EM564 FIRST PROJECT:HVDC TRANSFORMER DESIGN

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Specification

This project is relevant to design single phase high voltage frequency transformer.

The main idea of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer design should be carried out based on the specification given, using available materials

Specification of the transformer is shown below:

*Power: 6.5 MVA

*Operating Frequency: 500 Hz

*Input voltage: 3 kV

*Output voltage: 300 kV

*Operating temprature: 110 °C

```
S=6.5*10^6;
Vp=3000;
Vs=300000;
f=500;
w=2*pi*f;
mu=4*pi*10^-7;
turn_ratio=Vp/Vs;
lamination_factor=0.94;
winding_factor=0.25;
kw=0.94;
```

Choose Initial Material

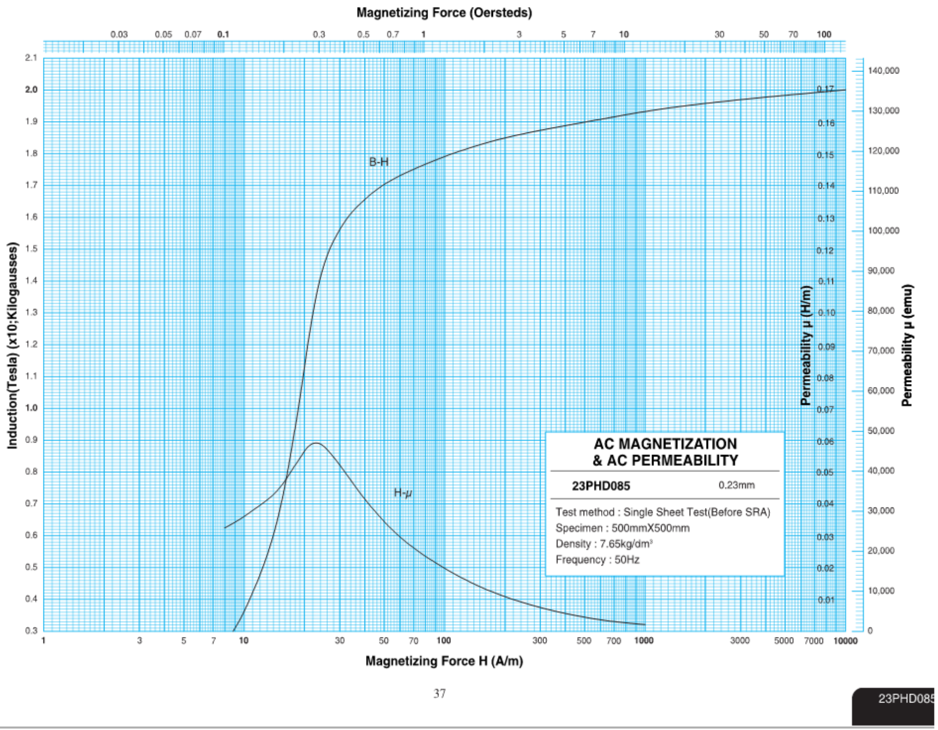
Generally, the name associated with the construction of a transformer is dependant upon how the primary and secondary windings are wound around the central laminated steel core. The two most common and basic designs of transformer construction are the Closed-core Transformer and the Shell-core Transformer. In the “closed-core” type (core form) transformer, the primary and secondary windings are wound outside and surround the core ring. In the “shell type” (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit

Choosen correctly dimension and type of the core is important. Because diameter of the core is increased, the number of turns in the transformer winding reduced. Reduction of number of turns, reduction in height of the core legs in-spite of reduction of core legs height increased in core diameter, results increase in overall diameter of magnetic core of transformer. This increased steel weight ultimately leads to increased core losses in transformer. Increased diameter of the core leads to increase in the main diameter on the winding. In – spite of increased diameter of the winding turns, reduced number of turns in the windings, leads to less copper loss in transformer. So, we go on increasing diameter of the transformer core, losses in the transformer core will be increased but at the same time, load loss or copper loss in transformer is reduced. On the other hand, if diameter of the core is decreased, the weight of the steel in the core is reduced; which leads to less core loss of transformer, but in the same time, this leads to increase in number of turns in the winding, means increase in copper weight, which leads to extra copper loss in transformer.

For this project 0.23 mm M3 shell type core is selected the reason of this is operating frequency. If other core material is selected, core loss can be very high. Due to same reason flux density should be low to decrease the losses, from the datasheet it can be seen

While determining the secondary turn number cross 0.05 because of the voltage drop

```
B=1.2;

core_density=7.65;

Np=20;

Ns=(Np/turn_ratio)*105/100;

pic = imread('magnetization.png');
figure;
imshow(pic);
```



Calculation of Thickness of Core Leg

Where kw is the core stacking factor, D (mm) is the width of core leg and Eu (mm) is the thickness of the core leg. The core stacking factor expresses the net cross-section area of the magnetic flux. Necessary equation is:

Vp=E=4.44*f*N*kw*B*Acore and E=Vt*N

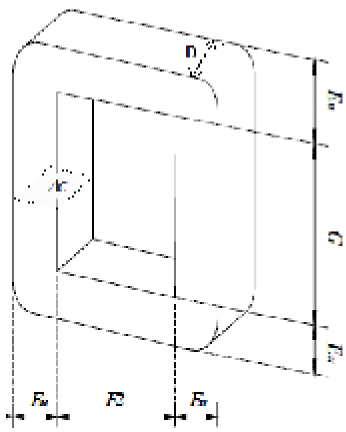
and

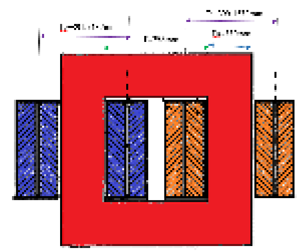
Acore=2*D(width of core leg)*Eu(thickness of the core leg)

The factor 1/2 appears because the assembling of every winding of shell type transformer require two cores

```
Ac=Vp/(4.44*f*Np*kw*B);
D=0.1;
Eu=Ac/(2*D);

core_shape = imread('shell_type_transformer.png');
core_dimension = imread('transformer_dimension.png');
figure;
subplot(1, 2, 1),
imshow(core_shape)
subplot(1, 2, 2),
```

```
imshow(core_dimension);
```





Wire Selection

Selecting the wrong size or type of cable can result in, at best, a system that does not operate correctly or as desired. The first rule is that the cable must be of the correct type for the voltage. This is related to the insulation breakdown voltage.

The 2nd rule is even simpler. This relates to the physical strength and durability of the cable.This rules are slighly more complicated and are related to the actual size of the conductor. This defines how much current the cable can safely carry.

The third rule is that the cable must be able to safely handle the current without overheating the cable and/ or it's insulation. This specification can be calculated from the current through the cable and the resistance of the cable

```
Ip=S/Vp;
Is=S/Vs;
J=3;
Ap=Ip/J;
As=Is/J;
```

Skin Depth Calculation

Sinusoidal currents in good conductors are not distributed uniformly over their cross section. Rather as frequency increases, the current tends to concentrate near the conductor surface, a phenomenon known as the skin effect. At very high frequency, the skin effect is so pronounced that current exist only over a very thin layer of any good conductor.

```
copper_mu=1.256629*10^-6;
q=1.68*10^-8; % resistivity of the copper for 20C
skin_dept=sqrt((2*q)/(copper_mu*w))*1000;
```

Primary Side Winding

While the conductor area is calculating, current density is take into acount and it is generally J=4-4.5, but in this application beccause of the high frequency and losses it is choosen a bit lower.

the other issue is to decide wire type and area. For the primary side the area is very big so to get correct area conductor use paralel strip conductor as known litz. Litz wire reduces the degree of the skin effect so it is preferred. It is used 12*6 mm^2 copper stripes and the edge is selected as 2x-x

```
copper_area_p=12*6;
paralel_branch=round(Ap/copper_area_p);
copper_window_primary=copper_area_p*paralel_branch*Np;
```

Secondary Side Winding

For the secondary side area is low so awg#8 is enough

```
copper_area_s=8.37;
copper_window_secondary=copper_area_s*Ns;
diameter_secondary_winding=sqrt(As*4/pi);

wire = imread('AWG size.png');
figure;
imshow(wire);
```

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	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

Window Area

When operating at high frequencies, the window fill factor, has to be taken into account For the window area it is considered primar and seconder winding distance for the insulation so there is a constant like fill factor=0.25 After finding total window area it can be thought a square core so it can be say G=F2

```
window_area=(copper_window_primary+copper_window_secondary)/
winding_factor;

G=round(sqrt(window_area));

F2=G;

winding_pitch_primary=G+[(Eu*1000)*(copper_window_primary/
window_area)];

winding_pitch_secondary=G+[(Eu*1000)*(copper_window_secondary/
window_area)];
```

Resistance of the Primary and Secondary Conductors

```
L_primary=pi*winding_pitch_primary*Np;
R_p=0.6;
R1=R_p*L_primary/1000/paralel_branch;
R1_70=R1*(1+0.003862*(70-20));

L_secondary=pi*winding_pitch_secondary*Ns;
R_s=2.061;
R2=(R_s*L_secondary)/1000;
R2_70=R2*(1+0.003862*(70-20));
```

Magnetizing and Leakage Inductance

For this part we use B-H curve shown in figure1 to calculate permeability (mu). From the datasheet for the B=1.2T match up to mu=0.058 to obtain primary and secondary leakage reactance 0.05 pu assume and X1=X2p for primary side

```
permeability=0.058;
L=[2*(F2+G+2*Eu*1000)]/1000;
reluctance=L/(permeability*Ac);
Lm=Np^2/reluctance;
Xm=2*pi*f*Lm;

Xes=0.05*Vp^2/S;
X1=Xes/2;
L1=X1/(2*pi*f);

X2p=X1;
X2=X2p/turn_ratio;
L2=X2/(2*pi*f);
```

Voltage Drop

For full load operation output voltage is calculated using circuit parameters.

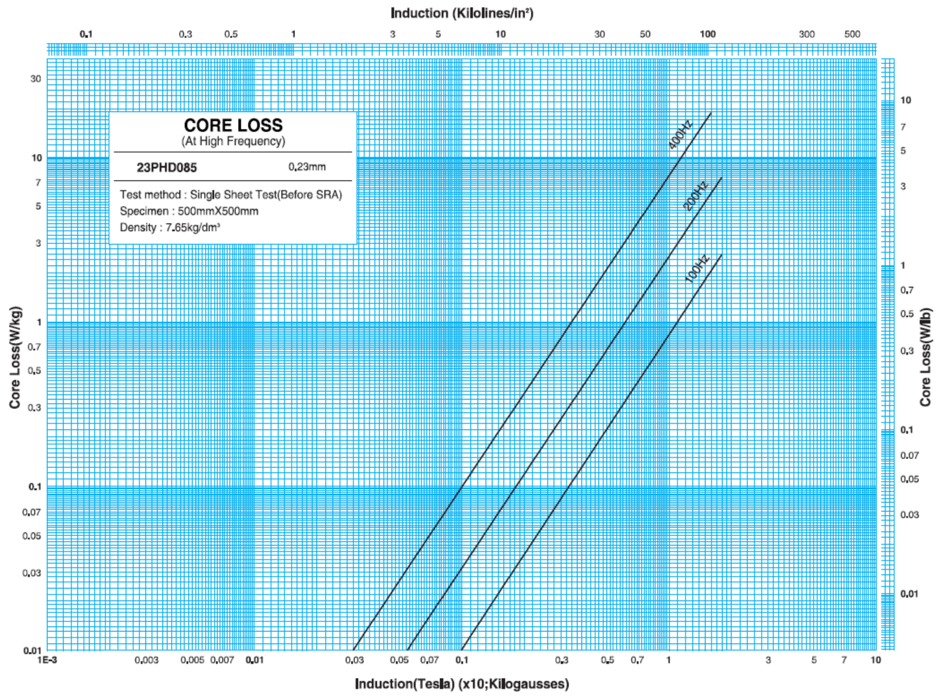
```
Vp_drop=((R1*10^-3+j*X1)*Ip);

Ep=abs(Vp-Vp_drop);

Vs_drop=Ep/turn_ratio;
```

Loss Calculation

To calculate core loss Steinmetz'e equation (Pcore=k*(f^a)*(B^b)) is used from the catalog 100 Hz and 200 Hz core loss value is chosen and by using this value 'a' is found.

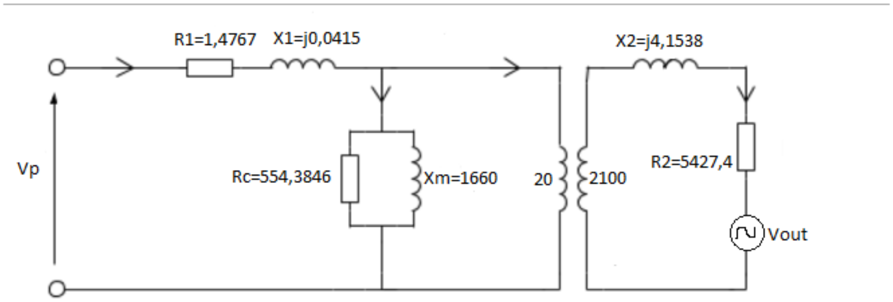
```
loss = imread('core_loss.png');
```

```
figure;
imshow(loss);
```



Core loss:

```
P_core_100=1.2;

P_core_200=3.4;

a=[log(P_core_100/P_core_200)]/[log(100/200)];

P_core_500=((500/100)^a)*P_core_100;

core_volume=Ac*4*((F2/1000)+Eu);

Mc=core_volume*core_density*1000;

core_loss=P_core_500*Mc;

Rc=Vp^2/core_loss;

equivalent = imread('equivalent circuit.png');
figure;
imshow(equivalent);
```



Copper loss:

```
copper_loss_p=R1*Ip^2/1000;

copper_loss_s=R2*Is^2/1000;

total_copper_loss=copper_loss_p+copper_loss_s;

%Full load copper loss

load_copper_loss_p=R1_70*Ip^2/1000;

load_copper_loss_s=R1_70*Is^2/1000;

total_load_copper_loss=load_copper_loss_p+load_copper_loss_s;

total_loss=total_copper_loss+core_loss+total_load_copper_loss;
```

Efficiency

```
P_out=S*0.96;

efficiency=P_out/(P_out+total_loss)*100;
```

Core- Copper Mass & Cost

For the cost calculation prize take from the http://www.lme.com/ website and approximately convert TL value

```
core_cost=15*Mc;

copper_density=8.94*10^3;  %g/m^3

V_wire=(L_primary*Ap*paralel_branch)+(L_secondary*As);

copper_mass=V_wire*10^-9*copper_density;
```

```
copper_cost=25*copper_mass/1000;

total_cost=core_cost+copper_cost;
```

Outputs

After complaining the design, this values are obtained:

```
fprintf('Primer turn number: %d\n',Np)
fprintf('Seconder turn number: %d\n',Ns)
```

```
Primer turn number: 20
Seconder turn number: 2100
```

Core Parameters

```
fprintf('Weigth of the core leg: %f mm\n',D*1000)
fprintf('Thickness of the core leg:%f mm\n',Eu*1000)
fprintf('Width of the core leg:%f mm\n',F2)
fprintf('Heigth of the core leg:%f mm\n',G)
fprintf('core cross section area:%f mm^2\n',Ac*10^6)
fprintf('core resistance:%f ohm\n',Rc)
fprintf('Lmagnetixation:j%f ohm\n',Xm)
fprintf('Core mass:%f kg\n',Mc)
fprintf('Core volume:%f m^3\n',core_volume)
fprintf('Core loss:%f W\n',core_loss)
fprintf('Stacking factor:%f \n',kw)
fprintf('Winding factor:%f \n',winding_factor)
fprintf('Core density:%f kg/dm^3 \n',core_density)
fprintf('Flux density:%f  T\n',B)
```

```
Weigth of the core leg: 100.000000 mm
Thickness of the core leg:299.501629 mm
Width of the core leg:358.000000 mm
Heigth of the core leg:358.000000 mm
core cross section area:59900.325858 mm^2
core resistance:554.384589 ohm
Lmagnetixation:j1660.008141 ohm
Core mass:1205.167593 kg
Core volume:0.157538 m^3
Core loss:16234.217507 W
Stacking factor:0.940000
Winding factor:0.250000
Core density:7.650000 kg/dm^3
Flux density:1.200000  T
```

Primary Side

```
fprintf('Primary voltage:%f kV\n',Vp/1000)
fprintf('Current density:%f A/mm^2\n',J)
fprintf('Primary current:%f A\n',Ip)
fprintf('Primary conductor area:%f mm^2\n',Ap)
fprintf('Primary resistance:%f*10^-3 ohm\n',R1)
fprintf('L1:%f H\n',L1)
```

```
fprintf('Primary inductance:j%f ohm\n',X1)
fprintf('Paralel conductor number:%d\n',paralel_branch)
fprintf('Primary copper loss:%f W\n',copper_loss_p)
fprintf('Primary coil average distance:%f mm\n',winding_pitch_primary)
```

Primary voltage:3.000000 kV
Current density:3.000000 A/mm^2
Primary current:2166.666667 A
Primary conductor area:722.222222 mm^2
*Primary resistance:1.476743*10^-3 ohm*
L1:0.000011 H
Primary inductance:j0.034615 ohm
Paralel conductor number:10
Primary copper loss:6932.486580 W
Primary coil average distance:391.718168 mm

Secondary Side

```
fprintf('Secondary voltage:%f kV\n',Vs/1000)
fprintf('Secondary current:%f A\n',Is)
fprintf('Secondary conductor area:%f mm^2\n',As)
fprintf('Secondary resistance:%f*10^-3  ohm\n',R2)
fprintf('L2:%f H\n',L2)
fprintf('Secondary inductance:j%f ohm\n',X2)
fprintf('Secondary copper loss:%f W\n',copper_loss_s)
fprintf('Secondary coil average distance:%f mm
\n',winding_pitch_secondary)
```

Secondary voltage:300.000000 kV
Secondary current:21.666667 A
Secondary conductor area:7.222222 mm^2
*Secondary resistance:5427.391738*10^-3 ohm*
L2:0.001102 H
Secondary inductance:j3.461538 ohm
Secondary copper loss:2547.858899 W
Secondary coil average distance:399.157239 mm

Losses

```
fprintf('Total copper loss:%f W\n',total_copper_loss)
fprintf('Core loss:%f W\n',core_loss)
fprintf('Full load copper loss:%f W\n',total_load_copper_loss)
fprintf('Total loss:%f W\n',total_loss)
```

Total copper loss:9480.345480 W
Core loss:16234.217507 W
Full load copper loss:8271.976854 W
Total loss:33986.539840 W

Efficiency

```
fprintf('Efficiency:%f \n',efficiency)
```

Efficiency:99.458294

Cost

```
fprintf('Copper mass:%f  gr\n',copper_mass)
fprintf('Copper cost:%f  TL\n',copper_cost)
fprintf('Core cost:%f TL \n',core_cost)
fprintf('Total cost:%f TL \n',total_cost)
```

```
Copper mass:1759.167661  gr
Copper cost:43.979192  TL
Core cost:18077.513888 TL
Total cost:18121.493079 TL
```

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