PRACTICAL PROCESS IN HIGH FREQUENCY DISTRIBUTION TRANSFORMER DESIGN

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Abstract: This paper details the practical, step-by-step experience encountered in the design and development of a 2 kHz, 3.5kVA distribution transformer. Two conventional design methods were used respectively for the design: the Area Product approach, and the Core Geometry approach. The Area Product approach uses the product of the Core Window area and the Core sectional area as the principal design criteria, while the Core Geometry approach uses voltage regulation as the principal design criterion. When a common criterion was used for the design process, both approaches yielded an identical end result.

I. INTRODUCTION

The transformer is an electromagnetic energy conversion device, which converts electrical energy from one voltage/current level to another voltage/current level. The conversion is a two phase process – electrical to magnetic and magnetic to electrical respectively. In use, the magnetic conversion phase is not apparent and tends to be taken for granted. Yet, the magnetic phase is usually the focal point of a transformer design process.

The basic goal in transformer design is to maximize efficiency and minimize cost. Many factors affect the achievement of this goal. These factors present constraints, which require mitigation, compromise or tradeoff depending on the design objectives or operating environments. These factors include weight, volume, surface area, temperature rise, copper losses, iron (core) losses, efficiency, power handling capability, regulation and current density. The design process starts with defining and understanding the transformer specifications.

The distribution transformer design project on which this paper is based has the following basic specifications:

Input voltage	= 110V
Output voltage	= 2000V
Output power	= 3.5 KVA
Operating frequency	= 2 KHz
Efficiency	= 97%\

By extension

Input current I_{in}	= 31.82A
Output current I_o	= 1.75 A

II. DESIGN METHODS

Two principal approaches are used in transformer design – the Area Product (A_P) and the Core Geometry (K_g) approach, respectively.

Area Product (A_P) refers to the product of available core window area and the core sectional area of the core i.e.,

$$A_P = W_a A_c \ (cm^4) \qquad (1)$$

Where W_a = available core window and
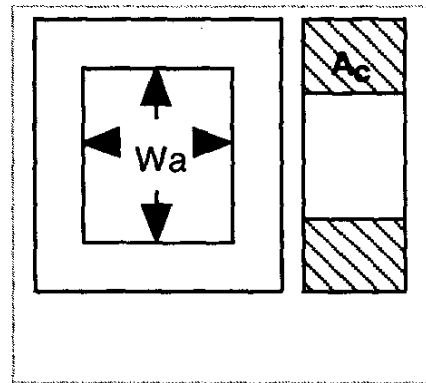A_c = Core sectional area in cm^2.

Figure 1. Window-Core Area Product

A_P design approach takes advantage of manufacturer's numeric codes used to identify cores. These numeric codes summarize the core dimensions and electrical properties. Computing an A_P value in a design process allows the designer to obtain easily, from manufacturers catalog, physical and technical data about cores with the same or approximate A_P value

The Core Geometry (K_g) approach is very suitable when the copper and core losses are the dominant constraint in a magnetic device. These losses affect the transformer output and hence "voltage regulation" is the principal design variable in the approach. The geometrical constant K_g is a measure of the effective magnetic size of the core. This design approach is relatively more recent in use than the A_p approach and does not yet have direct linkage with manufacturers' catalog data as with A_p.

Recent developments [1] made in transformer design have attempted to cross link the geometrical constant K_g with the area product constant A_p

Both the K_g and A_p approaches presented in this paper are based on the procedures developed in transformer texts [1][2] to illustrate the step-by-step transformer design process.

III. DESIGN USING THE A_P APPROACH

1. Calculate the output power P_o

In the specification output power P_o is 3.5 kVA or 3.5kW at unity power factor loading condition.

2. Calculate the total power handling capacity, also unconventionally referred to as total apparent power, P_t.

This is the combined power that must be carried by the transformer primary and secondary windings respectively. Used as illustrated in Figure 2,

$$P_t = P_{in} + P_o \quad W \tag{2a}$$

Considering efficiency (η)

$$P_{in} = P_o/\eta \tag{2b}$$

Hence $P_t = P_o/\eta + P_o \tag{3}$
$$= 3,500/0.97 + 3,500 = 7,108.25 \; W$$

It may be noted that P_t is a function, not only of demand power, but also of application. For example, in some applications involving center tap transformers, P_t could increase by a factor of up to 2.83 x P_{in} [1][2]

3. Calculate the area product A_P

Considering window utilization factor, operating frequency, maximum flux density, current density, it has been shown [1] that:

$$A_p = W_a \times A_c = \{(P_t \times 10^4)/(K_f B_m K_u K_j)\}^x \; cm^4 \tag{4}$$

Where: $K_f = 4.44$ = Sine waveform coefficient. (Note – for square waveform, value is 4.0) [1]

B_m = Maximum flux density. In this project
$\quad B_m =1$ tesla
K_u = Core window utilization factor:
$\quad$ typically 0.4 [1][2]

K_j = Current density constant. This is a factor that relates A_p value to core configuration. Values vary according to core type and specified temperature increase. In this

project, "Lamination core" type is used at allowable temperature rise (ΔT) is $50°C$. For this specification, $K_j(\Delta T) = 534$. [1]. See Table 1 – Core Configuration constants.

x - This is an exponent that relates A_p value to core type. Lamination core used in this project has exponent = 1.14. See Table I.

f - Operating frequency (2,000 Hz)

In this approach, the designer decides the maximum operating flux density B_m based on a number of factors including margin for saturation, losses, efficiency and physical size and weight.
Substituting values in (4),

$$A_p = [(3500/0.97+3500) \times 10^4]/(4.44 \times 1 \times 2000 \times 0.4 \times 534)^{1.14}$$
$$= 62.24 \; cm^4$$

4. Select core of equivalent A_p value. A_p value is one of the data that most core manufacturers provide as part of core specification. For a given A_p value, manufacturers provide other specific data associated with the A_p value of the given core. It is best to choose an A_p value that is about 10% higher than actual value calculated in eqn. 4 to compensate for stacking. A good gauge is that:

$$A_{p(product\;data)} \times Stacking \; factor \geq A_{p(calculated)}$$

From Table II– Standard EI lamination, the nearest core to the calculated A_p value of is the part # 175EI-.25. It has the following associated data:

$A_p = 73.196 \; cm^4$
Mean Length Turn (MLT) = 18.5 cm
Mean Magnetic Path Length (MPL) = 26.7 cm
Core sectional Area (A_c) = 4.9395 cm^2
Window area, (W_a) = 14.8 cm^2
Core surface area, (A_t) = 489.0 cm^2
Core weight, (W_{tfe})= 0.977 Kg = 977 grams

From the parameters of step 4, the design process continues as described below:

5. Calculate the Transformer Primary Turns, N_p

From the extended Faraday equation

$$N_p = (V_p \times 10^4)/K_f B_m A_c \; Turns. \tag{5}$$
$$= 28 \; turns \; [Note: A_c \; is \; specified \; in \; cm^2]$$

6. Calculate primary Current I_p

$$I_p = (Po/\eta)/V_p \tag{6}$$
$$= (3,500/0.97)/110 = 32.80 \; Amps$$

122

7. Calculate Current Density

$$J = I / A_{w(B)} \qquad (7)$$

But bare wire size has not been established at this point. However, developments [1] in transformer design gives:

$$J = K_j A_p^{(y)} \qquad (8)$$

K_j and y are factors that relate A_p value to current density depending on core type and for the assumption that copper loss = iron loss.

From Table I, $y = -0.12$ for lamination.

Hence $J = 534 \times 73.196^{-0.12} = 319$ A/cm^2

8. Compute the Bare Wire size $A_{w(B)}$:

$$J = I / A_{w(B)}. \qquad (9)$$
$$= 32.8/319 = 0.1028 \text{ cm}^2$$

9. Select wire size.

From Table III– Round Wire, the nearest standard wire size within 10% of calculated value is AWG #7. Bare wire size $A_{w(B)} = 0.1055$ cm^2 and its resistance R, is 16.34 $\mu\Omega$/cm.

10. Calculate Primary Winding Resistance (R_p)

$$R = \rho\_/A \qquad (10)$$

Where _ = total conductor length in meter
A = conductor cross sectional area in m^2

$$R_p = (MLT)N(\mu\Omega/cm) \times 10^{-6} \qquad (11)$$
$$= 18.5 \times 28 \times 16.34 \times 10^{-6}$$
$$= 0.00846 \ \Omega \text{ at } 20°C$$

At 50 °C temperature rise, resistance is different and must be corrected for. The correction factor is:

$$\_ = [1 + \gamma_{20}(\Delta T)]$$
$\gamma_{20} = 0.0039$ = temperature constant for copper wire.
$$\_ = [1 + 0.0039 \times 50] = 1.197$$
$$R_{p(70°C)} = \_R_{p(20°C)} = 1.197 \times 0.00846 = 0.01\Omega$$

11. Calculate Primary copper loss $P_{L(p)}$
$$P_{L(p)} = I^2 R_p \ \text{Watts} = 32.802^2 \times 0.01 = 10.8W$$

12. Calculate number of secondary turns. N_s

$$N_s = N_p V_s / V_p \qquad (12)$$
$$= 509 \text{ Turns}$$

13. Calculate Secondary Current I_s and Secondary bare wire size $A_{w(B)secondary}$ respectively:

$$I_s = I_p N_p / N_s \qquad (13)$$
$$= (32.802)(28)/509 = 1.802 \text{ Amps.}$$

$$A_{w(B)secondary} = I_s/J = (1.802)/319 = 0.00566 \text{ cm}^2$$

14. Select wire size from wire table.

Nearest wire size within 10% of value is AWG 20
$A_{w(B)secondary} = 0.005188$ cm^2
Resistance/cm = 332.3 $\mu\Omega$/cm at 20°C

15. Calculate secondary resistance R_s for $\Delta T = 50°C$
$$R_{s(70°C)} = (MLT)(N)(\mu\Omega/cm) \times 10^{-6} \times \_$$
$$= (18.5)(509)(332.3) \times 10^{-6} \times 1.197 = 3.74 \ \Omega$$

16. Calculate secondary copper loss $P_{L(s)}$

$$P_{L(s)} = I^2 R_s \ W = 11.47 \ W \qquad (14)$$

17. Calculate the transformer total copper loss P_{cu}

$$P_{cu} = P_{L(p)} + P_{L(s)} \qquad (15)$$
$$= 10.8 + 11.47 = 22.27 \ W$$

18. Calculate what the total losses should be (copper + iron) to satisfy efficiency requirement,

$$P_{(total\ loss)} = P_o/\eta - P_o \qquad (16)$$
$$= (3,500/0.97) - 3,500$$
$$= 108.25 \ W$$

19. Calculate iron loss portion of total loss: P_{fe}

$$P_{fe} = P_{(total\ loss)} - P_{cu} \qquad (17)$$
$$= 108.25 - 22.27 = 85.93 \ W$$

20. Calculate the core loss in milliwatts per gram for easy cross-referencing with core loss curves.

$$\text{Core loss} = P_{fe} / W_{tfe} \times 10^{-3} \qquad (18)$$
$$= 85.93 (977 \times 10^{-3})$$
$$= 84.0 \ mW/g$$

21. Determine from core-loss curves [1][2] what core material (alloy and thickness) will produce iron loss closest to the calculated iron loss.

From curves a number of alloys and thickness will meet or better the requirement. Thinner lamination will produce less losses, but will mean more laminations and higher labor cost to assemble than thicker laminations. Given the choices, operating cost vs. differential capital and labor

123

costs are trade-off parameters to consider: In the project 48 Nickel, 52 Fe, 6mil Alloy core material is chosen.

The watts/kg rating of this chosen core is given as:

$$\text{Watts/kilogram [1]} = 0.719(10^{-3})f^{(1.470)}B^{(1.92)} \quad (19)$$
$$= 0.719(10^{-3})2000^{(1.470)}1.0^{(1.92)}$$
$$= 51.20 \text{ W/Kg.}$$

The corresponding total iron loss:

$$P_{fe} = (\text{Watts/Kg}) \times \text{Core weight (kg)}$$
$$P_{fe} = 51.20 \times 0.977 = 50.02 \text{ W.}$$

It may be noted that selection of this core material increases the transformer efficiency from originally specified 97% to 97.99%

22. Calculate the power loss density, ie., watt loss/unit area, ψ.

$$\psi = (P_{cu} + P_{fe})/\text{Total core area } (A_t) \quad (20)$$
$$= (22.27 + 50.0) \text{ W}/489.0 \text{ cm}^2$$
$$= 0.148 \text{ W/ cm}^2 \text{ core loss } (P_{fe})$$

The transformer basic design using the A_p method is now complete

IV. DESIGN USING THE K_g APPROACH

In the project design exercise, one secondary objective was also to verify if the final transformer design parameters would differ according to design approach used. For this verification, it meant that in addition to the basic specifications, the principal design criteria in both approaches must be identical. In the Ap approach, the principal design criteria is W_aA_c while in K_g, it is voltage regulation α.

For specification equivalence, we established that both approaches must respectively meet a voltage regulation α of about 0.5%. In the K_g procedure, the designer specifies the transformer regulation, and designs around the regulation.

The transformer design process using the K_g approach with $\alpha = 0.5\%$, is summarized below:
The steps to calculate the output power P_o and total power handling capacity and choosing the desired operating flux density are the same as in the Ap approach.
3. Calculate the Electrical constant K_e

$$K_e = 0.145 \times K_f^2 f^2 B_m^2 10^{-4} \quad (21)$$
$$= 0.145 \times 4.44^2 \times 2000^2 \times 1^2 \times 10^{-4}$$
$$= 1,143.39$$
Where: $K_f = 4.44 = $ Sine waveform coefficient.

(Note: for square waveform, value is 4.0) [1]
$B_m = $ Maximum flux density = 1 tesla
$f = $ Operating frequency = 2,000 Hz

4. Calculate the core geometry K_g

The constant K_g is the core geometry coefficient and is determined by the geometry according to the equation [1]:

$$K_g = P_t/2K_e\alpha \quad (22)$$
$$= 7108.247/2 \times 1143.39 \times 0.5$$
$$= 6.217 \text{ cm}^5$$

Where α is the target transformer regulation.

5. Select appropriate core geometry K_g from the lamination table.

As a guide, the appropriate value is one that is approximately 20% larger than calculated because the core geometry is listed in gross terms [1]. Hence the value to look for in the table is $K_{g(gross)} = 6.217 \times 1.20 = 7.460$. A value slightly above the calculated value is recommended.

From a standard EI lamination Table II, the identified core has the following parameters:

EI Lamination: 175EI-.25
Kg(gross)= 7.81777cm^5

$A_p = 73.196 \text{ cm}^4$
MLT = 18.5 cm
$A_c = 4.9395 \text{ cm}^2$
$W_a = 14.8 \text{ cm}^2$
$A_t = 489.0 \text{ cm}^2$
MPL = 26.7 cm
$W_{tfe} = 0.977 \text{ Kg} = 977 \text{ g}$

6. Calculate the effective Kg

$$\text{Effective } K_g = K_{g(gross)} \times (\text{Stacking Factor})^2 \quad (23)$$

A 6-mil lamination will be used.
Corresponding Stacking Factor SF=0.9. $SF^2 = 0.81$
See Table IV: $K_g = 0.81 \times 7.8177 = 6.332 \text{cm}^5$

7. Calculate the effective iron area $A_{c(effective)}$.

$$A_{c(effective)} = SF \times A_c \quad (24)$$
$$= 0.9 \times 4.939 = 4.446 \text{ cm}^2$$

Consequently, transformer volume and weight are:

$$\text{Volume} = K_v \times (A_p \times SF)^{0.75} \quad (25)$$

$$\text{Weight} = K_w \times (A_p \times SF)^{0.75} \quad (26)$$

124

Where, from Table I, K_v is a constant relating Kg to lamination core volume = 19.7

Kw is a constant relating Kg to lamination core weight = 68.2

Substituting values:

Volume of transformer = 19.7 x (73.196x0.9) $^{0.75}$
                       = 455.526cm^3

Weight of transformer = 68.2 x (73.196x0.9) $^{0.75}$
                       = 1577g

Other steps in the design process are similar to the A_p approach.

The Transformer design parameters are summarized below:

V. DESIGN PARAMETERS

Input Voltage:	110V (sinusoidal voltage)
Output Voltage:	2000V
Output Power:	3.5 KVA
Operating frequency:	2000Hz
Efficiency:	97%
Regulation:	0.5 %
Flux density:	1 Tesla
Power handling Capability P_t:	7108.25 W

Area product A_p:	62.23 cm^4
Core: EI Lamination core selected.	
Catalogue # 175EI - .25	
A_p (gross):	73.2 cm^4
W_{tfe} (gross)-core:	976.5 gram
Ac (gross)-core:	4.94 cm^2
MLT- Mean length turn	18.5 cm
Stacking factor SF:	0.90
A_t (Core Surface Area):	489 cm^2
Designed parameters:	
Area product:	65.88 cm^2
Volume of transformer:	455.5 cm^3
Core Cross-sectional area:	4.45 cm^2
Number of primary turns N_p:	28
Number of secondary turns N_s:	509
Primary current I_p:	32.87 A
Secondary current:	1.8A
Current density:	319. A/ cm^2
Primary wire size:	AWG 7
Secondary wire size:	AWG 20
Primary winding resistance:	0.01 ohms
Secondary winding resistance:	3.74 ohms
Core loss:	50.0W
Copper losses:	22.27W
Total power losses:	72.27 W
Designed efficiency: η_d :	97.988%
Loss Watt per area:	0.148 Watt/ cm^2

VI. TESTS

After the transformer is built, a number of tests can be done to verify the design parameters and functional integrity of the product. Depending on design standard, specifications, operating and environmental conditions, tests can vary from basic to the rigorous Mil-Std 981 [3].

A. Resistance Test

This test is carried out to verify the wire resistance from ambient temperature to operating temperature. A bridge resistance meter is more accurately used for this test. For

The tests intended for this project are the basic test, which includes Resistance test, Insulation test, open and short circuit and voltage regulation tests. The figures below illustrate circuits for some of the basic transformer tests.

operating temperature resistance, the rated load is applied to the transformer for a reasonable period of time and resistance measurements are taken immediately after the power to the load is removed.
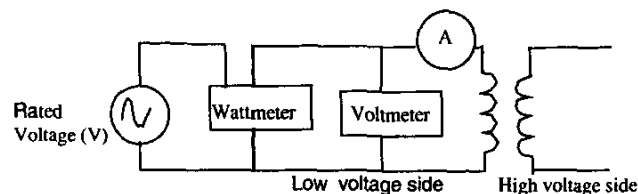

Figure 2. Open Circuit Test Connections

The open circuit test measures the transformer iron losses, the hysteresis and eddy current losses combined. The wattmeter measures the iron losses under the assumption that winding losses are minimum since the transformer is not loaded. The hysteresis and eddy current losses can be calculated respectively, if necessary, from the test data.
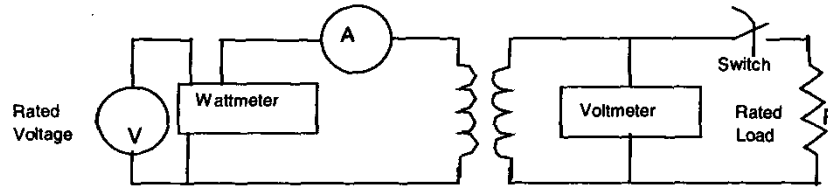
C. Voltage Regulation Test

Figure 3. Circuit for Voltage Regulation Test

The voltage regulation [VR] test verifies the transformer output variation between no-load and full load conditions. Test results are substituted into (27):

$$VR = [(V_{No-Load} - V_{Full\ Load})/ V_{Full\ Load}] \times 100\% \qquad (27)$$
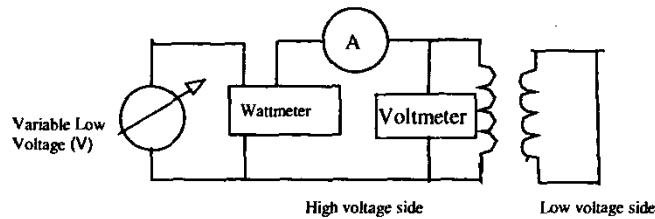
D. Short-circuit test

Figure 4. Short Circuit Test Connections

The short circuit test measures the copper (winding) losses. The Wattmeter reading is assumed to represent copper losses only. The assumption is that at full load the Copper losses are much higher than Core losses.
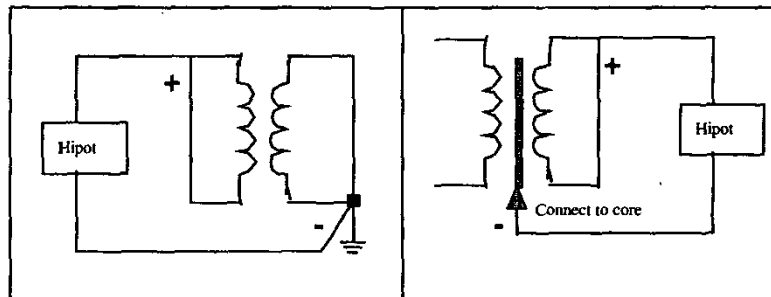
E. Insulation Tests

Figure 5. Connections for Insulation Test

126

Insulation tests measure the insulation integrity between primary winding and secondary winding, and winding and core respectively.

VII. CONCLUSION

A practical, step-by-step experience in the design of a 2 kHz, 3.5kVA distribution transformer using the Area Product (AP) and the core Geometry (Kg) approaches respectively has been presented. Both approaches yielded identical end results. The design is the first phase of a NASA sponsored project to investigate implications of high voltage/high frequency distribution systems in space environment.

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APPENDIX

Table I. Core Configuration Constants* [1]

CORE	Kj 25°C	Kj 50°C	(x)	Ks	Kw	Kv	(y)
Pot core	433	632	1.2	33.8	48	14.5	-0.17
Laminations	366	534	1.14	41.3	68.2	19.7	-0.12
C core	323	468	1.16	39.2	66.6	17.9	-0.14

* (x) and (y) are exponents in equations for Ap and J

Table II. Partial Standard EE and EI Lamination [2]

Part #	D cm	Ht cm	Wth cm	Lt cm	G cm	MPL cm	Wtfe grams	Wtcu grams	MLT cm	Ac cm²	Wa cm²	Ap Cm⁴	Kg Cm⁵	At cm²
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
100EI-1	2.54	6.35	5.08	7.62	3.81	15.2	712	253.9	14.8	6.452	4.839	31.217	5.4596	212.9
36EI-.25	1.032	10.795	7.382	14.605	6.668	27.9	893.8	1558	20.7	4.259	21.17	90.161	7.4217	585.5
175EI-.25	1.111	11.113	5.556	13.335	6.668	26.7	976.5	974.8	18.5	4.94	14.82	73.196	7.8177	489
87EI-2	4.445	5.556	6.668	6.668	3.334	13.3	962	232.4	17.6	9.879	3.705	36.598	8.1983	217.3
138EI-.5	1.746	8.731	5.239	10.478	5.239	21	940	539	16.6	6.099	9.148	55.793	8.2147	335.4

Table III: Partial Round Wire Table [2]

AWG	Bare Area	Resistance	Heavy	Synthetics			
	cm sq $(10^{\wedge}\text{-}3)$	mW/ 20°C	Area cm^2	Diameter cm	Turns per cm	Turns per cm^2	Weight gram/cm
6	133	11.55	139.8	0.422	2.37	4.295	1.189
7	105.5	16.34	111.4	0.377	2.65	6.75	0.944
8	83.6	20.6	88.8	0.336	2.97	8.47	0.749
19	6.53	268.9	7.539	0.098	10.19	79.85	0.0594
20	5.188	332.3	6.065	0.08789	11.37	98.98	0.0473
21	4.116	418.9	4.837	0.0785	12.75	124	0.0376

Table IV. Stacking Factor [2]

Thickness, mils	SF
4	0.9
6	0.9
14	0.95
18	0.95

128