Transformer Design for a X-Ray Device

high-frequency, high-voltage transformer that will be used in a X-Ray device

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Abstract

In this report, it is supposed to design a high-frequency, high-voltage transformer that will be used in a X-Ray device.The transformer design will be given step by step.

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Chapter 1. Introduction

The specs of the transformer are as follows:
* Single Phase, High Frequency High Voltage Transformer
* Primary Winding Voltage ± 417 V (peak to peak 834 V for pulsing)
* Secondary Winding Voltage ± 12.5 kV (peak to peak 25 kV for pulsing)
* Rated Power 30 kW (for maximum 100 milisecond)
* Switching Frequency Minimum 100 kHz
* Ambient Temperature 0-40 °C

Chapter 2. Core Selection

```
% In this code, it is supposed to design a high-frequency,
% high-voltage transformer that will be used in a X-Ray device.
%-----------------------------------------------------------------------
% Huseyin YURUK
%----------------------------------------
% Following design guide is used:
% Magnetics Ferrite Power Design 2013
%----------------------------------------
% Core Selection by WaAc product
% The power handling capacity of a transformer core can also be determined
% by its
% WaAc product, where Wa is the available core window area, and Ac is
% the effective
% core cross-sectional area.
% Area Product Distribution (WaAc)
% WaAc = (Po * Dcma) / (Kt * Bmax * f)
% where
% WaAc = Product of window area and core area (cm4)
% Po = Power Out (watts)
% Dcma = Current Density (cir. mils/amp)
% Bmax = Flux Density (gauss)
% ƒ = frequency (hertz)
% Kt = Topology constant  (Full-bridge = 0.0014)
Po = 30 * 10^3;     % input parameter [W]
f = 100 * 10^3;     % input parameter [Hz]
Kt = 0.0014;
% for cir. mils to mm^2 see below link
% conversion see http://www.convertunits.com/from/mm%5E2/to/circular+mil
% 1mm^2 ~1973.5 cir. mils
J = 2.5;            % current density [A/mm^2]
Dcma = 1973.5 / J;  % [cir. mils/A]
Bmax = 0.47 * 10^4; % P type core has the 0.47T max. flux density
WaAc = Po * Dcma / (Kt * Bmax * f);     %[cm^4]

% core properties 49925UC
% selected core dimensions [mm]
% A_dim = 101.6;
% B_dim = 57.1;
% C_dim = 25.4;
% D_dim = 31.7;
% E_dim = 50.8;
% radius_acoil = C_dim/2 + D_dim/2;   % [mm]
% Vol_core  = ((A_dim*2*B_dim*C_dim) - (2*D_dim*E_dim*C_dim)) * 10^-3;    %[cm^3]
% Ac = 645 * 10^-2;           % [cm^2] Ae effective are for the choosen ferrite
% Wa = 2 * D_dim*E_dim * 10^-2; % available core window area [cm^2]
% core_mass = 2*988*10^-3;    %[kg]
% le_dim = 2*245;             %[mm] effective length core
% Al = 6200;                  %[nH/1T^2]
% mu_r = 5000;                %[-]
% graph_core_loss_100deg = 350;   %[mW/cm^3]
```

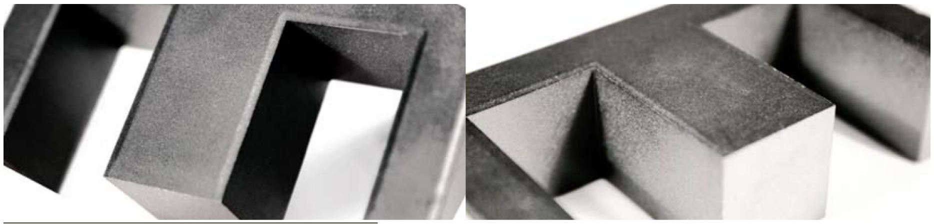
```
% graph_core_loss_40deg = graph_core_loss_100deg * 2; %[mW/cm^3]
% price_core = 2*17.38;         % [$]


% core properties 48020EC
% selected core dimensions [mm]
A_dim = 80.0;
B_dim = 38.1;
C_dim = 19.8;
D_dim = 28.2;
E_dim = 59.1;
F_dim = 19.8;
M_dim = 19.65;
radius_acoil = F_dim/2 + M_dim/2;   % [mm]
Vol_core  = ((A_dim*2*B_dim*C_dim) - (2*2*D_dim*M_dim*C_dim)) * 10^-3;    %[cm^3]
Ac = 645 * 10^-2;           % [cm^2] Ae effective are for the choosen ferrite
Wa = 2 * 2* D_dim*E_dim * 10^-2; % available core window area [cm^2]
core_mass = 2*357*10^-3;    %[kg]
le_dim = 2*184;             %[mm] effective length core
Al = 5080;                  %[nH/1T^2]
mu_r = 5000;                %[-]
graph_core_loss_100deg = 350;   %[mW/cm^3]
graph_core_loss_40deg = graph_core_loss_100deg * 2; %[mW/cm^3]
price_core = 2*3.25;         % [$]




%%%%%%
```

Using the equation shown above, the WaAc product is calculated.

WaAc = 35.9909 [cm^4]

Then the Area Product Distribution (WaAc) Chart is used to select the appropriate core.

From the Magnetics Ferrite Catalog (2013) E core is selected. The details are given below.



E, I Cores

40 mm – 100 mm

E cores are less expensive than pot cores, and have the advantage of simple bobbin winding plus easy assembly. E cores do not, however, offer self-shielding. Lamination size E cores are available to fit commercially offered bobbins previously designed to fit the strip stampings of standard lamination sizes. Metric and DIN sizes are also available. E cores can be pressed to different thicknesses, providing a selection of cross-sectional areas. E cores can be mounted in different directions and, if desired, provide a low profile.

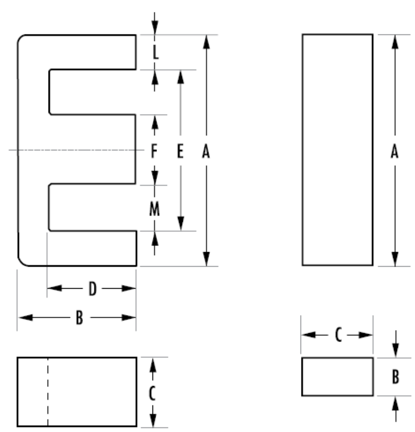
Typical applications for E cores include differential mode, power and telecom inductors, as well as, broadband, power, converter and inverter transformers.

P Material

A low-medium frequency general-purpose power converter material. Engineered for lowest losses between 80 - 100°C. Available in almost all core sizes and shapes.

Initial Perm (25°C; ≤ 10 kHz) .... 2,500 ± 25%
Saturation Flux Density (4,700 G at 15 Oe, 25°C) .... 470 mT, 11.9 A-T/cm
Curie Temperature .... 210°C

Typical applications for E cores include differential mode, power and telecom inductors, as well as, broadband, power, converter and inverter transformers.
The selected Ecore (48020EC) has a 32 cm^4 WaAc product which is very close to desired WaAc product 35.9909. But in the catalog at 100kHz it's power rating is given as 4.5kW. Since the transformer will be used at 30kW maximum for 100ms, it can handle this amount of power for small pulse width without problem.



TYPE/SIZE	ORDERING CODE	MAGNETIC DATA l_e (mm)	A_e (mm²)	A min (mm²)	V_e (mm³)	WaAc (cm⁴)	Weight (grams per set)	HARDWARE Bobbins	Clips
E 80/38/20	0_48020EC	184	392	392	72,300	31.6	357	✓	

TYPE/SIZE	ORDERING CODE	DIMENSIONS (mm) A	B	C	D	E	F	L	M
E 80/38/20	0_48020EC	80.0 ± 1.6	38.1 ± 0.3	19.8 ± 0.4	28.2 ± 0.3	59.1 min	19.8 ± 0.4	11.25 nom	19.45 min

Chapter 3. Determine # of Turns

```
% The calculation of primary and secondary turns
% and the wire size selection
% Np = Vp * 10^8 / (4 * B * Ac * f)
% Ns = (Vs / Vp ) * Np
% Ip = Pin / Vp_rms
% Is = Po / Vs_rms
% where
% Np = number of turns on the primary
% Ns = number of turns on the secondary
% Ip = primary current
% Is = secondary current
% Ac = core area in cm^2
Vin = 417;                 % input parameter
Vout = 12.5 * 10^3;        % input parameter
Vp_peak = Vin * 4 / pi();      % 1st harmonic peak value
Vs_peak = Vout * 4 / pi();      % 1st harmonic peak value
B = 0.2 * 10^4;               % operating B value
n_eff = 0.98;                 % 98% efficiency assumed
Vp_rms = Vp_peak / sqrt(2);     % rms value
Vs_rms = Vs_peak / sqrt(2);    % rms value
Np = Vp_peak * 10^8 / (4*B*Ac*f); %[-]
Ns = (Vs_rms / Vp_rms) * Np;     % [-] this is theoritical
H_field = B * 10^-4 / (mu_r*mu0);   % [A] H_field should be satisfied to get B
Ns_desired = ((round(Np)*Ip)-H_field) / Is; %[-] to get desired H_field
H_field_result = (round(Np)*Ip) - (ceil(Ns_desired)*Is); %[A] with new Ns
B_result = H_field_result * (mu_r*mu0) / 10^-4; % [gauss] with new H
Ns = Ns_desired;
Pin = Po / n_eff;
Ip = Pin / Vp_rms;
Is = Po / Vs_rms;

%%%%%%
```

Using the equation shown above, the Np, Ns, Ip, Is are calculated.

```
Np =  10.2896    take Np as 10
Ns =  293.9369     take Ns as 294
Ip = 81.5387
Is = 2.6657
```

Note that according to these values the reultant B value has 1.9894e+03 [Gauss], which is very close to selected design parameter 2000.
The resultant H field is calculated as above and the result is 31.6629 [A]

Chapter 4. Window Utilization & Cable Selection

```
% Approximately primary and secondary wire size are can be calculated
% as follows:
% Ku * Wa = Np*Awp + Ns*Aws
% Ku is fill factor
% Ku = s1*s2*s3*s4
% s1: wire isulation,  conductor area/wire area
% s2: fill factor,  wound area/usable window area
% s3: effective window, usable window area/window area
% s4: insulation factor, sable window area/usable window area + insulation
% Note that at 100Khz to minimize skin effect AWG26 is used
% for more details see below link
% http://coefs.uncc.edu/mnoras/files/2013/03/
% Transformer-and-Inductor-Design-Handbook_Chapter_4.pdf
% assume
% Np*Awp = 1.1 * Ns*Aws (to allow for losses)

% for AWG26 @100kHz
s1 = 0.79;
s2 = 0.61;
s3 = 0.6;
s4 = 1;
Ku = s1*s2*s3*s4;

Aws = Ku * Wa * 10^2 / (2.1 * Ns);   % [mm^2]
Awp = 1.1 * Ns * Aws / Np;          % [mm^2]

% mm^2   %requirred wire size for choosen current density
Awp_req = Ip / J;
Aws_req = Is / J;

%%%%%%
```

```
Due to 100Khz operation to minimize skin effect AWG26 cable size is used.
By regarding the window utilization factor Ku which is calculated as Ku = 0.2891,
allowable wire area
for primary side is Awp = 98.1255  [mm^2]
for secondary side is Aws = 3.1227 [mm^2]

From the choosen current density J = 2.5000 [A/mm^2] , requirred wire size
for primary side Awp_req = 32.6155
for secondary side Aws_req = 1.0663
```

Chapter 5. Losses

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Copper Losses

```
% copper losses will be calculated
% length of one turn coil will be calculated as follow
% primary and secondary window area assumed equal
% radius of the coil, radius_acoil = C/2 + D/2; [mm]
% length of the coil, length_acoil = 2 * pi * radius_acoil
% where C, D see dimensions
% total coil length:
% for primary side Np * length_acoil * 10^-3
% for secondary side Ns * length_acoil * 10^-3

Icarry_cap_AWG26 = 0.361;       %[A] current rate for the AWG26 size cable
area_AWG26 = 0.129;             % [mm^2]
ohm_AWG26 = 0.13386;            % [Ohm/m]
Icarry_cap_AWG26_J = J * area_AWG26; % [A] current rate by considering J value

length_acoil = 2 * pi()* radius_acoil;  % [mm]

% primary side loss calculation
Nstrand_pri = ceil(Ip / Icarry_cap_AWG26);  % number of AWG26 size cable
tot_length_coil_pri = round(Np) * length_acoil * 10^-3; % [m]
res_coil_pri = ohm_AWG26 * tot_length_coil_pri / Nstrand_pri;   % [ohm]
loss_coil_pri = Ip^2 * res_coil_pri;       % [W]

% secondary side loss calculation
Nstrand_sec = ceil(Is / Icarry_cap_AWG26);  % number of AWG26 size cable
tot_length_coil_sec = ceil(Ns) * length_acoil * 10^-3; % [m]
res_coil_sec = ohm_AWG26 * tot_length_coil_sec / Nstrand_sec;   % [ohm]
loss_coil_sec = Is^2 * res_coil_sec;       % [W]

tot_loss_copper = loss_coil_pri + loss_coil_sec;    %[W]
%%%%%%
```

```
Copper loss calculation of the primary and secondary side is given above.
Total loss of the copper is calculated as 9.2130
```

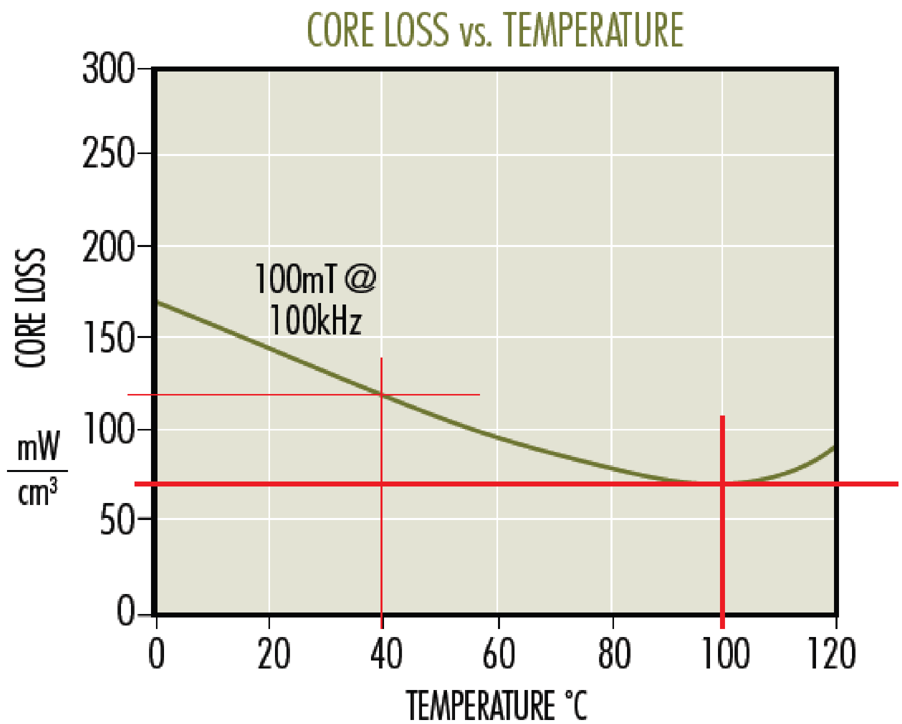
AWG	Diameter [inches]	Diameter [mm]	Area [mm²]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	190	200 Hz
0 (1/0)	0.3249	8.25246	53.5	0.0983	0.322424	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	75	500 Hz
4	0.2043	5.18922	21.2	0.2485	0.81508	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	37	1100 Hz
7	0.1443	3.66522	10.5	0.4982	1.634096	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	9.3	4150 Hz
13	0.072	1.8288	2.62	2.003	6.56984	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	1.8	21 kHz
20	0.032	0.8128	0.518	10.15	33.292	1.5	27 kHz
21	0.0285	0.7239	0.41	12.8	41.984	1.2	33 kHz
22	0.0254	0.64516	0.326	16.14	52.9392	0.92	42 kHz
23	0.0226	0.57404	0.258	20.36	66.7808	0.729	53 kHz
24	0.0201	0.51054	0.205	25.67	84.1976	0.577	68 kHz
25	0.0179	0.45466	0.162	32.37	106.1736	0.457	85 kHz
26	0.0159	0.40386	0.129	40.81	133.8568	0.361	107 kHz
27	0.0142	0.36068	0.102	51.47	168.8216	0.288	130 kHz
28	0.0126	0.32004	0.081	64.9	212.872	0.226	170 kHz
29	0.0113	0.28702	0.0642	81.83	268.4024	0.182	210 kHz
30	0.01	0.254	0.0509	103.2	338.496	0.142	270 kHz
31	0.0089	0.22606	0.0404	130.1	426.728	0.113	340 kHz
32	0.008	0.2032	0.032	164.1	538.248	0.091	430 kHz
33	0.0071	0.18034	0.0254	206.9	678.632	0.072	540 kHz
34	0.0063	0.16002	0.0201	260.9	855.752	0.056	690 kHz
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

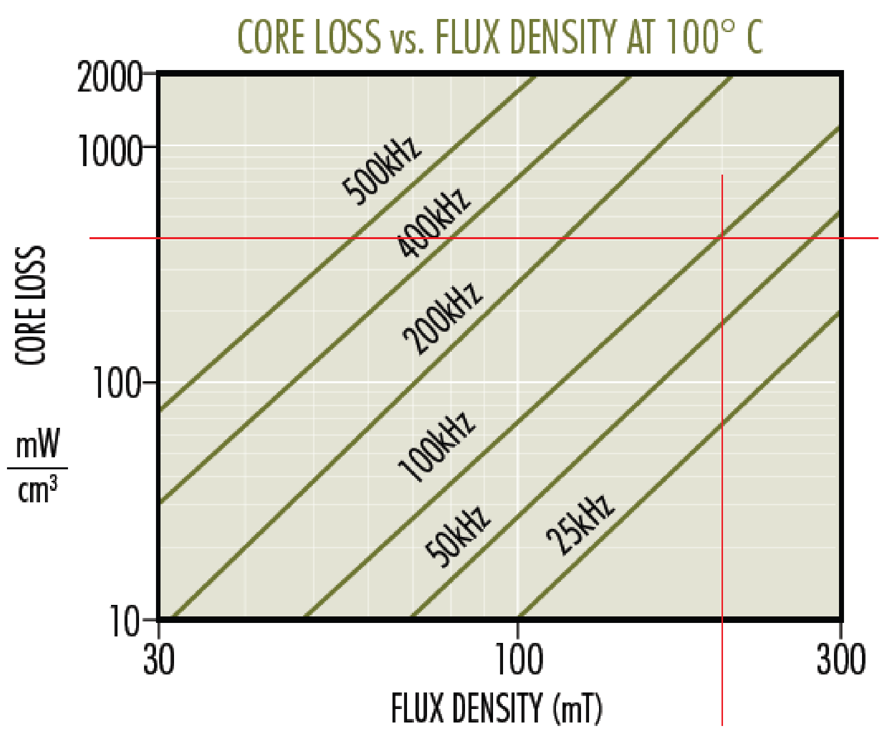
Core Losses

```
% core losses will be calculated as follows
% volume of the core:
% Volume = ((A*2B*C) - (2D*E*C)) * 10^-3  [cm^3]
% core loss mW/cm^3 will be determined
% @operating B, @operating f, @operating temperature

core_loss = Vol_core * graph_core_loss_40deg * 10^-3;   %[W]
%%%%%%
```

```
Core loss calculation is given above, the result is 53.7696
```





Efficiency

```
% efficiency will be calculate as follows
```

```
% neff = 100 * Po / (Po + Total_Loss) [%]
% Total loss includes copper and core losses

tot_loss = core_loss + tot_loss_copper;     %[W]
neff_res = 100* Po / (Po + tot_loss);       %[%]
%%%%%%
```

Efficiency of the transformer is calculated as above and the result is 99.7905.

Chapter 6. Other Parameters

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Mass

```
% mass of the transformer will be calculate as follows
% copper mass:
% total length of the copper * copper area * density of the copper
% total mass = total copper mass + total core mass

density_copper = 8.96;      % [g/cm^3]

copper_vol_pri = tot_length_coil_pri * Nstrand_pri * area_AWG26;   %[cm^3]
copper_mass_pri = copper_vol_pri * density_copper * 10^-3;    %[kg]

copper_vol_sec = tot_length_coil_sec * Nstrand_sec * area_AWG26;   %[cm^3]
copper_mass_sec = copper_vol_sec * density_copper * 10^-3;    %[kg]

mass_transformer = copper_mass_pri + copper_mass_sec + core_mass; %[kg]
%%%%%%
```

Mass of the transformer is calculated as above and the result is 1.3747 kg.

Magnetics

```
% transformer reluctance, magnetizing inductance will be calculated
% R = le / (u * Ac)
% Lm = Npri ^2 / R
% H field intensity = B / u
mu0 = 4 * pi() * 10^-7;     %[-]
Reluctance = le_dim * 10^-3 / (mu_r*mu0*Ac*10^-4);
Lm = round(Np)^2 / Reluctance * 10^3;     %[mH]
Lm_Al = Al*round(Np)^2*10^-6;  %[mH]
%%%%%%
```

Magnetizing inductance is calculated as above.
Lm = 1.1013 mH.

Price

```
% core and copper price is calculated as follows
```

```
price_copper = 4.7; %[$/kg]
tot_price_copper = (copper_mass_pri + copper_mass_sec) * price_copper; %[$]

price_trans = tot_price_copper + price_core; %[$]
%%%%%%
```

```
Transformer cost (only copper and core are included) is approximately 9.6051$.
```

Chapter 7. Summary

Table 7.1. Transformer Design Parameters

Parameters	**Values**
WaAc, area product distribution [cm^4]	35.9909
B, magnetic (operating) flux density [Tesla]	0.2000
Np, # of primary turns [-]	10
Ns, # of secondary turns [-]	294
Ip, primary rms current [A]	81.5387
Is, secondary rms current [A]	2.6657
Rpri, resistance of primary side [Ohm]	7.3407e-04
Rsec, resistance of secondary side [Ohm]	0.6097
copper loss [W]	9.2130
core loss [W]	53.7696
efficiency [%]	99.7905
copper mass [kg]	0.6475
core mass [kg]	0.7140
Lm, magnetizing inductance [mH]	1.1013
H, magnetic field intensity [A]	31.6629
copper price [$]	3.1051
core price [$]	6.5000