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
% selected core dimensions [mm]
A_dim = 101.6;
B_dim = 57.1;
C_dim = 25.4;
D_dim = 31.7;
E_dim = 50.8;
Ac = 645 * 10^-2;           % [cm^2] Ae effective are for the choosen ferrite
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;         % [$]
```

%%%%%%

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.

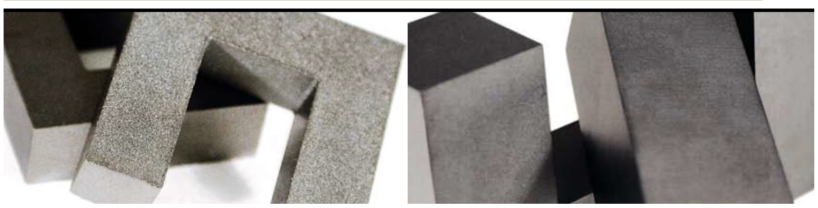
From the Magnetics Ferrite Catalog (2013) U core is selected. The detail are given below.

Typical Power Handling Chart

Power in Watts				Pot, RS, DS	E Cores	RM, PQ, EP	UU, UI, UR	ETD, EER, EC	EFD, Planar	Toroid
20 kHz	50 kHz	100 kHz	250 kHz							
11700	19000	26500	51500		49928 EE		49330 UU 49332 UU 49920 UU 49925 UI 49925 UU			49725 TC 49740 TC

U, I Cores

U cores are ideal for power transformer applications. The long legs of U core support low leakage inductance designs and facilitate superior voltage isolation. U/I combinations provide for economical assembly.



P Material

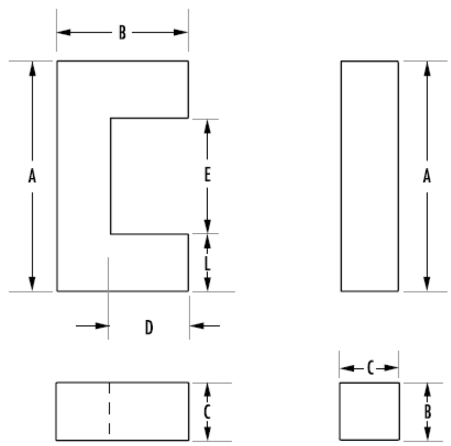
A low-medium frequency general-purpose power converter material. Engineered for lowest losses between 80 - 100°C. Available in almost all core sizes and shapes.

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

U cores are ideal for power transformer applications.
The long legs of U core support low
leakage inductance designs
and facilitate superior voltage isolation.

		MAGNETIC DATA						HARDWARE	
TYPE/SIZE	ORDERING CODE	l_e (mm)	A_e (mm²)	A min (mm²)	V_e (mm³)	WaAc (cm⁴)	Weight (grams per set)	Bobbins	Clips
U 102/57/25	**0_49925UC**	308	645	645	199,000	121	988		

		DIMENSIONS (mm)					
TYPE/SIZE	ORDERING CODE	A	B	C	D	E	L
U 102/57/25	**0_49925UC**	101.6 ± 1.5	57.1 ± 0.4	25.4 ± 0.6	31.7 ± 0.75	50.8 ± 1	25.4 ± 0.8



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;
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 =  308.4398     take Ns as 308
Ip = 81.5387
Is = 2.6657
```

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;

Wa = 2 * D_dim*E_dim * 10^-2; % available core window area cm^2
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 = 47.4065  [mm^2]
for secondary side is Aws = 1.4377 [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

radius_acoil = C_dim/2 + D_dim/2;   % [mm]
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 = round(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 13.6336
```

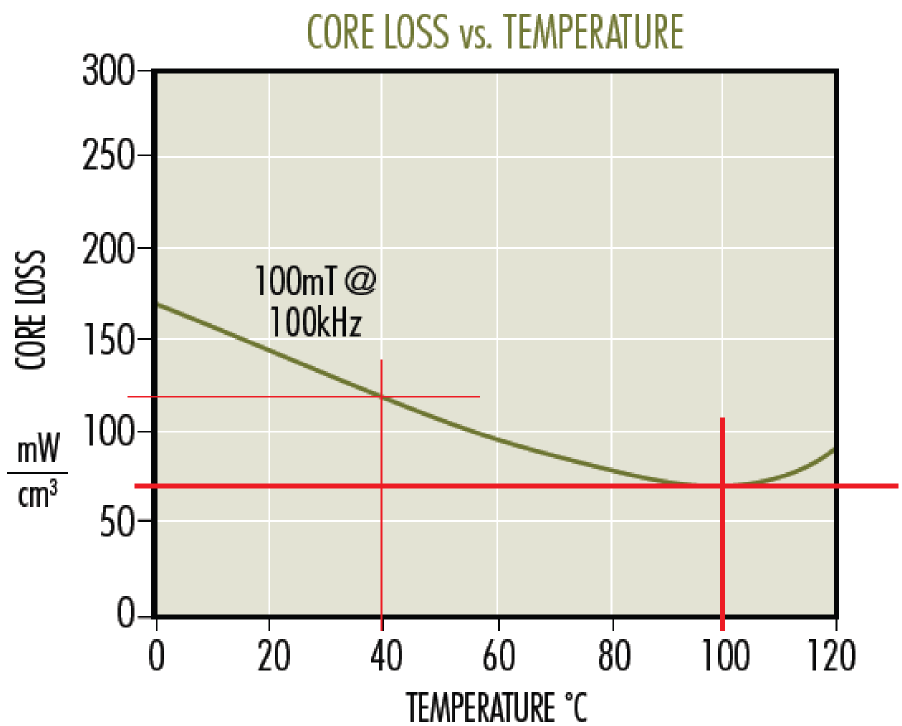
AWG	Diameter [inches]	Diameter [mm]	Area [mm²]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	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

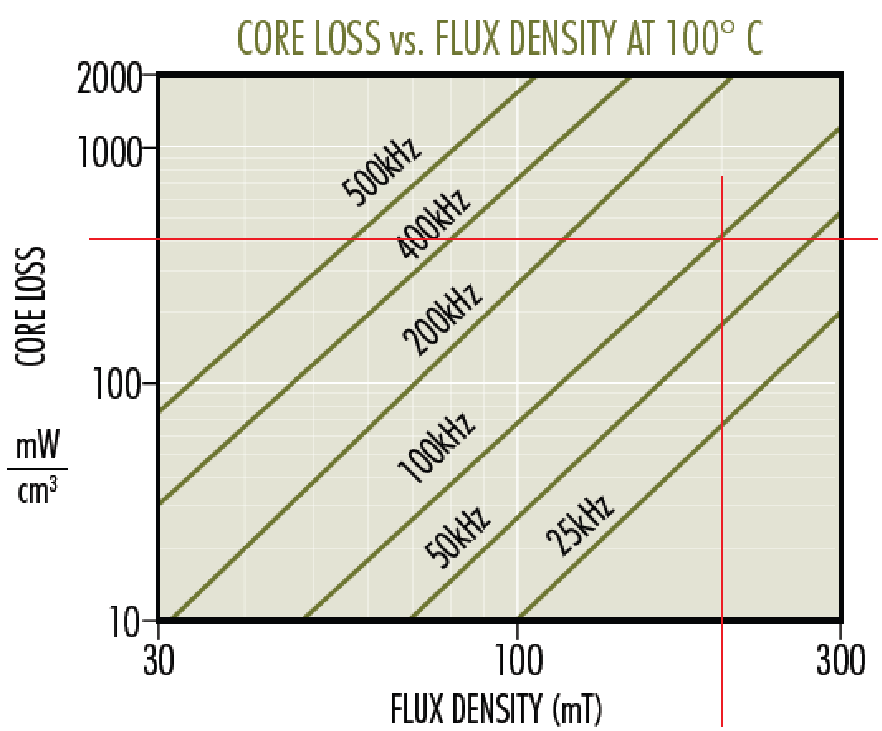
Core Losses

```
% 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

Vol_core  = ((A_dim*2*B_dim*C_dim) - (2*D_dim*E_dim*C_dim)) * 10^-3;    %[cm^3]
core_loss = Vol_core * graph_core_loss_40deg * 10^-3;   %[W]
%%%%%%
```

```
Core loss calculation is given above, the result is 149.0320
```





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 99.4607.

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 2.9555 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]
H_field = B * 10^-4 / (mu_r*mu0);


%%%%%%
```

Magnetizing inductance and field intensity are calculated as above.
Lm = 0.8271 mH.
H = 31.8310 A.

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 39.3635$.
```

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 [-]	308
Ip, primary rms current [A]	81.5387
Is, secondary rms current [A]	2.6657
copper loss [W]	13.6336
core loss [W]	149.0320
efficiency [%]	99.4607
copper mass [kg]	0.9372
core mass [kg]	1.9760
Lm, magnetizing inductance [mH]	0.8271
H, magnetic field intensity [A]	31.8310
copper price [$]	4.6035
core price [$]	34.7600