Power System Harmonic Effects on Distribution Transformers and New Design Considerations for K Factor Transformers

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ABSTRACT

This paper presents the effects of harmonic distortion of load current & voltages on distribution transformers, the standard ways of calculating the harmonic effects & design & development of K Factor transformer, which can operate under a specific harmonic environment. The usage of non-linear loads on power systems has increased the awareness of the potential reduction of a transformer's life due to increased heat losses. The performance analysis of transformers in a harmonic environment requires knowledge of the load mix, details of the load current harmonic content & total THD. The additional heating experienced by a transformer depends on the harmonic content of the load current & the design principals of the transformer.

Both No load & Load losses are affected by the presence of harmonics in load currents. But the variation in load losses contributes more to excessive heat generation in distribution transformer. Increment in no load losses in a distribution transformer due to harmonics is less compared to the load loss but it has a significant contribution to the capitalization cost when operating in longer term.

The load loss components get affected by the harmonic current loading are the I2R loss, winding eddy current loss & the other stray losses.

The K-FACTOR method is an approximation of the total stray loss heating effect, including the fundamental and harmonic contributions & finally new design techniques for K-FACTOR transformers are discussed. In designing of K-FACTOR transformers different design techniques like parallel conductor arrangement for windings, lower flux density & introduction of static shields are discussed & the estimated results are compared with actual implemented results.

Index Terms

Harmonics, Transformer losses & heating, K FACTOR, Isolation transformers

1.0 INTRODUCTION

The present design trend in electrical load devices is to increase energy efficiency with solid-state electronics. One of the major drawbacks of this trend is the harmonics injection to the power system. Almost all the utilities have expressed concern about overheating of oil immersed distribution transformers that supply the non-linear loads.

Transformer thermal response to sinusoidal loads is properly evaluated at the transformer design stage, but it's actual response to non-linear loads should be estimated after proper evaluation of actual load conditions. The increasing usage of non-linear loads on electrical power systems is causing greater concern for the possible loss of transformer life. Manufacturers of distribution transformers have developed a rating system called K-FACTOR, a design which is capable of withstanding the effects of harmonic load currents. Application of this rating system to specify a transformer for a particular environment requires knowledge of the fundamental & harmonic load currents predicted. In almost all the cases field measurements are required to diagnose problems at a specific location, by analyzing load currents. In addition to the transformer evaluation, some utility companies are establishing current harmonic distortion limits at customer connections in order to improve overall service quality based on the new IEEE 519 standard. These developments increase the need for monitoring of harmonic currents both at utility ties to industrial & commercial customers and at transformers.

2.0 GENERAL LIMITATIONS & EFFECTS OF TRANSFORMER OVERHEATING

The actual life duration of a transformer depends to a high degree on extraordinary events, such as over heating [1] due to harmonic load currents.

Decisive for the survival after such events, which can occur either separately or in combination are,

(I) The severity of the event.

(II) The transformer design.

(III) The temperature of the various part of the transformer.

(IV) The concentration of moisture in the insulation & in the oil.

(V) The concentration of oxygen & other gases in the insulation & in the oil.

(VI) The number, size & type of impurity particles.

The normal life expectancy is a conventional reference basis for continuous duty under normal ambient temperature & rated operating conditions. The application of a load in excess of rated load (Here, author considers the frequency spectrum) will cause over heating & involves a degree of risk & accelerated ageing.

The consequences of non-linear loading are as follows.

(a) The temperatures of windings, cleats, leads, insulation & oil increase & can reach unacceptable levels.

(b) The leakage flux density outside the active parts increases, causing additional eddy current heating in metallic parts linked by the flux.

(c) The combination of the main flux & the increased leakage & zero sequence flux imposes restrictions on possible core over excitation.

(d) As the temperature changes, the moisture & gas content in the insulation & in oil will change.

(e) Bushings, tap changers, cable-end connections and current transformers will also be exposed to higher stresses, which encroach upon their design & application margins.

Short - term risks

The main risk, for short-term failures, is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress. These bubbles may develop in the paper insulation, when hot spot temperature rises suddenly above a critical temperature.

Long-term risks

Cumulative thermal deterioration of the mechanical properties of the conductor insulation will accelerate at high temperatures. If this deterioration proceeds far enough, it may reduce the effective life of the transformer.

3.0 EFFECTS OF NON-SINUSOIDAL VOLTAGES & CURRENTS

The principal effect of non-sinusoidal voltages on the transformer's performance is the generation of extra losses in the core[2].

Non-sinusoidal currents generate extra losses & heating of the conductors, enclosures, clamps, bolts etc, thus reducing the efficiency of the transformer & accelerating the loss of life of the insulation due to the additional heating of the windings. This will lead to a reduction in expected life span of a distribution transformer & the method of calculating the reduction in life span is clearly explained in IEC 354, *Loading guide for oil- immersed power transformers.*

An additional effects of harmonics in the network is possible oscillations between the transformer and line capacitances or any installed capacitors.

4.0 TRANSFORMER HARMONIC CONCERNS

The industry has recognized for many years that voltages and currents with frequencies other than 50/60 Hz results in additional heating in iron-cored devices may be motors or transformers. This fact is recognized in standard ANSI/IEEE C 57.12.00-2000, IEEE Standard General Requirements for Liquid immersed-Distribution, Power & Regulating Transformers & IEC 60076 Power Transformers, which states that power transformers should not be expected to carry load currents with harmonic factor in excess of 5% of rating. In actual practice how ever, non-linear loads are routinely connected to the power system by customers with little regard to their harmonic currents, or the impact on equipment serving the load.

Another standard ANSI / IEEE

C 57.110- 1998, IEEE Recommended Practice for Establishing Transformer Capacity When Supplying Non-sinusoidal Load Currents, recognizes that harmonic rich load currents are possible & describes a method for de-rating a transformer due to the higher frequencies contained in the load current.

5.0 REVIEW OF TRANSFORMER LOSSES

Transformer losses are categorized as no-load loss (excitation loss); load loss (impedance loss); and total loss (the sum of no-load loss and load loss). This can be expressed by the equation (1).

$$P_T = P_C + P_{LL} \qquad \text{---(1)}$$

Where

P_T Total loss, watt

P_C Core or No load loss, watt

P_{LL} Load loss, watt

Load loss is subdivided into I^2R loss and "stray loss". Stray loss is determined by subtracting the I^2R loss (calculated from the measured resistance) from the measured load loss (impedance loss).

"Stray loss" can be defined as the loss due to stray electromagnetic flux in the winding, core, core clamps, magnetic shields, enclosure or tank walls, etc [3]. Thus, the stray loss is subdivided into winding stray loss and stray loss in components other than the windings (P_{OSL}). The winding stray loss includes winding conductor strand eddy-current loss and loss due to circulating currents between strands or parallel winding circuits. All of this loss may be considered to constitute winding eddy-current loss, P_{EC}. The total load loss can then be stated by equation (2)

$$P_{LL} = P + P_{EC} + P_{OSL} \text{ watt} \qquad \text{---(2)}$$

6.0 HARMONIC EFFECTS ON TRANSFORMER LOSSES

The contribution made by harmonic currents to different loss components of the transformer is described in this section. The loss components get affected by the harmonic current loading are the I^2R loss, winding eddy current loss and the other stray losses.

(a) Harmonic current effect on I^2R loss

If the rms value of the load current is increased due to harmonic component, the I^2R loss will be increase accordingly.

(b) Harmonic current effect on P_{EC}

Winding eddy current loss (P_{EC}) in the power frequency spectrum tends to be proportional to the square of the load current and the square of frequency. It is this characteristic that can cause excessive winding loss and hence abnormal winding temperature rise in transformers supplying load currents.

(c) Harmonic current effect on P_{OSL}

It is recognized that other stray loss (P_{OSL}) in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current. However, these losses will not increase at a rate proportional to the square of the frequency, as in winding eddy losses. Studies at manufacturers and other researchers have shown that the eddy current loss in bus bars, connecting and structural parts increase by a harmonic exponent factor of 0.8 or less [4].

(d) DC Components of load current

Harmonic load currents are frequently accompanied by a dc component in the load current. A dc component of load current will increase the transformer core loss slightly, but will increase the magnetizing current and audible sound level more substantially. Relatively small dc components (up to the rms magnitude of the transformer excitation current at rated voltage) are expected to have no effect on the load carrying capability of a transformer determined by this recommended practice. Higher dc current components may adversely affect transformer capability and should be avoided.

(e) Effect on top oil rise

For liquid-filled transformers, the top oil rise (θ_{TO}) will increase as the total load losses increase with harmonic loading. Any increase in other stray loss (P_{OSL}) will primarily affect the top oil rise.

7.0 METHODS OF HARMONIC EFFECTS EVALUATION

Two methods of calculations are there based on data availability.

The first is intended to illustrate calculations by those with access to detailed information on loss density distribution within each of the transformer winding. The second method is less accurate and is intended for use by those with access to transformer certified test report data only.

8.0 INTRODUCTION TO THE CONCEPT OF K-FACTOR

The definition for the K FACTOR can be given as follows according to the IEE Std. C57.110-1998

K-FACTOR – "A rating optionally applied to a transformer indicating its suitability for use with loads that draw non-sinusoidal currents."

The K – FACTOR = $\sum_{h=1}^{\infty} I_h(pu)^2 h^2$

This K-factor is only an indicative value and the authors' main objective is to design and manufacture a oil filled distribution transformer which can operate for a specific K-Factor value without loosing it's expected life span.

9.0 NEW DESIGN CONSIDERATIONS FOR K-FACTOR TRANSFORMERS

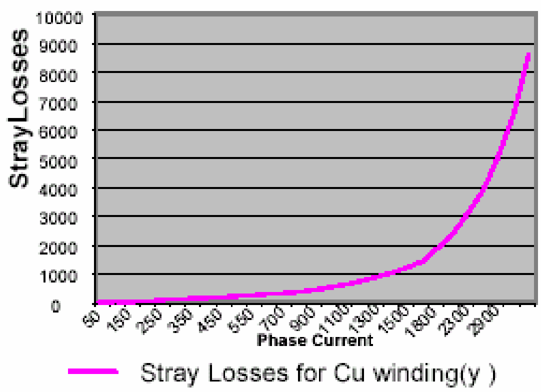
Considerations for the transformer core [15]

Generally distribution transformer core is manufactured with various types of CRGO (Cold Rolled Grain Oriented) steel and the steel grade is decided upon the losses requirements imposed by the utilities and it's basically designer's choice. For typical 50Hz distribution transformer design superior grade CRGO like 27 ZH 100 or H-1 is used and typical design flux density would be the knee point of the specific B-H curve.

Study of Stray loss variation with the transformer Capacity

In this study fourteen types of distribution transformers were considered for evaluation and the stray losses were tabulated as follows against rms phase current.

All the testing were conducted at 50Hz.



Stray loss control

A minimum stray loss can be achieved by analyzing systematically, the source of leakage flux and its path. Various methods are mentioned below.

Magnetic Yoke Shields

Magnetic shields, made up of core laminations are used under yokes as shown in fig 3.2. A large proportion of the axial leakage flux is fed back in to the yokes. The yoke clamp assembly is shielded and reduction of radial flux to tank side is also achieved. In this research the author propose to use completely non-metallic material for core clamping with magnetic shields.

Magnetic shunts

The magnetic shunts consisting of packets of core laminations are fixed inside the tank to absorb stray flux. The thickness of lamination packets is decided by the flux density used.

Reduction of losses in windings Subdivision of conductors radially reduces the eddy current loss due to axial leakage field. Similarly, subdivision of conductors axially reduces the eddy current loss due to radial component of leakage field. To reduce radial component of leakage flux, it is essential that ampere- turn of HV and LV windings shall be perfectly balanced, which in turn gives the reduced eddy current loss due to radial component of leakage flux. It is worth mentioning here that large unbalance in ampere –turns may lead to very high stray loss. To eliminate the circulating current between parallel strands of a turn, transposition is essential. This leads to positioning of strands of a turn, such that flux linkage is the same, thus equalizing the induced emf in each strand.

Losses due to leads

Losses due to high current leads can be reduced by spacing them suitably from metallic structures. The field effect of leads can be eliminated by positioning together the current carrying leads of opposite direction. In three-phase connection, the leads of all three phases can be grouped together so that the net vertical effect of field is minimum. Losses due to leads can be reduced by shielding the nearby surfaces by non-metallic material. High current bushing mounting plate has high eddy current losses. This can be reduced by putting the non-magnetic inserts to break eddy current path or by using a non-metallic steel plate.

Effect on insulation class

The insulation, for a transformer immersed in oil, pressboard, crepe tubing and paper. All in temperature class A, (105^0C). The rate of aging of insulation is very dependant on the service temperature, which depend on the loading.

According to IEC 354 a decrease/increase of 6^0C will double/halve the life of an insulator.

Therefore it is recommended to use class H, (150^0C) insulation to with stand local overheating.

Impact on the neutral

When the harmonic current frequencies include harmonic orders having multiples of three (3,6.9…etc), zero sequence currents flow in the neutral. To overcome this situation the recommended action is to double the size of the neutral conductor.

Usage of Electrostatic Grounding Shields

The electrostatic shields which is placed between primary and secondary windings tends to reduce capacitive coupling between the windings. This basically reduces the transients between the two windings. Line disturbances produced by the converter equipments connected to the transformer secondary will be reduced, but will not be eliminated on the primary side of the transformer. The shields are not intended to reduce the harmonic currents, but by virtue of their magnetic coupling to windings carrying such currents, additional heat losses are induced. The electrostatic shields are a supplement but not necessarily a replacement for harmonic current filtering.

The electrostatic shields also serve as protection to the secondary side of the transformer from transients that may occur on the high voltage winding. This is specially important for transformers with ungrounded secondaries. Transients on the high voltage side of a transformer can dramatically increase the surge voltage seen on an ungrounded secondary winding from what may have been expected for a grounded winding. This may damage transformer windings and parts or equipment connected on the secondary side of the transformer. The presence of an electrostatic grounding shields between primary and secondary windings reduces the magnitude of the transient coupled to the secondary windings and it appears that the harmonics are attenuated by factors varying from a low of 1.9 to high of 5.4. The average attenuation is approximately 3 [19].

10.0 RESULTS

The main objective of the case study is to verify the performance of the designed K factor transformer comparing it with conventional oil immersed unit.

The conventional transformer was designed with standard parameters and the new K factor transformer was designed by considering the facts mentioned in the paper.

The basic specifications of the transformers are given in the table 1 and the parameters considered are given in table 2.

Table 1 – Transformer specifications

	CONVENTIONAL	K-FACTOR
CAPACITY (kVA)	5	5
INPUT VOLTAGE (V)	230	230
NO. OF PHASES	1	1
TYPE	Oil immersed	Oil immersed
OUTPUT VOLTAGE (V)	230	230
% IMPEDANCE	5.6	5.6
NO LOAD LOSSES @ 50HZ	30.00	31.60
I^2R LOSSES @ 50HZ	66.49	66.50
STRAY LOSSES @50HZ	5.06	5.00

Table 2 – Parameters considered

PARAMETER	CONVENTIONAL	K-FACTOR
Flux Density (T)	1.70	1.55
Primary Current Density (A/mm^2)	2.56	2.04
Secondary Current Density (A/Sq-mm)	2.56	2.04
Electrical clearances	Standard	< Standard
Parallel conductors	No	2
Magnetic Shields	No	Yes
Electrostatic Shields	No	Yes

Two temperature rise tests were done at 50Hz, according to the guide lines given by IEC 60076 and the tabulated results are as in table 3.

Table 3 – Top oil temperature

	CONVENTIONAL	K-FACTOR
Top oil temp. (°C)	38	37.6

According to above results it can be considered that the performance of both transformers under nominal conditions are the same.

The second temperature test was carried out with a harmonic load the arrangement is as in figure 1.

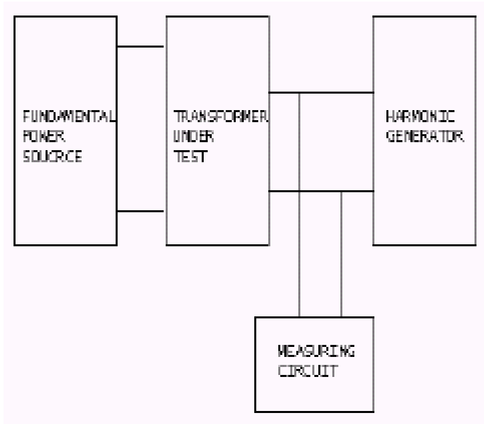


Figure 1 – Harmonic Load Test Arrangement

The basic circuit arrangement of the harmonic generator is as in the figure 2.

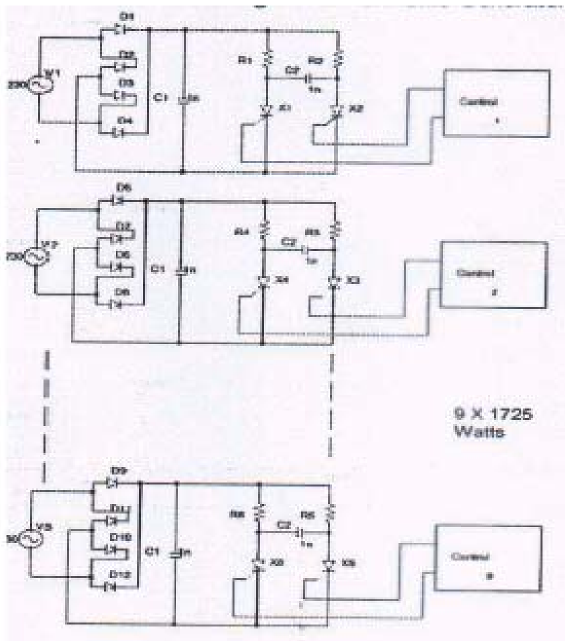


Figure 2 – Schematic diagram of harmonic generator

The circuit consists of 9 parallel circuits and only 3 circuits were used for the experiment.

The harmonic load profile was analyzed with CIRCUTAR power analyzer and the equivalent K factor for the harmonic condition was calculated as indicated in IEEE C.57.110-1998.

Table 4 – K factor calculation

h	Ih/I1	$(Ih/I1)^2$	h^2	$(Ih/I1)^2h^2$
1	1.000	1.00000	1	1.00000
2	0.044	0.00194	4	0.00776
3	0.092	0.00846	9	0.07614
4	0.022	0.00048	16	0.00768
5	0.412	0.16974	25	4.24350
6	0.018	0.00032	36	0.01152
7	0.199	0.03960	49	1.94040
8	0.010	0.00010	64	0.00640
9	0.018	0.00032	81	0.02592
10	0.015	0.00023	100	0.02300
11	0.046	0.00212	121	0.25652
12	0.010	0.00010	144	0.01440
13	0.048	0.00230	169	0.38870
		K-FACTOR		**8.00194**

Two temperature rise tests were done at 50Hz, according to the guidelines given by IEEE Std C57.110-1998. The tabulated results are as in table 5.

Table 5 – Top Oil Temperature

	CONVENTIONAL	K-FACTOR
Top oil temp. (^{0}C)	54	47

In both the transformers temperature rise has gone up but in the K-factor transformer the top oil temperature remains in the acceptable limits.

So by observing the above results it can be concluded that the designed K-factor transformer can be used for a non-linear load, K value up to 8.

11.0 CONCLUSION

The new design considerations proposed, helped to reduce the effects of harmonics, and the experiments done with the 5kVA transformer certify the facts. It is observed that the current harmonics are playing a dominant role in additional heating effects, but always there should be a proper attention by the utility engineers, on the voltage harmonics also. The case study done with the 12-pulse transformer shows that there can be severe cases than expected.

The proposed modification done to the winding construction and the clamping structure has contributed significantly to the stray loss reduction. But for low capacity transformers (below 50kVA) experiences less effects due to harmonics as their construction it self can withstand to some extent.

There should be a proper dialog between the transformer designers and the utilities in order to mitigate theses conditions as the designers cannot always predict or assume the real situation at the customers end. It's very important to note that the transformers which are intended to supply loads with high harmonic current must be specified with a harmonic current distribution. The designer cannot "assume" nor can the user expect the designer to use "standard' or "typical" current distribution table. If the harmonic content of the load is unknown, then both the user and the transformer designer are at risk and reasonable steps should be taken to ensure a conservative design for the application. Guidelines on how this information is used to develop proper transformer sizing and new design techniques are provided in this thesis. But the appropriate calculations specific to the type of transformer design are the responsibility of the designer.

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