Derating of transformers under non-linear load current and non-sinusoidal voltage – an overview

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Abstract: The increasing application of non-linear loads in power system causes additional losses in transformers resulting in premature damage. Manufacturers and users of transformers realise the importance of this phenomenon and it is vital to adopt a procedure to prevent it thereby enhancing the reliability of power system. To achieve this, the most common method is derating of transformers. This paper intends to review derating of transformers under non-sinusoidal operation, for which all available approaches are classified into four major methods including IEEE recommended, analytical, experimental and finite elements based method. For each method, the fundamental theory, significant factors related to derating, test techniques as well as advantages and disadvantages are discussed. The methods are then evaluated and compared with each other from different points of view. Moreover, the overall trend of a more precise derating method is suggested. This review clarifies the research areas which require attention in the future to advance the subject.

1 Introduction

Transformer, as a static electrical equipment, is an essential part of any power system that its operation at high efficiency and reliability is an important consideration [1]. Traditionally, electrical, electromagnetic and mechanical aspects of transformers are considered under sinusoidal operation and its parameters are estimated under such conditions. Transformer losses directly affect transformer life span which is mainly determined by the remaining life of windings insulation. However, the standard life span of transformers is generally based on sinusoidal conditions.

In recent years, there has been a significant increase in non-linear loads which lead to non-sinusoidal currents. Some examples of non-linear loads are power electronic devices, uninterrupted power supplies, variable speed drives, personal computers and arc and induction furnaces. A non-sinusoidal current passing through the network impedance leads to a non-sinusoidal voltage drop. Therefore even for perfect sinusoidal voltage of power generator, loads bus voltage will be non-sinusoidal as shown in Fig. 1.

Harmonic voltage and current increase the losses, leading to temperature rise which causes accelerated ageing of transformer and eventually leads to insulation breakdown. In fact, transformer behaviour under non-sinusoidal conditions is influenced by its design specifications as well as imposed harmonic current and voltage. Therefore modern transformer design is an important consideration for its safe operation under non-sinusoidal conditions. In response to this challenge, transformers manufacturers take the following steps in a harmonic environment [2, 3]:

- Enlarge winding to reduce circulation of third harmonics in A-connected side.
- Use high quality core with lower magnetic flux density.
- Use transformer special connection for harmonics elimination.
- Use smaller and isolated conductors in parallel, transposed to reduce the heating impacts because of passing AC current.

In addition to the above-mentioned procedures adopted in the design stage, based on the magnitude and frequency of the current and voltage harmonics, harmonic filtering and derating techniques are applied to protect the transformer [3].

This paper deals with derating. When a transformer supplies non-linear loads, it is necessary to decrease its rated load for safe operation. In this paper, transformer derating methods are classified into four groups: (i) IEEE recommended methods, (ii) analytical methods, (iii) experimental methods and (iv) finite elements methods (FEM). The paper is organised as follows: fundamentals of transformer derating are discussed in Section 2. These include the impacts of harmonic environment on transformer loss components, harmonic content indices and thermal-insulation considerations relating to transformer derating. The main methods in transformer derating are explored in Section 3. Discussion and future trends in transformer derating are presented in Section 4 where the general trend of a more precise derating method is introduced. Finally, Section 5 concludes the paper.

2 Fundamentals of transformer derating

2.1 Transformer losses under harmonic operation

Oil-immersed and dry type transformer losses have been proposed in the Standards [4, 5]. These losses consist of no-load and load losses. Fig. 2 shows the classification of transformer losses under non-sinusoidal operating conditions.

The no-load losses depend on the amplitude of the fundamental and harmonic components of the voltage as well as phase angles of the voltage harmonics [4, 5].

Fourier series of an alternative non-sinusoidal current signal \( i(t) \) is

\[
i(t) = i_{dc} + \sum_{h=1}^{h_{max}} \sqrt{2} I_h \sin(h \omega t + \alpha_h)
\]  

(1)

where \( i_{dc} \) is the dc component of \( i(t) \), \( h_{max} \) is the maximum harmonic order existing in the signal, \( I_h \) is the rms current of harmonic order \( h \),
$\omega_0$ is the fundamental angular speed and $\alpha_h$ is the phase angle of harmonic $h$.

The dc Ohmic losses depend on the harmonics of the current passing through windings in which proximity and skin effects have not been included. By assuming zero dc component, Ohmic losses are estimated as

$$P_{\text{ohmic}} = R_{dc} I^2 = R_{dc} \left( I_1^2 + I_2^2 + \ldots + I_{\text{max}}^2 \right) = R_{dc} \sum_{h=1}^{h_{\text{max}}} I_h^2$$

where $R_{dc}$ is the dc resistance of the winding.

The stray losses consisting of ‘winding eddy current losses’ and ‘stray losses in other parts of the transformer’ are obtained by subtracting the Ohmic losses from load losses [4, 5]. Under harmonic environment, stray losses are dependant on the amplitude of current harmonics and their orders.

By passing alternating current through windings, three complex phenomena occur including skin, proximity and geometric effects [6–8] which lead to creation of winding eddy current losses. The winding eddy current losses arise from eddy current in winding strands or parallel windings, as shown in Fig. 3. Winding eddy current losses in harmonic environment are proportional to the square of the amplitude of current harmonics and the square of their orders [9–11]. Therefore winding eddy current losses for harmonic loads are calculated as follows [9–11]

$$P_{EC-\text{non sin}} = P_{EC-R} \sum_{h=1}^{h_{\text{max}}} \left( \frac{I_h}{I_R} \right)^2 h^2$$

where $P_{EC-R}$ is the winding eddy current losses for sinusoidal rated load, $P_{EC-\text{non sin}}$ is the corresponding losses for non-sinusoidal load and $I_R$ is the rated rms current.

Leakage fluxes linking the metallic parts of the transformer such as core, clamps and tank cause ‘other stray losses’ in the transformer. These leakage fluxes would induce voltage, current and generate losses. Other stray losses for harmonic loads are calculated as follows [10, 11]

$$P_{OSL-\text{non sin}} = P_{OSL-R} \sum_{h=1}^{h_{\text{max}}} \left( \frac{I_h}{I_R} \right)^2 h^2$$

where $P_{OSL-R}$ is the other stray losses at rated sinusoidal load and $P_{OSL-\text{non sin}}$ is the corresponding losses under non-sinusoidal loads.

To reduce other stray losses in magnetic shunt, tank, clamp and other metallic parts of the transformer, low permeability materials must be used in these parts [12, 13]. Moreover, specific geometries of bushing mounted plates and magnetic shunts have been proposed using especial material to reduce stray losses in transformer tank [14–16].

### 2.2 Harmonic content indices

Harmonic content of a signal can be estimated using appropriate indices. Crest factor, total harmonic distortion (THD) and $K$-factor can be used to estimate the load harmonic content [2, 17]. Moreover, $F_{HL}$ [9–11] and $F_{HL-STR}$ [10, 11] have been introduced to estimate the ratio of winding eddy current losses and other stray.
losses for non-sinusoidal load current to their corresponding sinusoidal condition, respectively.

Stray losses depend on the amplitude and the frequency of current harmonics. In the first two proposed indices, load current frequency characteristics are not included; however, in K-factor, $F_{\text{HL}}$ and $F_{\text{HIL-STR}}$, the load harmonic frequency characteristics are taken into account.

### 2.3 Thermal-insulation requirements in transformer derating

In most equipment, heat distribution is non-uniform and the region with the highest temperature experiences more stress. Aging or destruction of insulation refers to the loss of insulation properties. When considering aging, the hot-spot is taken into account exclusively. The hot-spot is the dominant factor which determines the insulation ageing rate of the equipment.

Arrhenius reaction rate theory states that

$$\text{per unit life} = A[e^{(B/kT)}]$$  \hspace{1cm} (5)

where $T_h$ is the winding hot-spot temperature and $A$ and $B$ are the parameters estimated based on the insulation life span. $(5)$ indicates the impact of the hot-spot temperature on in reduction of transformer life. Overall, there are several factors involved making it a complicated task to estimate the life span of the transformer [18–21].

Under non-linear load current where $I_1$ is equal to 1 pu, transformer losses increase leading to a rise in the temperature of different parts of the transformer and eventually the hot-spot temperature [22, 23]. Therefore from insulation point of view, premature aging of the transformer insulation supplying non-linear load current with $I_1 = 1\text{pu}$ is inevitable and a derating technique needs to be applied to ensure that the hot-spot temperature does not go beyond the permissible value.

### 3 Different methods for transformer derating

The main idea behind transformer derating is to decrease the rating of the transformer so that premature destruction is avoided. Based on this concept, there are two general approaches for derating. In the ‘first derating approach’, no-load losses are not included. This is because of the fact that the main risk is the increase in load losses which leads to winding temperature rise. Secondly, it is evident from experiments that increased no-load losses because of harmonic voltage are not a limiting factor in transformer derating [9–11]. In this approach, the strategy for transformer derating under non-sinusoidal load is that the total load losses, the load losses in each winding and the loss density in the region with maximum eddy current losses should not exceed that of the sinusoidal rated load. Therefore harmonic load should not increase the hot-spot temperature compared with the sinusoidal rated load. Hence, transformer load losses are considered to be a prominent factor in this regard. In the ‘second derating approach’, by considering transformer as a lumped parameter system, identical total losses under non-sinusoidal and rated sinusoidal operation are taken into consideration in the derating process. To this end, transformer load is reduced until total losses under the two aforementioned conditions are identical.

#### 3.1 IEEE recommended methods

In the IEEE recommendations [9–11], the most fundamental factor in derating of transformer is the distribution of load losses in the windings. Therefore based on the ‘first derating approach’, identical maximum load losses density in the windings under rated sinusoidal and non-sinusoidal conditions is considered as prominent factor in the derating process. Fig. 2 shows that the load losses in the windings consist of dc Ohmic and winding eddy current losses. The dc Ohmic losses are uniformly distributed in the windings. Therefore to maximise load losses at a given point in the winding, winding eddy current losses at that point must also be at a maximum. Hence, two methods are introduced according to the knowledge of the eddy current losses in the LV and HV windings as well as the region with maximum eddy current losses in the windings. In the first method, mainly used by designer engineers, there is detailed data relating to winding eddy current losses density distribution within each transformer winding. In the second method, suitable for ordinary users, maximum winding eddy current losses density is obtained from the transformer test report. Hence, the first method is more accurate in comparison with the second one. Eventually, a simple equation has been derived using maximum winding eddy current losses density and harmonic loss factor ($F_{\text{HL}}$), to derate the transformer based on applying conservative assumptions which reduce the accuracy of the second method.

The difference of the second method in the three IEEE recommendations is that in [9] the total stray losses is taken to be equal to the winding eddy current losses, and this drawback leads to highly conservative results. However, in [10, 11], depending on the transformer type (dry or oil immersed), winding eddy current losses have been considered as a part of the total stray losses and this improves the results.

There are two serious drawbacks in the second method of IEEE recommendations as follows:

These methods are conservative; therefore their economic justifications are not clear.

Transformer is derated under the assumption that it is in ‘usual service condition’ (USC) while distribution transformers mainly operate in unusual conditions such as unbalanced load and voltage. Hence, this method is not feasible for transformer derating under unusual service conditions (unUSC).

#### 3.2 Analytical methods

Modelling a physical phenomenon is an important stage in any engineering problem. More or less, any phenomenon is expressed in terms of algebraic, differential and integral equations related to the relevant variables of the phenomenon. Mathematical description of a physical phenomenon is called analytical modelling. Hence, an analytical model is defined as a set of equations which explains the necessary characteristics of a physical system in terms of its variables [24, 25]. Analytical solution yields the value of the desired unknown quantities of a physical system at any location. Generally, in large scale systems, such as transformers, the geometries are complex and it is difficult to include the properties of the materials in the governing equations. Therefore analytical method is not applicable since it requires the solution of ordinary or partial differential equations [26]. In addition, in the derating process, some physical phenomena such as skin, proximity and geometric effects must be included. Hence, introducing a comprehensive analytical method for predicting transformer performance under non-sinusoidal operating conditions is very difficult.

The effect of non-sinusoidal supply voltage on transformer excitation current using piece-linearising of ‘flux-linkage/magnetisation current ($V-I_m$)’ and ‘applied voltage to transformer/ core losses current ($V-I_c$)’ has been investigated in [27]. It has been concluded that the phase angle of the harmonic voltage affects distortion of the harmonic current and high-order voltage harmonics have less impact on the excitation current of the transformer. However, in transformer core losses estimation, the minor loops generated by voltage harmonics are important because of magnetic core hysteresis. However, this has not been included in core losses estimation.

Non-linear behaviour factors such as saturation, anisotropy, oriented and non-oriented grain laminations [28] and dependence of core losses on peak flux density of the fundamental component...
and the amplitudes and the phase angles of the harmonic components [29] have been modelled in [30]. This method is applied in time and frequency domains using magnetic characteristics and transformer parameters. In [30], core losses and Ohmic losses have been estimated and then based on the ‘second derating approach’ the transformer load is reduced iteratively such that the total transformer losses under non-sinusoidal operation becomes equal to that of the rated sinusoidal case.

In the ‘first derating approach’, the load losses in the region with maximum winding eddy current losses density in non-sinusoidal case are taken to be equal to the corresponding losses in the rated sinusoidal case. Therefore accurate stray losses estimation plays a key role in derating of transformers. Winding eddy current losses have been estimated in [6–8, 31–33]. In [8], a simple analytical method for estimating winding stray losses has been proposed in which the skin, proximity and geometric effects have been emphasised. This method is applicable to transformers carrying current from DC to high frequency. Experimental results and proposed analytical model results show good agreement. The common drawback in [6, 8, 31–33] is the inaccuracies involved with estimation of B and H because of the use of basic analytical equations.

To estimate stray losses of transformer under sinusoidal conditions, integral equations method (IEM) has been suggested in [34]. The IEM requires a large size matrix to consider penetration depth because of skin effect, and this can be considered as a drawback. To overcome this, a combination of IEM and surface impedance model has been recommended for stray losses estimation. Furthermore, simulation results have shown that copper shield largely decreases (51.84%) the tank stray losses [34].

A transformer has been modelled in time domain and steady-state including non-linear characteristics and core asymmetry [35] by introducing a non-linear reluctance function for each leg of the transformer using [36]. In [35], referring to [37], the necessity of including core losses has been emphasised, hence the ‘second derating approach’ has been used to derate the transformer. However, in modelling core losses, a constant resistance has been used which indicates dependency of the core losses on the magnitude and phase angle of the voltage harmonics have not been taken into account. The second point is that in the modelling, series impedances have been assumed constant while they depend strongly on the frequency [38]. Furthermore, the stray losses of the transformer are taken to be 5% of total losses, while the stray losses particularly under non-sinusoidal conditions, have a strong dependency on the material and the geometry of the transformer.

In [39], a transformer has been derated under non-sinusoidal load considering ambient temperature and load variations based on thermal equations [40] and insulation considerations [41]. Keeping in mind the standard life of transformer insulation (7500 days), the load profile of the transformer is reduced such that the life reduction in one day is restricted to its normal daily life reduction. Thermal and electrical equations are therefore jointly analysed and used in transformer derating.

A transformer charging electric vehicle has been derated in [42]. The hot-spot has been estimated using [41], and reducing the linear load has prevented further reduction of transformer life. Keeping in mind the wide application of PWM inverter in variable speed drives, [43] has investigated the impact of different parameters of PWM including amplitude modulation ratio, switching frequency and dc link voltage on core eddy current losses.

Bagheri et al. [44] has analysed the impact of incandescent, fluorescent, compact fluorescent and light emitting diode lamps. For this, the IEEE recommendation [10] has been used in transformer derating under individual and combined aforementioned loads based on their current harmonics frequency spectrum.

### 3.3 Experimental method

In the ‘second derating approach’ it was mentioned that to prevent premature destruction of transformer under non-sinusoidal operating conditions, the total losses must be equal to the corresponding losses under rated sinusoidal conditions. Therefore one can use an experimental method to measure the total transformer losses. In this derating method, transformer losses are measured, then transformer load is reduced such that the total losses under two conditions are identical without taking into account the materials and their geometries.

If a voltage with harmonic content is applied to a transformer, its losses can be estimated using a computer aided measurement circuit as reported in [45]. In traditional methods, voltage and current are measured and transformer losses are estimated directly based on the difference between the input and output powers. Normally, transformer has high efficiency (low losses); therefore a small error in loss computation causes a large error in the measurement. This will be intensified when transformers operate under non-sinusoidal load and voltage conditions, since conventional watt-meters are not accurate enough in these cases. To reduce the measurement error, the losses can be indirectly measured as follows

\[
\Delta P = P_{in} - P_{out} = A + B
\]

\[
A = \frac{1}{T} \int_{0}^{T} \left[ i_a(t) (v_a(t) - v_a(t)) \right] dt,
\]

\[
B = \frac{1}{T} \int_{0}^{T} \left[ v_a(t) (i_{in}(t) - i_{out}(t)) \right] dt
\]

where \(A\) is the Ohmic losses and \(B\) is the core losses. The proof for (6) has been given in Appendix 1.

Eventually, ‘second derating approach’ has been applied to derate a transformer using estimated Ohmic losses and core losses.

Losses of single and three-phase transformers under linear and non-linear loads have been estimated in [46] using the measurement circuit shown in Fig. 4. To decrease loss measurement error of an ungrounded three-phase transformer, not only losses have been indirectly estimated, but also voltage and current signals have been transferred to the primary side. The losses, as shown in Appendix 2, can be estimated as follows

\[
\Delta P = P_{in} - P_{out} = C + D
\]

\[
C = \frac{1}{T} \int_{0}^{T} \left[ \bar{i}_d(t) \times (v_{dc}(t) - v_{ac}(t)) + \bar{i}_b(t) \times (v_{bc}(t) - v_{ac}(t)) \right] dt
\]

\[
D = \frac{1}{T} \int_{0}^{T} \left[ v_{dc}(t) \times (i_{in}(t) - i_{out}(t)) + v_{bc}(t) \times (i_{in}(t) - i_{out}(t)) \right] dt
\]

where \(C\) and \(D\) represent the Ohmic losses and core losses, respectively. Based on the ‘second derating approach’, the transformer is then derated.

In [45, 46], potential transformer (PT) and current transformer (CT) have been used for measurements. These devices filter the dc values, and therefore the dc related loss does not enter the process of the losses estimation. On the other hand, since voltage and current phase angles affect loss estimation, phase angle displacement caused by CT and PT leads to measurement error.

In [47], Ohmic losses and core losses have been obtained by back-to-back connection of two single-phase transformers using (6) and the transformer has been derated based on the ‘second derating approach’. Owing to direct measurement of the required signal of (6), the maximum measurement error is considerably decreased compared with the indirect method in [45, 46]. Fig. 5 shows the measurement circuit and transformers connection. Since in this method, PT and CT are replaced by voltage and current shunts, respectively, their drawbacks are eliminated.

In [48], derating of transformer has been estimated by direct measurement of the transformer equivalent resistance for each harmonic. To do this, measurement of winding resistance losses \((R_{OSL,R})\) and other stray losses \((R_{OSL,LS})\) at rated sinusoidal load are defined. Ultimately, AC winding resistance for harmonic order \(h\) is
as follows [9]

\[ R_h = R_{dc} + R_{EC-R} h^2 + R_{OSL-R} h^{0.8} \]  \hspace{1cm} (8)

FEM results and direct measurement of winding AC resistance show that (8) cannot adequately express the AC winding resistance at high frequencies. In fact, eddy current losses over a frequency range vary, therefore a single derating technique cannot be applied for all frequencies.

Load losses as Ohmic losses and winding eddy current losses have been used to determine the AC winding resistance as follows [49]

\[ R_{AC} = R_{dc} + R_{EC-R} \times h^2 \]  \hspace{1cm} (9)

To estimate \(R_{EC-R}\) and \(R_{dc}\), short circuit tests over different frequencies and a back-to-back connected transformer supplying non-linear load are employed where transformer is supplied by reduced and rated voltage, respectively. These two tests provide different estimates of \(R_{EC-R}\) and \(R_{dc}\). The reason for this difference is the level of applied voltages. Since in short circuit test, transformer operates in the linear part of BH curve, this method is more accurate. Eventually, based on \(K\)-factor, core losses, \(R_{EC-R}\) and \(R_{dc}\), a transformer derating equation has been introduced according to the ‘second derating approach’. However, other stray losses have been accounted for core losses while according to standards [4, 5], other stray losses are part of the load losses; however, core losses is part of no-load losses and basically they have a different nature.

According to the ‘second derating approach’, losses and derating of three-phase ungrounded \(\Delta\Delta\), \(YY\) and \(\Delta\gamma\) connections have been evaluated in [50]. This paper has introduced a new digital data acquisition scheme for measurement where voltage divider-optocoupler and current shunt-optocoupler have been used in place of PTs and CTs, respectively. The scheme can therefore remove the drawbacks of using CT and PT.

In [51], a grounded three-phase transformer has been derated based on the ‘second derating approach’ by measuring Ohmic losses and core losses under sinusoidal and non-sinusoidal operation with CT and PT, and the impact of different dc bias current and supply voltage in \(\Delta\gamma\) grounded transformer losses have been studied.

### 3.4 Finite elements method

Solving governing Maxwell equations of an electromagnetic system is commonly difficult except for simple geometries. Therefore FEM is proposed for problems with complex geometries. In FEM, the system is divided into a number of meshes and electromagnetic equations in each mesh are approximated by a simple function. Fine meshes lead to more accurate results but longer computation time. Hence, a compromise between accuracy and computation time is normally made. The benefit of breaking the system geometry into small elements is that a small problem with difficult solution is converted into a relatively large problem with simple solution. Fig. 6 presents a three-phase transformer magnetic flux density pattern using FEM where the geometry and magnetic parameters of the transformer are taken into account. Having the magnetic field distribution, it is also possible to estimate the magnetic field density, the force exerted on the windings and the induced voltage. This analysis includes all physical properties of the materials, geometries, saturation, proximity effect and skin effect [52, 53]. In addition, FEM can be employed to analyse the performance of transformers under unbalanced load and voltage...
conditions [54]. FEM has also been used in [55] to investigate the capability of transformer analysis under non-sinusoidal voltage and current. The simulated and test results are in good agreement. Transformer losses can be estimated by FEM, and its thermal analysis is carried out [56]. In [56], the modelling of transformer consists of three parts including windings, core, and air, but the impact of transformer tank has not been included. Furthermore, most distribution transformers supplying non-linear loads are oil-immersed, but in [56], air-cooled transformer has been proposed.

In [57], FEM and IEEE recommendation [9] have been used to estimate harmonic loss factor \( F_{dl} \) based on its original definition (ratio of winding eddy current losses with non-sinusoidal load to its corresponding losses with sinusoidal rated supply) and recommended equation in [9], respectively. Finally, based on the derating trend introduced in [9] and estimated harmonic loss factors under the two above-mentioned procedures, the derating results indicate that the IEEE recommendation is conservative.

In [58], derating of a 50 kVA distribution transformer has been presented using combination of the ‘second derating approach’, IEEE recommendation [9] and time stepping FEM under both non-linear load and unbalanced over-voltage. In [58] a mixed derating concept has been introduced and the transformer has been derated under the above-mentioned condition which leads to the increase of both load and no-load losses. It is concluded that IEEE recommendation leads to a higher derating factor (DF) and it can be considered as a conservative method. Furthermore, an increase in the distortion of load current leads to a higher degree of conservative derating. The results of derating for four different non-linear loads are summarised in Table 1. However, it has not been paid attention that IEEE recommendation method is for the transformers operating under ‘USC’, since according to standard [59] the rated supply voltage in ‘USC’ must be balanced. As evidence, it has been shown in [60] that even unidirectional saturation of the core increases the transformer stray losses considerably. Therefore equations [9] for derating of transformer under unbalanced over-voltage are not accurate.

In [60], because of geo-magnetically induced current (GIC), which leads to dc bias of transformer, the tank stray losses have been estimated by two-dimensional (2D) FEM. GIC causes a unidirectional saturation of transformer, and therefore stray fluxes strongly increase which increases the losses of the tank. Moreover, the impact of magnetic shunt has been investigated, and it has been inferred that magnetic shunt largely decreases stray losses of the tank. In addition, the results indicate that the nature of the transformer load (leading or lagging) influences the tank losses. This shows the weakness of the harmonic content indices to include harmonics phase angles under non-sinusoidal operating conditions. Furthermore, since the main idea for this phenomenon has been unidirectional saturation, it is expected that the increase of stray losses for over-voltage (balanced or unbalanced conditions) occurs more strongly because of doubly-directional saturation. Furthermore, because of asymmetrical distribution of tank losses, using 2D-FEM for estimation of tank stray losses in [60] leads to a high degree of error [61].

In [61], the goal is to estimate the winding eddy current losses and other stray losses of high voltage DC converter transformer using two- and three-dimensional (3D) FEM, respectively. In this paper, first, winding eddy current losses at rated frequency are estimated and then (3) is used to evaluate the losses under non-sinusoidal current. In addition, stray losses consisting of eddy current and hysteresis losses in the tank and the top and bottom clamps are estimated at rated frequency using 3D FEM. Finally, stray losses in the mentioned parts and under non-linear load current are evaluated using (4).

Zhu et al., [62] has devised a novel approach using 3D FEM to estimate stray losses of single-phase power transformer which consists of core, magnetic shield, tank, clamps and tie plane. This has been carried out in spite of the contrast between the large dimensions of power transformer itself and very small skin effect. Ohmic and stray losses of LV and HV windings are estimated in time and frequency domains using FEM [63]. The drawback of the frequency domain analysis is that transformer is a non-linear system and superposition theorem cannot be applied to estimate the total losses by summation of the losses at different frequencies. In addition, in frequency domain, linear solver is applied for solving the magnetic problem which considers the non-linear magnetic core as a linear magnetic material. Frequency domain analysis can lead to a higher error especially in unUSC such as over-voltage. In fact under such conditions, stray magnetic fields increase significantly because of core doubly-saturation which

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<th>Table 1 Derating results for a 50 kVA transformer using IEEE and FE methods</th>
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IET Electr. Power Appl., 2015, Vol. 9, Iss. 7, pp. 486–495
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cannot be modelled in frequency domain because of core modelling as a linear magnetic material. Therefore it is inferred that calculated losses in time domain have a higher accuracy compared with that of the frequency domain, but its computation time is longer.

4 Discussion and future trends

4.1 Overall settings

There are two major approaches in transformer derating. In the ‘first derating approach’, load losses in the region with the highest winding eddy current losses density are considered as the basis of transformer derating. Tests have shown that voltage harmonics are not a limiting factor in transformer derating. In the ‘second derating approach’, total losses are considered as the basis for derating where non-uniform distribution of temperature is neglected. In fact, in this approach, the impact of transformer loss components on hot-spot temperature rise is assumed identical. However, the effect of core losses as a heat generating source is not deniable. It is therefore recommended that by thermal analysis, the impact of core losses variation is further investigated because of non-sinusoidal voltage.

IEEE recommendation method is an efficient and simple method that derates transformer conservatively by analysing load current harmonics and using transformer technical specifications. However, this method does not include the phase angles of the current harmonics. Moreover, in IEEE recommendation, it is not possible to estimate transformer derating under unUSCs. Hence, IEEE method needs to be modified to derate transformer more economically and also to consider the impact of harmonics phase angles of current in the derating procedure. In addition, it must be able to derate transformers under unUSC.

Analytical methods aim to introduce a model for transformer loss estimation under non-sinusoidal operation considering complex factors affecting losses, particularly under non-sinusoidal conditions. Therefore this method has serious limitations and cannot be considered as a powerful method. There are many limiting problems in applying analytical methods including skin and proximity effects, saturation, hysteresis, non-uniform flux distribution, leakage fluxes, core lamination, thermal-insulation properties, cooling system, effects of geometry and materials which need to be investigated further.

Experimental methods measure the transformer losses throughout the structure. In this method, transformer losses merely consist of core and Ohmic losses. Therefore load losses components are not individually measured. Hence, there is no difference in derating for dry and oil-immersed transformers by this procedure. To improve this method, assuming the necessity of other stray losses inclusion in derating of oil-immersed transformer, a procedure must be followed which can measure transformer losses components according to IEEE standards [4, 5], so that effective losses components in oil-immersed and dry transformers derating are taken into account. In addition, keeping in mind the prominent role of maximum winding eddy current losses density in the derating process, the experimental method must be modified in a way that it considers the above-mentioned parameter in its proposed derating method rather than presenting a method based only on loss measurement.

In derating using FEM, transformers losses are estimated with high accuracy taking into account all geometrical specifications and materials properties. However, FEM modelling requires precise data relating to transformer structure. In addition, high computing time can be mentioned as the most serious drawback of FEM especially under non-sinusoidal conditions. Generally, it seems that FEM can be considered as the most powerful derating method.

Based on the current literature review, derating of transformer using IEEE recommendations, analytical methods, experimental and FEMs have a number of advantages and disadvantages. The features of different methods have been summarised in Table 2.

Core losses under non-linear load remain almost constant but Ohmic and stray losses rise. When a transformer operates under unbalanced over-voltage conditions, in addition to Ohmic and stray losses, core losses increase. To derate the transformer under both non-linear load and unbalanced over-voltage, keeping in mind that as the tests indicate, core temperature rise is not a limiting factor in the derating of transformer for the case of harmonic voltage, the impact of core losses must be included in a particular way in the derating process.

In the presence of dc bias current or over-voltage condition causing unidirectional and bidirectional saturation, respectively, the leakage fluxes increase. Under harmonic conditions, considering the presence of harmonic fluxes, the losses related to these fluxes increase considerably. Hence, derating of transformer under such unUSC must be treated in a particular way.

4.2 Proposed method

Based on the review, it was pointed out that methods consisting of IEEE recommendations, analytical, experimental and FE have a number of drawbacks. Therefore derating of transformer needs further investigations. Obviously, the most reliable base in this field is the concept of winding insulation aging. Among the four above-mentioned methods, IEEE recommendations and FEM can suitably include this concept and its requirements. Therefore in [58], FEM has been used for transformer derating based on the assumptions given in IEEE recommendations [9]. However, according to one of these assumptions, winding eddy current losses have been taken to be equal to the stray losses. Hence, although the proposed method in [58] is a progress in transformer derating, it seems that the method is still conservative and needs further improvement.

In the second and third versions of IEEE recommendations [10, 11], by a simple assumption, contribution of the winding eddy current losses from the stray losses have been determined. However, because of disregarding transformer characteristics under consideration, it is expected that this rough assumption decreases the accuracy of the transformer derating calculations. It has been noted in these recommendations that the presented methods have high accuracy in transformers with small conductors and low harmonics loads. Hence, in the case which one of these items is ignored, the derating will be conservative. To resolve this drawback, which in fact arises from inaccuracy of the winding eddy current estimation, a method must be followed as such that these losses are calculated very precisely. To realise this, underlying the method introduced in [58], FE analysis can be used to estimate winding eddy current losses directly. Having these losses, DF is estimated as follows [10, 11]

\[
DF = \frac{1 + \text{Max}\{F_{\text{EC}}^\text{EC-R}\}}{1 + F_{\text{IL}} \times \text{Max}\{F_{\text{EC}}^\text{EC-R}\}}
\] (10)

where Max\{F_{\text{EC}}^\text{EC-R}\} is the maximum winding eddy current losses at the hot-spot [10, 11]. In fact, F_{\text{IL}} is the ratio of winding eddy current losses under non-sinusoidal load current condition and the corresponding sinusoidal load. The IEEE recommendations estimate this factor merely by using harmonic characteristics of the load current as follows

\[
F_{\text{IL}}(\text{IEEE}) = \frac{\sum_{i=1}^{n_{\text{har}}} P_{\text{har}}^2}{\sum_{i=1}^{n_{\text{har}}} P_{\text{har}}^2}
\] (11)

Therefore in the suggested method, F_{\text{IL}} is estimated directly based on the two estimated winding eddy current losses using FEM while in the IEEE recommendation method, this coefficient is evaluated using (11).

To clarify this, a six-pulse power electronics converter is used as a non-linear load. This load generates 6k±1 (k integer) harmonics. Four non-linear loads according to Table 3 are considered to...
investigate the distortion impact. Table 4 summarises the results obtained from loss analysis of a 50 kVA distribution transformer using FEM. Finally, DF and derated power under non-linear loads are estimated using the two methods. The derating results using the suggested method and the IEEE recommendation are listed in Table 5. In N.L.1, the discrepancy between the two methods is small while this increases to 6.48% in the case of N.L.4. Therefore in spite of improvements in the second and third versions of the IEEE recommendations, still FEM based method is more reliable and economic particularly for loads with high harmonic distortion and/or in transformers with thick conductors.

### Table 2: Comparison of derating methods

<table>
<thead>
<tr>
<th>Compared aspects</th>
<th>IEEE recommendations</th>
<th>Analytical</th>
<th>Experimental</th>
<th>FE</th>
</tr>
</thead>
<tbody>
<tr>
<td>included losses in the method</td>
<td>no</td>
<td>depending on paper procedure</td>
<td>depending on paper procedure</td>
<td>depending on paper procedure</td>
</tr>
<tr>
<td>on-load losses</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>dependency of method on transformer detailed data</td>
<td>low</td>
<td>depending on modelling accuracy</td>
<td>independent</td>
<td>high</td>
</tr>
<tr>
<td>capability of investigation in USC taking into account thermal-insulation considerations</td>
<td>do not have</td>
<td>have</td>
<td>have</td>
<td>have</td>
</tr>
<tr>
<td>taking into account phase angles of voltage and current harmonics accuracy (based on loss estimation point of view)</td>
<td>no</td>
<td>has capability</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>computation time</td>
<td>short</td>
<td>short</td>
<td>short</td>
<td>short</td>
</tr>
<tr>
<td>cost</td>
<td>low</td>
<td>very low</td>
<td>almost easy</td>
<td>difficult</td>
</tr>
<tr>
<td>ease of application</td>
<td>very easy</td>
<td>almost easy</td>
<td>difficult</td>
<td>yes</td>
</tr>
<tr>
<td>taking into account saturation, hysteresis, magnetic field distribution, skin and proximity effects, magnetic shield, cooling system etc.</td>
<td>included as usual</td>
<td>by difficulty and high approximation and sometimes, impossible</td>
<td>accurate</td>
<td>impossible</td>
</tr>
</tbody>
</table>

### Table 3: Harmonic characteristics of four non-linear loads (per unit)

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>N.L.1</th>
<th>N.L.2</th>
<th>N.L.3</th>
<th>N.L.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.18</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>7</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>11</td>
<td>0.04</td>
<td>0.07</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>13</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>17</td>
<td>0.01</td>
<td>0.04</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>THD (%)</td>
<td>18.22</td>
<td>24.04</td>
<td>30.53</td>
<td>37.33</td>
</tr>
</tbody>
</table>

### Table 4: Calculated transformer losses under rated and non-linear loads

<table>
<thead>
<tr>
<th>ohmic losses (W)</th>
<th>winding eddy current losses (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated load</td>
<td>N.L.1</td>
</tr>
<tr>
<td>845.13</td>
<td>837.19</td>
</tr>
<tr>
<td>18.08</td>
<td>39.97</td>
</tr>
</tbody>
</table>

### Table 5: DFs and derated power of the transformer based on IEEE and proposed methods

<table>
<thead>
<tr>
<th>N.L.1</th>
<th>N.L.2</th>
<th>N.L.3</th>
<th>N.L.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{HL(IEEE)}} )</td>
<td>2.259</td>
<td>4.258</td>
<td>7.775</td>
</tr>
<tr>
<td>( F_{\text{HL(prop)}} )</td>
<td>2.211</td>
<td>3.763</td>
<td>6.167</td>
</tr>
<tr>
<td>( D\text{F}_{\text{IEEE}} )</td>
<td>0.934</td>
<td>0.652</td>
<td>0.748</td>
</tr>
<tr>
<td>( D\text{F}_{\text{prop}} )</td>
<td>0.936</td>
<td>0.670</td>
<td>0.798</td>
</tr>
<tr>
<td>( S_{\text{derated(IEEE)}} ) (kVA)</td>
<td>46.705</td>
<td>42.595</td>
<td>37.415</td>
</tr>
<tr>
<td>( S_{\text{derated(prop)}} ) (kVA)</td>
<td>46.820</td>
<td>43.515</td>
<td>39.910</td>
</tr>
</tbody>
</table>

### 5 Conclusions

Non-linear loads lead to the operation of transformers under non-sinusoidal conditions. Transformer load losses increase under harmonic load current. The loss increase causes the temperature rise of different parts of the transformer including the hot-spot. Hot-spot temperature is the most prominent factor in transformer life estimation. Hence, an appropriate technique must be applied for derating to prevent premature damage.

Core losses depend on the amplitude, frequency and waveform of the applied voltage and in fact it is more sensitive to the applied voltage waveform. Therefore core losses must be taken into consideration in the case of non-sinusoidal voltage where the voltage harmonics phase angles significantly influence the applied voltage waveform. On the other hand, the impact of current harmonics phase angles on stray losses estimation must be taken into account. Hence, one important factor in transformer losses under non-sinusoidal operating conditions is the phase angles of voltage and current harmonics which must be taken into account in the transformer derating process.

Derating based on the IEEE recommendation is higher than the required value. The IEEE recommendation is therefore considered as a conservative method which may not be economically justifiable.

Among the derating methods for non-sinusoidal operation, FEM can be considered as the most powerful method which includes all the structural features of transformer but its computation is costly and in some cases such as onsite application, FEM may not be the best method. The IEEE recommendations, experimental and analytical methods can be considered as the next efficient methods in the derating of transformer, respectively.

Under harmonic load current conditions, stray losses play a key role in the derating process. Magnetic shield reduces the stray losses of tank considerably, and this leads to an increase in the loading capability and the efficiency of transformer especially under non-sinusoidal conditions.

By reviewing the literature, the methods shortcomings are specified. Furthermore, the necessity of precise estimation of winding eddy current losses under non-sinusoidal operating conditions is emphasised. Hence, by considering one of the existing methods and with a view to its drawbacks, the concept of a more accurate derating method is proposed in which winding eddy current losses are directly estimated using 2D-FEM.

The future trends of the research in transformer derating under harmonic operation tend to be towards methods based on the hot-spot of the transformer. Hence, in addition to electromagnetic analysis in
which only transformer losses are proposed, transformer must be
considered for valid derating method. Hence, any appropriate method in transformer derating is
one which considers both electromagnetic and thermal aspects.

6 References

4 C57.12.90: ‘IEEE standard test code for liquid-immersed distribution, power, and regulating transformers’, 2010
5 C57.12.91: ‘IEEE test code for dry-type power and power transformers – redline’, 2012
6 Lammeraner, J., Staff: ‘Eddy currents’ (CRS, Cleveland, OH, 1966)
9 C57.110: ‘IEEE recommended practice for establishing transformer derating for non-sinusoidal load currents’, 2009
10 C57.110: ‘IEEE recommended practice for establishing transformer derating for non-sinusoidal load currents’, 1999
26 C57.12.00: ‘IEEE standard test code for liquid-immersed distribution, power, and regulating transformers – redline’, 2010
The transformer is ungrounded leading to the following relationships between the phases current

\[
\begin{align*}
    i_A(t) + i_B(t) + i_C(t) &= 0 \\
    i_A(t) + i_B(t) + i_C(t) &= 0 \Rightarrow i_C(t) = -(i_A(t) + i_B(t))
\end{align*}
\]

By substituting (13) into (12) and also transferring voltage and current quantities from the secondary to the primary side, we have

\[
\Delta P = \frac{1}{T} \int_0^T \left[ v_{aC}(t)i_A(t) + v_{BC}(t)i_B(t) + v_{BC}(t)i_C(t) \right] dt - \frac{1}{T} \int_0^T \left[ v_a(t)i_A(t) + v_b(t)i_B(t) + v_c(t)i_C(t) \right] dt
\]

\[
\Delta P = \frac{1}{T} \left[ \int_0^T \left[ v_{aC}(t)i_A(t) + v_{BC}(t)i_B(t) - v_a(t)(i_A(t) + i_B(t)) \right] dt \right]
\]

\[
\Rightarrow \Delta P = \frac{1}{T} \left[ \int_0^T \left[ v_{aC}(t)(i_A(t) - i_B(t)) + v_{BC}(t)(i_B(t) - i_A(t)) \right] dt \right]
\]