Main Transformer Design

For this particular transformer design, core type and size is chosen as ETD34 and material is N87 Ferrite. It is an E-Shaped core, and is un-gapped to avoid storing of energy. First consideration is choosing number of primary turns. In order to achieve a reliable transformer design, “worst-case” scenarios have to be evaluated. Primary turns can be estimated via either choosing a “worst-case” peak flux density or peak magnetising current. Peak flux density can be easily decided from ETD34 datasheets, where B_{sat} is given as 490mT and 390mT for 25˚C and 100˚C respectively. Operating condition of 100˚C is extreme in this context, hence B_{sat} is chosen as 490mT. Table below shows the name, symbol, value and unit of necessary variables to be used in transformer design calculations.

Variable	Variable	Value	Unit
Effective Magnetic Cross Section	A_e	97.1µ	m^2
Effective Magnetic Volume	V_e	7.63µ	m^3
Winding Cross Section	A_N	122µ	m^2
Inductance Factor	A_L	2600n	H
Saturation Magnetization	B_{sat}	490m @ 25˚C	T
Mean Turn Length	MTL	60.5	mm
Duty Cycle	d	0.4	-
Period	T	10µ	s
Switching Frequency	f	100k	Hz

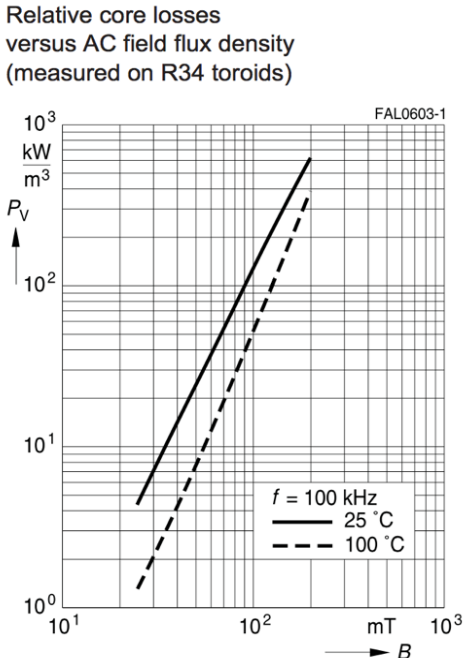

Figure 1 – Graph of Relative Core Losses vs AC Field Flux Density

Utilization of PLECS to get “worst-case” V_s, highest value of voltage transformer will experience in steady state condition, will give an idea of relationship between parameters. Following the formulae with value of Vs as 38.34V:

$$\emptyset_{max} = (V_s \cdot d \cdot T) / N_1 \text{ , where } \emptyset_{max} = B_{max} \cdot A_e$$

$$\hat{\imath}_{mag} = (V_s \cdot d \cdot T) / L_{mag} \text{ , where } L_{mag} = N^2 A_L$$

$$P_v = 4 \cdot (B_{max} - 200) + 600 \text{ [1]}$$

$$P_{core\ loss} = P_v \cdot V_e \text{ [2]}$$

[1] – Figure 1 is taken from the datasheet of ETD34 N87. Formula for P_v is deduced from the slope of 25˚C (black line). P_v has unit of kW/m^3, which is why formula [2] is required to produce a value for core loss in terms of W per set.

Table below can be produced. First row is initial start for calculation and can't be valid since N_1 is not an integer, hence row 1 is marked as red.

N_1	$Ø_{max}$ (μWb)	B_{max} (mT)	L_{mag} (μH)	$\hat{\imath}_{mag}$ (A)	P_v (kW/m^3)	P (W/set)
3.22	47.5790	490.000	26.958	5.689	1760.00	13.43
4	38.3400	394.850	41.6	3.687	1379.40	10.53
5	30.6720	315.880	65.0	2.359	1063.52	8.12
6	25.5600	263.234	93.6	1.638	852.94	6.51
7	21.9086	225.629	127.4	1.204	702.52	5.36
8	19.1700	197.425	166.4	0.922	589.70	4.50
9	17.0400	175.489	210.6	0.728	501.96	3.83
10	15.3360	157.940	260.0	0.590	431.76	3.29
11	13.9418	143.582	314.6	0.487	374.33	2.86
12	12.7800	131.617	374.4	0.410	326.47	2.49
13	11.7969	121.492	439.4	0.349	285.97	2.18
14	10.9543	112.815	509.6	0.301	251.26	1.92

It can be observed that with increasing N_1, maximum magnetization, peak magnetizing current and core loss is decreased, while L_{mag} value is increased. Here a low copper loss and peak magnetizing current is prioritized to get better efficiency, while considering a suitable peak flux density. On the other hand, theoretical turns ratio (N2/N1) for the forward converter was calculated as 15/14 = 1.07. Therefore, choosing N_1 as 14 ensures that determined turns ratio is met (meaning N_2 is 15), and results with a sensible peak magnetizing current and core loss.

Now that primary and secondary turn values are set, wire thickness can be determined according to K_{fill} factor, skin depth (∂) and i_{rms} effecting each winding.

- Starting current density value (J) is chosen as 5A/mm^2. Typical values range between 3-6 A/mm^2. [3]
- Skin depth (∂) at 100kHz is given as 0.206mm.

For N_1, $i_{rms_1} \approx 2.30$A (PLECS Simulation):

$$A_{turn} = i_{rms\_1} / J = 2.3 / 5 = 0.461\text{mm}^2$$

$$A_{turn} = (\pi \cdot D^2)/4, \text{ where } D = 0.7653\text{mm} \;\&\; r = 0.383\text{mm}$$

[3]- Typical range for current density is acknowledged via a website source on transformer design → https://talema.com/smps-transformer-design/

- r calculated is bigger than skin depth, hence smaller wire has to be used and Litz wire method is required.
- Wire_26 has a radius smaller than skin depth: $r = 0.2mm < \partial = 0.206mm$.

$$A_{W\_26} = \pi \cdot r^2 = \pi \cdot (0.2)^2 = 0.126mm^2$$

$$A_{turn} / A_{W\_26} = 3.65 \approx 4 \text{ strands of wire twisted together}$$

$$A_{W\_26} \cdot 4 = 0.504mm^2$$

- New A_{turn} is $0.504mm^2$, and so J_{new} is around $4.6 A/mm^2$.

$$A_{cu} = A_{turn} \cdot N_1 = 0.504 \cdot 14 = 7.056mm^2 = 7.0566\mu m^2 \quad \& \quad A_N / 2 = 61\mu m^2$$

- A_N is divided by two due to having two windings. Space is shared between the two.

$$K_{fill} = A_{cu} / A_{N\_half} = 7.0566 / 61 = 0.1157$$

- Calculated $K_{fill} < 0.5$, meaning winding will fit. Yet it is a small value indicating that the transformer has space more than enough.

For N_2, $i_{rms\_2} \approx 2.05A$ (PLECS Simulation):

$$A_{turn} = i_{rms\_2} / J = 2.05 / 5 = 0.410mm^2$$

$$A_{turn} = (\pi \cdot D^2)/4, \text{ where } D = 0.7225mm \text{ \& } r = 0.361mm$$

- Wire_26 is used with 4 strands of wire, same as primary side.
- New A_{turn} is $0.504mm^2$, and so J_{new} is around $4.07 A/mm^2$.

$$A_{cu} = A_{turn} \cdot N_2 = 0.504 \cdot 15 = 7.56mm^2 = 7.56\mu m^2 \quad \& \quad A_N / 2 = 61\mu m^2$$

$$K_{fill} = A_{cu} / A_{N\_half} = 7.56 / 61 = 0.1239$$

After deciding on which wire to use for both sides, copper losses can be calculated by finding AC and DC resistances of the windings. First of all, resistivity of Wire_26 has to be calculated separately because it will be used to get a value for $R_{(DC)}$. Nominal Resistance of Wire_26 is 0.1360 Ω/m, so assume 1 meter of wire is used.

$$\rho = (R \cdot A) / L = (R \cdot \pi \cdot r^2)/1m = [0.1360 \cdot \pi \cdot (0.0002)^2]/1 = 17.09 \cdot 10^{-9} \, m\Omega$$

For N_1:

$$l_{winding\_1} = MTL \cdot N_1 = 60.5 \cdot 14 = 847mm$$

$$R_{(DC\_1)} = (\rho \cdot l_{winding\_1})/A_{turn} = (17.09 \cdot 10^{-9} \cdot 0.847) / (0.504 \cdot 10^{-6}) \approx 0.029\Omega$$

$$R_{(AC\_1)} = 0.0350\Omega \text{ – found online} \quad \& \quad R_{(AC\_1)} < 2 \cdot R_{(DC\_1)} \text{ – Condition Met}$$

[1] – Figure 1 is taken from the datasheet of ETD34 N87. Formula for P_v is deduced from the slope of 25˚C (black line). P_v has unit of kW/m^3, which is why formula [2] is required to produce a value for core loss in terms of W per set.

For N_2:

$$l_{winding\_2} = MTL \cdot N_2 = 60.5 \cdot 15 = 907.5mm$$

$$R_{(DC\_2)} = (\rho \cdot l_{winding\_2})/A_{turn} = (17.09 \cdot 10^{-9} \cdot 0.9075) / (0.504 \cdot 10^{-6}) \approx 0.031\Omega$$

$R_{(AC\_2)} = 0.0375\Omega$ – found online & $R_{(AC\_2)} < 2 \cdot R_{(DC\_2)}$ – Condition Met

$$P_{copper\_1} = [R_{(AC\_1)} \cdot (i_{rms\_1})^2] + [R_{(DC\_1)} \cdot (i_{DC\_1})^2]$$

$$P_{copper\_2} = [R_{(AC\_2)} \cdot (i_{rms\_2})^2] + [R_{(DC\_2)} \cdot (i_{DC\_2})^2]$$

Hence; $P_{Total} = P_{copper\_1} + P_{copper\_2} + P_{core\ loss}$

Winding style of the transformer is as simple as possible, thus non-interleaved winding is decided for this particular transformer.

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[3]- Typical range for current density is acknowledged via a website source on transformer design → https://talema.com/smps-transformer-design/

REFERENCES

1) https://talema.com/smps-transformer-design/
2) https://chemandy.com/calculators/round-wire-ac-resistance-calculator.htm
3) SIFERRIT material N87 - Ferrites and Accessories Datasheet
4) https://www.tdk-electronics.tdk.com/inf/80/db/fer/etd_34_17_11.pdf

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[1] – Figure 1 is taken from the datasheet of ETD34 N87. Formula for P_v is deduced from the slope of 25˚C (black line). P_v has unit of kW/m^3, which is why formula [2] is required to produce a value for core loss in terms of W per set.