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Estimation of Temperature Rise in MVA Range Dry-Type Transformers and Practical Verification Based on Simulated Loading

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***Abstract*—Dry-type transformer becomes the preferable choice in many applications due to its construction specific advantages over oil-cooled transformers. However, the inherent low thermal conductivity of dry-type transformers gives the rise to high operating temperatures. The temperature rise of a transformer is an important factor deciding its safe operation and the useful life span. With the increase of the power rating of the transformers the amount of heat generated during its operation increases. Thus the construction of large dry-type transformers requires a detailed understanding of their thermal behavior. In this paper the development of a 1.2MVA single phase dry-type transformer is discussed. The constructed product was tested for a 1.2MVA loading condition base on simulated loading method. Further a comparison of measured vales against the theoretically predicted values is made.**

***Index Terms*—Dry-Type transformers, temperature rise, hotspot, winding temperature, thermal model, simulated loading**

I. Introduction

TRANSFORMER, as an important part of the transmission and distribution system, plays an important role in the safe operation of power grids[1]. In comparison with the oil-cooled transformer, dry-type transformer shows a good performance in fireproof performance, mechanical properties, die-electric strength, anti-short-circuit ability, heat resistance etc. Further, the feature of less pollution and convenient installation make it widely used. However the low thermal conductivity of the dray-type transformer makes its operating temperature higher than the oil-type/oil-cooled transformers. This directly influences the performance and the service life of dry-type transformers [2].The temperature rise is an important indicator of the safe operation of dry-type transformers. The excessive temperature is a main factor that shortens the service life of dry-type transformers [1]. Further, the modern applications often require high power transmissions and distributions which inevitably require a greater capacity and larger size. This increased the single capacity of a transformer causes higher losses, consequent local overheating problems, inconvenience due to larger size and costs. Therefore, it is necessary to make a good thermal design in order to manufacture compact size and efficient transformers [2].

The study discussed in the papers is based on a 1.2MVA single phase transformer developed for a laboratory application. This transformer is to be used in a partial accelerator arrangement in a research facility in the United Kingdom. The requirement of handling a power of 1.2MVA in single phase itself made the design of the transformer outstanding. Furthermore, the proper operation of the unit over a long period was a vital factor due to the nature of the application. A detailed study was carried out to arrive at reasonably accurate theoretical values for the predicted temperature rise of the transformer under its normal operating conditions. Several thermal models were considered. The results of these calculations were used in arriving at a compact design which would give a temperature rise that is below the values specified in transformer standards.

The developed product was subjected to a load test to evaluate the accuracy of the theoretically predicted temperature. It is generally not practical to carry out a full load test of a MVA range transformer under laboratory conditions. This situation is well identified in the transformer standard BSEN60076-11(Power Transformers Dry-Type Transformers) and a simulated loading method is defined for the load tests of larger transformers.

Even under the simulated loading conditions the transformer is supposed to be loaded with a power exceeding 85kVA. It is a quite challenging task to obtain a single phase power of 85kVA in practice. Therefore a test transformer was developed with the open delta vector configuration. This transformer was used as a phase conversion transformer for converting the three phase power in to a single phase power so that the single phase 1.2MVA transformer can be loaded.

The temperature rise obtained from this simulated loading method is compared with the theoretically predicted values.

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II. Theoretical Background

A. Thermal Modeling

The temperature rise of the transformer components is caused by all of the device's electrical losses, which are the no-load and load losses. It is known that the thermal behavior within the electromagnetic device is composed by conduction, convection (also known as heat advection) and radiation [8], [14].

The transformer can be considered to have a geometrically symmetric structure. Therefore a simplified model can be established. One of the limbs in a three phase transformer can be taken as the main research object in calculation. In the case of a single phase transformer with a high power rating similar to the product discussed in this paper where the UI construction is used (UI construction is suitable for single phase transformers with much lower power rating than the one discussed in this paper) one of the two limbs can be considered as the main research object [3]. The construction of the limb of a transformer similar to the one investigated is illustrated in the Fig. 1. This simplified construction is very much useful in the thermal analysis especially in the analysis of the thermal field distribution.

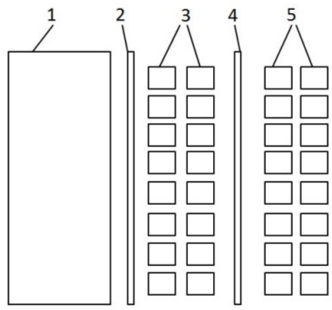

Fig. 1. Simplified diagram of a transformer coil structure . 1. Si-Steel core, 2. Primary winding to core insulation barrier, 3. Primary winding 4. Primary winding to Secondary winding insulation barrier, 5. Secondary winding; note: Depending on the design specific conditions designers use air ducts in between any of the above layers.

The transformer coil construction described in Fig. 1 can be illustrated with the three dimensional model developed for the evaluation of the overall construction as shown in the Fig 2. The exposure of the Si-steel core and the windings to the environment can be seen in this figure.

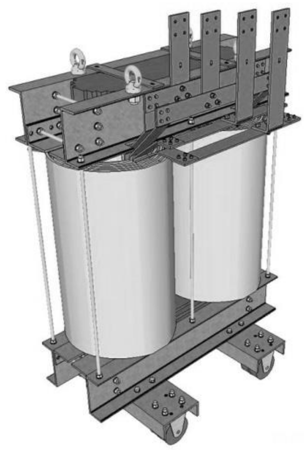

Fig. 2. Three dimensional model of the 1.2MVA transformer

When the transformer is in operation, part of the electromagnetic energy is transferred into heat energy, i.e. the transformer generates energy loss in the windings and other components, which is converted to heat. One part of the heat increases the transformer temperature and other part distributes to the sounding medium. The heat generating elements can be roughly divided into two parts which are the windings and the Si-steel core of the transformer [7].

B. Transformer core temperature rise

In a dry-type transformer as shown in the Fig.2 Si-steel core is one of the heating elements and these losses that generates the heat are called core losses, iron losses or no load losses of the transformer. These no load losses refer to the hysteresis loss and eddy current loss. The two losses are associated with Si-steel sheet material, magnetic density values and have a great relationship with the silicon sheet processing.

The heat dissipation area of the core can be divided into the exposed part and non-exposed part. The exposed area includes the upper surface of the iron yoke; Fig.2, the side surfaces of the upper and lower iron yokes and vertical outer surfaces coming out of the windings. The non-exposed area includes sides of the air ducts in the core and the surface of the iron core column which is surrounded by the winding or insulation, and so on. The thermal load of the transformer core can be expressed as follows [7], [17].

$$q_c = \frac{P_c}{\sigma_a + k_d \sigma_b} \tag{1}$$

Where

$$k_d = 0.56\sqrt[4]{a^{1.6}/H}$$

q_c; A core of the effective surface load (W/m^2),
P_c; The core loss (W),
σ_a; Exposed area, (m^2)
σ_b; Non-exposed area (m^2)
a; Width of the air duct (mm)
H; The average height of the core

An empirical algorithm is commonly used for the calculation of temperature rise in the transformer core. This to a certain extent satisfies the needs of most engineering applications [1], [14], [15]. The empirical coefficients are generally different for the different core materials and for different physical structures. In the calculation of average temperature rise for a core made of stacked silicon steel sheets, the empirical coefficients k, n take the values of 0.36 and 0.8. Thus the core temperature rise model can be expressed is as follows [1].

$$\tau_c = 0.36 q_c^{0.8} = 0.36\left(\frac{P_c}{S_c}\right)^{0.8} \tag{2}$$

Where

τ_c; The core temperature rise (^{o}C),
q_c; A core of the effective surface load (W/m^2),
P_c; The core loss (W),
S_c; The core and the effective radiating area (m^2),

The core loss P_c mainly consists of two parts: the hysteresis loss P_h and the eddy current loss P_e.

$$P_h = \eta f B_{max}^{1.6} V \text{ x}10^{-3} \tag{3}$$

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$$P_e = \eta d^2 f^2 B_{max}^{1.6} V \text{ x}10^{-3} \quad (4)$$

$$P_c = P_h + P_e \quad (5)$$

Where
η; The coefficient of the hysteresis of the core material,
f; Is the frequency (Hz),
B_{max}; The maximum flux density (T),

C. *The temperature rise the transformer windings*

The dry-type transformer windings are the main components of heat generating elements [2]. The heat of the primary winding and the secondary windings are mainly caused by the respective load losses. The load loss includes the basic loss and additional loss. The basic loss refers to the winding DC resistance component of the conductor loss. DC resistance loss is the main reason leading to the winding temperature, so during normal engineering practice, only DC resistance loss is considered in computing [1],[14]. However based on the author's previous research work [19] in this particular study additional factor of 5% was added to account the additional AC losses due to the presence of winding eddy current losses.

Winding temperature rise calculation model and the core temperature rise calculation model use the same principle, just with different values of empirical coefficients. The winding temperature rise calculation is as follows [1].

$$\tau_w = kq_w^n = k(P_w/S_w)^n \quad (6)$$

Where
τ_w; The winding temperature rise (^{o}C),
q_w; The winding surface load (W/m^2),
S_w; The effective winding cooling area (m^2),

The calculation process for the winding loss is as follows:

$$P_w = P_k\beta^2 = P_k(\frac{S_{js}}{S_e})^2 \quad (7)$$

Where
P_k; The transformer short circuit active power (kW),
S_{js}; The transformer computational load (kVA),
S_e; The rated capacity of the transformer (kVA),

K and *n* are empirical coefficients and they are related to the winding process and the materials. For low voltage windings, when all surfaces are in contact with the inner air ways generally K=0.66 For windings with subsection cylindrical windings, which is vertical air duct therefore there two axial radiating surfaces where K becomes 0.46[2].

The values of K and n are also calculated based on the historical test results of the Carroll & Meynell Transformers Ltd.

III. Product Construction

The 1.2MVA single phase transformer was designed and constructed as per requested specific per-turn induction ratio. It was required to maintain specific voltages in the primary side of the transformer and the secondary side of the transformer as described in the transformer schematic diagram in the Fig. 3, which made the selection of the number of turns and the size of the core restrictive to some extent.

The transformer was constructed utilizing the 'UI' type core construction. Given the size of the transformer it was decided to base the core area profile on a step system of cross-sections to give a cylindrical coil construction. The material chosen for the coil former was a silicone coated glass mat that is wound to the required thickness. This material meets the Class H insulation system requirement.

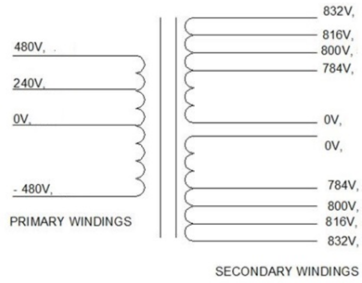

Fig. 3. Transformer schematic diagram

The conductors consisted of multiple sections of rectangular copper strips which were bunched together to obtain the acceptable current density. In deciding the appropriate conductor cross-section the temperature rise was estimated as explained in the section II C and a certain iterative approach was used to arrive at the most suitable conductor cross-section. In order to avoid issues of circulating currents between the inner and outer strips of the conductor bunch being generated a single transposition of the wires in the middle of the coils was used; the optimum number of transposition for the size of the transformer was decided based on a detailed study on the construction explanation of which goes beyond the scope of this paper. This transposition balances the total lengths and winding areas to within a ± 1% tolerance for all conductors. This balances the individual resistances and inductances of the windings which reduces any additional heat generated due to circulating currents. The drawing in the Fig. 4 illustrates the construction of the coil.

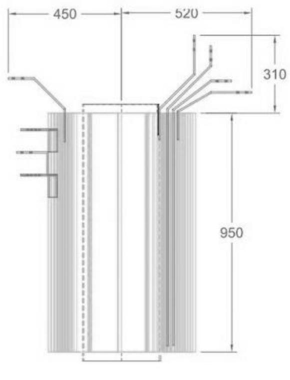

Fig. 4. Construction of one of the two coils

The core material and the operating flux density was decided based on the amount of heat generated due to core losses described in equation (3), (4) and (5). Based on the calculated temperature rise as explained in section II B an iterative approach was made to decide on the optimum design flux density for the application. Though the

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transformer was constructed with a class H insulation system it was decided to limit the temperature rise to the vales of a class F system. This was to ensure the expected long life operation of the transformer and to account for any potential over load possibilities due to the nature of the application in the particle accelerator laboratory setup where the transformer intended to be used.

IV. EXPERIMENTAL PROCEDURE

A. *Simulated loading method*

It was decided to carry out a load test on the constructed transformer. One of the objectives was to get a verification of the theoretically predicted values of the temperature rise. The second objective was to subject the transformer to the full load condition and to stress it for the design thermal condition as a certain quality assurance step before it goes through the expensive installation in the laboratory.

Carrying of a load test on a MVA range transformer is not very much practical in a laboratory set up due to the amount of power involved. This situation is addressed in the standard BSEN60076-11 where a simulated load test is defined.

In the simulated load test method temperature rise is established combining the short-circuit (load loss-winding losses) and open circuit test (no-load loss – core losses). The winding short circuit test is carried out with a rated current of 1160A in the primary and 670A in the secondary. The windings were loaded under this condition until the steady state of the transformer core and the windings was researched. The temperature rise is measured based on the resistance method. The testing arrangement is shown in the Fig. 5

Fig. 5. 1.2MVA transformer testing arrangement

The open circuit test was carried out by loading the primary of the open circuit transformer with a voltage of 960V at the rated frequency of 50Hz. Test was continued until the steady state condition of the windings and the magnetic core was achieved. The total winding temperature that would be researched at a power of 1.2MVA is then calculated as per the formula given below [BSEN 60076-11].

$$\Delta\theta_c^1 = \Delta\theta_c\left[1+\left(\frac{\Delta\theta_e}{\Delta\theta_c}\right)^{\frac{1}{k_1}}\right]^{k_1}; \qquad (8)$$

Where

$\Delta\theta_c^1$; is the total winding temperature,

$\Delta\theta_c$;is the winding temperature rise at the short circuit test,

$\Delta\theta_e$; is the individual winding temperature rise at the open circuit test,

k_1; =0.8 for natural air cooling and 0.9 for forced air cooling.

B. *Supply of high single phase power*

Even though the load test was carried out based on the simulated loading method due to the high power rating of the transformer required supply power level for the load test comes to about 85kVA. Since the product under discussion is a single phase transformer this power has to be obtained in one phase. Obtaining a power of 85kVA in a single phase was a considerable challenge in making the testing setup. In order to achieve this 90kVA open delta phase conversion transformer was constructed. Fig. 6.

Fig. 6. 90kVA open delta phase conversion transformer

This is a transformer constructed with a three phase 3UI type core only with two windings. The center limb of the core is left open without a winding on it. However elimination of the center limb is not possible for the operation of the magnetic circuit. The primary is supplied with a three phase supply with an open delta arrangement and the two secondary windings are connected in series to form the required single phase supply. By the use of this transformer the required single phase power of about 85kVA was obtained.

C. *Load testing process*

With the use of the above open delta phase conversion transformer the core of the 1.2MVA transformer was loaded as explained in the section IV A. The temperature was recorded over a period of 25 hours. The test was carried out until the temperature of the transformer core showed an increase of less than one degree per hour. The measured temperature values were corrected for the ambient temperature variations.

Immediately after the above no-lad test the short circuit test was started as explained in section IV A. When the secondary winding was loaded to the rated current of 670A primary voltage of about 76V could be seen indicating a power of approximately 88kVA. This also shows a short circuit impedance of about 7.9% in the 1.2MVA transformer which is well over the 5% minimum requirement for a transformer of this power range as per BSEN 60076. The short circuit test was also carried out for a period of approximately 24 hours and the measured temperature was corrected for the ambient temperature variations. Here again it could be seen that after about 24hour period the rise in the windings was less than one degree per hour. Furthermore

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based on the plotted graphs and extrapolated lines of best fit it could be seen that the temperature of the windings had researched well over 95% of the steady state conditions.

In addition to recording the measured temperature the resistance of each winding was recoded. As per the definition in BSEN 60076 the temperature of each section of the coils were calculated based on the resistance method.

V. Discussion

The temperature rise of the core obtained during the no-load test is shown in the Fig. 7. Based on the equations (3), (4), and (5) and with the data obtained from the core material manufactures the core loss was calculated which amounted to approximately 958W. The estimated temperature rise of the core based on the equation (2) and the calculated core loss value was 75.52 ^{0}C. The measured value on the experiment was 66 ^{0}C. It could be seen that the predicted value of the core temperature was slightly higher than measured value. However considering the overall practical assumptions made during the calculation process level of accuracy researched can be considered as very satisfactory.

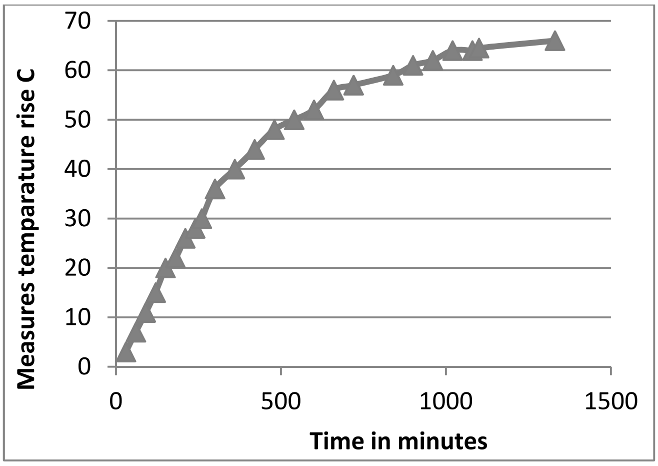

Fig. 7. Temperature rise of the core at the open circuit test

The measured temperature rise of the outer surface of the coils were as shown in the Fig.8

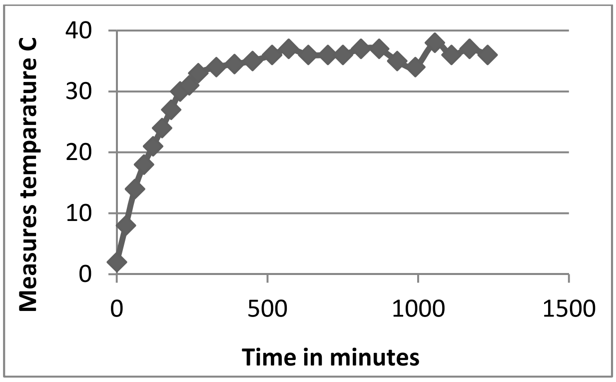

Fig. 8. Temperature rise of the windings at the open circuit test

The values obtained for the temperature rise of the windings based on resistance method are shown in Fig.9.

COIL	CALCULATED TEM. RISE IN °C RESISTANCE METHOD
PRIM LEFT COIL	95.6
PRIM RIGHT COIL	104.5
SEC LEFT COIL	93.8
SEC RIGHT COIL	110.1

Fig. 9. Calculated temperature rise of coils based on resistance method

The above temperature values were extrapolated based on the simulated load test formula (8); this gives the temperature rise of the windings as shown in the Fig. 10.

COIL	TEMPARATURE RISE OF THE COILS AS PER SIMULATED LOAD TEST METHOD °C
PRIM LEFT COIL	110.7
PRIM RIGHT COIL	112.5
SEC LEFT COIL	96.4
SEC RIGHT COIL	112.18

Fig. 10. The temperature rise of coils based on simulated load test method

The calculated temperature rise of the windings at the design stage based on equation (6) and with the parameters adjusted based on experience at Carroll & Meynell Transformers Ltd was 102.4^{0}C.

As far as the prediction of the winding temperature rise is concerned the actual values show about 10^{0}C higher value than the predicted vales. It could be assumed that this is due to additional eddy current loess happening in the windings with high thickness. Though an additional provision of 5% loses was added to the conductor loses it might be necessary to look in to this correction factor in more detail in the case of large transformer with thick winding conductors where the possibility of increased eddy current losses is present. The authors intend to investigate this factor in the future research work.

VI. Conclusion

The theoretical predictions made for the temperature rise in both the core and windings in the 1.2MVA transformer were reasonably accurate when compared with the actual values obtained based on the simulated loading method. There is a certain deviation amounting up to about +/- 10^{0}C for the 1.2MVA transformer investigated. These could be due to potential errors in estimating the total winding losses, core losses and due to the limitations in the thermal models. This level of verified accuracy gives reasonable confidence in finalizing the designs of transformers of this power range. However authors intend to make further improvements to the thermal models to arrive at grater better accuracy especially taking the eddy current losses in the windings into account.

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