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Choice of Core Material in Transformers Feeding Non-Linear Loads

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Abstract—*Transformers are usually designed to operate at rated frequency and sinusoidal waveform. Non-linear loads on transformer leads deviation in its performance causing increase power losses and accelerated heating. This result is early fatigue of insulation, premature failure and reduction of the useful life of the transformer. Geometry of the transformer has radial symmetry along each phase, but this is not so axially. This causes imbalance of magneto-motive force of coils and thus gives rise to leakage flux. In this paper the Effect of voltage harmonics on no-load losses has been investigated and a comparison has been made between CRGO steel and amorphous alloy used material in the construction of core of the transformers. This has been extended to load dependent stray losses caused by leakage flux.*

1. INTRODUCTION

Transformers are usually designed to operate at the rated frequency and linear load. Presence of harmonics is generally seen as power quality problem both by power utilities and organized consumers. Nevertheless, increasing proportion of non-linear loads [12] has been found to have severe effect on losses and life of transformers [3]. It is seen that database, in respect of presence of harmonics is insufficient and, therefore, use of Intelligent Control and Monitoring System (ICMS), as an inbuilt feature of energy accounting meters, is considered essential [10]. This would help to build ageing index of transformers, in presence of harmonics

Harmonic currents are generally generated by non-linear loads and adversely affect, almost, every component in the power system, creating an additional dielectric, thermal, and/or mechanical stresses. The harmonic currents dissipate into the network and in the process voltage drop along the power system creates harmonic voltages. These harmonic voltages lead to distortion in power supply despite power generators producing nearly sinusoidal voltages.

Growing population of nonlinear loads at lowest consumer ends, leading to formation of cluster of non-linear loads, is a matter of serious concern from the perspective of ageing and volume of transformers [11]. Some researchers have proposed use of Delta/Star/ Delta transformer for such loads. Taking a dig into topology of transformer, Delta-Fork topology has been proposed for power supply in such applications [11]. Other remedial measures for supplying cluster of non-linear loads are a) use CTC conductor for LV coils, c) use of amorphous alloy strips as magnetic shunts on tank walls, b) use of aluminum shields around connecting leads of LV side [11], and d) determine worst case hot spot temperature using FEM tools and their validation on prototype as ongoing exercise to continual improvements in design.

Typically 82% of the total losses in a transformer are specified as load losses [8], out of this about 87% is resistive loss (P_{DC}) in the windings. Remaining of the load losses comprise of about 8% as stray losses in the winding and remaining 92% other stray losses which occur in structural components. This typical proportion changes drastically in presence of the current harmonics, as discussed above.

Stray losses in the structural components are since caused by leakage flux and, therefore, it is dependent on the percentage impedance of the transformer. In large transformers and furnace transformers, which require large short -circuit impedance, problems of stray losses in structural components become more intricate. Analytical determination of these stray losses is more difficult and, therefore, researchers have been attempting it by parts viz, flitch plate [14], tank cover [13, 16, 17, 19] and other parts separately. Except for losses in the cover plate, reference to these stray losses in other components has been made for completeness of the text.

Effect of voltage harmonics on no-load losses has also been investigated and a comparison has been made between CRGO steel and amorphous alloy used in the construction of core of the transformers. These findings can be extrapolated to reduce stray losses caused by leakage flux in structural components and enclosures.

2. CORE LOSSES

No load loss or core loss appears because of time variable nature of electromagnetic flux passing through the core and constitute hysteresis loss and eddy current loss. Since distribution transformers are always under service, and moreover the large number of them in the network, it makes the overall no-load losses quite high. These losses are function of frequency and maximum flux density of the core and are independent of ideal load currents [11].

Effect of Voltage Harmonics on Core Losses:

Voltage harmonics, found during field investigations are quite small and well within permissible limits as per IEEE. This is perhaps the reason that effect of voltage harmonics on core losses is generally ignored either during life assessment or derating of transformer. However, Jain [9] has observed significant voltage harmonics on low voltage supply to 135 kW DC drive at a Sugar Factory (THD_V= 5.9%) and a computer lab (THD_V= 7.1%). The latter is a specific case of voltage harmonics at low voltage, where complete network impedance is seen by the harmonic current and this causes voltage harmonics to appear at the PCC. As regards DC drive at low voltage, but this being the largest load of the industry it is connected to the power supply with least impedance network. It has composition of voltage harmonics : V_3=0.2%, V_5= 4.2%, V_7= 1%, V_9= 0.2%, V_{11}=2.9% and V_{13}= 1.5%, as percentage of fundamental. Accordingly, this is being taken as a case of voltage harmonics for analyzing their influence on the core losses.

Classically core loss has two components hysteresis loss and eddy current loss [1, 6, 18, 20] and is expressed as –

$$P_{NL} = (k_1 f B_{max}^n + k_2 f^2 B_{max}^2 t^2)$$ Watts per Kg (1)

Hysteresis Loss (P_{hy}) + Eddy Current Loss (P_{ec})

Here,

k1 and k2 - are material constants

B_{max} - is the crest value of the flux density,

f - is the frequency of supply voltage,

t - is the thickness of lamination,

n - is the Steinmetz exponent, this is again dependent on material characteristics and operating flux density.

Initially the Steinmetz exponent was taken to be 1.6, however, with newer materials operating at higher flux densities, it is taken in the range of 1.6 to 2.5. Kulkarni [15] has suggested its value as '2' for cold rolled laminations and shall be accordingly it has been used in this thesis. Electrical Research and Development Association (ERDA) has published a report [2] on performance of transformer under harmonics. The core losses declared by lamination manufacturer are combined losses. However, ERDA has used proportion of hysteresis to eddy current losses in CRGO steel and Amorphous alloy as 1:2 and 3:1, respectively. Reduction in proportion of eddy losses in amorphous alloy is attributed to thin films of alloy, a base material, used to create strips for construction of transformer core. Typical core losses for 100 KVA transformer using CRGO and Amorphous Alloy are 256 and 60 watts. The ERDA has simplified the equation (2) taking B_{max} to be independent of frequency as under –

$$P_{NL} = (a_{hy} f + a_{ec} f^2) \quad \text{Watts per Kg (2)}$$

Hasegawa [4, 5], has also compared CRGO with amorphous alloy and using similar equation as under and compared the parameters as given in Table 1.

$$P_{NL} = (c_1 f + \frac{c_2 d^l f^m B^n}{d}) \quad \text{Watts per Kg (3)}$$

The hysteresis losses are since dependent upon 'B_{max}' also and thus making 'P_{hy}' independent of 'B_{max}' would lead to error in comparison. Amorphous alloy as compared to CRGO steel is ten times thinner and has resistivity about 3.6 times than the CRGO steel, and this makes it superior from the consideration of eddy current losses.

Table 1: Comparison of parameters of Amorphous Alloy and CRGO Steel

Property/ Exponent	AM Core	Steel Core
r	~130 mW-cm	~50 mW-cm
d	~20 mm	0.2 mm
m	~ 1.5	~ 2
n	~ 2	~ 2

As per fundamental equation, voltage is proportional to product of 'f' and 'B_{max}'. In other words for a certain voltage B_{max} shall be inversely proportional to frequency. This linear relationship in magnitude of B_{max} and 'f' is valid so long as the waveform is sinusoidal. However, distortion in voltage waveform has been analyzed using superimposition theorem on voltage harmonics. Accordingly, the equation (4) can be written as a function of voltage and frequency as also brought out by Blume et al. [1] and Vasutinsky [20] as under -

$$P_{NL} = \left[k_1 (hf) \left(K \frac{V_h}{(h)} \right)^2 + k_2 (hf)^2 \left(K \frac{V_h}{(h)} \right)^2 t^2 \right]$$

$$= \left[K_1 \left(f \frac{V_h^2}{(h)} \right) + K_2 (f V_h)^2 \right] \quad (4)$$

Here,

K - A proportionality constant of the product

($f B_{max}$) w.r.t. voltage,

K_1 - A new constant $(= k_1 K^2)$

K_2 - A the new constant $(= k_2 K^2 t^2)$

f – Fundamental frequency

Since the loss function (P_{NL}), in equation (4), has harmonic order as a variable in 'P_{hy}' and hence it would be incorrect to relate 'THD_V' to the change in losses as proposed by ERDA [2] and Hasegawa [4, 5]. However, for the typical distorted voltage it is found that that increase in 'P_{NL}' in respect of CRGO steel is 4% while for Amorphous alloy it is 1.4% as shown in the Table 2. Thus amorphous core, in addition to low eddy current loss is found is found to be friendlier to voltage harmonics as compared to CRGO steel. The behaviour of core materials to voltage harmonics is open for further investigations.

3. AMORPHOUS ALLOY CORE TRANSFORMERS:

Use of amorphous alloy core in transformers helps in reduction of the no-load losses. Amorphous core is less sensitive to voltage harmonics, as compared to CRGO steel laminations, as already discussed. Distribution networks are generally radial and constitute tail ends of the power system. Thus at tail end of the network voltage regulation exceeds the permissible limits due to high system impedance at the PCC [11]. This situation gets aggravated in presence of harmonics and is prone to increase in THD_v exceeding the permissible limits. Thus, amorphous core for transformers in such applications is considered to be a better choice. The construction of core type three-phase transformer using CRGO steel laminations is shown in Figure 1. The stepped core construction makes it possible to optimize transformer winding by for improving space factor [20]. Despite thin films of amorphous alloy, its use has been possible in transformer by compacting them into strips of uniform thickness. These strips are used to construct wound core as shown in Figure 2-A.

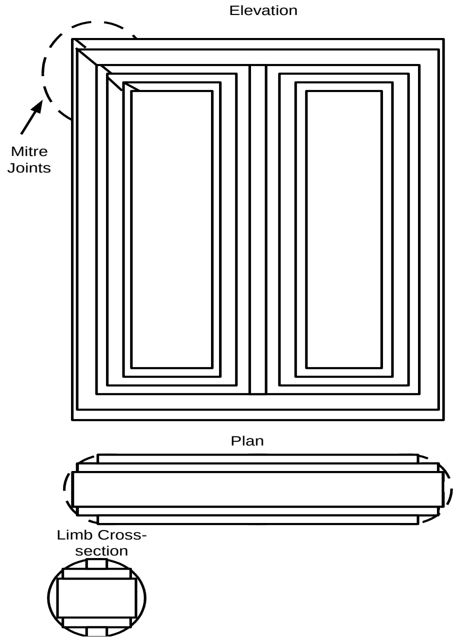
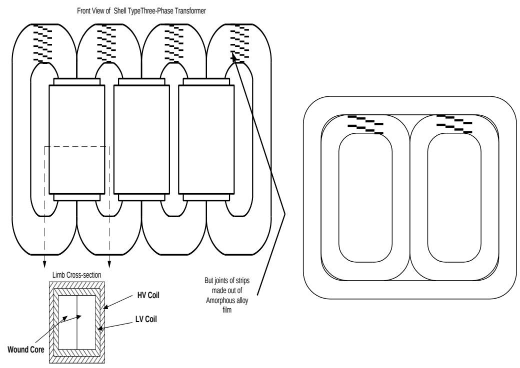


Figure 1: Construction of Three-Phase Shell Type Transformer with CRGO Steel



A. Shell Type Construction B. Core Type Construction

Figure 2: Construction of Core of Amorphous Alloy Type Transformer

Initially, it was possible to create wound cores of identical size and thus shell type transformers were built. A further improvement in handling and manufacturing of amorphous core has made it possible to construct geometry suitable for construction of core type transformer as shown in Figure 2-B. Stepped cross-section of the core is not possible with wound core, specially made out of amorphous alloy. Thus amorphous alloy cores have rectangular cross section. Use of rectangular transformer for electronic applications is quite common and is attributed to its size and VA rating. Although, distribution transformers are of small capacity in power network, the choice of rectangular core is not a preferred option. However, merits of amorphous alloy, despite constraints of construction, its use has been made in wound core construction in distribution transformers. The rectangular cross-section of wound core, apart from other electrical design consideration viz. mean length of the turn, heating of coils, and electrical stress at corners, experiences an increase in the mechanical stresses at corners of the winding as per Von Mises criteria also known as Von Mises stress [21, 22]. These stresses are critical under short circuit.

4. AMORPHOUS ALLOY MAGNETIC SHIELDS:

Stray losses constitute about 15% of load losses. Use of magnetic shunts and replacement of flitch plates with non-magnetic material has been attempted. Characteristics of amorphous alloy, exhibiting low eddy current loss, can be advantageously used for providing magnetic shunts for leakage flux along the structural components and is an area of exploration. Losses in cover plates have been a matter of concern in converter and high current transformers. Use of aluminum shield to reduce the losses in cover-plate has been demonstrated earlier. Such a shield on leads of LT terminals in converter and high current transformers, and transformer feeding cluster of non-linear loads is considered essential. However, utility of such shields around leads is constricted in case high proportion of third harmonic and zero-sequence currents in the load.

5. CONCLUSIONS

Effect of harmonics on core losses reveals that amorphous alloy is less sensitive to no-load losses as compared to CRGO steel laminations. Therefore use of amorphous core transformers would help to reduce effect of voltage harmonics, caused by non-linear loads, in distribution transformers. Further, transformers having high impedance and non-linear loads, such as traction, welding and furnace transformers, are suitable for use of amorphous alloy magnetic shields. Use of amorphous alloy in core necessitates rectangular cross-section, which has, however, affects short-circuit strength of transformers and hence needs special care during design.

Table 2: Analysis of Effect of Voltage Harmonics on Core Losses

Particu-lars	**Freque-ncy (Hz)**	**Harm o-nic Order**	**Composi-tion**	**Core Losses in CRGO Steel (in Watts)**			**Core Losses in Amorphous Alloy (in Watts)**		
				Hys-tere-sis Loss	**Eddy Current Loss**	**Total Loss**	**Hystere-sis Loss**	**Eddy Cur-rent Loss**	**Total Loss**
Base Case	50	1	100%	85.33	170.67	256	45	15	60
	Constants calculated using equation (4)			K_1	K_2		K_1	K_2	
				1.7067	0.0683		0.90	0.01	
Typical Voltage Distorted Voltage	50	1	99.85%	85.08	170.17	255.3	44.87	14.96	59.824
	150	3	0.20%	0.01	1.70	1.7	0.00	0.15	0.153
	250	5	4.20%	0.00	7.50	7.5	0.00	0.66	0.660
	350	7	1%	0.00	1.88	1.9	0.00	0.16	0.165
	450	9	0.20%	0.00	0.02	0.02	0.00	0.00	0.002
	550	11	2.90%	0.00	0.04	0.04	0.00	0.00	0.003
	650	13	1.50%	0.00	0.02	0.02	0.00	0.00	0.002
	Total Losses with distorted voltage					**266.4**			**60.81**

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