Step by step design procedure of Flyback transformer

Step by step design of Flyback transformer for QR mode

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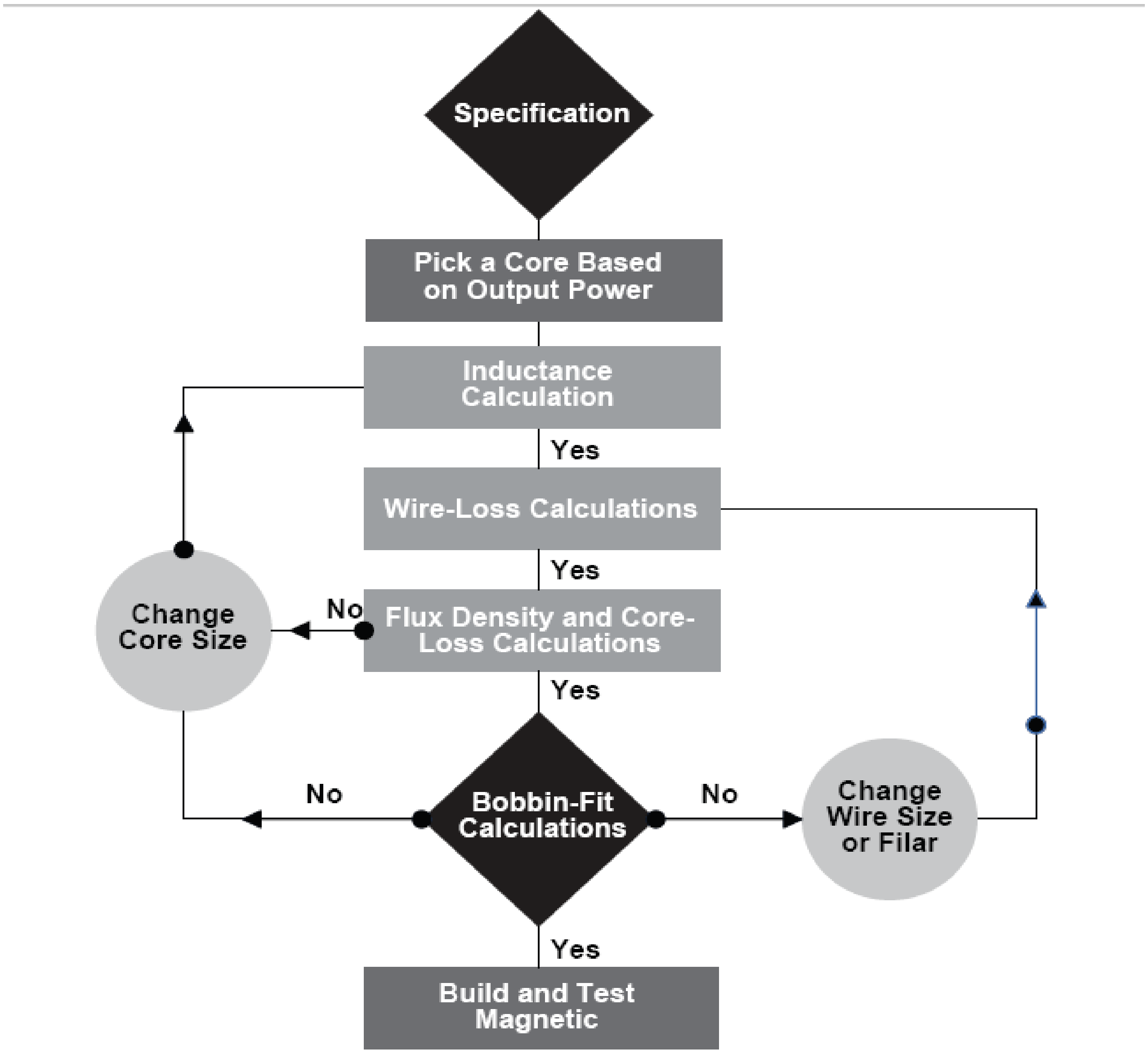
1. Flow Diagram



		SI	CGS	CGS to SI
Flux Density	B	Tesla	Gauss	10^{-4}
Field Intensity	H	A-T/m	Oersteds	$1{,}000/4\pi$
Permeability	μ	$4\pi \times 10^{-7}$	1	$4\pi \times 10^{-7}$
Area	Ae	m^2	cm^2	10^{-4}
Length	*le, lg*	m	cm	10^{-2}

Table 1 – Magnetic parameters and conversion factors.

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2. Basic definition and terminology

Inductance

$$\text{Linductance} = \frac{.4 \times \pi \times N^2 \times (Ae) \times 10^{-9}}{lg + \frac{le}{\mu}}$$

$$\text{Lind} = Al \times N^2$$

Where:

Linductance = Henry's
μ = core permeability
N = number of turns
Ae = core cross-section (mm^2)
le = core magnetic path length (mm)
lg = gap (mm)

Since manufacture specified all data data in mm

Core Geometry

$$le = \frac{\pi(OD - ID)}{\ln\left(\frac{OD}{ID}\right)} \qquad (3)$$

Where:

OD = outside diameter of core (mm)
ID = inside diameter of core (mm)
N = number of turns
Ae = core cross-section (effective area) mm^2
le = Mean magnetic path length (mm)

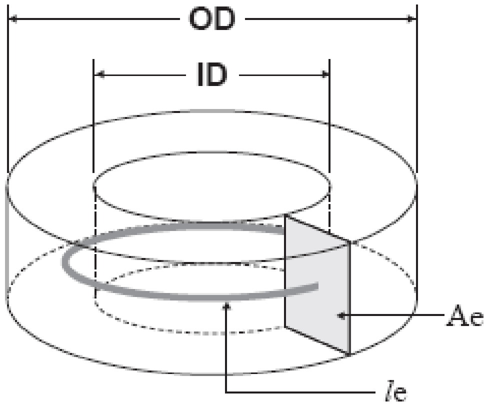

Figure 2 – le is a simple calculation with a toroid.

Since manufacture specified in mm, Convert mm to m for SI unit

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Ampere's Law

Ampere's law states that the total magnetic force along a closed path is proportional to the ampere-turns in a winding that the path passes through. SI unit.

$$H \approx \frac{N \times I}{le} \text{ amper-turns/meter (A-T/m)}$$

Where:

H = magnetizing force (ampere-turns/meter)
N = number of turns
le = core magnetic path length (m)
I = peak magnetizing current (amperes)

Faraday's Law

The total magnetic flux, Φ, passing through a surface of area, Ae, is related to the flux density, β. The flux rate of change is proportional to the volts per turn applied to a winding. If a secondary winding is coupled to all of the flux in a primary winding, then all of the volts per turn in the primary will be induced in the secondary winding. Lines of flux follow a closed path and have no beginning or end. In the SI system, flux density is expressed in tesla

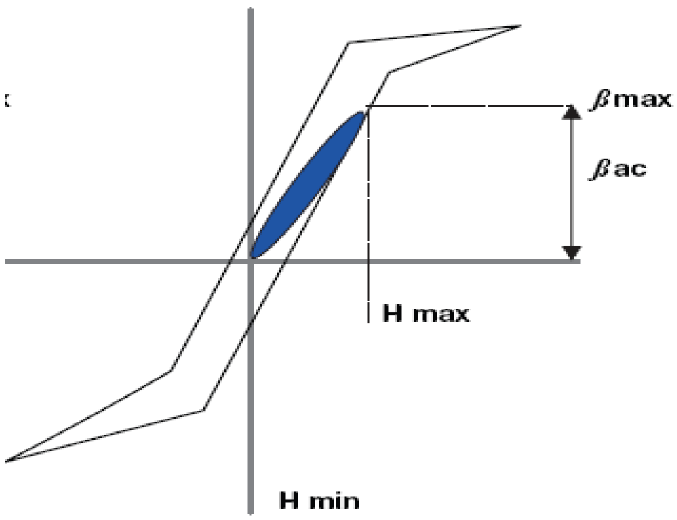
$$\text{SI}: \quad \Delta\Phi = \frac{1}{N}\int E \times dt$$

$$E = N \times \frac{d\Phi}{dt} \approx N \times Ae \times \frac{d\beta}{dt} \Rightarrow \beta = \frac{\int E \times dt}{N \times Ae}$$

Where:

β = flux density (tesla)
N = number of turns
Ae = effective core area (m^2)
E = voltage across coil (volts)

BH Curves



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H is proportional to I (current); therefore, as the peak-to-peak current in a magnetic increases, the excursion of the flux also increases. At the top part of the BH curve, B flattens out; at this point the magnetic is in saturation. Once the current in a magnetic drives the flux to saturation, the core no longer exhibits magnetic properties and the magnetic becomes a wire. Thus it is important to calculate the flux density for a given design to make sure that you don't saturate the core. βac is peak-to-peak flux density; βmax is the peak flux density. βmax assumes square wave excitation.

$$\beta ac = \frac{Vin \times Ton}{Ae \times Np} \qquad \beta\, max = \frac{Lp \times Ip}{Ae \times Np}$$

β = flux density in tesla
Np = number of primary turns
Ton = on time (sec)
Ae = effective core area (m2)
Vin = voltage (volts)
Lp = primary inductance (Henry's)
Ip = peak primary current (A)

Core Loss

The power loss in a core is related to half the AC flux density of the core and the frequency applied to the core.To determine core loss, manufacturers normally provide a graph of power loss as a function of peak flux density and core material.

βacpeak = $\frac{\beta ac}{2}$

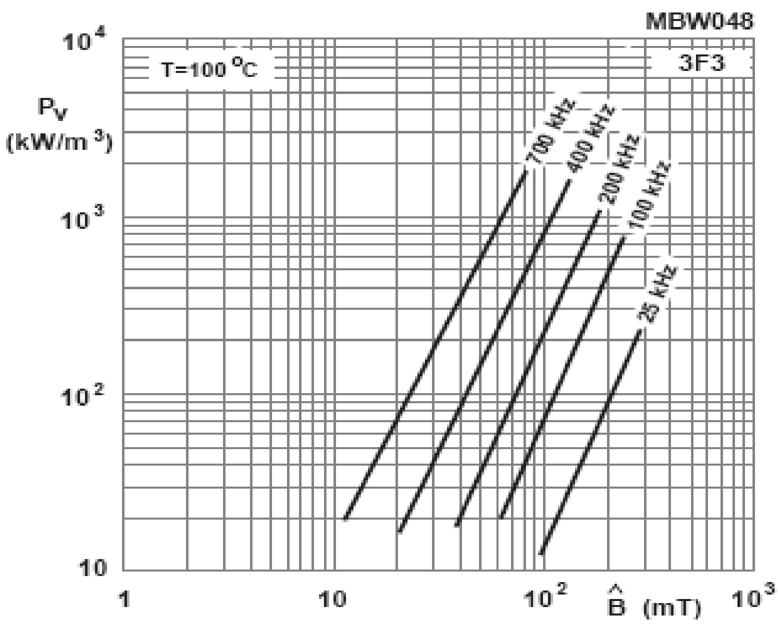

Figure 4 – Power loss as a function of one-half of peak-to-peak flux density (courtesy of Ferroxcube).

$$Pcore\ loss = Pv\left(\frac{KW}{m^3}\right) \times Ve\ (m^3)$$

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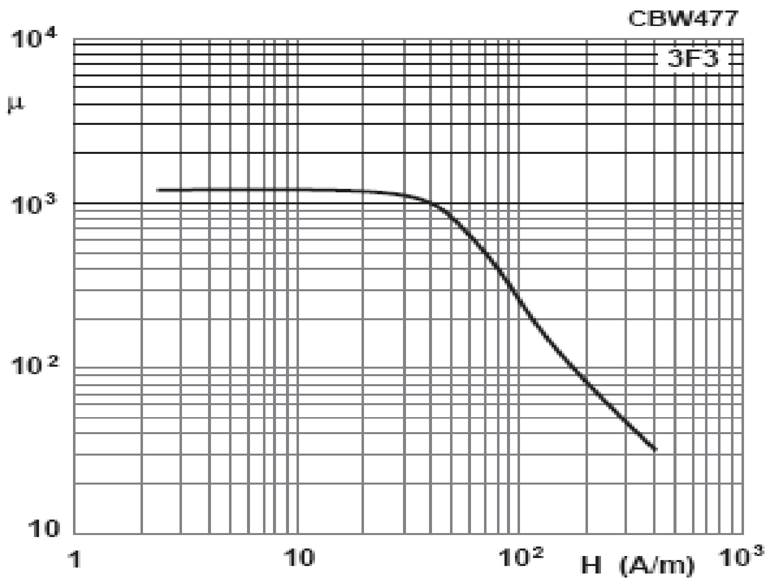
Permeability and Inductance Rolloff	
 *Figure 5 – Permeability as a function of magnetizing force (H) (courtesy of Ferroxcube).*	*As current is increased in a magnetic and the flux density gets closer to core saturation, the permeability starts to roll off. Permeability is an important parameter, because as permeability rolls off, the inductance decreases (as shown in Equation 1). If the inductance decreases, the peak to-peak current goes up in the magnetic; this causes the flux density to increase and push the core closer to saturation. Therefore, permeability can cause a snowball effect as the core gets closer to saturation.*

3. Design Specification

General				
Topology	Quasi-Resonant Flyback			
Main Output Power	10	W		
Maximum Switching Frequency at Full Load	140	kHz	140000	Hz
Input				
Minimum Input Voltage	85	VAC	76	VDC
Maximum Input Voltage	265	VAC	375	VDC
Primary Peak Current	1.155	A		
Primary RMS Current	0.425	A		
Outputs				
Secondary Output Voltage	5	V		
Secondary Peak Current	13.861	A		
Secondary RMS Current	5.382	A		
Bias Voltage	16	V		
Bias Current	50	mA	0.05	A
Inductance and Turns Ratio				
Primary Inductance	190.918	µH	0.000190918	H
Leakage Inductance	3.818	µH	0.000003818	H
Primary to Secondary Turns Ratio	12			

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4. Core Selection		
Core selection is based on size, material and gap. These factors work together to determine the core loss and inductance per turn of the core.		
Output Power Level	***Recommended Core Types***	
0-10W	EFD15 SEE16 EF16 EPC17 EE19 EF(D)20 EPC25 EF(D)25	
10-20W	EE19 EPC19 EF(D)20 EE or EI22 EF(D)25 EPC25	
20-30W	EI25 EF(D)25 EPC25 EPC30 EF(D)30	
30-50W	EI28 EER28(L) ETD29 EF(D)30 EER35	
50-70W	EER28L ETD34 EER35 ETD39	
70-100W	ETD34 EER35 ETD39 EER40 E21	
For 10 W application I have choosen below core		
Part No	EFD20/10/7-3F3-A-100	
Manufacturer	Ferroxcube	
Core Name	EFD20	
Material	3F3	
Al	0.000000082	82*10^-9
Note: the Al required is not standard the core gap had to be custom-cut to obtain the necessary Al		

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5. Calculate Inductance and Turns Based on Al			
Np	48	Turns	
Ns	4	Turns	

$$Np = \left(\frac{Lp}{Al}\right)^{1/2}$$

$$Ns = \frac{Np}{\text{Turns ratio}}$$

6. Calculate Copper Loss			
Current density, J, is a rule of thumb that says a wire should not handle any more than 400 A/cm^2			
J	400	A/cm^2	Assume
Primary Wire Area	0.0010625	cm^2	
Skin depth at 100°C	0.0203	cm	

$$\text{Primary wire area} = \frac{\text{Iprimary\_rms}}{J}$$

$$\text{Skin depth at } 100°C = \frac{7.6}{\sqrt{f}}$$

Determine annular inner ring area at 100°C		
Since we have not yet determined the correct wire gauge so calculate from 26AWG to 32AWG		
Area ring 26AWG 100°C = area 26AWG	0.001287	cm^2
Area ring 28AWG 100°C = area 28AWG	0.00081	cm^2
Area ring 30AWG 100°C = area 30AWG	0.000509	cm^2
Area ring 30AWG 100°C = area 30AWG	0.00032	cm^2

Note : when the skin depth is greater than the radius of the wire, we must set the ring area equal to the area of the wire.

AWG	Copper Diameter in cm	Copper Radius in cm	Copper Area in cm^2	Ω/cm at 100°C
26	0.04	0.02	0.001287	0.001789
28	0.032	0.016	0.00081	0.002845
30	0.025	0.0125	0.000509	0.004523
32	0.02	0.01	0.00032	0.007192

$$\text{Rskin 26AWG } 100°C = \frac{\text{Area 26AWG cm}^2}{\text{Area ring 26AWG } 100°C \text{ cm}^2}$$

Rskin 26AWG 100°C	1	
Rskin 28AWG 100°C	1	
Rskin 30AWG 100°C	1	
Rskin 32AWG 100°C	1	
Determine wire resistance due to skin effects		
Rcopper 26AWG 100°C	0.001287	ohms/cm
Rcopper 28AWG 100°C	0.00081	ohms/cm
Rcopper 30AWG 100°C	0.000509	ohms/cm
Rcopper 32AWG 100°C	0.00032	ohms/cm

Rcopper 26AWG 100°C = wire 26AWG ohms/cm 100°C x Rskin 26AWG 100°C

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Determine the number of primary wires in parallel required:		
Numbers of wires primary 26AWG	0.826	
Numbers of wires primary 28AWG	1.312	
Numbers of wires primary 30WG	2.087	
Numbers of wires primary 32AWG	3.320	

$$\text{Numbers of wires primary 26AWG} = \frac{\text{Area required primary cm}^2}{\dfrac{\text{Area 26AWG cm}}{\text{Rskin 26AWG 100°C}}}$$

Determine primary copper loss		
Number of primary wires	1	
length per turn	0.0341	m
Rcopper primary resistance 26AWG	0.0021176268642	ohm
Pcopper primary loss 26AWG	0.0003824963524	W

$$\text{Rcopper primary resistance 26AWG} = \text{Rcopper 26AWG 100°C} \times \text{Np} \times \frac{\text{Length per turn cm}}{\text{Number of primary wires}}$$

$$\text{Pcopper primary loss 26AWG} = \text{Iprimary rms}^2 \times \text{Rcopper primary 26AWG}$$

Determine secondary wire AWG and losses		
Secondary wire area	0.0135	m^2
Number of wires secondary 28AWG	17	5.000
Rcopper secondary 28AWG	0.01910	ohms
Pcopper secondary loss 28AWG	0.103	W

$$\text{Secondary wire area} = \frac{\text{Isecondary\_rms}}{\text{J}}$$

$$\text{Number of wires secondary 28AWG} = \frac{\text{Secondary wire area cm}^2}{\dfrac{\text{Area 28AWG cm}}{\text{Rskin 28AWG 100°C}}}$$

$$\text{Rcopper secondary 28AWG} = \text{Rcopper 28AWG 100°C} \times \text{Ns} \times \frac{\text{Length per turn cm}}{\text{Number of wires secondary}}$$

$$\text{Pcopper secondary loss 28AWG} = \text{Isecondary rms}^2 \times \text{Rcopper secondary 28AWG}$$

Determine bias wire AWG and losses:		
number of bias wires	1.000	
Number of turns bias winding (Nsb)	12.867	
Rcopper bias 32AWG	0.000140	ohm
Pcopper bias loss 32AWG	3.5E-07	W

$$\text{Number of turns bias winding (Nsb)} = \text{Ns} \times \frac{\text{Vbias}}{\text{Vout}}$$

$$\text{Rcopper bias 32AWG=Rcopper 32AWG 100°C} \times \text{Nsb} \times \frac{\text{Length per turn cm}}{\text{Number of bias wires}}$$

$$\text{Pcopper bias loss 32AWG} = \text{Ibias rms}^2 \times \text{Rcopper bias 32AWG}$$

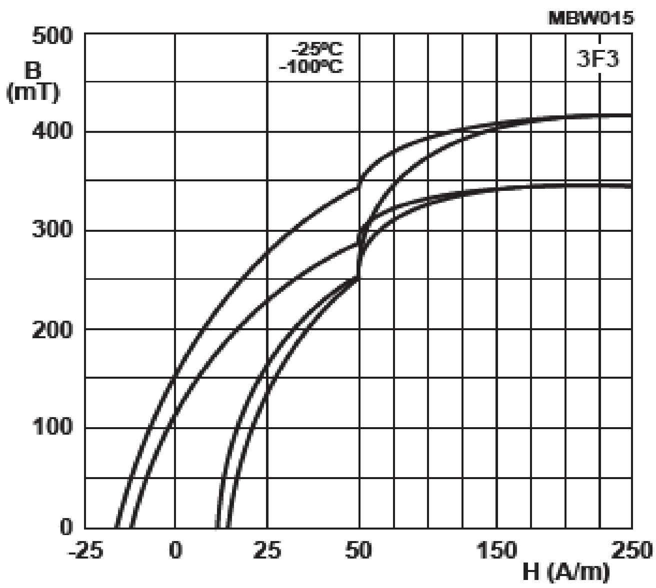
7. Calculate Flux Density and Core Loss

Effective core parameters from manufacture datasheet

core factor(Σ(I/A))	1.52	mm^-1		
Effective volume (Ve)	1460	mm^3	0.00000146	m^3
Effective length	47	mm		
Effective Area(Ae)	31	mm^2	0.000031	m^2
Minimum Area(Amin)	29	mm^2		
Mass of core half (m)	3.5	g		
βac	0.147	Tesla		
βmax	0.147	Tesla		

For a flyback converter running in discontinuous current mode, the AC flux density, βac, is equal to the maximum flux density, βmax .

$$\beta ac = \frac{\text{Vin min} \times \text{Tonmax}}{\text{Ae} \times \text{Np}} \qquad \beta \max = \frac{\text{Lp} \times \text{Ipri\_p}}{\text{Ae} \times \text{Np}}$$



the saturation point for the given core is about 250 mT. So this design is about 60 percent of maximum flux.

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B-H Curve		
Determine core loss:		
Bunipolar	0.000	Tesla
Pcore	60	kW/m3
Pcore loss	0.0000876	W
Total magnetic power dissipation	1.0E-01	W

$$\text{Bunipolar} = \frac{\beta ac}{2}$$

$$\text{Pcore loss} = \text{Pcore} \times \text{Ve per m}^3$$

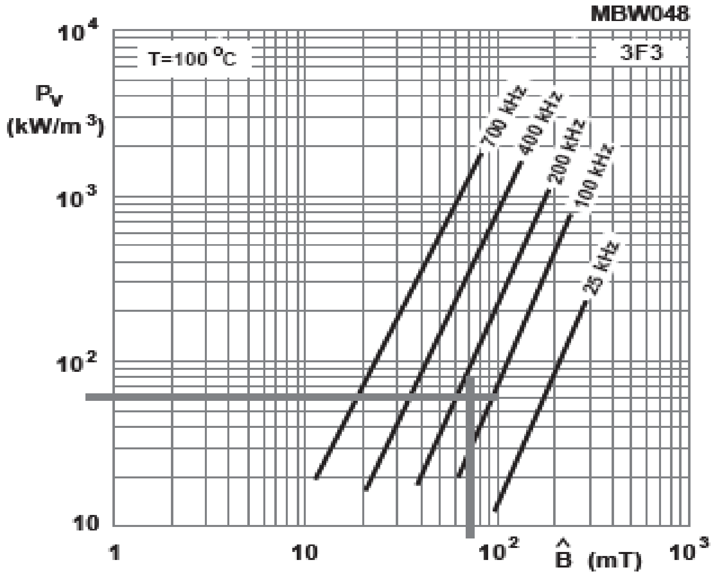

Figure 15 – Specific power loss as a function of peak flux density with frequency as a parameter (courtesy of Ferroxcube).

8. Bobbin Fit Factor

Winding data and area product for EFD20/10/7 coil former (SMD) with 10-solder pads

Number of Sections	Winding Area (mm^2)	Minimum Winding Width (mm)	Average Length of Turn (mm)	Area Product Ae x Aw (mm^2)	Type Number
1	27.7	13.5	34.1	859	CPHS-EFD20-1S-10P

Figure 16 – Winding data (courtesy of Ferroxcube).

AWG	Copper Diameter in cm with Insulation	Copper Area in cm^2 with Insulation
26	0.046	0.001671
28	0.037	0.001083
30	0.03	0.000704
32	0.024	0.000459

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$$\text{Turns per layer 26AWG} = \frac{\text{Bobbin width cm}}{\text{Diameter 26AWG with isolation}} - 2$$

$$\text{Buildup in cm} = \frac{\text{Winding area cm}^2}{\text{Bobbin width cm}}$$

$$\text{Layers} = \frac{\text{Buildup in cm}}{\text{Diameter 26AWG with isolation}}$$

Bobbin width	1.35	cm
Turns per layer 26AWG	27.34782609	
Turns per layer 28AWG	34.48648649	
Turns per layer 30 AWG	43	
Winding area	0.277	cm^2
Buildup	0.205	cm
Layers	4.460547504	
Total bobbin turns 26AWG	121.9862774	
Total turns needed	81.22442307	
Winding factor	0.665848855	

$$\text{Total bobbin turns 26AWG} = \text{turns per layer} \times \text{layers}$$

$$\begin{aligned}\text{Total turns needed} \\ &= \text{Np} \times \text{number of primary wires} + \text{Ns} \times \text{number of secondary wires} \\ &+ \text{Nsb} \times \text{number of bias wires} = 81\end{aligned}$$

$$\text{Winding factor} = \frac{\text{Total turns needed}}{\text{Total bobbin turns 26AWG}}$$

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Reference : "Power Transformer Design" by Lloyd H. Dixon.
Ferroxcube. Soft Ferrites and Accessories.

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