# EE564 First Project: Transformer Design a for X-Ray Device

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# ID


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```
function []=meka_mutlu_XRAY()
```

# Specifications

- **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 millisecond)
- **Switching Frequency:** Minimum 100 kHz
- **Ambient Temperature:** 0-40 °C

```
Prated      = 30e3; % Rated power [W]
fs          = 100e3; % switching frequency [Hz]

Vp_peak     = 417; % Primary side peak voltage [V]
Vp_fund_peak= Vp_peak*4/pi; % Peak of fundamental of primary voltage [V]
Vp_f_rms    = Vp_fund_peak/sqrt(2); % RMS value of fundamental [V]

Vs_peak     = 12.5e3; % Secondary side peak voltage [V]
Vs_fund_peak= Vs_peak*4/pi; % Peak of fundamental of secondary voltage [V]
Vs_f_rms    = Vs_fund_peak/sqrt(2); % RMS value of fundamental [V]

Ip_rms      = Prated/Vp_f_rms; % Primary side RMS current [A]
Is_rms      = Prated/Vs_f_rms;  % Secondary side RMS current [A]
fprintf('The RMS value of primary side current is %2.2f A.',Ip_rms)
```

```
The RMS value of primary side current is 79.91 A.
```

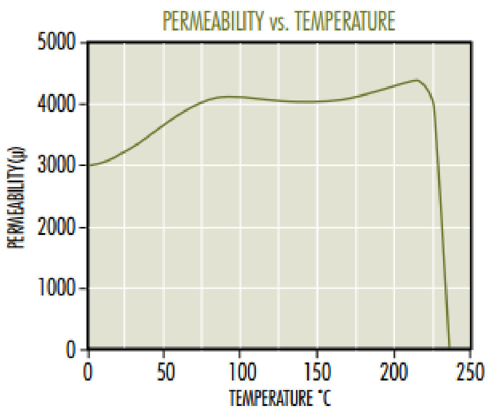
```
fprintf('The RMS value of secondary side current is %1.2f A.',Is_rms)
```

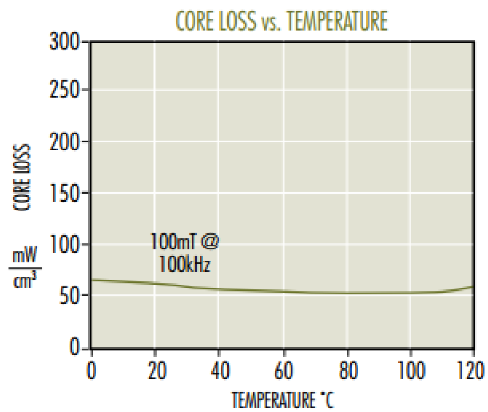
*The RMS value of secondary side current is 2.67 A.*

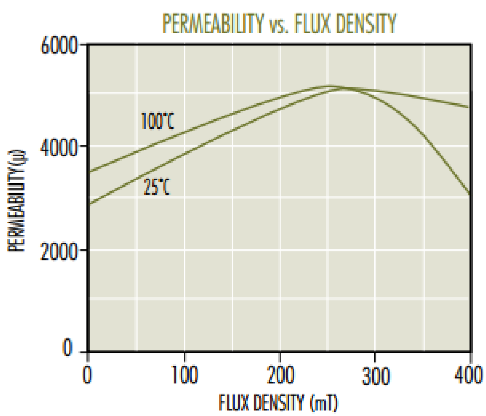
# Choosing Initial Material

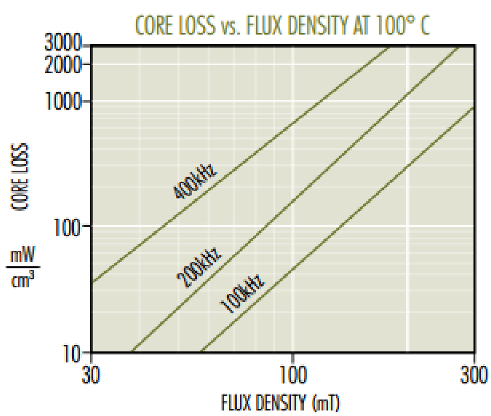
First step of transformer design is selecting an appropriate core material. After some researches on internet and company application guides, it is decided to use a ferrite material for XRAY transformer application at 100kHz switching frequency.

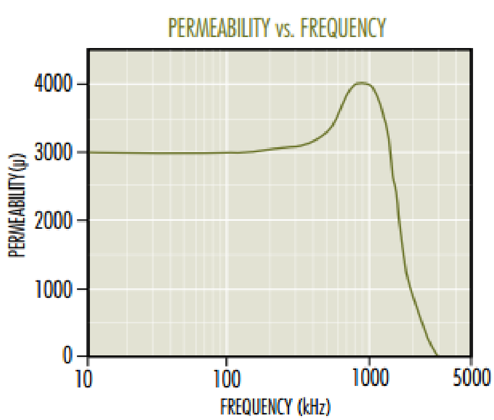
After this decision, Magnetics' ferrite catalog is read and different types of materials are compared. In that comprasion, power losses of materials at 25°C and 100kHz is used as basic elimination parameter and it is decided to use T material. It is possible to find its parametets below:



# Choosing Operation Flux Density

For the second phase of design, it is going to be choosen operation flux density. T material's saturation flux density is 470mT for this project's defined temperature range. Our value should be smaller than saturation point. But how much? Let's consider over the formula below:

$$e = -\frac{2*\pi}{\sqrt{2}} N 2\pi f B_{peak} * A$$

If only selectable parameters are considered, it is possible to see the trade-off between number of turns, flux density and area. Selecting high number of turns come with dificulties of cabling and copper losses. Cable size is decided over current values so it is constant in this discussion. Area is important for transformer's size and weight values. It also effects cable length and core loss (over volume). Flux density is directly related with core losses.

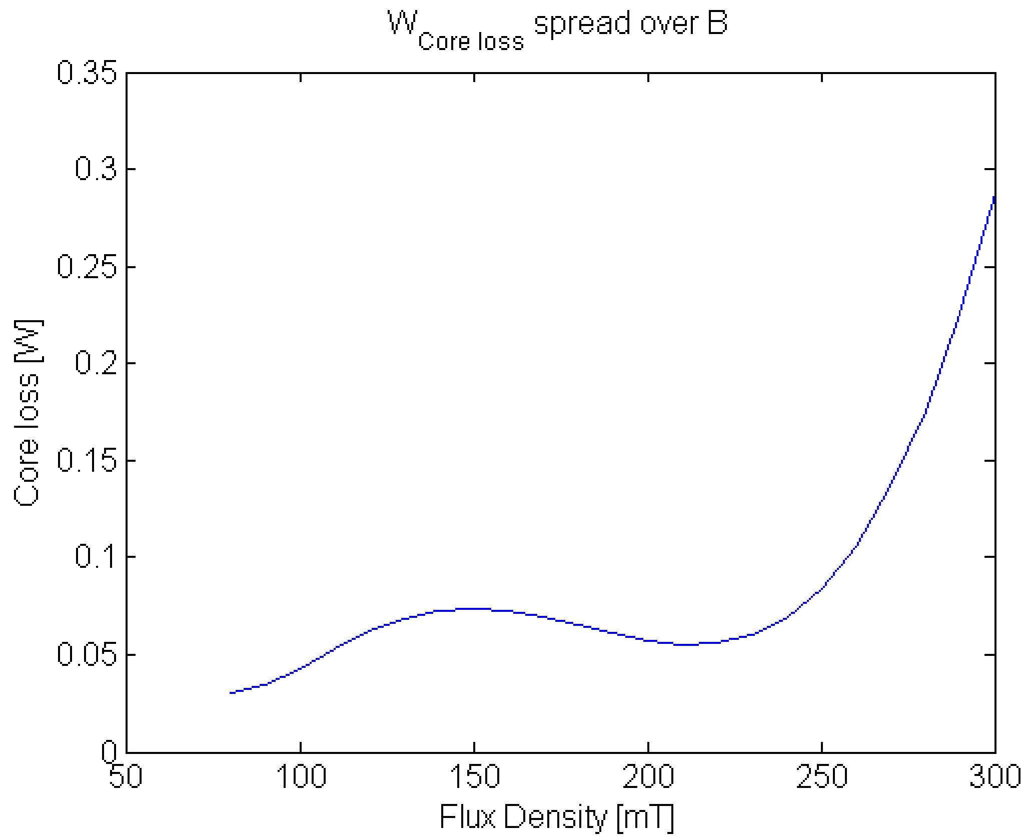
As B is increased, core loss is increased (nonlinearly). If we take BxA value constant, then increasing B will decrease A and therefore volume and weight will be less and it means less core loss. So here, by assuming area and volume are proportional, an optimization will be made over core loss.

```
B_opr = optimize_B(); %[T]
fprintf('The operation point of flux density is selected as %d mT.',B_opr*10^3)
```

```
The operation point of flux density is selected as 80 mT.
```

Flux density vs core loss graphic has some missing points due to its nonlinearity. To be able to find required missing points Lagrange polynomial method is used (Function used in this project was written by me during my 3rd class undergraduate studies). After completion is done, assuming area effects volume proportionally, a basic multiplication is made. In coreloss plot unit and magnitude aren't considered but result shows how core loss changes as operation point of flux density is increased.

```
plot(B_req, Coreloss);
set(gca,'FontSize',12);
xlabel('Flux Density [mT]');
ylabel('Core loss [W]');
title('W_{Core loss} spread over B');
```




This plot shows us selecting an arbitrary operation point may result bad efficiecny. Selecting the 2nd minimum point 210mT may be an advantage to not have a bigger transformer and still have less core lose. But if the absolute minimum point is considered and 80mT is selected, than core loss will be 85% smaller. It may mean having 2.5 times bigger transformer but it is going to be possible to compansate this value by changing number of turns. Also here, it is needed to be asked: "Should it be really small?". Perhaps this XRAY machine will be put in somewhere and stay there until someone needs to clean under it. A small research is done about "portable" XRAY machines. Here is the smallest result:


This XRAY machine is for dentists and just 60W. So our transformer is used for something bigger:

| No. | Name | Parameters |
| --- | --- | --- |
| 01 | Input power | Power supply voltage: AC220V ± 22 v; Power frequency: 50/60 hz ± 1 hz; |
| 02 | Output | kV: 40kv ~ 120 kV, mA: 16 mA ~ 200 mA, Working frequency: ≥30 kHz |
| 03 | Working environment | Environmental temperature: + 10 °C ~ + 40 °C; Relative humidity: 30% ~ 75%; Atmospheric pressure: 70 kpa ~ 106 kpa. |

This one's specs are given and when maximum points of voltage and current are multiplied result is 24kW and still smaller than our application. In such big machines, size of transformer may be ignored, its weight is also not so dominant. To be able to operate in a condition with less core loss 80mT is selected as operation flux density.

# Determination of Core Dimensions & Number of turns

Independetly from core dimensions and number of turns, diameter of cable might be determined. Because of skin effect, ac current tends to flow on the outside of a conductor. On a wire the current density looks like a hollow tube. Since the inside isn't used for AC current flow, it makes sense to eliminate as much of the hollow part as possible.

Here is a practical AWG calculator : http://daycounter.com/Calculators/SkinEffect/Skin-Effect-Calculator.phtml

It suggests "AWG 25" for our application at 100 kHz but because it isn't so easy to find odd AWG numbered cables, AWG 24 will be used.

```
A_awg24 = 0.205*10^-6; %[m^2]
fprintf('Cross-section area of a AWG 24 wire is %0.2d m^2.',A_awg24)
```

```
Cross-section area of a AWG 24 wire is 2.05e-07 m^2.
```

But how many parallel cables? For this purpose, Adiabatic equation will be used. Detailed derivations about this process may be found at http://www.openelectrical.org/wiki/index.php?title=Adiabatic_Short_Circuit_Temperature_Rise The resultant formula is given below:

$$A = \frac{\sqrt{i^2 t}}{k}$$

In this formula, A is the minimum cross-sectional area of conductor in $mm^2$ and k is the Adiabatic constant that might be calculated by formula below.

$$k = \sqrt{\frac{c_p \rho_d \delta T}{\rho_r}}$$

Luckily, at the same website another formula is exist for Adiabatic constant for only copper conductors:

$$k = 226\sqrt{ln(1 + \frac{T_f - T_i}{234.5 + T_i})}$$

Here, only required part is initial and final temperatures. If we take initial value as 25 and let it rise 0.5 degrees, than Adiabatic constant will be :

```
k_adb = 226*sqrt(log(1+(25.5-25)/(234.5+25)));
A_cbl_p = (sqrt((Ip_rms^2)*0.1)/k_adb)*(10^-6);
A_cbl_s = (sqrt((Is_rms^2)*0.1)/k_adb)*(10^-6);
```

From calculated cross-section area of cable we understand that how many parallel cables need to be used for desired temperature rise:

```
N_cbl_prl_p = ceil(A_cbl_p/A_awg24);
N_cbl_prl_s = ceil(A_cbl_s/A_awg24);

fprintf('%d parallel cables for primary and %d for secondary side will be OK.',N_c
```

```
13 parallel cables for primary and 1 for secondary side will be OK.
```

Normally AWG 24 has much less current capability but for 100 miliseconds of operation, it will be fine.

Here, using induced voltage formula, it is needed to decide number of turns and core dimensions together considering the minimum loss. Core material was already seleted as T material from Magnetics' ferrite catalog. Following that decision and considering different types of cores, 5 types of core geometries are selected as candidates. Best one for total of copper and core losses will be selected as the final one. Candidates are:

- OT44022EC
- OT45724EC
- OT45528EC
- OT45530EC
- OT46527EC

```
Cores =['OT44022EC';'OT45724EC';'OT45528EC';'OT45530EC';'OT46527EC'];
```

Their cross-section area and core volume parameters are as follow and will be used for coreloss calculations. Volumes are multiplied by 2 because it is planned to use two cores as a couple without airgap. Also their window areas are calculated to be able to see if we will be able to have enough space for selected wires with selected number of turns.

```
Ae_T = [233 337 353 420 540]*10^-6; %[m^2]
Ve_T = [227 360 440 520 790]*2*10^(-7); %[m^3]
Aw_T = [14.8*8.65 14.6*9.03 18.5*10.15 18.5*10.15 22*12.72]*2*10^-6; %[m^2]
```

```
Lp_T = [12.2+20 18.8+18.8 17.2+21 17.2+24.61 20+27.4]*2*10^-3; %[m]
Le_T = [97 107 124 123 147]*10^-3; %[m]
Masses = [114 179 212 255 410]*2; %[g]
```

Now we have possible values for cross-section are and from here it is possible to jump corresponding number of turns values. Following "Fundamentals of Power Electronics, Chapter:14" from University of Colorado fill factor is taken as 0.5 for our application. http://ecee.colorado.edu/~ecen5797/course_material/Ch14slides.pdf

```
Ku = 0.5;
```

By considering all parameters, core geometry will be choosen to have the minimum copper lose.

```
Selected_core = Core_selection();
N_turn_p = N_turns_p(Selected_core);
N_turn_s = N_turns_s(Selected_core);
Cu_loss = Cu_losses(Selected_core);
Core_loss = Corelosses(Selected_core);

fprintf('For the best efficiency %s is selected.',Cores(Selected_core,:))
```

*For the best efficiency OT46527EC is selected.*

```
fprintf('With this selection %d primary and %d secondary turns are determined.',N_
```

*With this selection 4 primary and 94 secondary turns are determined.*

```
fprintf('For these wires and turns %1.2f W is our copper loss.',Cu_loss)
```

*For these wires and turns 42.26 W is our copper loss.*

```
fprintf('For two of selected cores, %1.2f W will be our core loss.',Core_loss)
```

*For two of selected cores, 4.74 W will be our core loss.*

# Determination of efficiency, mass and cost

```
Total_loss = Cu_loss+Core_loss;
Eff = (Prated)/(Prated+Total_loss)*100;
fprintf('For %1.2f W total loss, efficiency is %2.2f %%.',Total_loss,Eff)
```

*For 47.00 W total loss, efficiency is 99.84 %.*

For selected core, let us calculate the total mass:

```
Core_mass = Masses(Selected_core); %[g]
V_wire_p = N_turn_p*N_cbl_prl_p*(1/Ku)*Lp_T(Selected_core)*A_awg24; %[m^3]
V_wire_s = N_turn_s*N_cbl_prl_s*(1/Ku)*Lp_T(Selected_core)*A_awg24; %[m^3]
Cu_density = 8.94*10^3; %[g/m^3]
Copper_mass = (V_wire_p+V_wire_s)*(Cu_density);
Total_mass = Copper_mass + Core_mass;
fprintf('Calculated total mass of transformer is %3.2f grams.',Total_mass)
```

*Calculated total mass of transformer is 820.05 grams.*

```
fprintf('With aditional materials we may take it as %3.0f grams.',round(Total_mass
```

```
With aditional materials we may take it as 984 grams.
```

Unit copper price is about 4.7 $/kg and selected cores cost more or less 3.5 $/set. Because two sets are used in each transformer:

```
Price_Cu = 4.7*Copper_mass/1000; %[$]
Price_total = ceil(Price_Cu+7); %[$]
fprintf('Total cost of transformer is %2.2f dolars.',Price_total)
```

```
Total cost of transformer is 8.00 dolars.
```

# Calculation of Electrical Parameters

Using wires' information resistances of both sides will be calculated;

$$R = \frac{\rho l}{A}$$

```
R_p = rho_Cu*Lp_T(Selected_core)*(1/Ku)*N_turn_p/(N_cbl_prl_p*A_awg24);
R_s = rho_Cu*Lp_T(Selected_core)*(1/Ku)*N_turn_s/(N_cbl_prl_s*A_awg24);
R_core = (Vp_f_rms^2)/Core_loss;

fprintf('Primary side resistance is %2.2f miliohm.',R_p*10^3)
```

```
Primary side resistance is 4.78 miliohm.
```

```
fprintf('Secondary side resistance is %2.2f ohm.',R_s)
```

```
Secondary side resistance is 1.46 ohm.
```

```
fprintf('Core resistance is %2.2f kiloohm.',R_core*10^-3)
```

```
Core resistance is 29.74 kiloohm.
```

To be able to calculate magnetizing inductance:

```
mu = 3000*4*pi*10^-7;
H = B_opr/mu;
I_mag = H*Le_T(Selected_core)/N_turn_p;
Zmag = Vp_f_rms/I_mag;
Xmag = sqrt((Zmag^2)-(R_core^-2));
Lmag = Xmag/(2*pi*fs);
fprintf('Magnetizing inductance is %2.2f miliHenry.',Lmag*10^3)
```

```
Magnetizing inductance is 0.77 miliHenry.
```

```
    function [output] = optimize_B()
        B_given = [80 90 100 200 300]; % [mT]
        Coreloss_coef = [25 32 45 120 900]*1.2*10^-3; % [W/cm^3]
% 1.2 multiplier is added due to difference between 100 degree and room
% temperature.
        B_req = 80:10:300; %[mT]
        for i=1:length(B_req)
            Coreloss_coef2(i)=lagrange(B_given, Coreloss_coef, B_req(i));
            Coreloss(i) = Coreloss_coef2(i)*B_req(1)/B_req(i);
        end;
```

```
        output = B_req(find(Coreloss==min(Coreloss)))*10^-3; % [T]
    end

    function L=lagrange(x,y,k)
        n=length(x);
        l=1;
        L=0;
        for i=1:n
            for j=1:n
                if i~=j
                    l=l*(k-x(j))/(x(i)-x(j));
                end;
            end;
            L=L+l*y(i);
            l=1;
        end;
    end;

    function [output] = Core_selection()
        Corelosses = Ve_T.*10^6*25*1.2*10^-3; % [W]
        rho_Cu = 1.678*10^-8;
        for i=1:length(Ae_T)
            N_turns_p(i) = ceil(Vp_f_rms/((4.44)*2*pi*fs*B_opr*Ae_T(i)));
            N_turns_s(i) = ceil(Vs_f_rms/((4.44)*2*pi*fs*B_opr*Ae_T(i)));
            Area_max(i) = 0.5*Ku*Aw_T(i);
            Area_used(i) = ((N_cbl_prl_p*N_turns_p(i))+(N_cbl_prl_s*N_turns_s(i)))
            if(Area_used(i)>Area_max(i))
                Cu_losses(i) = 2142;  %for elimination
            else;
            Cu_losses(i) = (Ip_rms^2)*rho_Cu*N_turns_p(i)*Lp_T(i)*(1/Ku)/(A_awg24*
            Cu_losses(i) = (Cu_losses(i)+((Is_rms^2)*(rho_Cu*N_turns_s(i)*Lp_T(i)*
            end;
            Total_loss(i) = Corelosses(i) + Cu_losses(i);
        end;
        output =find(Total_loss==min(Total_loss));
    end;

end
```

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