Course Assignments

Foil Thickness Design & Fidelity Analysis of Core Loss Estimation Techniques

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EE 6102 (High-Frequency Magnetics in Power Electronics) – Autumn 2022

Assignment 2 (Sept 7, 2022)

Due by 12 noon on Thursday, September 22, 2022

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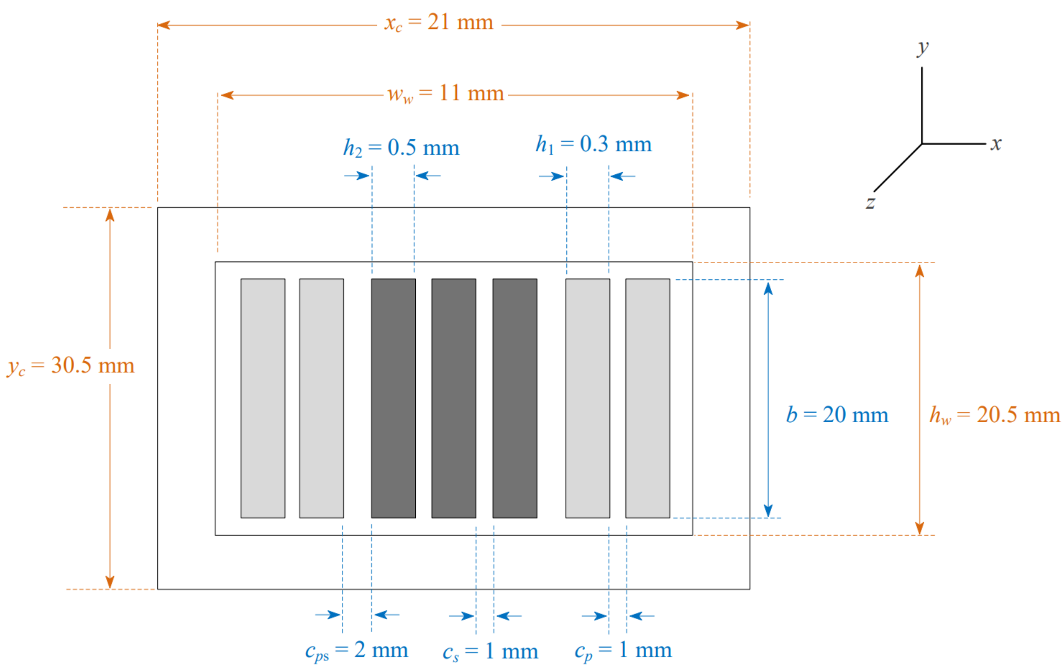
1. i) In the transformer structure shown below, each of the four primary winding layers carries a current of 6 A (peak value), while each of the three secondary layers calculate carries 8 A. The frequency of the current is f = 100 kHz, the relative permeability of the core material is μ_r = 3000 and the conductivity of the winding material is $\sigma = 6 \times 10^7$ /Ohm-m. Calculate the losses (per meter length of the conductor in the z-direction) in each layer of the primary and secondary windings. Use a spreadsheet or MATLAB code to calculate the losses. [Hint: Draw the H-field plot along the window, calculate the field-ratio '*m*' for each layer and use Dowell's equation] **[10 marks]**

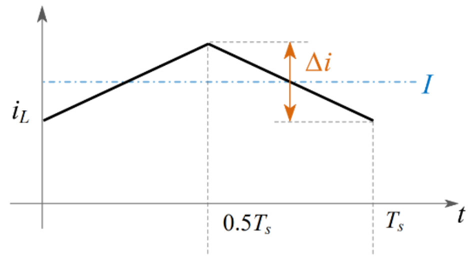


ii) Also, draw and simulate the geometry in Ansys Maxwell 2D (eddy current simulation) to find the losses in each layer and compare the analytically calculated values with the simulation values. (Summarize your results in a Table, highlighting percentage diff. between analysis and simulation.) **[10 marks]**

Note: Apart from submitting the hard-copy, you must e-mail the spreadsheet/MATLAB file and Ansys Maxwell file that you created to the instructor and TAs. (Mention "EE6102_Asmnt2_Q1_YourName" in the e-mail subject.)

Optimum Foil Thickness Design

2. The figure below illustrates the current waveform i_L of an inductor that you have to design.



The average value of i_L is I = 10 A, the time-period T_s = 5 us, while the peak-peak ripple Δi is a design variable. The inductance L is related to Δi by the following relation.

$$L = \frac{12.(0.5T_s)}{\Delta i}$$

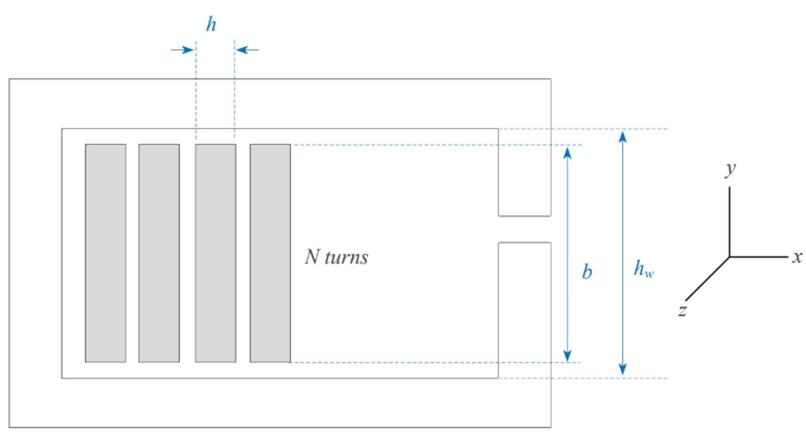
Also, the ripple ratio 'r' is defined as follows.

$$r = \frac{\Delta i}{I_{dc}}$$

You have a C core available in lab with core area A_c = 60 mm^2 and saturation flux-density of the core material B_{sat} = 0.4 T. The following discrete values of r are to be considered for the design – r ={0.2,0.4,0.6,0.8,1}.

i) Find how the number of turns N should be varied (for different r) so that the maximum flux-density B_{pk} is always equal to 80 % of B_{sat}. **[3 marks]**

ii) You plan to design the inductor using foil windings. As shown in the Figure below, the foils are to be arranged in the core window so that there is a single turn in each layer and the foil width (b) ≈ the height of the core window (h_w) = 20 mm. The conductivity of the winding material is σ = 6 x 10^7 /Ohm-m.



Optimum Foil Thickness Design

For each value of *r*, determine the optimum foil thickness which minimizes the total winding losses (dc+ac for all layers). Ignore additional fringing loss due to the air-gap and assume for a given *r*, all winding layers use same thickness foil.

Note : Since the current ripple is non-sinusoidal, you need to perform a Fourier series breakup of Δi and add up losses for different frequency components. Consider the first 10 non-zero frequency components of Δi and use the following relation for the 'k'-th harmonic components of Δi. **[15 marks]**

$$\Delta i = \frac{8}{\pi^2} \sum_{k=1,3,5}^{\infty} \left(\frac{(-1)^{(k-1/)2}}{k^2} \sin \frac{k\pi t}{T} \right)$$

Use an Excel spreadsheet/ MATLAB code for performing the design and use Dowell's equation-based analytical approach for predicting the winding losses.

iii) For each value of *r* (and corresponding optimal foil thickness), plot the dc losses, ac losses and total losses (per meter length of the conductor in the z-direction) in a histogram-type plot to compare the different designs **[2 marks]**

Note: Apart from submitting the hard-copy, you must e-mail the spreadsheet/MATLAB file that you use for your design to the instructor and TAs. (Mention "EE6102_Asmnt2_Q2_YourName" in the e-mail subject.)

Department of Electrical Engineering, IIT Bombay

EE 6102 (High-Frequency Magnetics in Power Electronics) – Autumn 2022

Assignment 4 (Oct 31, 2022)

Due by 7 p.m. on Tuesday, November 8, 2022

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1. The following plot shows the specific core loss for sinusoidal excitation for the 3C85 core material. Determine the values of the Steinmetz parameters k, α, β in the following freq. ranges – a) f_{r1}: {25-50 kHz}, b) f_{r2}: {50 -100 kHz}, c) f_{r3}: {100 – 200 kHz}. **[5 marks]**

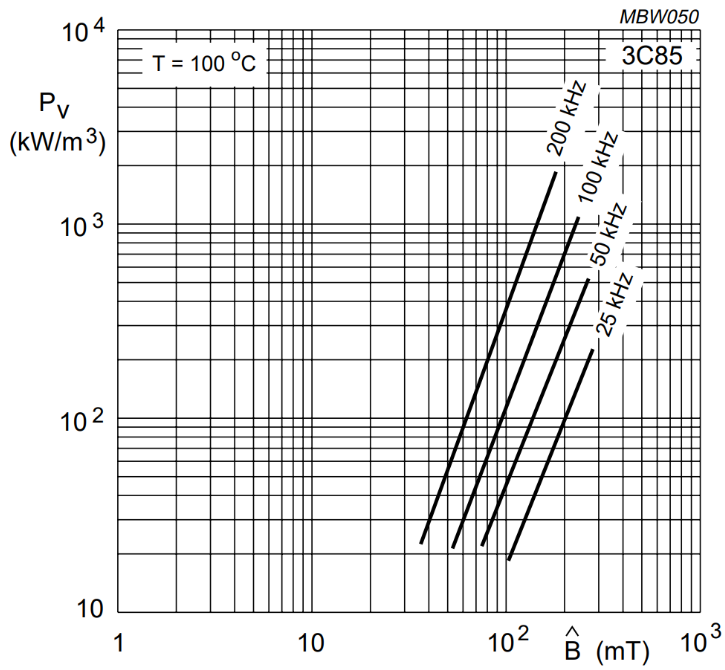


Fig. 1.

2. The flux-density (B) within a magnetic core has a triangular waveshape, as depicted in Fig. 2. The peak value $\boldsymbol{B_m}$ of the flux-density waveform is **220 mT** and the **frequency f is 20 kHz**. The **duty-cycle D of the flux waveform is varied from 0.1 to 0.9, keeping B_m and f constant**. The core is EE 42/21/15 (**volume of 17.3 cm^3**) made of **3C85** material, discussed in Q1. Compare the predicted losses in the core across the duty-cycle range for the following methods – Theoritical Techniques

   i) Original Steinmetz equation, ii) Fourier series approach, iii) Apparent frequency method, iv) Modified Steinmetz equation, v) Generalized Steinmetz equation, and vi) Improved Generalized Steinmetz equation.

   Use values of Steinmetz parameters as determined in Q1. For operating frequencies below f_{r1} and above f_{r3} use values for f_{r1} and f_{r3} respectively. **[15 marks]**

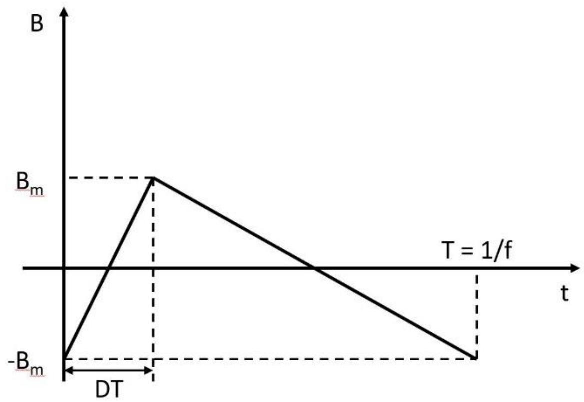


Fig. 2.

3. The EE 42/21/15 core mentioned in Q2 is used to build an inductor with a 4 -turn foil winding, as shown in in Fig. 3. X-Y dimensions of the core are shown in Fig. 3 and its depth in the Z-direction is 10 mm. Steinmetz parameters for the core material can be taken as $\boldsymbol{k = 12, \alpha = 1.3, \beta = 2.55}$.

   i) The inductor has the following flux waveform $\boldsymbol{B(t) = A[(c\sin(2\pi f.t) + (1-c)\sin(3.\ 2\pi f.t)]}$, where $\boldsymbol{A = 200}$ **mT**, $\boldsymbol{f = 20}$ **kHz**. Find the losses in the core using **Ansys Maxwell transient simulation** for $\boldsymbol{c = 1, 0.5, 0.25}$. Compare the losses from simulation with theoretically-predicted losses (using Original Steinmetz equation) for c = 1. **[8 + 2 = 10 marks]** [Hint: Start with assigning a suitable current excitation which results in the desired B. Ignore the reluctance of the core while determining B for a given current excitation.]

   Comparison of Core losses from Theoretical V/s ANSYS

   ii) Find the losses in the core (using Ansys transient simulation) **for the flux waveform of Fig. 2** (B_m = 220 mT, f = 20 kHz) for $\boldsymbol{D = 0.1, 0.3, 0.5, 0.7, 0.9}$. **[10 marks]**

   For every duty get the 5 Fourier coefficients and angle and enter in ANSYS

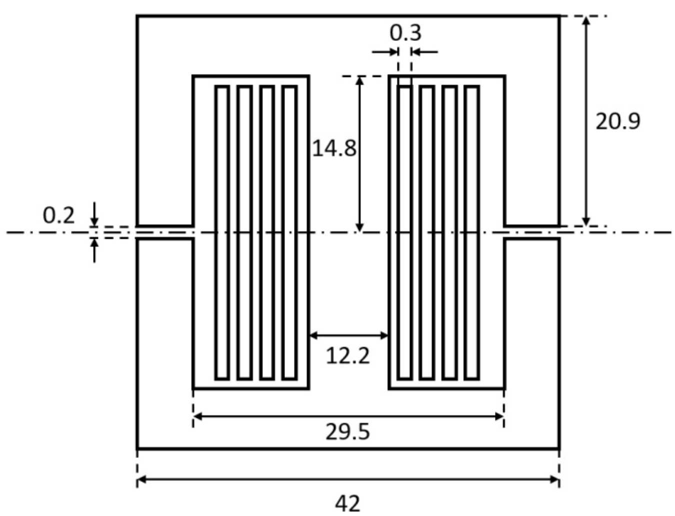
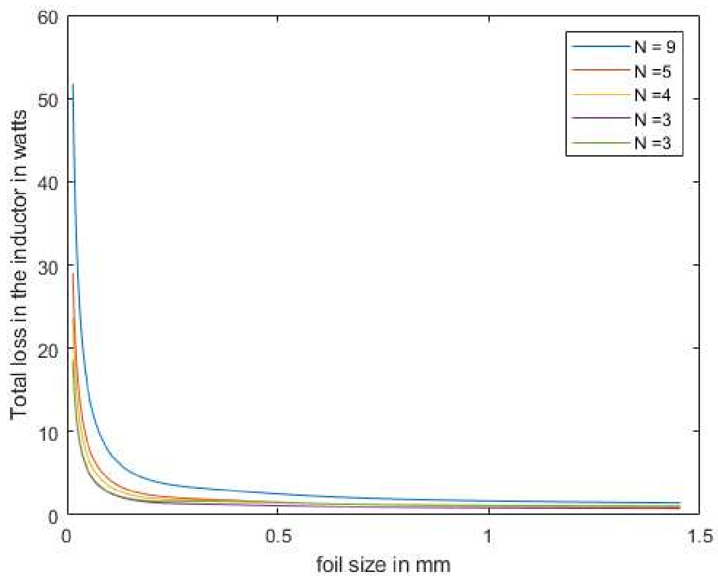


Fig. 3 (all dimensions in mm).

OPTIMUM h Estimation

Contents

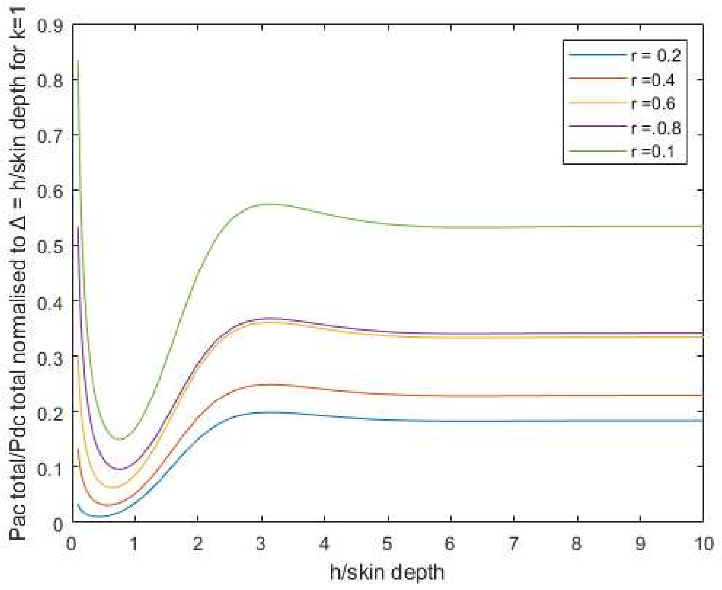

```
clear all;
close all;
clc;

%Definitions

f=200e3;
w=2*pi*f;
idc=10;


sigma=6e7; % conductivity in (ohm m)^-1
skin_depth=(1/(pi*0.999*4*pi*(1e-7)*f*sigma))^0.5; %in meters
b=20; %in mm

r=[0.2,0.4,0.6,0.8,1];
N=[9,5,4,3,3]; %Different values of foil layers as per values of ripple ratio.

%computes square of rms current at different frequency components for
%various values of N

for m=1:5

    for k=1:2:20
        iac_sqr(k,m) = ((4*r(m)*idc/(sqrt(2)*pi^2))^2) * (-1)^(k-1) * (1/k^4);
    end

end

% contains rms value of current for all the 5 values of r
irms_m = ((idc^2) + sum(iac_sqr)).^0.5;

for m=1:5
    count_h=0;
    for h=0.1*skin_depth:0.02*skin_depth:10*skin_depth
        count_h = count_h + 1;

       rdc = 1e3*N(m)/(sigma*b*h); %computes dc value of resistance for a particular value of h
        for n=1:2:20
            delta_n = sqrt(n)*(h/skin_depth); %equation 1

            F1_delta_n = (sinh(2*delta_n)+ sin(2*delta_n))/(cosh(2*delta_n)-cos(2*delta_n)); %equation 2

            F2_delta_n= ((cos(delta_n)*sinh(delta_n))+(sin(delta_n)*cosh(delta_n)))/((cosh(2*delta_n))-(cos(2*delta_n))); %equation 3



            k_p_n = delta_n*((F1_delta_n) + (2/3)*(N(m)^2-1)*(F1_delta_n -2*(F2_delta_n))); %product of equation 1,2,3




            pdc_harmonic(n) = iac_sqr(n,m)*rdc; % dc loss due to current of a freq component flowing in complete cross section of foil of size h.
            pac(n) = pdc_harmonic(n)*k_p_n ; %ac loss due to individual harmonic components


        end

        pac_total(m,count_h) = sum(pac); %Total AC losses for a particular value of m at different values of h
        pdc(m,count_h) = idc^2*rdc; %Total DC loss for various values of foil size  for diff values of m
        ptot(m,count_h) = pac_total(m,count_h) + pdc(m,count_h); %Total losses in the foil for various values of m and foil size
        ratio(m,count_h)= pac_total(m,count_h)/pdc(m,count_h);
        delta_funda = h/skin_depth;
        ratio_normalised(m,count_h)= (pac_total(m,count_h)/pdc(m,count_h))/delta_funda;

    end

end

%Stores foil size array for ploting purpose in meters
h_array = 0.1*skin_depth:0.02*skin_depth:10*skin_depth;

%Plotting Total Power loss in the inductor for different values of foil_layers
figure();
for i=1:5
    plot(h_array*10^3,ptot(i,:));
    hold on;
    xlabel('foil size in mm') ;
    ylabel('Total loss in the inductor in watts');

end
legend('N = 9','N =5','N =4','N =3','N =3');
```

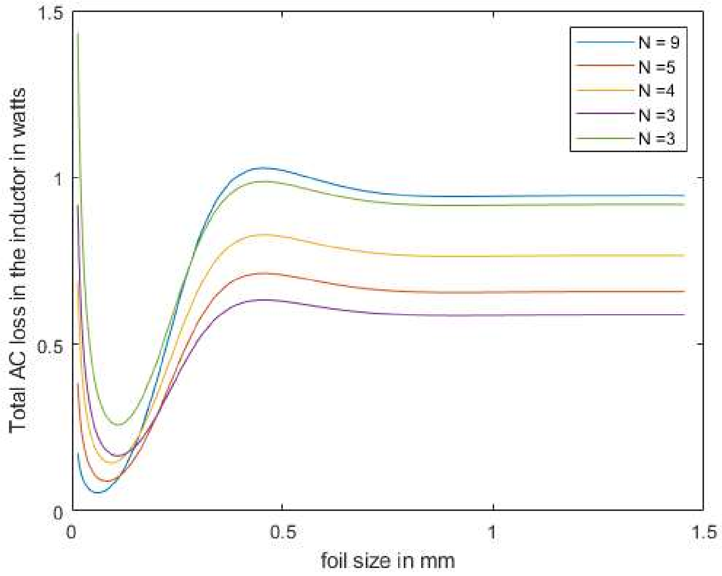


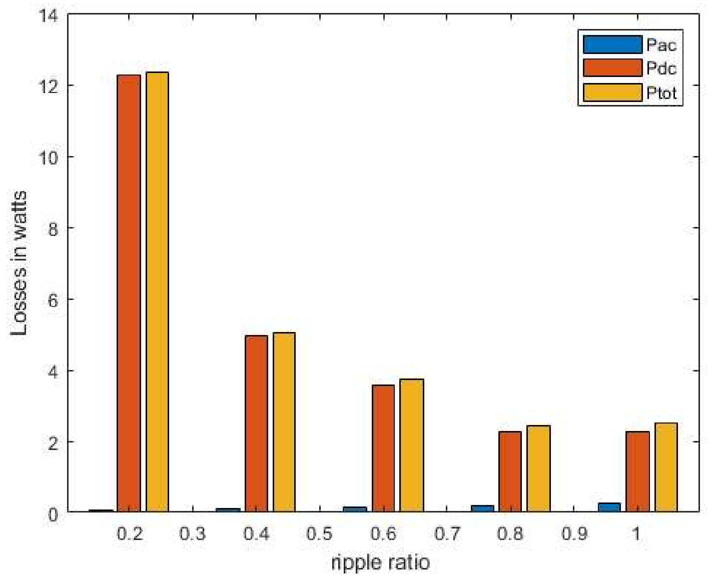
Optimum h calculation is as follows!

```
delta_array = h_array/skin_depth;
figure();
for l=1:5
    plot(delta_array,ratio_normalised(l,:));
    hold on;
    xlabel('h/skin depth') ;
    ylabel('Pac total/Pdc total normalised to Δ = h/skin depth for k=1');
end
legend('r = 0.2','r =0.4','r =0.6','r =.0.8','r =0.1');

figure();
for j=1:5
    plot(h_array*10^3,pac_total(j,:));
    hold on;
    xlabel('foil size in mm') ;
    ylabel('Total AC loss in the inductor in watts');
end
legend('N = 9','N =5','N =4','N =3','N =3');

% [M1,I1] = min(pac_total(1,:));
% [M2,I2] = min(pac_total(2,:));
% [M3,I3] = min(pac_total(3,:));
% [M4,I4]=  min(pac_total(4,:));
% [M5,I5]=  min(pac_total(5,:));

%Ques 2 Part 3

[L1,G1] = min(ratio_normalised(1,:));
[L2,G2] = min(ratio_normalised(2,:));
[L3,G3] = min(ratio_normalised(3,:));
[L4,G4]=  min(ratio_normalised(4,:));
[L5,G5]=  min(ratio_normalised(5,:));

delta_opt = [delta_array(G1),delta_array(G2),delta_array(G3),delta_array(G4),delta_array(G5)];
G = [G1,G2,G3,G4,G5];

for i4 = 1:5
pac_opt(i4) = pac_total(i4,G(i4));
pdc_opt(i4) = pdc(i4,G(i4));
ptot_opt(i4) = pac_opt(i4) + pdc_opt(i4);
end

figure();
y = [pac_opt;pdc_opt;ptot_opt];
bar(r,y,'grouped');
xlabel('ripple ratio ') ;
ylabel('Losses in watts');
legend('Pac','Pdc','Ptot');

% hopt = [h_array(I1),h_array(I2),h_array(I3),h_array(I4),h_array(I5)]; %in m
% delta_opt = (hopt/skin_depth);
% I = [I1,I2,I3,I4,I5];
% for i4 = 1:5
% pac_opt(i4) = pac_total(i4,I(i4));
% pdc_opt(i4) = pdc(i4,I(i4));
% ptot_opt(i4) = pac_opt(i4) + pdc_opt(i4);
% end
% figure();
% y = [pac_opt;pdc_opt;ptot_opt];
% bar(r,y,'grouped');
```

```
% delta_array = h_array/skin_depth;
% legend()
```







Q1.)

f_{r1}: (25- 50 KHz) ; f_{r2}(50-100KHz) ; f_{r3}(100-200KHz)

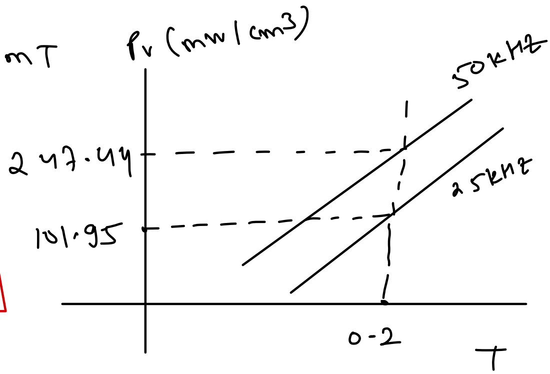
WKT; As per steinmitz loss Equation

$$P_v = K f^{\alpha} B_m^{\beta}$$ → Peak flux density.

$$\log P_v = \log K + \alpha \log f + \beta \log B_m$$

a) In the given range (25-50KHz) assume that the slope of curve (β) doesn't change and k is also constant for a fixed Bm value.

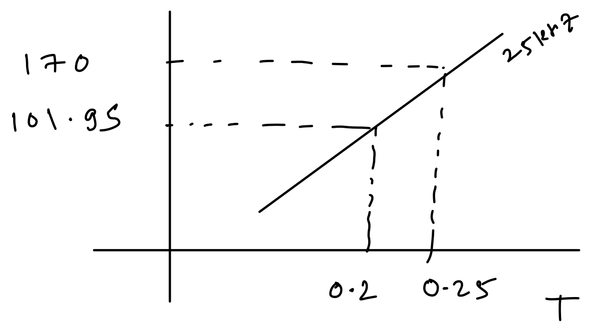
As per curves; $B_m = 200mT$



$$\alpha = \frac{\log(P_{v2}/P_{v1})}{\log(f_2/f_1)}$$

$$\alpha = \frac{\log(247.44/101.95)}{\log(50/25)} = \boxed{1.27}$$

$$\beta = \frac{\log(P_{v2}/P_{v1})}{\log(B_{m2}/B_{m1})}$$



$$\beta = \frac{\log(170/101.95)}{\log(0.25/0.2)}$$

$$\boxed{\beta = 2.29}$$

At; 25KHZ; $B_m = 0.2T$, $P_v = 101.95\ mW/cm^3$

$$P_v = K f^{\alpha} B_m^{\beta} \Rightarrow K = \frac{P_v}{f^{\alpha} B_m^{\beta}}$$

$$K = \frac{101.95 \times 10^{3}}{(25\times10^3)^{1.27}\ (0.2)^{2.29}}$$

$$\boxed{K = 10.56}$$

b) f_r : {50 − 100KHZ}

$$\boxed{\alpha = \frac{\log(681/247.4)}{\log(100/50)} = 1.46}$$

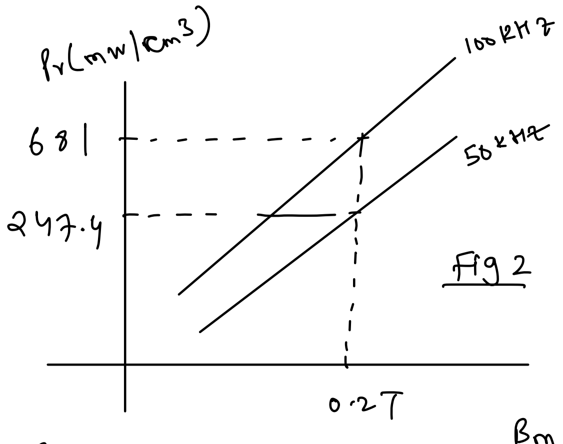


Fig 2

From Fig3

$$\boxed{\beta = \frac{\log(418.68/247.4)}{\log(0.224/0.2)} = 4.64}$$

$$K = \frac{418.68 \times 10^{3}}{(50\times10^3)^{1.46}\ (0.224)^{4.64}}$$

$$\boxed{K = 59.63}$$

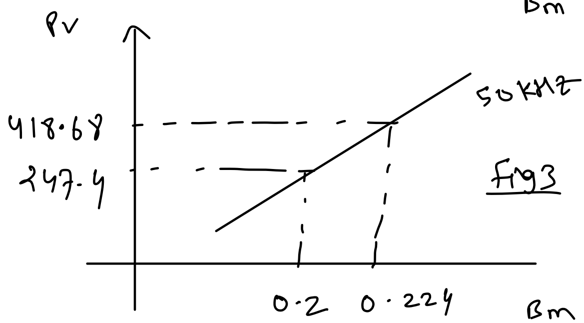
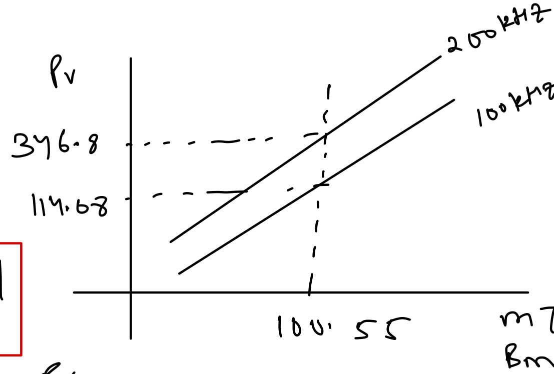


Fig3

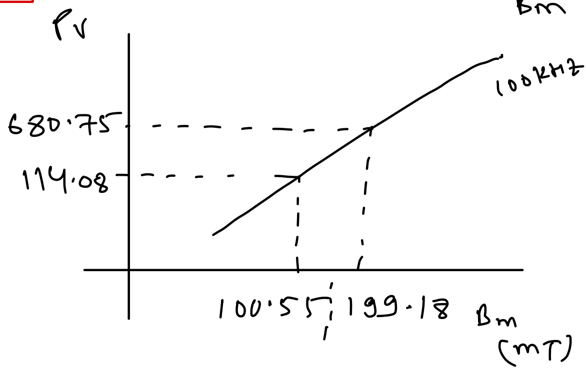
c) freq (100 – 200 kHz)

$$\boxed{\alpha = \frac{\log(346.8/114.68)}{\log(200/100)} = 1.59}$$



$$\boxed{\beta = \frac{\log(680.75/114.08)}{\log(199.18/100.55)} = 2.61}$$

$$k = \frac{114.08 \times 10^{3}}{(100 \times 10^{3})^{1.59}\,(0.1)^{2.61}}$$



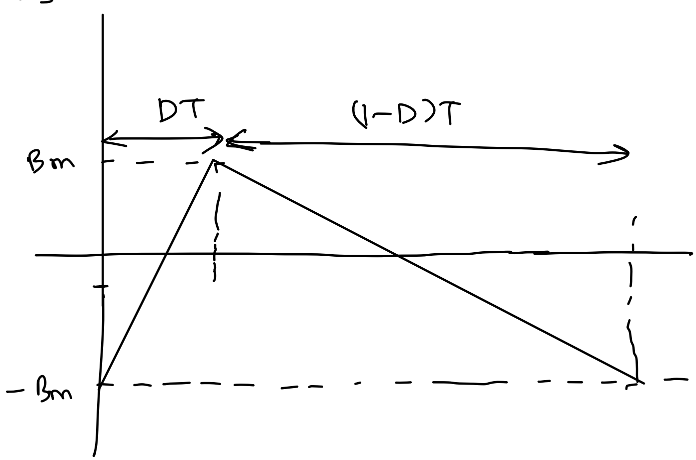
$$\boxed{k = 0.52}$$

Q2.

$f = 20\,\text{kHz}$; $B_m = 220\,\text{mT}$; $0.1 \le D \le 0.9$; $Vol = 17.3\,\text{cm}^3$

core material 3C85

(i) Steinmetz equation depends only on freq and Bm for calculation of core loss for a specific core material and Temperature.



using α, β, K of 25KHZ, as calculated in Q1.

$\alpha = 1.27$, $\beta = 2.29$, $K = 10.56$

$$P_v = 10.56 \times (28\times10^3)^{1.27} (0.22)^{2.29} \; W/m^3$$

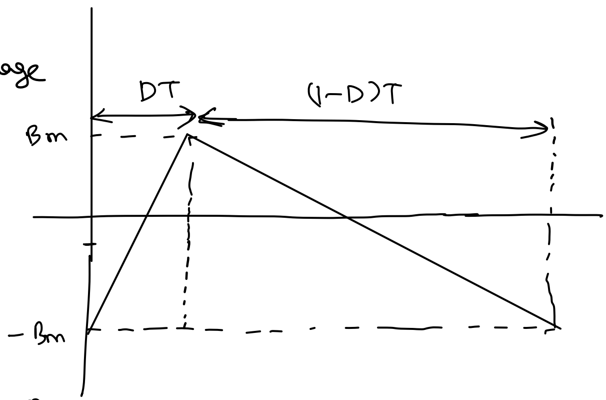
$$P_v = 95.52 \; mW/cm^3$$

$$Loss = 95.52 \times 17.3 \; cm^3$$

$$\boxed{Loss = 1652.56 \; mW}$$

(ii) Fourier Series approach.

Given waveform has zero average

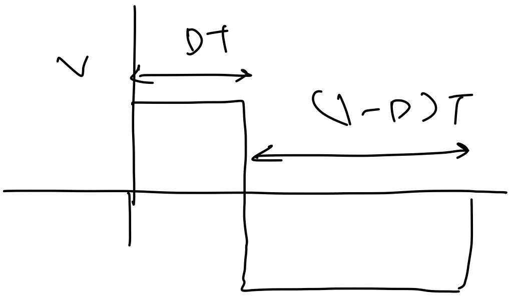


$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t$$

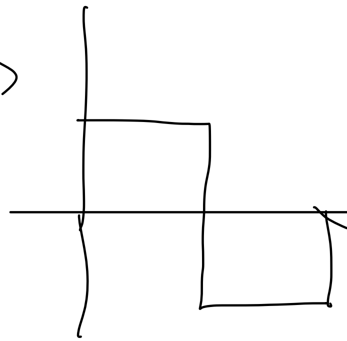
$$a_n = \frac{2}{T}\int_0^T f(t) \cos n\omega_0 t \, dt$$

$$b_n = \frac{2}{T}\int_0^T f(t) \sin n\omega_0 t \, dt$$

(iii) <u>Apparent frequency Method.</u>

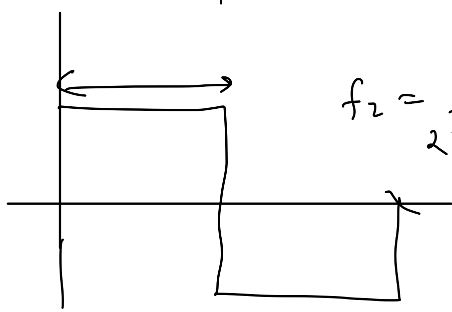


$\Rightarrow$



$$f_1 = \frac{1}{2DT}$$

$+$



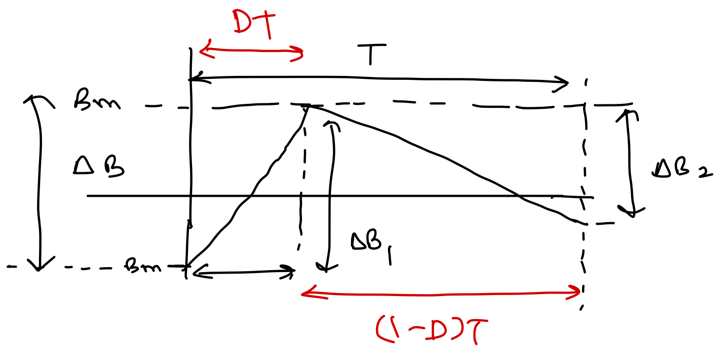
$$f_2 = \frac{1}{2T(1-D)}$$

$$\boxed{P_{Tot} = D P_1\Big|_{f_1} + (1-D) P_2\Big|_{f_2}}$$

→ Calculations using above formula done in Excel.

(iv) <u>modified Steinmetz equation</u>

$$f_{sin} = \frac{2}{\pi^2} \sum_{K=1}^{\infty} \left(\frac{\Delta B_K}{\Delta B}\right)^2 \frac{1}{\Delta t_K}$$



$$f_{sin} = \frac{2}{\pi^2}\left[\left(\frac{2\cancel{B_m}}{2\cancel{B_m}}\right)^2 \cdot \frac{1}{DT} + \left(\frac{2\cancel{B_m}}{2\cancel{B_m}}\right)^2 \cdot \frac{1}{(1-D)T}\right]$$

$$\boxed{f_{sin} = \frac{2}{\pi^2} f \left[\frac{1}{D(1-D)}\right]} \qquad -(1)$$

$$\boxed{P_v = K \, (f_{sin})^{\alpha-1} \, (\Delta B)^{\beta} \, f} \qquad -(2)$$

$$\Delta B = 2B_m = 2 \times 0.22 = 0.44$$

$$f = 20\,\text{KHZ}; \quad 0.1 \leq D \leq 0.9$$

<u>Excel - Ques 2</u>

(v)

As per GSE method.

$$P(t) = K_1 \left|\frac{dB}{dt}\right|^{\alpha} |B(t)|^{\beta-\alpha}$$

$$B(t) = B_m \sin w_o t \; ; \; \frac{dB}{dt} = B_m w_o \cos w_o t$$

$$P_v = \frac{1}{T}\int_0^T P(t)\,dt$$

$$P_v = \frac{K_1 B_m^{\beta} f^{\alpha}}{\cancel{T} \times 2\pi \cancel{f}} \int_0^T (2\pi)^{\alpha} |\cos w_o t|^{\alpha} |\sin w_o t|^{\beta-\alpha} \, d w t$$

(1) —

$$P_v = K_1 B_m^{\beta} f^{\alpha} \int_0^T (2\pi)^{\alpha-1} |\cos\theta|^{\alpha} |\sin\theta|^{\beta-\alpha} d\theta$$

For; freq = 20 kHz; $\boxed{\alpha = 1.27;\ \beta = 2.29;\ k = 10.56}$

from Q1.

→ Using Numerical Integration in MATLAB

$$\int_0^{2\pi} |\cos\theta|^{1.27} |\sin\theta|^{1.02} d\theta = 1.7432$$

Comparing Eqn (1) with $K f^{\alpha} B_m^{\beta}$

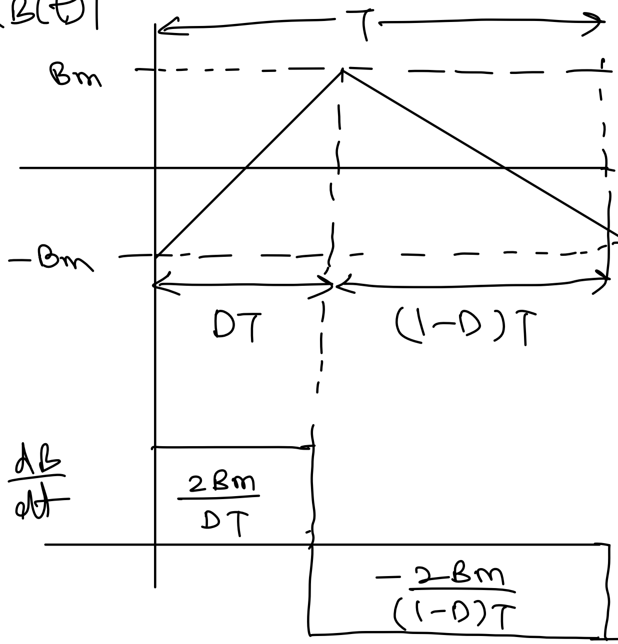
$$K_1 = \frac{K}{\int_0^{2\pi} (2\pi)^{\alpha-1} |\cos\theta|^{\alpha} |\sin\theta|^{\beta-\alpha}}$$

$$\boxed{K_1 = \frac{10.56}{(2\pi)^{0.27} \times 1.7432} = 3.688}$$

<u>For our waveform.</u>

$$P(t) = K_1 \left|\frac{dB}{dt}\right|^{\alpha} |B(t)|^{\beta-\alpha}$$

$$B(t) = \begin{cases} \dfrac{2B_m t}{DT} - B_m & ; \ 0 < t < DT \\[2ex] \dfrac{-2B_m t}{T(1-D)} + B_m\left(\dfrac{1+D}{1-D}\right) & \& \ DT < t < T \end{cases}$$



$K_1 = 3.888$ and $\alpha = 1.27$; $\beta = 2.29$

$$P_V = 3.888 f \left[\int_0^{DT} \left(\frac{0.44}{DT}\right)^{1.27} \left| \frac{0.44t}{DT} - 0.22 \right|^{1.02} dt \right.$$

$$+ \int_{DT}^{T} \left(\frac{0.44}{(1-D)T} \right)^{1.27} \left| \frac{-0.44t}{T(1-D)} + 0.22\left(\frac{1+D}{1-D}\right) \right|^{1.02} dt$$

(vi) IGSE method

$$P(t) = k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}$$

k_i as derived in class;

$$K_i = \frac{K}{2^{\beta+1}\pi^{\alpha-1}\left(0.276 + \frac{1.706}{\alpha+1.359}\right)}$$

writting P_v for our wave form

$$P_v = \frac{k_i}{T}\left[\int_0^{DT}\left(\frac{2B_m}{DT}\right)^{\alpha}(2B_m)^{\beta-\alpha}\,dt + \int_{DT}^{T}\left|\frac{-2B_m}{T(1-D)}\right|^{\alpha}(2B_m)^{\beta-\alpha}\,dt\right]$$

Calculating k_i and P_v from MATLAB script.

$$\boxed{P_v = \frac{k_i}{T}\left[(2B_m)^{\beta}(DT)^{1-\alpha} + (2B_m)^{\beta}\left[(1-D)T\right]^{1-\alpha}\right]}$$

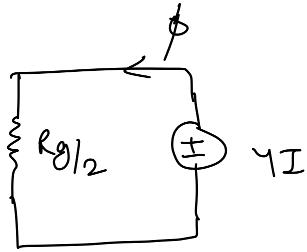
Q3.)

i) Given; $K = 12$; $\alpha = 1.3$; $\beta = 2.55$; $A = 0.2$; $f = 20\,kHz$

$$B(t) = A\left[C\sin(2\pi f t) + (1-C)\sin(3.2\pi f t)\right]$$

At $C = 1$

$$B(t) = 0.2\sin(2\pi \times 20\times10^3 t)$$



$$BA_c = \frac{4I}{R_g}\times 2 \;;\quad R_g = \frac{l}{\mu_0\mu_r A_g}$$

$$R_g = \frac{l_g}{4\pi\times10^{-7}\times1} = \frac{0.2\times10^{-3}}{4\pi\times10^{-7}} = 2.5465\times10^{6}\ AT/wb$$

$$I = \frac{BA_c\times R_g}{8} = \frac{0.2\times10\times12.2\times10^{-6}\times R_g}{8}$$

$\boxed{I = 7.7668\,A}$ $\Rightarrow$ To be used in ANSYS

$\boxed{\text{Average Loss By ANSYS} = 0.7454\,W}$

Using Steinmitz equation.

$$P = (12)\times(20\times10^3)^{1.3}\,(0.2)^{2.55}\times10^{-6}\times12.4423$$

$\boxed{P = 0.9617\,W}$

found out by Ansys.

Conclusion :- At c=1 the Equation of excitation is purely sinusoidal and the Steinmeitz equation assumes flux density to be uniform throughout the core But it is varying in space of the core which is evident from the $\bar{B}$ distribution curve in ANSYS.

ANSYS considers this space varying flux density for calculation of loss hence loss due to ANSYS is < loss due to Steinmeitz.

Avg loss By Steinmitz = 0.9617 W

$$\boxed{\text{Loss By Steinmeitz} = 1.29 \times \text{Loss By ANSYS.}}$$

C = 0.5

$$B(t) = 0.1\sin(2\pi f t) + 0.1\sin(6\pi f t)$$

$$\frac{A_c R_g}{8} = 38.8338$$

$$I \text{ due to } B_m = 0.1 = 0.1 \times 38.8338 = 3.88\,A$$

$$\boxed{I(t) = 3.88 \sin(2\pi f t) + 3.88 \sin(6\pi f t)}$$

$\boxed{\text{Loss By ANSYS} = 0.7584\ W}$

At $c = 0.25$

$$B(t) = 0.05 \sin(2\pi f t) + 0.15 \sin(6\pi f t)$$

$$I(t) = 1.942 \sin(2\pi f t) + 5.825 \sin(6\pi f t)$$

$\boxed{\text{Loss By ANSYS} = 1.6378\ W}$

(ii)

Duty	ANSYS Loss (W)
0.1	0.9935
0.3	0.8018
0.5	0.7981
0.7	0.8122
0.9	0.9928

$\Rightarrow$ Graphs shown Below.

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Assignment 4

HFMD

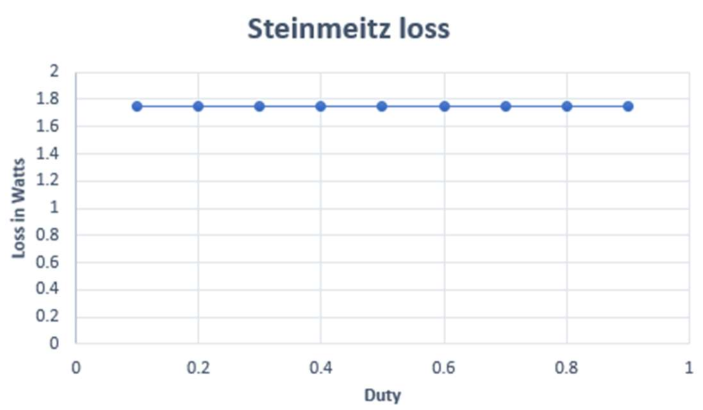
Ques 2

Given Values of Alpha, Beta and K for given range of values

	Bm	f	
	0.22	20000	
	fr1(25Khz - 50Khz)	fr2(50Khz - 100Khz)	fr3(100Khz - 200Khz)
K	10.56	59.63	0.52
alpha	1.27	1.46	1.59
beta	2.29	4.64	2.61

Steinmetz Equation

		Original Steinmetz Equation
d	1-d	P(w)
0.1	0.9	1.744811046
0.2	0.8	1.744811046
0.3	0.7	1.744811046
0.4	0.6	1.744811046
0.5	0.5	1.744811046
0.6	0.4	1.744811046
0.7	0.3	1.744811046
0.8	0.2	1.744811046
0.9	0.1	1.744811046



Apparerent Freq Method				
f1(Khz)	f2(Khz)	P2(mw/cm^3)	P1(mw/cm^3)	Ptot(W)
100	11.11111111	45.28181961	1057.562514	2.53462108
50	12.5	52.58811135	305.8466745	1.786048955
33.33333333	14.28571429	62.30707251	182.7544092	1.703034032
25	16.66666667	75.78090183	126.8223126	1.664216164
20	20	95.52563906	95.52563906	1.652593556
16.66666667	25	126.8223126	75.78090183	1.664216164
14.28571429	33.33333333	182.7544092	62.30707251	1.703034032
12.5	50	305.8466745	52.58811135	1.786048955
11.11111111	100	1057.562514	45.28181961	2.53462108

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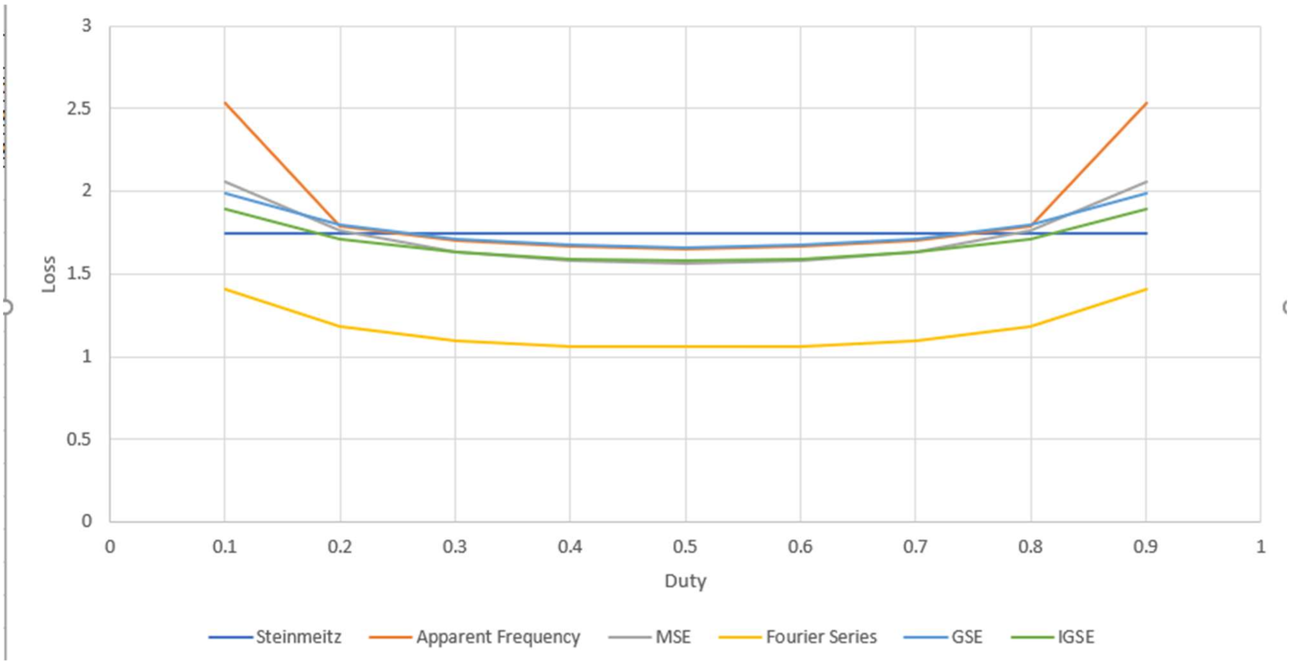
MSE			
d		fsin(Khz)	P(W)
0.1		45.03163717	2.057490056
0.2		25.33029591	1.761452057
0.3		19.29927307	1.636756269
0.4		16.88686394	1.578796617
0.5		16.21138938	1.561490765
0.6		16.88686394	1.578796617
0.7		19.29927307	1.636756269
0.8		25.33029591	1.761452057
0.9		45.03163717	2.057490056

IGSE	
d	P(w)
0.1	1.896
0.2	1.7094
0.3	1.6299
0.4	1.5928
0.5	1.5817
0.6	1.5928
0.7	1.6299
0.8	1.7094
0.9	1.896

Fourier Series	P(w) considering 100 harmonics.
d	
0.1	1.4045
0.2	1.1833
0.3	1.0939
0.4	1.0577
0.5	1.0569
0.6	1.0577
0.7	1.0939
0.8	1.1833
0.9	1.4045

GSE		
d	1-d	P(w)
0.1	0.9	1.9921
0.2	0.8	1.796
0.3	0.7	1.7125
0.4	0.6	1.6735
0.5	0.5	1.6618
0.6	0.4	1.6735
0.7	0.3	1.7125
0.8	0.2	1.796
0.9	0.1	1.9921



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Comparison comments:

The comparison between core loss prediction by above methods and measurement results under square excitations with variable D is shown in above figure. Apparently, the core loss increases approximately symmetrically with D gradually lower or higher than 0.5. It is clear that the original SE is not applicable to estimate core loss for square excitations due to its non-dependency on duty cycle. It can be seen that the IGSE has relatively better accuracy than MSE in extreme duty cycle region (D close to 0 or 1), although both the two methods can reflect the changing trend of core loss with D. On the contrary, the SE exhibits satisfactory accuracy than MSE and IGSE with respect to normal duty cycle range (D near 0.5). As D approaches 0 or 1 from 0.5 gradually, the accuracy of SE decreases rapidly, where the IGSE shows relatively good prediction instead.

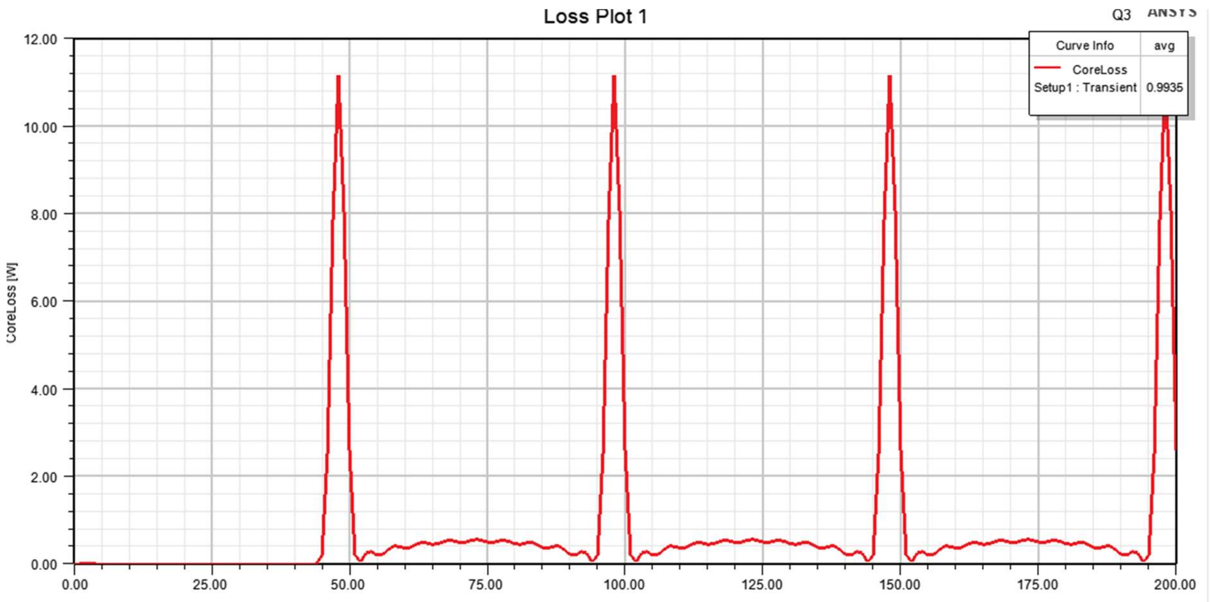
Ques 3

Part 2

Current equations used for simulation is given below

D=0.1

5.9443*cos(2*pi*20000*Time-1.2566) + 2.8267*cos(2*2*pi*20000*Time-0.9425) + 1.7292*cos(2*3*pi*20000*Time-0.6283) + 1.1434*cos(2*4*pi*20000*Time-0.3142) + 0.7694*cos(2*5*pi*20000*Time) + 0.5082*cos(2*6*pi*20000*Time+0.3142) +0.3176*cos(2*7*pi*20000*Time+0.6283)+0.1767*cos(2*8*pi*20000*Time+0.9425)+0.0734*cos(2*9*pi*20000*Time+1.2566)



D=0.3

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6.8605*cos(2*pi*20000*Time-0.3142) + 1.0600*cos(2*2*pi*20000*Time+0.9425) + 0.4711*cos(2*3*pi*20000*Time-0.9425) + 0.4288*cos(2*4*pi*20000*Time+0.3142) + 0*cos(2*5*pi*20000*Time+0.2406) +0.1906*cos(2*6*pi*20000*Time-0.3142)+0.0865*cos(2*7*pi*20000*Time+0.9425)+0.0663*cos(2*8*pi*20000*Time-0.9425)+0.0847*cos(2*9*pi*20000*Time+0.3142)

<u>D=0.5</u>

6.9250*cos(2*pi*20000*Time) + 0*cos(2*2*pi*20000*Time) + 0.7694*cos(2*3*pi*20000*Time) + 0*cos(2*4*pi*20000*Time) + 0.2770*cos(2*5*pi*20000*Time) +0*cos(2*6*pi*20000*Time)+0.1413*cos(2*7*pi*20000*Time)+0*cos(2*8*pi*20000*Time)+0.0855 *cos(2*9*pi*20000*Time)

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D=0.7

6.6696*cos(2*pi*20000*Time+0.6283) + 1.9602*cos(2*2*pi*20000*Time-0.3142) + 0.2831*cos(2*3*pi*20000*Time-1.2566) + 0.3029*cos(2*4*pi*20000*Time+0.9425) + 0.3298*cos(2*5*pi*20000*Time) +0.1346*cos(2*6*pi*20000*Time-0.9425)+0.0520*cos(2*7*pi*20000*Time+1.2566)+0.1225*cos(2*8*pi*20000*Time+0.3142)+0.0823*cos(2*9*pi*20000*Time-0.6283)

D=0.9

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5.9443*cos(2*pi*20000*Time+1.2566) + 2.8267*cos(2*2*pi*20000*Time+0.9425) + 1.7292*cos(2*3*pi*20000*Time+0.6283) + 1.1434*cos(2*4*pi*20000*Time+0.3142) + 0.7694*cos(2*5*pi*20000*Time) + 0.5082*cos(2*6*pi*20000*Time-0.3142)+0.3176*cos(2*7*pi*20000*Time-0.6283)+0.1767*cos(2*8*pi*20000*Time-0.9425)+0.0734*cos(2*9*pi*20000*Time-1.2566)