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Design Analysis and Parametric Modeling of Harmonics Effects on a 1.5kva Single Phase Wooden Cross Cutting Machine Step Down Transformer

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Abstract

This paper aims at x-raying the design analysis and parametric modeling of harmonics effects on a 1.5KVA single phase wooden cross cutting machine step down electric service transformer. The literature survey was considered and the research work was realised through analytical designs and parametric modeling of harmonics effects on a single phase, core type electric service transformer which steps down the 240volts mains voltage to the appropriate voltage level of 120volts. The electric service transformer has efficiency of 96.02% with maximum load efficiency of 42.69%, and 5.07% of total losses in the system. This research work will be relevant to transformer designers and students, as it exposes the full design analysis and calculations of transformers; and its basic parametric models.

Keywords: *Design and analysis, losses, model, magnetic flux density, parametric, transformer calculations*

1.0 INTRODUCTION

Transformers are veritable tools in electrical power system and their functions are significant especially in stepping up and stepping down (transformation) of voltages/currents for appropriate usage. The advent of transformer has given leverage to long transmission of electricity from the point of production to the point of consumption. Electricity is a particularly attractive form of energy that can be easily produced, transmitted and transformed into other form of energy [1]. The transformation of voltage and current in electricity supply is carried out by an apparatus called the transformer. "Transformers are very useful in many electrical circuits. Consequently, the transformer is a device which plays a vital and essential role in many facets of electrical engineering" [2]. Therefore, "Transformer is a static (stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit" [3]. It can raise or lower the voltage in a circuit but with corresponding decrease or increase in current [3].The importance of transformer in voltage transformation in our everyday life cannot be overemphasized [4]. Transformer forms the basis for the design, construction and operation of many electrical and electronics devices [4]. The principle of operation is based on the basic principle of electromagnetic induction which was discovered by Michael Faraday in 1813 [4].

Transformers are basically passive devices for transforming voltage and current [5]. One of the windings, generally termed as secondary winding, transforms energy through the principle of mutual induction and delivers power to the load [5]. The voltage levels at the primary and secondary windings are usually different and any increase or decrease of the secondary voltage is accompanied by corresponding decrease or increase in current [5]. Transformers are among the most efficient machines; 95% efficiency being common in lower capacity ranges, while an efficiency of the order of 99% is achievable in high capacity range [5].

According to Evbogbai and Obiazi [6], transformers can be manufactured from locally materials as reported in their work titled "Design and construction of small power transformers using locally available materials". The study showed that electrical machines could be constructed locally since Nigeria is blessed with iron, steel, and the availability of copper and aluminum conductors for the windings [4].

In this research work we trying to get clear cut for design analysis and parametric modeling of harmonics effect of a 1.5KVA single phase wooden cross cutting machine step down transformer in carpentry workshop of the School of Engineering Technology, National Institute of Construction Technology, Uromi, Nigeria.

1.2 TYPES OF TRANSFORMERS IN TERMS OF CONSTRUCTION

Transformers are classified according to their construction into two main types namely: Core and Shell types [7]:

a. **Core Type Transformer**
   Every transformer consists of a magnetic circuit of laminated iron core with which the electric circuits, primary and secondary are linked. The coils in this type are cylindrical in form and placed one inside the other with proper insulation between them. The portion of

the core over which comes the windings is called limb or leg whereas the core which connects the two limbs are called the yoke. The cross - sectional area of the yoke is normally greater than that of the limb but it may be equal also.

b. Shell Type Transformer

In the shell type of transformer, both the windings, low voltage (L.V) and high voltage (H.V) are put around the central limb. The winding is called the Sandwich winding where flat rectangular or circular coils, alternately L.V and H.V., are arranged one above the other with the necessary insulation between them. The cross - sectional area of the central limb is twice that of the side limbs as it carries double the flux than the side limbs. Consequently, the width of the central limb is twice that of the side limbs keeping the same core depth throughout.

1.3 MATERIALS AND METHODS

A 1.5KVA, 240volts, single phase transformer transform the mains voltage to 120volts; 12.5amps to power a single phase wooden cross cutting machine in the Civil Engineering Department of the School of Engineering Technology in the National Institute of Construction Technology, Uromi, Edo State, Nigeria. The transformer was designed using indigenous knowledge in view of local materials available for its realization. The harmonics effect was analyzed to mitigate any possible losses that may be caused by it. The wooden cross cutting machine, its function is to provide cross cutting wooden materials for a specified purpose(s). The wooden cross cutting machine provides human-machine interface with its function of optimizing cutting in wooden materials.

1.4 DESIGN SPECIFICATIONS AND ANALYSIS

1.4.1 DESIGN SPECIFICATIONS

The machine design procedure for core and shell types of power and distribution transformers have been reported by [5 & 7]. The design differences lies on the specifications of the machine to be designed and plan.

The following are the specifications of the single phase wooden cross cutting machine step down electric service transformer that the design strives to achieve.

Power rating, $S = 1.5KVA$
Input voltage, $V_1 = 240V$
Output voltage, $V_2 = 120V$
Frequency, $F = 50Hz$
Maximum flux density, $B_m = 1.25wbm^{-2}$
Current density, $\delta = 2.5A/mm^2 = 2.5x10^6\ Amp/m^2$
Constant $K = 0.8$

Window space factor $K_w = \dfrac{10}{30 + kv} = 0.33$

Type of construction : core type
Cooling medium : Air Natural Air Natural (ANAN)

1.4.2 DESIGN ANALYSIS AND CALCULATIONS

Core - Design

The voltage per turn, $E_t = K\sqrt{S}$ (1)

$E_t = 0.98V$

Calculating the core area, A_i

$$A_i = \frac{E_t}{4.44FB_m} \quad (2)$$

$A_i = 35cm^2$

Calculating the magnetic flux, ϕ_m

$$\phi_m = A_i B_m \quad (3)$$

$\phi_m = 4.38$ mWb

Calculating the diameter of circumscribing circle around core, d

Since the transformer is core type and square section that is to be used.

$A_{gross} = 0.5d^2$ (4)

$A_i = k_s A_{gi}$ (5)

Assuming stacking factor $k_s = 0.9$

$$\Rightarrow d = \sqrt{\frac{A_i}{.0.9\ x\ 0.5}} \quad (6)$$

d = 8.82cm

Calculating the width of lamination

Since, the core is to be square section,

Width of lamination is (a) = 0.71d (7)
= 6.26cm

Calculating the net window area (A_w)

The expression for the output power of a single phase transformer is:

$KVA_{1-ph} = S = 2.22f\ B_m A_i A_w\ K_w\ \delta x10^{-3}$ (8)

$A_w = S\ x10^3/2.22f\ B_m A_i K_w\ \delta$

$A_w = 32.18\ cm^2$

However, $A_w = H_w\ xW_w$ (9)

Window Design

Calculating the core dimensions

The centre - to - centre distance of the core is twice the core width, i.e (stack)

This will be equal to 2x0.71d = 1.42d (10)

= 12.52cm

Centre - to - centre distance between limbs

Limbs = W_w x d (11)

W_w x d = 12.52

W_w = 12.52 - d

W_w = 3.7cm

Therefore, H_w = 8.70cm

Calculating overall core height, H

The overall core height, H

H = H_w + 2(0.71d) (12)

H = 21.22cm

Calculating the overall with of core, W

The overall width of core, W

W = W_w + d + 0.71d (13)

W = 18.78cm

Yoke Design

Calculating the stack height, S_h

Stack height, S_h

$$Sh = \frac{A_i}{0.9\ x\ 0.71d} \quad (14)$$

$$= \frac{35}{0.9\ x\ 0.71\ x\ 8.82} = 6.21cm$$

Calculating the number of lamination, n_L

$$n_L = \frac{\text{stack height}}{\text{thickness of laminar}} \quad (15)$$

n_L = 207

Calculating the current for both primary and secondary circuits

Given the output power, S = 1.5KVA

The primary voltage (Input voltage) V_1 = 240V

Input current at the primary winding of the transformer is:

$I_1 = S/ V_1$ (16)

I_1 = 6.25A

$I_2 = S/ V_2$ (17)

I_2 = 12.5A

Given the voltage per turn, E_t = 0.98V

Calculating the primary turn, T_1

$T_1 = V_1/ E_t$ (18)

T_1 = 245 turns

Calculating the secondary turn, T_2

$T_2 = V_2/ E_t$ (19)

T_2 = 122 turns

Calculating the conductor size for the primary and secondary windings

The cross sectional of the conductor is:

$A = I/\delta$ (20)

Calculating the primary conductor size, A_1

From equation 20, $A_1 = I_1/\delta$

$A_1 = 2.5mm^2$

Calculating the secondary conductor size, A_2

From equation 20, $A_2 = I_2/\delta$

$A_2 = 5mm^2$

Calculating the diameter of the conductor

Area, $A = \pi d^2/4$ (21)

$$\therefore d = \sqrt{\frac{4a}{\pi}} \quad (22)$$

Where d = diameter of the conductor

Calculating the diameter of the primary conductor, d_1

$$d_1 = \sqrt{\frac{4x2.5}{\pi}} = 1.7mm$$

Calculating the diameter of the secondary conductor, d_2

$$d_2 = \sqrt{\frac{4x5}{\pi}} = 2.52mm$$

d_1 corresponds to standard wire gauge of 15

d_2 corresponds to standard wire gauge of 12

Calculating the window space factor, k_w

$$K_w = \frac{10}{30 + kv} = 0.33 \quad (23)$$

Calculating the mean length per turn (L_{mt}) for both primary and secondary coils

$L_{mt} = (L_{mt1} + L_{mt2})/2 = \pi D_m = \pi[d + W_w/2]$ (24)

L_{mt} = 0.3352m

Calculating the length of primary turns, L_1

Length of primary coils, $L_1 = L_{mt}$ x T_1 (25)

L_1 = 82.12m ≈ 82m

Calculating the length of secondary turns, L_2

Length of secondary coils, $L_2 = L_{mt}$ x T_2 (26)

L_2 = 40.89m ≈ 41m

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Calculating the resistance of the primary winding, R_1

$R_1 = \rho L_1 / A_1$ (27)

$R_1 = 0.5584\Omega$

Calculating the resistance of the secondary winding, R_2

$R_2 = \rho L_2 / A_2$ (28)

$R_2 = 0.1390\ \Omega$

Calculating the yoke dimensions

Calculating the depth of the yoke, D_y

$D_y = a = 2 \times 0.71d$ (29)

$D_y = 12.52cm$

Calculating the area of the yoke, A_y

$A_y = 1.2A_y = 1.2 \times 0.5d^2 = 0.6\ d^2$ (30)

$A_y = 46.68cm^2$

Calculating the height of the yoke, h_y

$h_y = A_y/D_y$ (31)

$h_y = 3.73cm$

Calculating the weight of the iron core, W_{ic}

Weight of iron core =
(iron volume) x (iron density) (32)

Volume of iron core = total length of mean flux path (L_m) x iron area (A_i) (33)

$L_m = 2[W_w + d] + 2[H_w + a]$ (34)

$L_m = 54.96cm$

Volume of iron core = Lm x A_i (35)

$= 1923.6cm^3$

Weight of iron core (W_{ic}) = Lm x A_i x D (36)

$= 1923.6 \times 7.870 \times 10^{-3} = 15.138kg$

Calculating the weight of both primary and secondary coils or windings, W_c

The weight of primary coils or winding, W_{c1}

$W_{c1} = DA_1LmtT_1$

(37)

$W_{c1} = 1.83kg$

The weight of secondary coils or winding, W_{c2}

$W_{c2} = DA_2LmtT_2$ (38)

$W_{c2} = 1.82kg$

Total weight of copper in transformer, W_T

$W_T = W_{c1} + W_{c2}$ (39)

$= 3.65kg$

Calculating the total copper loss, P_c

$P_c = I_1^2R_1 + I_2^2R_2$

(40)

$P_c = 43.53$ watts

Calculating resistance drop per unit in the coils or winding for both primary and secondary

Calculating the resistance drop per unit winding for primary

P.U. resistance drop, $\varepsilon_{r1} = I_1R_1/V_1$ (41)

$\varepsilon_{r1} = 0.0145pu$

Calculating resistance drop per unit winding for secondary

P.U. resistance drop, $\varepsilon_{r2} = I_2R_2/V_2$ (42)

$\varepsilon_{r2} = 0.01458pu$

Calculating the inductance of coils or turns for both primary and secondary windings

Calculating the inductance of primary turns, L_{L1}

$L_{L1} = T_1\Phi/I_1$ (43)

$L_{L1} = 171.70\ H$

Calculating the inductance of secondary turns, L_{L2}

$L_{L2} = T_2\Phi/I_2$ (44)

$L_{L2} = 42.75\ H$

Calculating the weight of iron in core and yoke assembly

Weight of two limbs in a core = $2h_wA_iD_L$ (45)

$= 4.628kg$

Weight of one yoke = WA_yD_L (46)

$= 6.663kg$

Calculating the core losses in limb and yoke

Core loss in limb = 2 x weight of limb (47)

= 9.256Watts

Core loss in yoke = 1.4 x weight of yoke (48)

= 9.328Watts

Total core loss (Iron loss) (P_i) =
core loss in yoke + core loss in limb (49)

$P_i = 18.584$Watts

Total losses in the transformer (P_T) = copper losses (P_c) + iron losses (P_i)

$P_T = P_c + P_i$ (50)

$P_T = 62 \times 10^{-3}$ kW

Calculating the load for maximum efficiency

For maximum efficiency to occur:

$X^2P_c = P_i$ (51)

$$\Rightarrow X = \sqrt{\frac{P_i}{Pc}} \quad (52)$$

X = 0.4269

Meaning that the maximum efficiency occurs at 0.4269 times of full load. Recall that the maximum efficiency of a distribution (service) transformer occurs at or near 1/2 full load.

Calculating the efficiency of the service transformer

Efficiency at full load and unity P.F (η_T) = [Output power/Output power + losses] x 100

η_T = [Output power/Input power] X 100 (53)

η_T = 96.02%

1.5 PARAMETRIC MODELING AND ANALYSIS OF HARMONICS EFFECTS ON ELECTRIC SERVICE TRANSFORMER

The impact of harmonics currents on transformers is more serious on convectional conductors because the resistive skin effect is enhanced within closely - spaced transformer windings [8]. Harmonics are one of the major power quality problems that exists. Harmonics are complex waveforms produced due to the superposition of sinusoidal waves of different frequencies [3]. The flux density in transformer is usually maintained at a fairly high value in order to keep the required volume of iron to the minimum; but due to the non-linearity of magnetisation curve, some third harmonic distortions are always produced [3].

Most electric service transformers are highly vulnerable to overheating, leading to insulation damage which causes the premature failure of the transformer. As reported by [8], "The failure rate of transformer caused by harmonics effect is very high in India; around 25% per annum, which is favourably comparable to international norms of 1 - 2%". Therefore, an attempt was made in this research work to analyse and carry out the parametric modeling of harmonics effect on the 1.5KVA service transformer.

1.5.1 CAUSES OF HARMONICS AND EFFECTS ON ELECTRIC SERVICE TRANSFORMER

The main sources or causes of harmonics in electrical power system are non-linear loads that produce harmonic voltage and current in the system. The nonlinear load that causes harmonics are as follows: transformers, converters, generators, motors, fluorescent lighting, electric ballast, arc welding machine etc.

The interest of harmonics effect is placed on the subject because of the harmfulness they have on power system and its equipment. The harmonics effect are enormous and they include: overheating, vibration, reduction of system efficiency, aging of system installation, poor system power factor, inaccurate operation of system protection equipment, humming of system machines, increase in system I^2R losses etc.

1.5.2 PARAMETRIC MODELING OF HARMONICS EFFECTS ON ELECTRIC SERVICE TRANSFORMER

"The effect of harmonics in electric service transformer increase the eddy current and hysteresis losses in the system. But transformers are designed to deliver the required power to the load with minimum losses at the fundamental frequency"; though the multiple integer of the fundamental frequency increases losses in the system. Hence, the harmonics of the devices in the system are modeled through the copper losses since the copper loss is the summation of eddy current loss (P_e) and hysteresis (P_h) losses in the system respectively. If the output voltage is small, then the output current increases which causes great heat and losses in the system. The total losses of a transformer are obtained by calculating the sum of these losses (P_c).

$$P_c = P_e + P_h = K_h f B^x_{pk} + K_e (f B_{pk})^2 \quad (54)$$

Modeling copper losses under linear load condition due to resistance is given as:

$$P_c = I^2_L (R_1 + R_2)/A^2 \quad (55)$$

Modeling nonlinear currents of different harmonic frequency:

$$I_L(t) = I_2 S_{in}(wt + \theta_2) + \sum_{h=1}^{\infty} I_2 h\, S_{in}(hwt + \theta_h) \quad (56)$$

When harmonic currents flow in the windings of the electric service transformer, then they produces a voltage drop across the device which lead to copper losses under harmonics which is modeled as (P_{ch}):

$$P_{ch} = \sum_{h=1}^{\infty} R_{h1} I_{h1}^2 + \sum_{h=1}^{\infty} R_{h2} I_{h2}^2 \quad (57)$$

Where P_{ch} is the copper losses under harmonic environment, R_{h1} and R_{h2} are the primary and secondary winding resistance in the h - order harmonic respectively, while I_{h1} and I_{h2} are the primary and secondary currents.

1.5.2.1 MODELING OF HARMONIC VOLTAGE AND CURRENT DISTORTIONS

The power quality of a system can be impressed by improving or better still minimising the harmonic voltage and current distortions in power utility devices. The most prominent thing is voltage and current which are non - sinusoidal quantities.

Harmonic voltage function is modeled as:

$$V_h(t) = \sum_{h=1}^{n} V_h \sqrt{2}\, Sin(hwt + Y_h) \quad (58)$$

Similarly, the harmonic current function is modeled as:

$$I_h(t) = \sum_{h=1}^{n} I_h \sqrt{2}\, Sin(hwt + Y - \phi_h) \quad (59)$$

Where V_h and I_h are the RMS of each h - harmonic of voltage and current respectively while ω, ϕ_h and Y_h are the angular frequency, Phase angle difference and phase angle respectively as well.

1.5.2.2 MODELING OF HARMONIC POWER DISTORTIONS

The harmonic active power is modeled as follows:

$$P_h = \sum_{h=1}^{n} V_h\, I_h\, Cos\phi_h \quad (60)$$

The harmonic reactive power is modeled as:

$$Q_h = \sum_{h=1}^{n} V_h\, I_h\, S_{in}\phi_h \quad (61)$$

While the harmonic apparent power is modeled as:

$$S_h = \sqrt{\sum_{h=1}^{n} V_h^2}\ \sqrt{\sum_{h=1}^{n} I_h^2} \quad (62)$$

1.5.2.3 MODELING OF TOTAL HARMONIC DISTORTION (THD)

The total harmonic distortion is expressed through the voltage and current distortion.

Hence, total voltage harmonic distortion V_{THD} is modeled as:

$$V_{THD} = \sqrt{\sum_{h=2}^{n} \left(\frac{V_h}{V_{(1)}}\right)^2} \quad (63)$$

Similarly, the total current harmonic distortion I_{THD} is modeled as:

$$I_{THD} = \sqrt{\sum_{h=2}^{n} \left(\frac{I_h}{I_{(1)}}\right)^2} \quad (64)$$

Consequently, the total harmonic distortion is the ratio between residue and effective value of fundamental wave function:

$$\delta_v = \frac{\sqrt{\sum_{h=1}^{n} V_h^2}}{V_1}\, x\, 100\% \quad (65)$$

1.5.2.4 MODELING OF HARMONIC LEVEL IN ELECTRIC SERVICE TRANSFORMER

The harmonic level of the electric service transformer can be determined by the ratio between the effective value of the considered harmonic and effective value of the fundamental as shown in the parametric model below:

$$Y_{Level} = \frac{V_h}{V_1}\, x\, 100\% \quad (66)$$

Where Y_{level} is the harmonic level of the transformer, V_1 is the fundamental voltage and V_h is the harmonic voltage considered.

1.6 MITIGATION OF HARMONIC EFFECT ON ELECTRIC SERVICE TRANSFORMER

Harmonics affect transformers primarily in two major ways: voltage harmonics and current harmonics. "The voltage harmonics produces additional losses in the transformer core as the higher frequency harmonic voltages set up hysteresis loops, which superimpose on the fundamental loop" [9]. "The second and a more serious effect of harmonics is due to harmonic frequency currents in the transformer windings" [9]. The harmonic currents increase the net RMS current flowing in the transformer windings which results in additional I^2R losses [9]. Winding eddy currents are circulating currents induced in the conductors by the leakage magnetic flux [9]. And this winding eddy current increases the losses in the system by causing temperature rise in the windings. In order to handle this losses and temperature effect the K - factor method is employed for transformers that supply nonlinear load.

The K - factor transformer is designed to accommodates the temperature rise caused by current harmonic in the transformer windings. In addition to the fundamental frequency losses. K - factor is a constant that specifies the ability of the transformer to handle harmonic heating, as a multiple of the normal eddy current losses which are developed by a sinusoidal current in the transformer windings.

A good engineering practice calls for the derating of transformer that serves nonlinear loads to an equivalent 80% of the nameplate KVA [8].

The parametric modeling of the K - factor is given as:

$$k = \sum I_h^2 h^2 \;(h = 1, 2, 3, \ldots n) \qquad (67)$$

1.7 CONCLUSION

Transformers are the major and most important equipment in electrical power system. Their role in changing voltage and current levels cannot be overemphasized in electrical power system. Hence, the full design analysis and parametric modeling of harmonics effect of a 1.5KVA single phase wooden cross cutting machine step down electric service transformer has been successfully presented in this research work.

The transformer designs have been obtained with step by step analysis and calculations in details. The methodology has been applied to 1.5KVA single phase electric service transformer with a rated frequency of 50Hz.

The importance of this research work lies on the fact that a step by step design analysis and calculations of a single phase electric service transformer was implemented with parametric modeling of harmonics effect on the system. Also, the work gives general guidelines to any person or designer who wants to carry out full design work of transformers and the construction of same.

List of Symbols and Abbreviations:

V_1 = Input voltage
V_2 = Output voltage
AC = Alternating current
I_1 = Input current
I_2 = Output current
W = Overall width of core
H = Overall height of core
h_y = Height of yoke
D_y = Depth of yoke
D_L = Density of lamination
D = Density
D_m = Mean diameter of turns
F = Frequency (Hertz)
K = Constant
δ = Current density (A/M^2)
K_w = Window space factor
B_m = Magnetic flux density (Telsa)
T_1 = Primary turns
T_2 = Secondary turns
A_w = Window area m^2
A_y = Area of yoke m^2
A_1 = Net core section m^2
A_1 = Primary conductor section m^2
A_2 = Secondary conductor section m^2
d_1 = Primary conductor diameter, mm
d_2 = Secondary conductor diameter, mm
a = Thickness of lamination
E_t = E.M.F. per turn
I_L = Load current
θ = Phase angle
L_h = Harmonic inductance
R_h = Harmonic resistance
η_T = Efficiency
I_h = Harmonic current
V_h = Harmonic voltage
δ_h = Total harmonic distortion
Y_L = Harmonic level
V_{THD} = Total harmonic distortion voltage
I_{THD} = Total harmonic distortion current
K = derating factor
L_{mt} = Mean length of turn
ω = Angular frequency
P_T = Total power loss
P_{ch} = Harmonic copper losses in power
L_L = Inductance of winding
Lm = Total length of mean flux path
ε_r = Resistance drop per unit of coils
W_c = Weight of coils
W_{ic} = Weight of iron core

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