Thermal Modelling of Power Transformers

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***Abstract* - Power transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network. One of the most important parameters governing a transformer's life expectancy is the hot-spot temperature value. The classical approach has been to consider the hot-spot temperature as the sum of the ambient temperature, the top-oil temperature rise in tank, and the hot-spot-to-top-oil (in tank) temperature gradient. When fibre optic probes were taken into use, winding hottest spot temperatures higher than those predicted by the loading guides during transient states after the load current increases, before the corresponding steady states have been reached. This paper presents new and more accurate temperature calculation method taking into account for findings hot spot temperature using IEEE standard using computer programming.**

***Index Terms* - power transformers, hot-spot temperature, top-oil temperature, bottom-oil temperature, non-linear thermal resistance, oil time constants.**

I. Introduction

A power transformer is a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at same frequency for the purpose of transmitting electrical power [1].

Power transformers are one of the most expensive components in an electricity system. Knowing their condition is essential to meet the goals of maximizing return on investment and lowering the total cost associated with transformer operation. The transformer winding hot-spot temperature is one of the most critical parameters when defining the power transformer thermal conditions and overloading capability beyond the nameplate rating. Therefore, in order to increase transformer operational efficiency and minimize the probability of an unexpected outage, several on-line and off-line monitoring systems have been developed [2], [3], [4], [5], [6]. Direct measurement of actual transformer winding temperatures using fibre optic probes has been increasing since the mid-1980s, [7], [8], [9], [10], [11] .But it is find that winding hottest spot temperatures higher than those predicted by the loading guides during transient states after the load current increases, before the corresponding steady states have been reached.

The paper represents winding temperature hot spot temperature using IEEE and IEC loading guides. The aim of this paper is to develop software which displays the loading of the transformer. The loading is calculated in a manner that incorporates the change in the season, load variations, cooling methods, etc.

II. IEEE Approach

A revision of the loading guide for power transformers is currently in progress. It is noted that the traditional hot-spot temperature calculation method uses a number of assumptions that are not correct:

- Oil temperature in the cooling duct is assumed to be the same as the top oil temperature
- The change in winding resistance with temperature is neglected
- The change in oil viscosity with temperature is neglected
- The effect of tap position is neglected
- The variation of ambient temperature is assumed to have an immediate effect on oil temperature.

Moreover, experimental work has shown that at the onset of a sudden overload, oil inertia induces a rapid rise of oil temperature in the winding cooling ducts that is not reflected by the top oil temperature in the tank. Therefore alternate sets of equations are being developed, taking into account all these factors.

An additional important evolution is the disappearance of the guide on definition of transformer "Thermal Duplicate" that was often used to provide default values for winding temperature rise at rated load. This reference will not be available anymore to provide support to the hot-spot temperature rise estimated by the manufacturer. This might reduce the credibility of transformer manufacturer in providing that critical thermal parameter.

ANSI/IEEE C57.91[12] is based on average characteristics of a wide range of transformer ratings and designs. The guide uses the top-oil rise and the hottest-spot conductor rise over top-oil to calculate the hottest-spot temp. and is defined by:

$$T_{HS}= T_A+ \Delta T_{TO}+\Delta T_H$$

Where

T_{HS}=winding hottest- spot temp,◦C

T_A is Average ambient temp during the load cycle, ◦C

ΔT_{TO} is the top-oil rise over the ambient temperature, and

ΔT_G is the winding hottest-spot temperature rise over top-oil temperature.

Figure 1 shows corresponding thermal diagram. The assumptions are:
• The oil temperature inside the windings increases linearly from bottom to top of the winding regardless of the cooling type,
• The temperature rise of conductor at any position up the winding increases linearly and parallel to the oil temperature rise,
• The hottest-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding, because of the increase in stray losses. To find hottest-spot temperature, the hottest-spot allowance (ΔTG) is added to the top oil temperature.

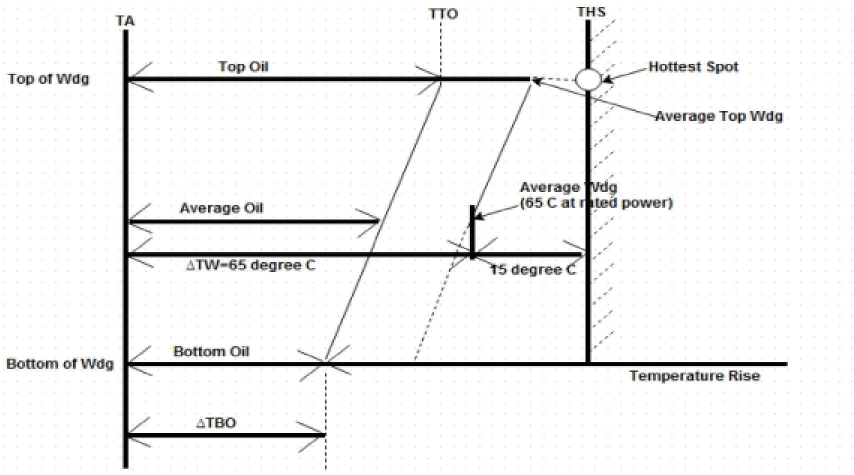

Figure: 1 Transformer's temperature profile for IEEE classical thermal model

The top-oil temperature rise under steady-state condition is proportional to the total transformer loss and given by:

Top oil rise over ambient

$\Delta T_{TO} = (\Delta T_{TO,U} - \Delta T_{TO,i})(1-\exp(-t/\tau_{TO}))$

$\Delta T_{TO,i} = \Delta T_{TO,R}[(K_i^2 R+1)/(R+1)]^n$

$\Delta T_{TO,U} = \Delta T_{TO,R}[(K_U^2 R+1)/(R+1)]^n$

Where

$\Delta T_{TO,i}$ = initial top oil rise over ambient temp for t=0, ◦C

$\Delta T_{TO,U}$ = ultimate top oil rise over ambient temp for load L, ◦C

R = ratio of load loss at rated load to no-load loss on the tap position to be studied

Oil time constant

For OA and FA cooling modes

C=0.06(weight of core and coil assembly in pounds) +0.04(weight of tank and fitting in pounds) +1.33(gallons of oil)

For forced-oil cooling modes

C=0.06(weight of core and coil assembly in pounds) +0.06(weight of tank and fitting in pounds) +1.93(gallons of oil)

The top oil time constant at rated KVA

$\tau_{TO,R} = C^* \Delta T_{TO,R}/P_{T,R}$

The top oil time constant

$\tau_{TO} = \tau_{TO,R} [(\Delta T_{TO,U}/\Delta T_{TO,R})-(\Delta T_{TO,i}/\Delta T_{TO,R})]/[(\Delta T\Theta_{TO,U}/\Delta T_{TO,R})^{1/n}-(\Delta T\Theta_{TO,i}/\Delta T_{TO,R})^{1/n}]$

$\Delta T_{TO} = kq^n$

Where, n=1.

Winding hot spot rise

Transient winding hottest spot temp rise over top-oil temp

$\Delta T_H = (\Delta T_{H,U} - \Delta T_{H,i})*(1-\exp(-t/\tau_W)) + \Delta T_{H,i}$

The initial hot spot rise over top oil

$\Delta T_{H,I} = \Delta T_{H,R} K_i^{2m}$

The ultimate hot-spot rise over top oil

$\Delta T_{H,U} = \Delta_{TH,R} K_u^{2m}$

The rated value of hot-spot rise over oil

III. $\Delta T_{H,R} = \Delta T_{H/A,R} - \Delta T_{TO,R}$

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Table:1 Exponent for temp rise equation

Types of cooling	m	n
OA	0.8	0.8
FA	0.8	0.9
Non-directed FOA or FOW	0.8	0.9
Directed FOA or FOW	1.0	1.0

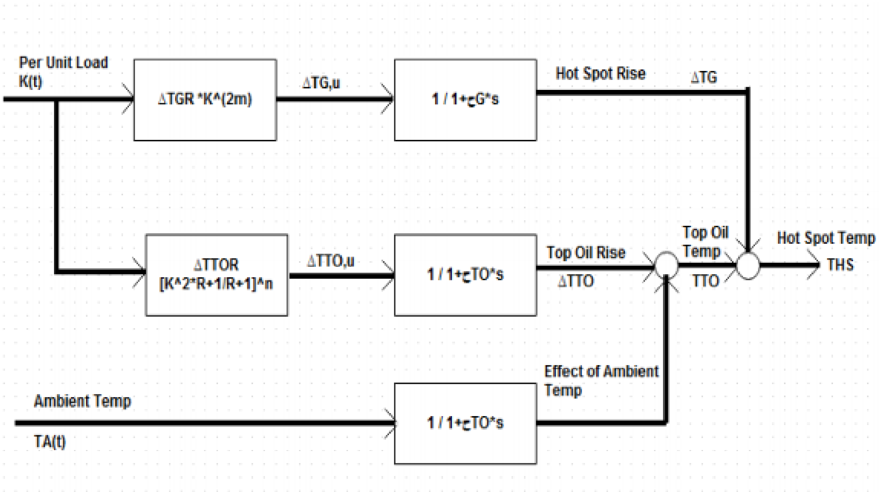


Figure:2 Block diagram of the modified transient heating equations

For Normal Life expectancy loading using the IEEE C57.91[12] standard

- This results when the transformer is operated continuously at a hottest spot conductor temperature of 110 deg C
- The standard allows a maximum temperature of 120 deg C only if the transformer has operated below 110 deg C for longer periods of time

For Planned Loading beyond Nameplate Rating using the IEEE C57.91[12] standard

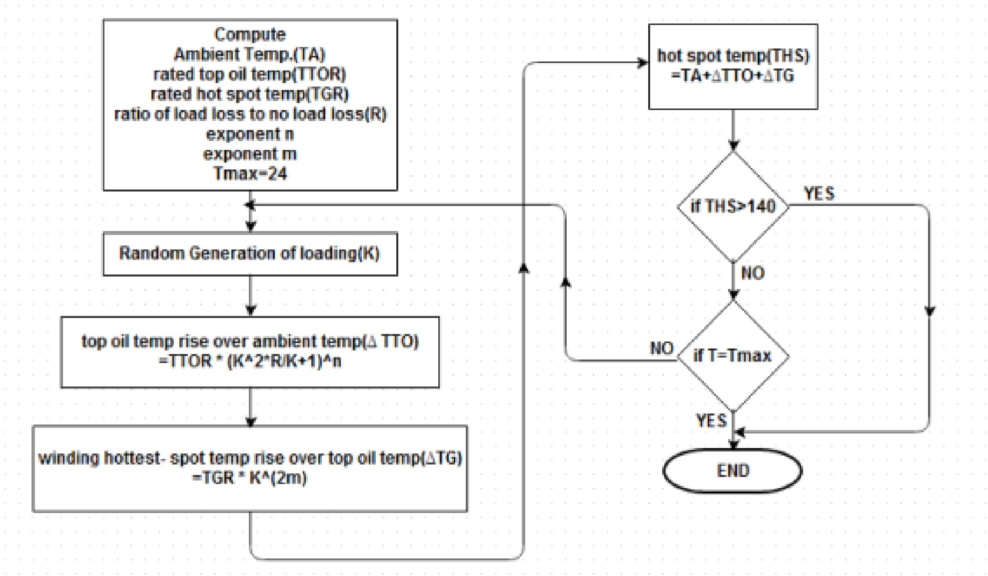
- Transformers that do not work at a continuous temperature of 110 deg C, can be loaded to a maximum temperature of 120-130 deg
- Loss of insulation life should be considered on the length of time at this temperature

For Long Term Emergency Loading using the IEEE C57.91[12] standard

- During contingency conditions, transformers hottest spot conductor temperature can reach 120-140 deg C
- Time will depend on loss of life
- It is ex0pected that such occurrences happen only 2-3 times during the life of the transformer

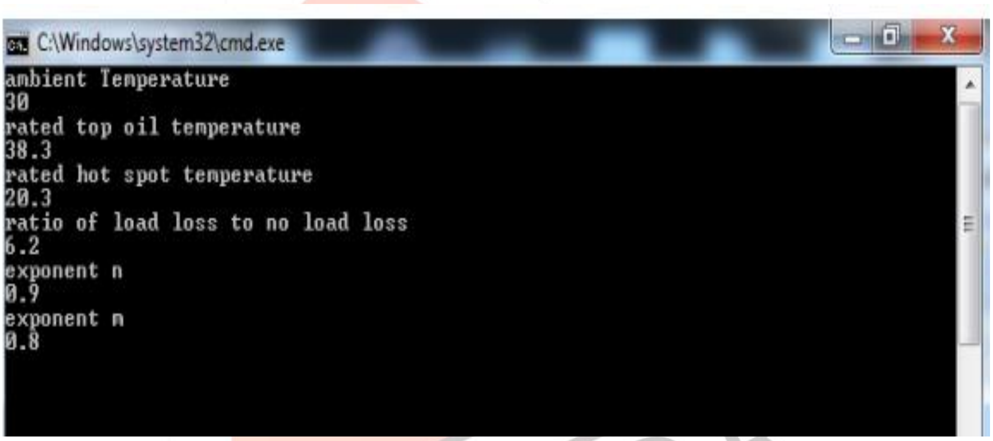
All these changes in IEEE and IEC loading guides indicate that hot-spot temperature calculation methods previous known were not adequate to assess accurately winding hot-spot temperature. Wide use of computers now allows for sophisticated calculation methods but it demonstrates that the quest of winding hot-spot temperature is not trivial and it raises new doubts considering the number of additional values that need to be collected to run the calculation. No wonder that the direct measurement of winding temperature with fiber optic sensors is the recommended practice for critical transformers.

IV. Flow Chart of Thermal Model



V. SIMULATION (USING VB.NET)

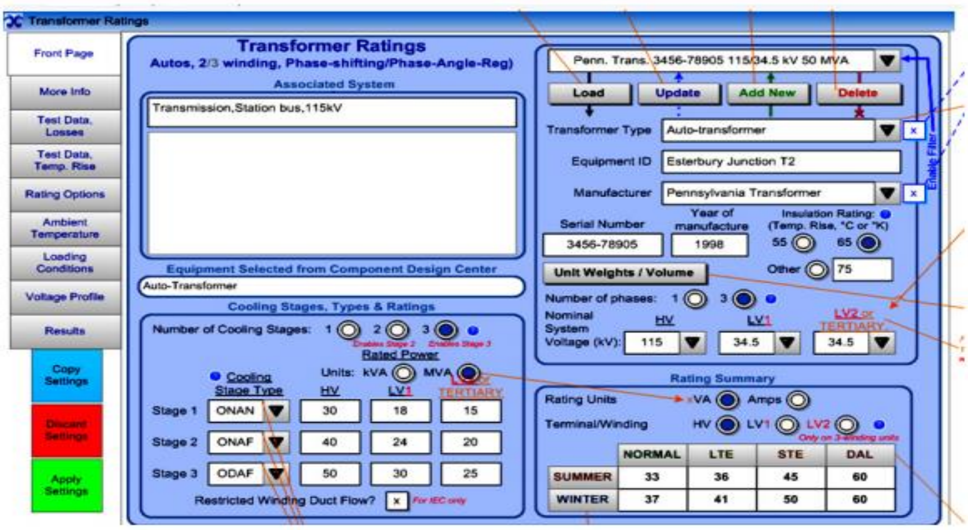
Input



Simulation Result

mHour	K	top oil rise over ambient	winding hottest- spot temp rise over top oil	hot spot temp
1	1.1	44.48	23.64	98.12
2	1.1	44.48	23.64	98.12
3	1.1	44.48	23.64	98.12
4	1.2	51.14	27.18	108.32
5	1.2	51.14	27.18	108.32
6	1	38.3	20.3	88.6
7	0.9	32.61	17.15	79.76
8	1	38.3	20.3	88.6
9	1.2	51.14	27.18	108.32
10	0.9	32.61	17.15	79.76
11	0.9	32.61	17.15	79.76
12	1	38.3	20.3	88.6
13	0.9	32.61	17.15	79.76
14	1	38.3	20.3	88.6
15	1.1	44.48	23.64	98.12
16	1.1	44.48	23.64	98.12
17	1.2	51.14	27.18	108.32
18	1	38.3	20.3	88.6
19	0.9	32.61	17.15	79.76
20	0.9	32.61	17.15	79.76
21	1	38.3	20.3	88.6
22	1	38.3	20.3	88.6
23	1.2	51.14	27.18	108.32
24	1.1	44.48	23.64	98.12

VI. Screen Shots of Transformer Thermal Model



VII. Conclusion

The hot spot temperature measurement using IEEE standards has complex calculation and requires lot of time. So as an integral part of this research, an interactive computer program has been developed to find hot spot temperature of transformer.

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