2.4 Calculation of the final winding temperature according to IEC standard

The highest average temperature θ_1 of the winding after short circuit can be calculated by Eq. (17)
For copper

$$\theta_1=\theta_0+\frac{2(\theta_0+235)}{\frac{106000}{J^2t}-1} \qquad (17)$$

Where;
θ_0 is the initial temperature, °C
J is the short circuit current density, A/mm^2
t is the duration, seconds.

3. Transformer testing procedures and tested results

3.1 Test procedures and results

For better test results and accuracy, during the transformer temperature test, following procedures are carefully prepared and implemented [18, 20-21]:

1. The tested transformer is sealed type oil-immersed distribution transformer of 400 kVA 3ph 50Hz 22000-400/230V Dyn 11.
2. Figs. 1 and 2 show the tested circuit of transformer open circuit and short circuit test respectively. Then, Fig. 3 shows the installation of type K thermocouples at the different points of transformer windings.
3. In test procedures, the increasing voltage supply at high side until the total loss (no load + load loss) was constant at 610 + 3949.3 = 4559.3 Watt, from open circuit and short circuit test.

It can be seen from Fig. 4 and Fig. 5 that both temperature on low voltage winding and high voltage winding tend to be constant after 12 hours of loading. Moreover, result clearly revealed that the winding temperature obtained from type K-thermocouple at the top positions give the higher temperature than the bottom or lower coil positions.

However, when compare the temperature of the top winding position (point 11 from Fig. 4 or point 10 from Fig. 5) and the top oil position (point 16 form Fig. 6), it can be found that top winding temperature is higher than top oil temperature for all 12 hours of testing. Therefore, in reality, power engineers usually use top oil temperature to represent and estimate the transformer winding temperature while loading conditions.

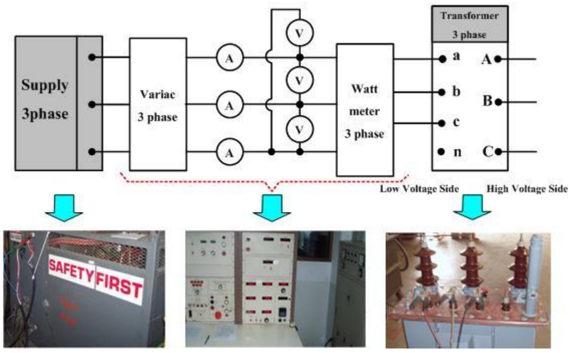

Figure.1 Open circuit test

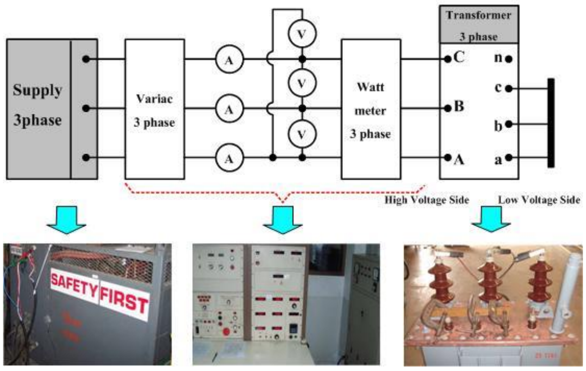

Figure.2 Short circuit test

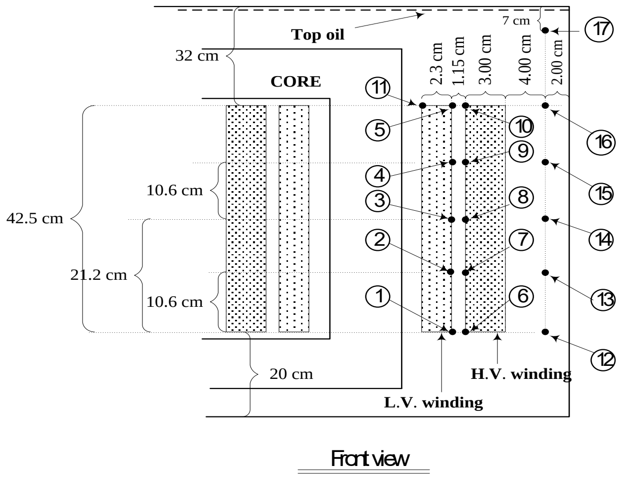

Figure.3 Thermocouple installation at different points of an oil-immersed distribution transformer [15, 18, 22]

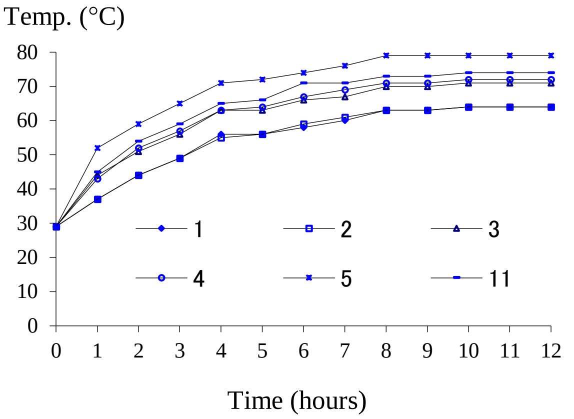

Figure.4 Low voltage temperature results at points 1,2,3,4,5 and 11

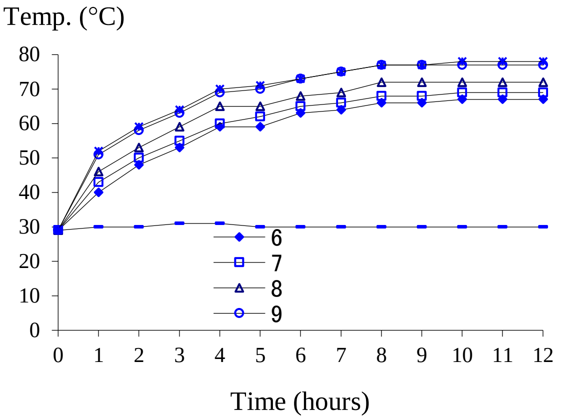

Figure.5 High voltage temperature results at points 6,7,8,9,10 and ambient temperature while testing

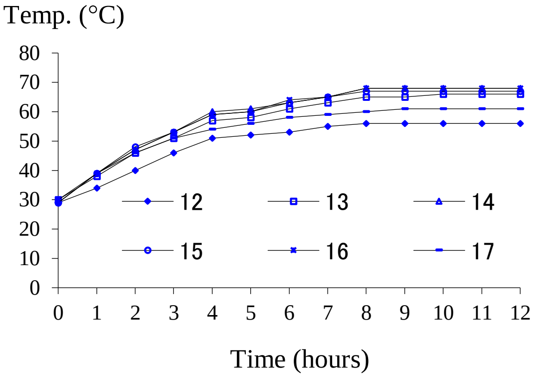

Figure.6 Oil temperature results at points 12-17

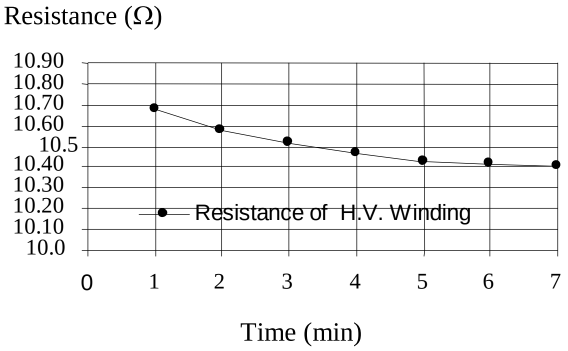

Figure.7 Result of HV-resistance after switch off load

Moreover, Fig. 7 and Fig. 8 show the winding resistance profiles in both high voltage coil (HV) and low voltage coil (LV) after disconnect load from transformer. The benefit of these two resistances profile will use for calculate the hottest spot of winding temperature.

3.2 Analysis result

From the test results, important variables and parameter are evaluated and calculated:

1. Θ_{wr} ([15, 18] give not more than 65 °C)
2. Top oil temp.(Θ_o)=73 °C (from [18] specific ≤105 °C)
3. Θ_{or} = 42 °C (from [15, 18] specific ≤ 60 °C)

The calculation of top oil temperature rise (point 17 of Fig. 3) can be found in Fig. 9 and it can be seen that this temperature is still meet the standard specified in [15].

3.3 Comparison between conductor hottest spot temperature from testing and calculation

The comparison between the hottest spot temperature of transformer winding both in low voltage side (LV) and high voltage side (HV) are shown in Figs. 10-11. It can be clearly seen that the hottest temperature obtained from the calculations are pretty closed to the one from the test procedures. Therefore, this finding is an advantage guideline for distribution transformer designer because the designer can use this technique and algorithm to estimate the hottest spot temperature instead of perform the real transformer test in the laboratory.

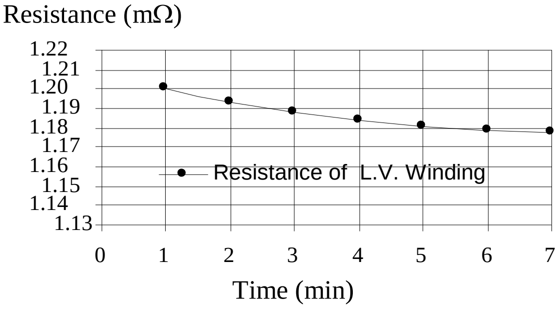

Figure.8 Result of LV-resistance after switch off load

Table 2. Technical data of tested transformer

Capacity(kVA)	400
High voltage(V)	22000
Low voltage(V)	400/230
No. of phase	3
Frequency(Hz)	50
Vector group	Dyn 11
Impedance(%)	4.0
Insulation Class	A
Cooling type	ONAN

Table 3. Calculation results of average winding temperature rise

Parameter	LV.winding	HV.winding
Θ_{w1} (°C)	31.00	31.00
R_{t1} (Ω)	0.00103	9.13
Θ_{w2} (°C)	78.80	76.70
R_{t2} (Ω)	0.00122	10.82
Θ_{wr} (°C)	47.80	45.70

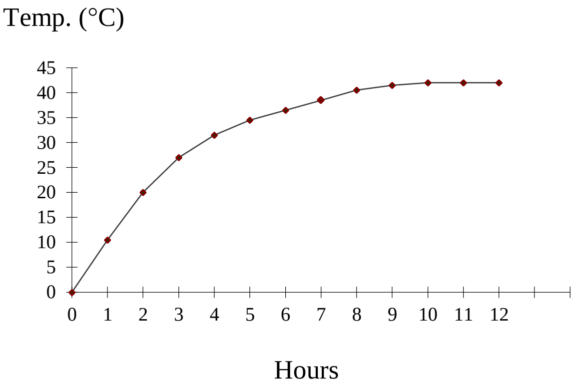

Figure.9 Top oil temp rise calculation (point 17 of Fig. 3) at rated load

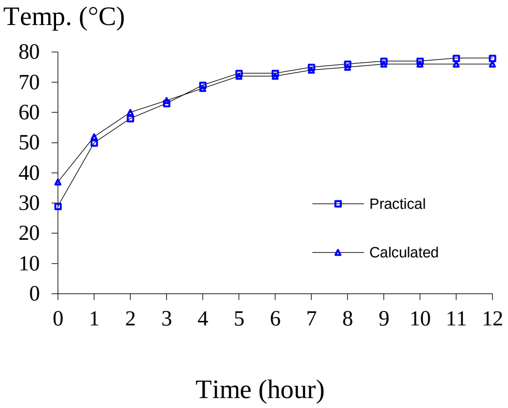

Figure.10 LV-conductor hottest spot temperature (Θ_h) comparison between testing and calculating at full load

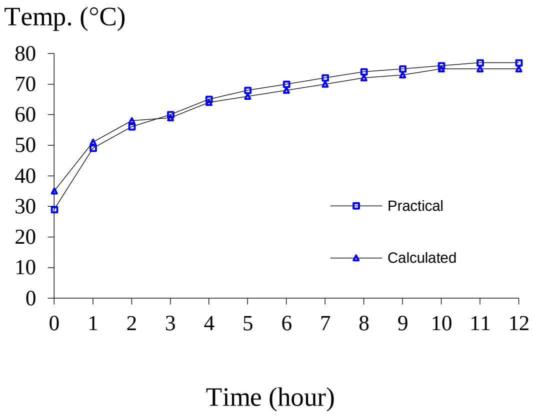

Figure.11 HV-conductor hottest spot temperature (Θ_h) comparison between testing and calculating at full load

Remark:

1. In Figs. 10 and 11, the assumption for ambient temperature is 30 °C when calculated hottest spot temperature of conductor (Θ_h).
2. From [16, 18], (Θ_h) ≤ 140 °C and (Θ_{hr}) ≤ 80 °C

3.4 Comparison of short circuit withstand parameter between traditional design and the newly proposed design

In this comparison, the traditional transformer design parameters [12] will be compared to the newly proposed design procedures of distribution transformer which already considering about improving short circuit capability. The newly proposed procedures in Fig. 12 will provide the new set of optimum designed parameters. One can find the numerical comparing result in Tables 4-8.

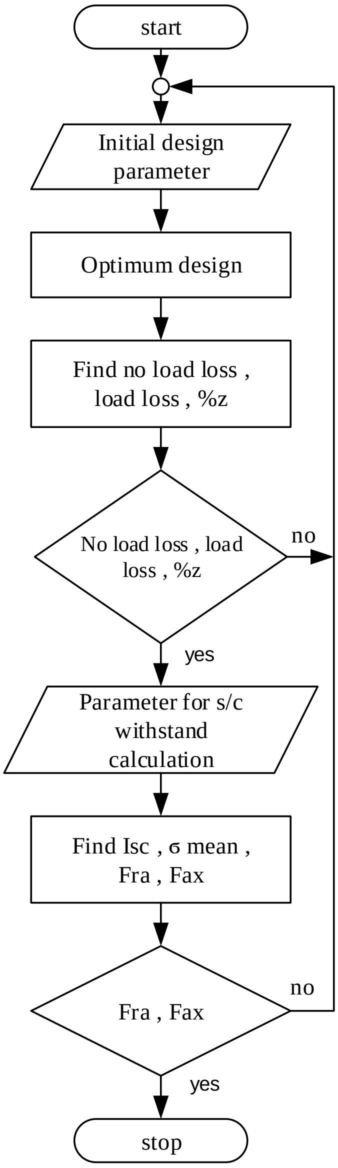

Figure.12 New proposed design algorithm and procedures considering short circuit withstand capability

The top oil temperature rise comparison between original regulation and new regulation of 400 kVA transformers at rated load are presented in Fig. 13.

It is clear that the new proposed design parameter will offer the lower temperature raised compare to the original design regulation.

Although the newly proposed designed algorithm for distribution transformer will offer the benefit in improving the short circuit current capability which will offer more system security. On the other hand, for the distribution utility side and consumer side, transformer losses and transformer lifetime are still the important concerns. Therefore,

Table 4. Comparison of transformer design parameter between original design regulation and the new regulation

Parameter	**400 kVA**	
	Original regulation	**New regulation**
1. No Load Loss, W		
-Guarantee	720	720
-Test	700.5	610.0
2. Load Loss, W		
- Guarantee	4150	4150
- Test	4040.3	3949.3
3. Total loss , W	4740.3	4559.3
4. Hottest-spot of top oil, °C	81.0	73.0
5. Hottest-spot of HV.wdg., °C	88.3	76.7
6. Hottest-spot of LV.wdg., °C	89.8	78.8
7. Top oil Temp. rise, °C		
- Guarantee	60	60
- Test	51.0	42.0
8. Winding Temp. rise, °C		
- Guarantee	65	65
- HV. Winding	60.3	45.7
- LV. Winding	61.8	47.8

Table 5. Parameter required for calculation at short circuit withstand test (HV side)

Parameter	**High voltage side**	
	Original	**New**
Reactance , %	3.77	4.18
Resistance, %	1.11	1.10
Per unit impedance	0.00393	0.00432
Resistance per phase at 75 °C , Ohm/phase	11.82	11.05
Winding height (mm) : Hw	425	365
Number of turn per limb : N	2700	2600
Current density of winding (A/mm^2) : J	2.38	2.52
Mean diameter of winding (mm) : Dm	285	162
Radial of winding 1 : a1	-	-
Radial of winding 2 : a2	31	30
Width of main duct (mm) : d	12	11.5

Table 6. Parameter required for calculation at short circuit withstand test (LV side)

Parameter	**Low voltage side**	
	Original	**New**
Reactance, %	3.77	4.18
Resistance, %	1.11	1.10
Per unit impedance	0.00393	0.00432
Resistance per phase at 75 °C, Ohm/phase	0.00146	0.00125
Winding height (mm) : Hw	465	385
Number of turn per limb : N	27	26
Current density of winding (A/mm^2) : J	2.61	2.48
Mean diameter of winding (mm) : Dm	207	212
Radial of winding 1 : a1	22	23
Radial of winding 2 : a2	-	-
Width of main duct (mm) : d	12	11.5

Table 7. Forces and final temperature calculation results at short circuit withstand test (HV side)

Parameter	**HV side**	
	Original	**New**
Asymmetrical short circuit current (A)	304.57	285.20
σ_t	34.53	34.40
Radial force	1491.49	1351.47
Axial force	99.45	98.80
Final winding temp. (°C)	155.55	151.65

Table 8. Forces and final temperature calculation results at short circuit withstand test (LV side)

Parameter	**LV side**	
	Original	**New**
Asymmetrical short circuit current (A)	29015.09	27169.38
σ_t	23.77	22.32
Radial force	892.06	848.97
Axial force	62.69	59.26
Final winding temp. (°C)	166.73	150.09

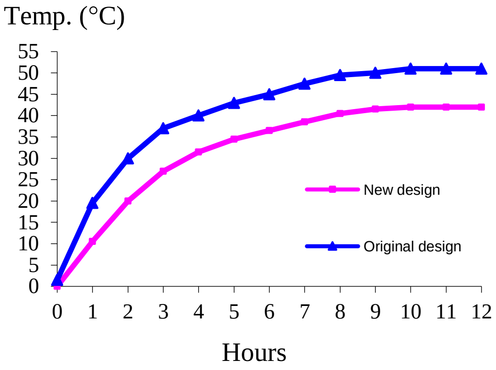

Figure.13 Top oil temperature rise comparison between original and new regulation 400 kVA at rated load

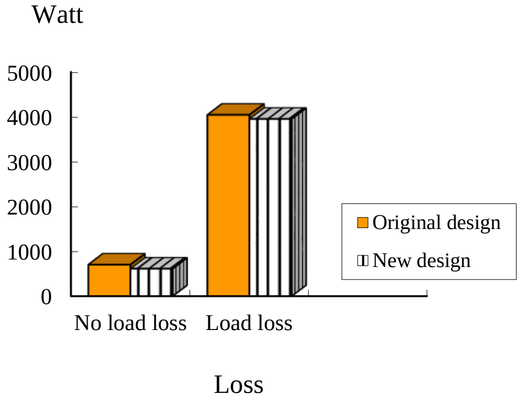

Figure.14 Loss comparison between original design compared to the newly proposed design/regulation

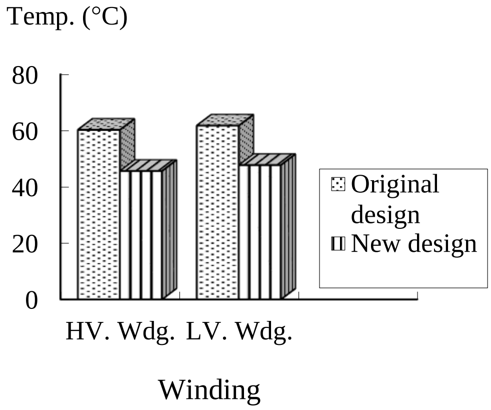

Figure.15 Winding temperature rise comparison between original and new regulation designs

Fig. 14 shows the loss comparison between original design and new proposed design. It is clear that the newly proposed design will offer lower losses which results in a better economics value, while Fig. 15 shows that the newly proposed design techniques will offer lower winding temperature rise which means a longer transformer lifetime.

4. Conclusion

From the test and analysis result, it is clear that information of temperatures obtained from the tested transformer during loading and short circuit will benefit for a newly proposed design algorithm to obtain more safety and economically of distribution transformer. In addition, result from Fig. 10 and 11, clearly show that it is only small difference between the measuring result and calculating result, therefore, this similarity trend can be used as a guideline for the distribution transformer design.

In conclusion, with the main finding and newly proposed design algorithm of this research, it can lower winding temperature of distribution transformer while loading or experiencing with short circuit conditions which mean it can prolong transformer insulation and extend transformer lifecycle time. Therefore, it not only provides more safety transformer to reinforce power system security but also provides a lower losses transformer result in economics benefit for both utilities and end users in distribution system.

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