Transformer Design for a X-Ray Device

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

Hüseyin YÜRÜK

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Publication date 18-Apr-2016 22:04:16

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

First of all core selection will be done, then primary and secondary number of turns will be calculated. After finding copper and core losses, efficiency will be determined. Then some of the transformer parameters are given like mass, inductance and price. As a summary parameters are given in the table and finally conclusion section will be written in this report.

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]
```

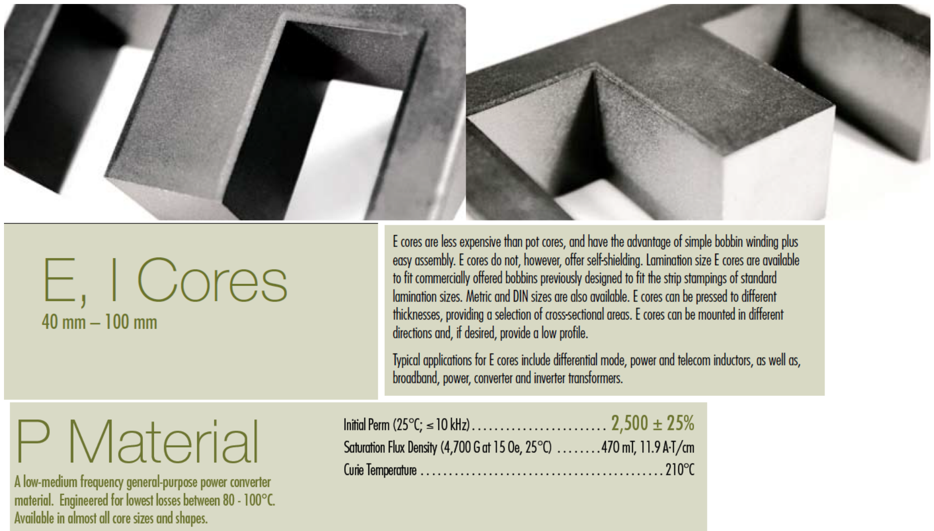
```
% graph_core_loss_40deg = graph_core_loss_100deg * 2; %[mW/cm^3]
% price_core = 2*17.38;         % [$]


% 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]
Vol_eff = 72.3; %[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;                %[-]
mu0 = 4 * pi() * 10^-7;     %[-]
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]

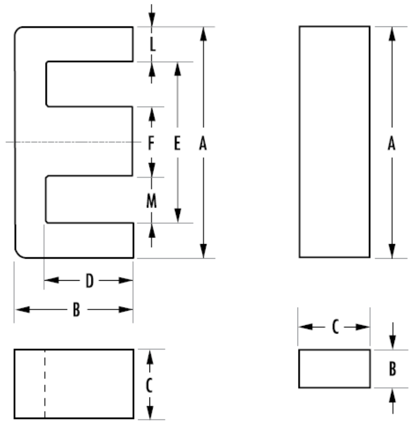
Then the Area Product Distribution (WaAc) Chart is used to select the appropriate core.

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



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.

Note that, Eddy current losses will increase rapidly with frequency. In bulk metals, these high frequency losses can be reduced by reducing the thickness of the material perpendicular to the flux flow. This is accomplished by using thin gauge tapes or laminations or by powdering and insulating the particles.
In ferrites, the same result is obtained by increasing the resistivity by many orders of magnitude. Thus, at the highest operating frequencies where further gauge or particle reduction is impractical, ferrites are the suitable materials.



TYPE/SIZE	ORDERING CODE	MAGNETIC DATA l_e (mm)	A_e (mm^2)	A min (mm^2)	V_e (mm^3)	WaAc (cm^4)	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
Pin = Po / n_eff;
Ip = Pin / Vp_rms;
Is = Po / Vs_rms;
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;

%%%%%%
```

```
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]
Ns value is re-calculated to get the desired magnetic field
strength H.
```

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


% 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 * ceil(Ns));   % [mm^2]
Awp = ceil(Ns) * Aws / round(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 = 91.7879  [mm^2]
for secondary side is Aws = 3.1220 [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 = F/2 + M/2; [mm]
% note that it is the midpoint of the window area
% 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]
%%%%%%
```

```
Note that avearage length of the one coil is considered as a circle which
has a radius at mitpoint of the window area (as can be seen above).
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

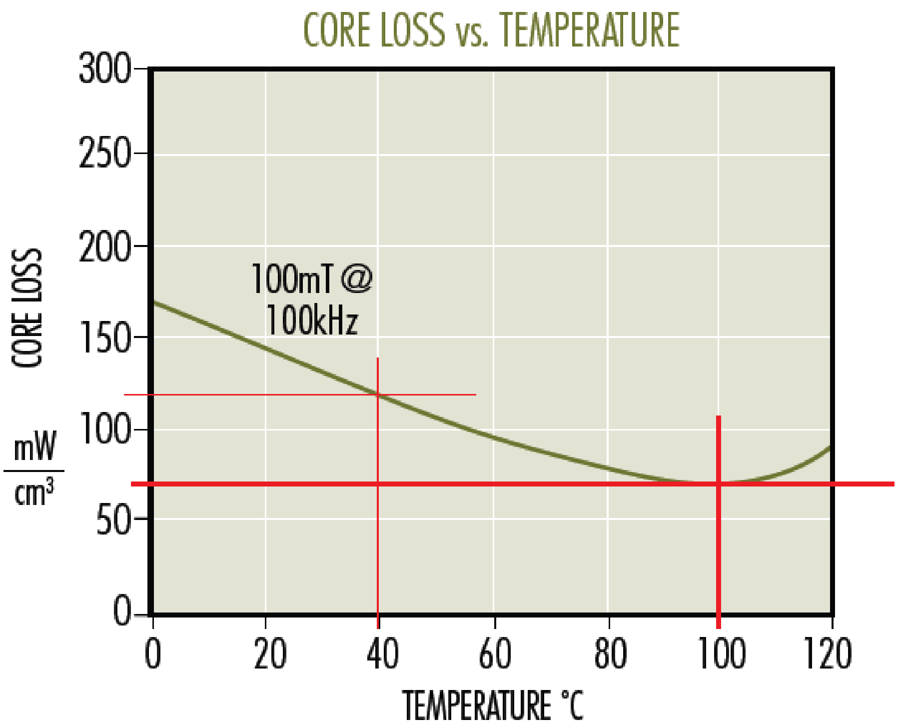
Core Losses

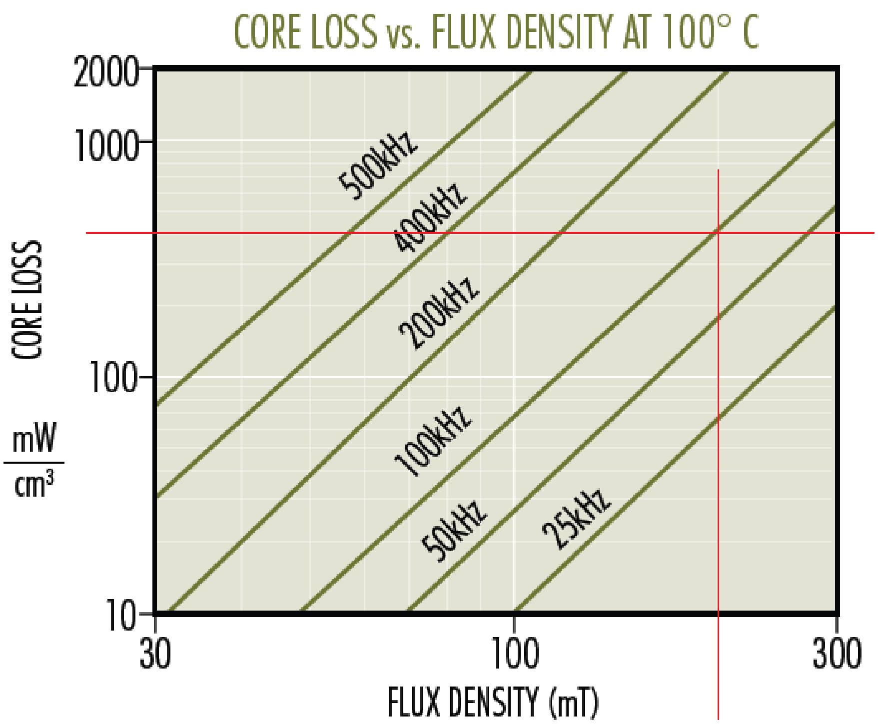
```
% core losses will be calculated as follows
% volume of the core:
% Volume = ((A*2B*C) - (2*2D*M*C)) * 10^-3  [cm^3]
% core loss mW/cm^3 will be determined
% @operating B, @operating f, @operating temperature

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

```
Theoritical core volume is calculated as above and the result is 76.8137.
```

```
Effectife core volume is given as 72.3000.
For core loss calculation, effective core volume is used.
Note also that at 40°, the loss of the core is approximately 2 times
than at 100°.
So core loss calculation is given above, and the result is 50.6100
```





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 99.8010.

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
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]	50.6100
efficiency [%]	99.8010
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

Chapter 8. Conclusion

This report has presented design consideration for a high-frequency, high-voltage transformer that will be used in a X-Ray device.
For this type of application ferrite materials is seleceted.
After calculating the WaAc product, the core (E core) and the metarial (P type) is selected from the Magnetics catalog.
Considering the requirred magnetic field strength H, the number of turns are calculated. By considering the frequency of the application (skin depth phenomena) the AWG cable size (AWG26) is selected.
Then losses of the copper and the core has determined.
To calculate the copper losses, a coil is assumed as a circle which has a radius at midpoint of the available window area.
To calculate the core losses effective core volume is taken, and the given loss value on the graph in the calatog is tuned with the given ambient temperature. The other parameters of the transformer like mass, inductance and price are also calculated in this report.

Chapter 9. References

https://www.mag-inc.com/.../MagneticsFerritePowerDesign2013.pdf
https://www.mag-inc.com/.../Magnetics2013FerriteCatalog.pdf
https://www.mag-inc.com/File%20Library/.../cg-01.pdf
http://www.convertunits.com/from/mm%5E2/to/circular+mil
https://www.electramania.com/conversion-charts-i63
http://coefs.uncc.edu/mnoras/files/2013/03/
Transformer-and-Inductor-Design-Handbook_Content.pdf