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Impact of unbalanced harmonic loads towards winding temperature rise using FEM modeling

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Article Info	ABSTRACT
	This paper investigates the hot spot temperature of transformer thermal model due to unbalanced harmonic loads from the network. The finite element method has been used to solve the coupling multiphysic for heat transfer in solid and fluid. All material properties in the model were been took into consideration such as copper as the coil material, iron as the core material and transformer oil as the coolant material for the transformer. The transient study on the model has been set for 1minutes using 30 degree celcius as the ambient temperature reference. The simulation hot spot temperature result has been compared for rated load (without harmonic) versus the unbalanced load (with harmonic) which shown in 2D regime. It can be clearly seen the significant increment of the hotspot temperature of the transformer from the rated load to the unbalanced harmonic load. The result has successfully shows the detection of the prospect failure of the transformer due to the harmonic current load in a form of winding loss that contributes to the hotspot temperature of the transformer.

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1. INTRODUCTION

As stated in international IEEE standard, harmonics are defined as currents or voltage with frequencies that are integer multiples of fundamental power frequency. The distortion in current and voltage wave shape which was created by the drawn current nonlinear loads in high amplitude short pulses, measured in term of total harmonics distortion (THD) [1]. The generated harmonics causes additional heating in transformer components by then induce the higher losses and degradation to transformer insulation which decreases the useful life of transformer and premature failure of transformer. The additional heating is one the root cause of eddy current induction and increasing in eddy current losses causes rise in temperature of transformer which results in premature failure of transformer. Other than that, harmonics it is also said as a causes in derating transformers capacity and may need to be derated to as much as 50% capacity when feeding loads with highly distorted current waveform [2] and [3].

In sequence from the risen eddy current losses, the transformer winding insulation deterioration is strongly affected which the insulation material will be deterioted and thus reduce the effective service life of transformer [4] and [5]. Thus, it is crucial to study the hot-spot localization in transformer in order to prevent massive loss either in aspect of cost or system production. However, it is a challenge to predict the hottest spot in the transformer. In recent research publications, a lot of methods have been applied to calculate the maximum temperature rise in transformers [6], [7], and [8]. In recent years the use of embedded temperature sensors which directly measure the maximum temperature in windings insulation has been in trend. As the evolving of optical fiber technology, fiber temperature sensors then have been developed and implemented in measuring

temperature in transformers [9], [10], [11], [12], and [13]. Although able to measure accurately the winding temperatures on-line, this approach is not practical to apply to existing in-service transformers. Other than that, the sensors has high possibility for it to have technical problem or broken and hence cannot give a clear indication of the transformer condition. There are many real site cases where the transformer is tripped due to the sensors failed to give an early warning sign of the transformer malfunction condition. Furthermore, it is difficult to justify the additional costs, particularly in applications on low-cost medium-voltage distribution transformers.

Another method to determine the temperature in transformer winding is detailed in the IEC 60076-2 Standard [14]. In order to provide a convenient method to determine the temperatures, several assumptions have been made. The calculation is achieved by determining the top-oil, bottom-oil and the average winding temperatures. The top-oil and bottom-oil temperature can be determined by immersing temperature sensors in the insulating liquid [15]. The average winding temperature is determined by measuring the total windings resistance (after disconnecting the transformer). This method is simple, quick and it is independent from the structure of transformers; hence, it could be applied for a wide range of transformer ratings. However, it is not practical for on-line monitoring implementation. Also, the additional temperature rise due to harmonic contamination was not taken into account. In the situation of harmonic, IEEE recommendation [16] suggested a correction. In this standard, the temperature rise in transformers under current harmonic condition was achieved by determining transformer losses followed by harmonic loss factors. In both standards, the hottest-spot temperature was calculated but the location of the hottest-spot was not revealed. Another approach to investigate the thermal stress on winding insulation in transformers is to utilize computer-based simulation software. The Finite Element Method (FEM) is an effective computational technique that has been developed to solve a wide range of engineering problems (structural, thermal, electromagnetic, etc). FEM has been utilised in investigation of temperature rise in transformers [17], [18], [19], [20], and [21]. In relevancy to its advantages, there were numerous papers that has published many physical models of electrical equipment such as the transformer. The FEM has been applied to the transformer model in order to prove its ability to solve any engineering problems with the most acccurate results [22], [23], [24] and [25]. In these papers, the structure of transformer was simplified in the simulation to reduce its complexity and the theory of conduction heat transfer in solid (i.e. winding conductor, core and insulation) was applied to solve the thermal problem.

2.   RESEARCH METHOD

In this study, the method has been divided into modeling of the transformer cross section and also data collection from the actual site which to be applied on the modeling. The FEM COMSOL software is used for the modeling purpose to simulate the thermal model under finite element environment.

2.1 The thermal model for the transformer

The figure below is illustrated the cross section of the oil type distribution transformer for three phase 2000 kVA rating size. By assumption that the design of the three phase transformer were physically similar, the transformer model in study has been potrayed in a single phase manner. Hence, it can solve the time constraint in the geometry assembly to get the result.
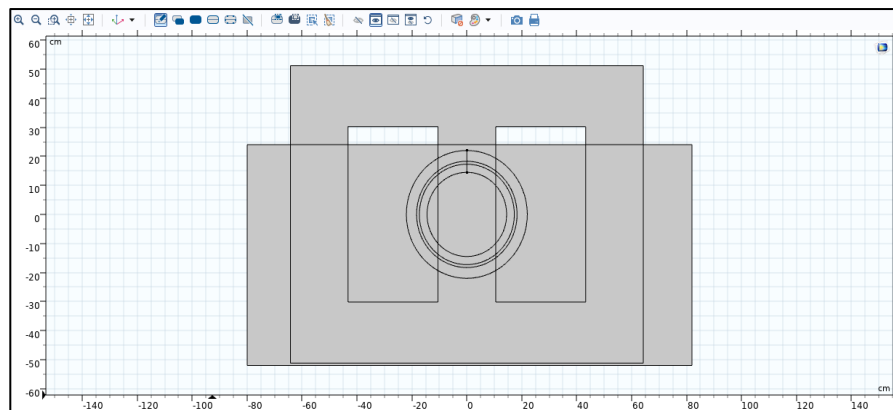

Figure 1. 2D cross section geometry of transformer thermal model

The cross section of 2D transformer geometry as in above figure had been modeled using Finite Element Method software which is known as COMSOL. The heat transfer of solid and liquid multiphysics interface was by then been applied on the transformer model. This coupling mutiphysics was dedicated to study the temperature rise of the transformer due to the losses which then contributed to the hotspot temperature of the transformer. The results were achieved by solving the governing equation for heat transfer in solid and liquid as shown below in the equation (1) and (2) respectively below [5, 16]:

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u.\nabla T + \nabla.q = d_z Q + q_0 \dots \qquad (1)$$

$$q = -d_z k \nabla T \dots \qquad (2)$$

Where dz is the thickness of the geometry, T is the temperature, ρ is the density, Cp is the specific heat capacity at constant pressure, k is the thermal conductivity, Q is the losses which act as a heat source in this study, q_0 is the convection heat flux and u is the velocity of the liquid.

2.2 The material properties of the transformer model

As for this study, there were three set of material types that had been applied on the transformer model which including copper for the transformer winding domain, iron for the transformer core domain and transformer oil for the coolant medium. Each of the material types has their own material properties as depicted in the Table 1-3.

Table 1. Material properties for copper

	Property	Variable	Value	Unit	Property group
☑	Heat capacity at constant pressure	Cp	385[J/(kg*K)]	J/(kg·K)	Basic
☑	Density	rho	8940[kg/m^3]	kg/m³	Basic
☑	Thermal conductivity	k_iso ; kii...	400[W/(m*K)]	W/(m·K)	Basic
	Relative permeability	mur_iso ;...	1	1	Basic
	Electrical conductivity	sigma_iso...	5.998e7[S/m]	S/m	Basic
	Relative permittivity	epsilonr_i...	1	1	Basic
	Surface emissivity	epsilon_rad	0.5	1	Basic
	Dynamic viscosity	mu	10	Pa·s	Basic
	Young's modulus	E	126e9[Pa]	Pa	Young's modulus and Poisson's ratio
	Poisson's ratio	nu	0.34	1	Young's modulus and Poisson's ratio
	Reference resistivity	rho0	1.667e-8[oh...	Ω·m	Linearized resistivity
	Resistivity temperature coefficient	alpha	3.862e-3[1/K]	1/K	Linearized resistivity

Table 2. Material properties for iron

	Property	Variable	Value	Unit	Property group
☑	Heat capacity at constant pressure	Cp	440[J/(kg*K)]	J/(kg·K)	Basic
☑	Density	rho	7870[kg/m^3]	kg/m³	Basic
☑	Thermal conductivity	k_iso ; kii =...	76.2[W/(m*K)]	W/(m·K)	Basic
	Relative permeability	mur_iso ; m...	4000	1	Basic
	Electrical conductivity	sigma_iso ;...	1.12e7[S/m]	S/m	Basic
	Coefficient of thermal expansion	alpha_iso ;...	12.2e-6[1/K]	1/K	Basic
	Relative permittivity	epsilonr_iso...	1	1	Basic
	Dynamic viscosity	mu	10	Pa·s	Basic
	Young's modulus	E	200e9[Pa]	Pa	Young's modulus and Poisson's ratio
	Poisson's ratio	nu	0.29	1	Young's modulus and Poisson's ratio

Table 3. Material properties for transformer oil

	Property	Variable	Value	Unit	Property group
☑	Heat capacity at constant pressure	Cp	Cp(T)	J/(kg·K)	Basic
☑	Density	rho	rho(T)	kg/m³	Basic
☑	Thermal conductivity	k_iso ; kii =...	k(T)	W/(m·K)	Basic
☑	Ratio of specific heats	gamma	0.5	1	Basic
	Dynamic viscosity	mu	eta(T)	Pa·s	Basic

2.3 Transformer thermal model hotspot external parameters

In this paper, the analogy of the simulation result was divided into two conditions which were simulation with the rated load for the transformer and another one was simulation with unbalanced load with harmonic current content. The total power losses from both condition were treated as the heat source in the governing equation in (1) and the simulation result of hotspot temperature from both condition was then being compared and analysed. The rated load and the unbalanced harmonic data were taken from the field measurement using power quality analyzer as depicted in the Table 4 below. Noted that the harmonic current content data that had been used for this paper were taken from the odd harmonic order started from 3rd until 15th which has been assembled for 24 hours period on normal working day hours.

Table 4. Parameter of the transformer

Trasformer rating	2000 kVA 3∅ 22kV/433V
Rated current	Primary: 52.49 A
	Secondary: 2666.74 A
Reference temperature	Ambient: 30°C
	Top oil rise: 55°C
	Average winding rise: 55°C
	Hottest-spot rise: 65°C

2.4 The hotspot temperature evaluation point

As in this paper, the hotspot temperature has been investigated on selected point of the cross section of the transformer model. In figure 3, the red dot which represented the coordinate point of (20,0) was selected to be evaluated for this hotspot temperature study. The significant purpose of this point selection is to see the transition of the temperature of the winding which has been immersed in the oil liquid that act as the coolant for the winding.
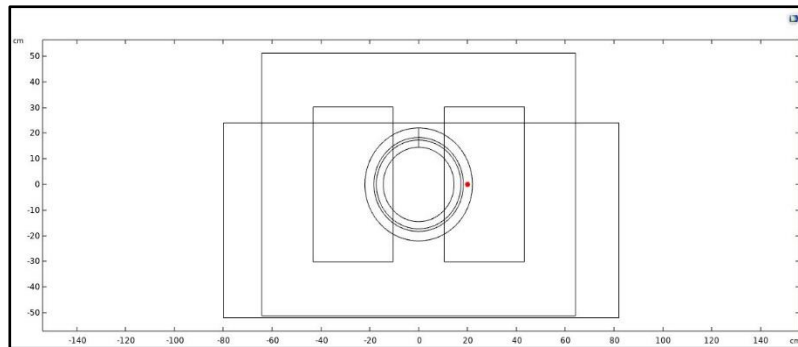

Figure 2: Hotspot evaluation point

2.5 Determination of hotspot temperature in IEEE standard

According to the C57.110-2008 IEEE standard [16], the sequential steps to calculate the hotspot temperature for oil-type transformer can be obtained by taking the consideration of the harmonic load factor. Most of manufacturing industry players were using this standard guideline in order to design their electrical equipment such as the transformer. Below are the summarized steps to determine the hotspot temperature on the winding of the transformer.

First of all, the transformer losses are generally the summation of no load losses and load losses as shown in the equation (3) below:

$$P_T = P_{NL} + P_{LL} ....$$ (3)

Where,

P_T = total loss in watt (W)
P_{NL} = no load loss in watt (W)
P_{LL} = load loss in watt (W)

The no load loss which normally provided by the manufacturer are the losses from the voltage excitation of the core. Meanwhile, the load loss can be divided into I²R loss and stray loss which caused by electromagnetic

flux in the winding and other part of the transformer. The stray loss is then can be divided into winding eddy loss, P_{EC} and stray loss, P_{OSL} in components other than the windings. The total load loss can be stated as in equation (4) below:

$$P_{LL} = P_{I^2R} + P_{EC} + P_{OSL} \dots$$ (4)

Where,

P_{LL} = load loss in watt (W)
P_{I^2R} = ohmic loss in watt (W)
P_{EC} = eddy current loss in watt (W)
P_{OSL} = other stray loss in watt (W)

Next in this section is the harmonic loss factor, FHL which is the main factor of the current harmonic impact on the winding eddy loss and other stray loss. These FHL were actually the ratio of the total losses due to the harmonics to the losses at the power frequency. The notation of the FHL for eddy current and other stray loss can be written as FHL_{ec} and FHL_{osl} respectively. Both eddy current loss and other stray loss were increased by these harmonic load factor as depicted in the equations (6) and (7). Thus, the updated transformer load losses in non-sinusoidal condition can be shown in equation (5) below:

$$P_{LL} = P_{I^2R} + FHL_{ec}P_{EC} + FHL_{osl}P_{OSL} \dots$$ (5)

$$FHL_{ec} = \frac{\sum_{h=1}^{h=max}\left[\frac{I_h}{I_1}\right]^2 h^2}{\sum_{h=1}^{h=max}\left[\frac{I_h}{I_1}\right]^2} \dots$$ (6)

$$FHL_{osl} = \frac{\sum_{h=1}^{h=max}\left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\sum_{h=1}^{h=max}\left[\frac{I_h}{I_1}\right]^2} \dots$$ (7)

Where,

h = harmonic order
FHL_{ec} = harmonic factor for eddy current loss
FHL_{osl} = harmonic factor for other stray loss

Finally, the formula to get the total hot spot temperature, (Θ_H) is by the summation of three division of the temperature which is the ambient temperature (Θ_A), winding rise temperature (Θ_g) and top oil rise temperature (Θ_{TO}) as in the following equation (8), (9) and (10):

$$\Theta_{TO} = \Theta_{TO-rated}\left(\frac{P_{LL-C} + P_{NL}}{P_{LL-rated} + P_{NL}}\right)^{0.8} \dots$$ (8)

$$\Theta_g = (\Theta_w - \Theta_{TO-rated})\left(1 + \frac{FHL_{ec}(P_{ec-rated\ pu})}{1 + P_{ec-rated\ pu}} \times P_{LL-pu}\right)^{0.8} \dots$$ (9)

$$\Theta_H = \Theta_A + \Theta_{TO} + \Theta_g \dots (10)$$

Where,

P_{LL-C} = corrected power loss in watt (W)
Θ_{TO} = oil temperature rise in degree celcius (℃)
Θ_w = winding temperature rise in degree celcius (℃)
Θ_A = ambient temperature in degree celcius (℃)
Θ_g = hottest spot conductor rise over top oil temperature in degree celcius (℃)
Θ_H = total hot spot temperature in degree celcius (℃)

3. RESULTS AND DISCUSSION

As been mentioned in the previous section, the model to illustrate the three phase transformer had been simplified to avoid complexity in calculation. In the final, the mesh of the model can be seen in the figure below. In the modeling, the mesh was selected for the finer mesh as to get the most optimum result in the simulation.
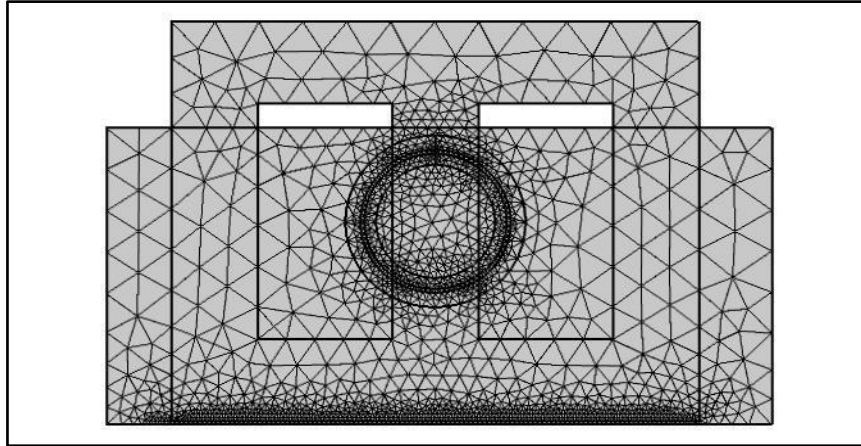

Figure 3. The discretised mesh of the transformer thermal model

3.1 Hot spot temperature under rated load (without harmonic)

In order to significantly observe the effect of harmonic content towards the hotspot temperature on the transformer winding, the thermal transformer model was initially being simulated with rated load at 50Hz frequency system. The temperature graph in figure 4 has shown the simulation result of the selected point that had mentioned earlier and the hottest spot temperature was discovered to be at 63.89°C for entire three phase of the transformer winding. Noted here that the hottest spot temperature under rated load has not exceeds the limit of the rated 65°C hottest spot rise. Hence to be said that the transformer is operated under an ideal state and its design lifetime expentancy is secured.
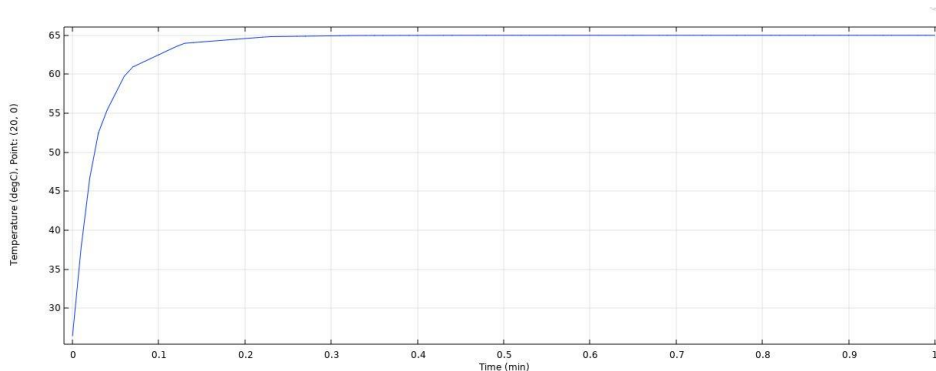

Figure 4. The hotspot temperature graph after completion of transient study with rated load.

3.2 Hot spot temperature under non-linear load (with harmonic)

The thermal transformer model were then tested with the nonlinear loads that conceived of harmonic current content along the phases. The analysis were done for unbalanced harmonic loads where each of phases had generated self power losses due to the eddy current which is the winding and other stray part of the model. Below figures 5-7 had illustrated the contribution of the harmonic current towards the total winding losses. Figure 5 had shown the hotspot temperature at Phase A of the transformer. The maximum hottest spot temperature of selected evaluation point was at 81.96°C and it has exceeded the 65°C reference hottest spot temperature.
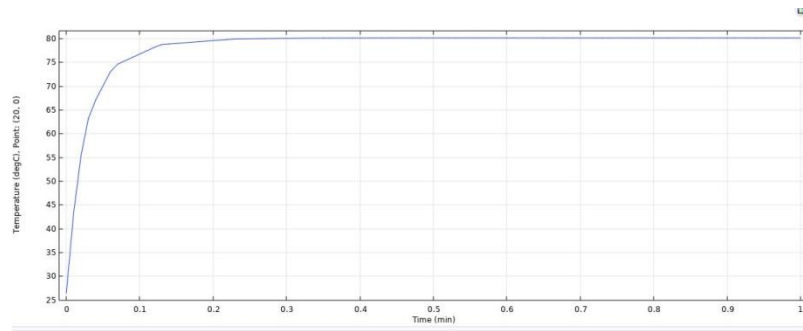
Figure 5. The temperature distribution after completion of transient study with phase A loading.

The next simulation was for the total loss at Phase B as illustrated in Figure 6. The maximum hottest spot temperature of this model had achieved was at 85.12°C which also has exceeded the 65°C reference hottest spot temperature. The hottest spot temperature in this phase was slightly higher than the phase A where about 3.16 difference in value.
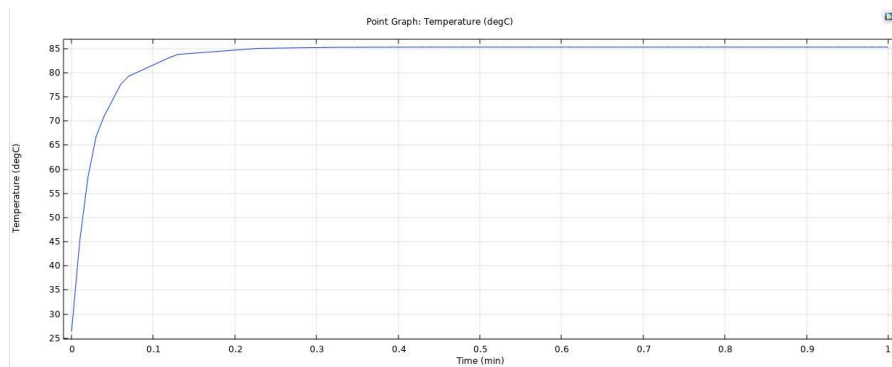

Figure 6. The temperature distribution after completion of transient study with phase B loading.

The final simulation on the thermal transformer model was for the total loss from the Phase C as in Figure 7. It has discovered the hottest spot temperature of this model was at 82.08°C which also exceeded the 65°C reference hottest spot temperature. The hottest spot value from this phase was to be at the middle when compared to the other two phases.
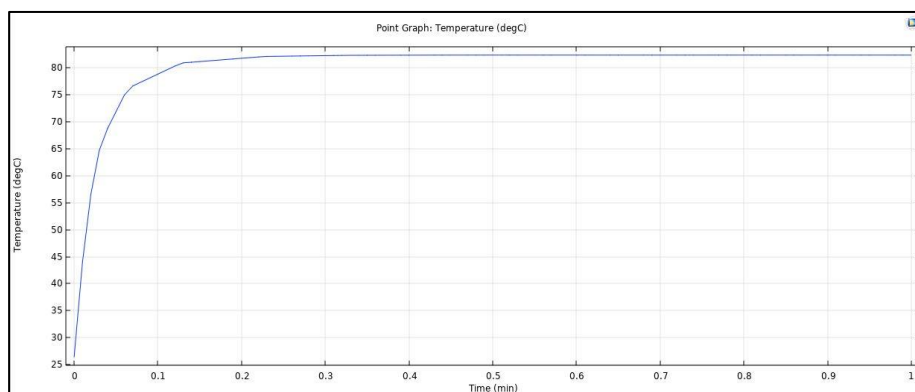

Figure 7. The temperature distribution after completion of transient study with phase C loading.

In summary, based on the simulation results from total phases, it has depicted the vivid visual of the temperature rise increment in all phases. This also means that harmonic load currents has shaken the quality of the oil transformer and also the transformer itself. The increment up to about 80°C in every phase has caused the transformer to be at the warning level. Other that than, the difference value of the temperature rise of each phases has clearly shown the significant of this study which is to analyse the thermal model under unbalanced harmonic loads condition. In any actual distribution network system, the normal loads will never be similar in

each of the phases. Hence, by only consider the balanced condition in any study or investigation for any critical system like transformer is said to be not accurate or not good enough.

3.3 Validation of hotspot temperature modeling in FEM modeling with IEEE Standard

As for this paper, the hotspot temperature results from the FEM modeling in COMSOL were validated with the International IEEE standard as depicted in the Table 5 below [2]. Based on the agreement from the standard, it clearly had shown that FEM method be able to generate precise result from its modeling and can terminate all the tedious manual calculations and lab tests in order to see the hotspot temperature from transformer. In addition, it also can solve the technical problem due to the broken sensors which is expected to give an indication of the transformer temperature condition level.

Table 5. Comparison hotspot temperature between FEM modelling and IEEE standard

Load	FEM Modeling	IEEE Standard
Rated Load	65.0°C	64.3°C
Load at Phase A	82.2°C	81.6°C
Load at Phase B	85.3°C	84.7°C
Load at Phase C	83.5°C	82.1°C

3.4 Comparison hot spot temperature with and without harmonic.

Figure 8 below had depicted the significant comparison between the hottest spot temperature under rated load (ideally without any harmonic content) and under nonlinear unbalanced load condition (with odd order harmonic current content). There was about 28.28%, 33.23% and 28.47% in hotspot temperature increment in Phase A, Phase B and Phase C respectively compared to the hottest spot temperature under rated load. By average, the total increment of hottest spot temperature was to be at 29.99%≈30% from the rated loads (without harmonic) toward the nonlinear loads (with harmonic).
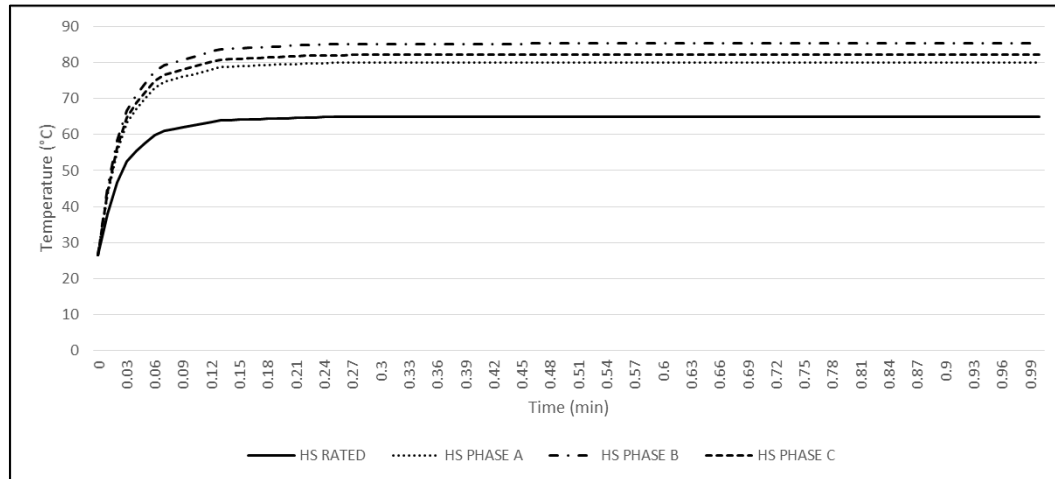

Figure 8. Hotspot temperature at rated load (without harmonic) and unbalanced nonlinear load (with harmonic)

4. CONCLUSION

As a conclusion, from the modeling result, it is proven that the winding loss that act as a heat source to the model has rise up the initial temperature in the transformer. Based on the simulation result, it has prove the significant of the study which is to analyse the temperature rise under unbalanced harmonic loads in order to obtain precise analysis. Hence by this precise analysis, it can be a best reference for research study in order to detect the premature failure of the transformer due to the additional heating that has increase the temperature on the transformer. Not limited in reserving the laborious maintenance works and cost, the detection of premature failure hence can avoid a massive loss that could be happen from the fatal transformer failure or breakdown.

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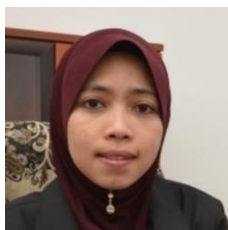
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