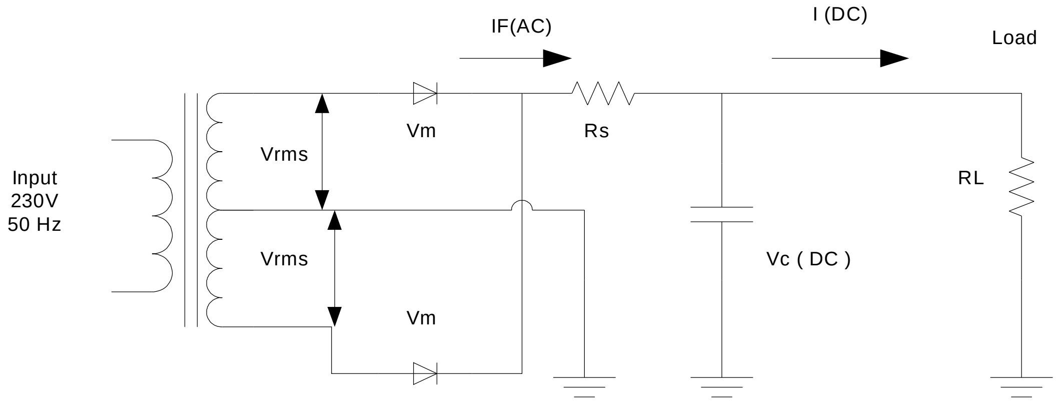
Design of Power Transformers

The recommended practice for deriving the specifications of power transformers used in single phase rectifier circuits with capacitor input filter is given below. The numerical values refer to the following example.



Part 1 :

Deriving transformer specifications

1.1 Determination of load resistance , R_L

DC voltage = 18 volts
DC current = 0.25 Amps

$R_L = V_{C(DC)} / I_{DC}$
$= 18$ Volts / 0.25 Amps = 72 ohms

1.2 Assume a value of source resistance R_S suitably , usually between 1 % to 10 % of R_L .

Let R_S / R_L be 5%

$R_S = 72 * 5 / 100 = 3.6$ ohms

1.3 From Fig.1 (ωCR_L vs r_f) determine ωCR_L required to reduce the ripple to a desired value for assumed R_S / R_L in %

For $R_S / R_L = 5\%$
$r_f = 5\%$
for a full wave rectifier from Fig.1 $\omega CR_L = 14$

1.4 $C = \omega CR_L / \omega R_L$

$\omega = 2 \times \Pi \times f$

f = mains supply frequency = 50 Hz in this document

$= 14 / (2 \times 3.14 \times 50 \times 72)$

$= 0.618 \times 10^{-3}$ F = 618 uF

A practical value could be 640uF.

New ωCR_L will be = $314 \times 640 \times 10^{-6} \times 72 = 14.25$

1.5 <u>Determination of conversion ratio</u>

Refer Fig 2 for HW (Half Wave) rectifier

Refer Fig 3 for FW (Full Wave) rectifier

Now for $R_S / R_L = 5\ \%$

$\omega CR_L = 14.25$

(from Fig.3) $(V_{C(DC)} / V_M) = 82\ \%$

1.6 To determine Vrms

From step 1.5 , VC(DC_) /VM = 82 %

$V_M = V_{C(DC)} / 0.82$

$= 18 / 0.82 = 22$V

Vrms = $V_M / \sqrt{2} = 15.5$

1.7 <u>RMS Current</u>

From Fig.4 , n = 1 for a HW rectifier

n = 2 for a FW rectifier

for $n\omega CR_L = 2 \times 14.25$ and $R_S/nR_L = 2.5\ \%$

$I_{F(RMS)} / I_{F(AV)} = 2.5$

But I F(AV) = I DC / 2 (for FW center tapped rectifier only)

$I_{F(RMS)} = 2.5 \times (0.25 / 2) = 0.312$ A

(for FW bridge and HW rectifiers $I_{F(av)} = I_{DC}$)

1.8 `Secondary Volt Amp rating (Sec. VA)

= Vrms x IF(RMS) …………for a FW bridge and HW rectifier

= Vrms x IF(RMS) ………… for a FW center tapped rectifier

Secondary VA = 15.5 x 0.312 x 2 = 9.7

The transformer specifications can now be summarized as follows

V_{rms} = 15.5 V   Sec VA = 9.7
I_{RMS} = 0.312 Amp

PART – II Design of the Transformer

V_{RMS} = 15.5 V (secondary voltage)
I_{RMS} = 0.312 Amp (secondary current)

Output VA (secondary VA) = 9.7

2.1 From Table 3 , a type 23 lamination in Grade 80 material is chosen . This has a power rating of 15 VA and η= 72 % (η is the efficiency of the core material) .

Primary VA = Secondary VA / η = 9.7/ 0.72 = 13.47 ≅15

Hence type 23 grade 80 lamination can be used .

2.2 Calculation of number of turns : (N_P and N_S)

Number of turns per volt (b)

B = 10^4 / (4.44 x f x B_{max} x A_{fe})
Where
B = turns per volt
f = mains frequency in Hz
A_{fe} = iron cross section area in cm^2
Bmax = maximum core flux in Tesla

From Table 2 , for type 23, Grade 80 lamination

A_{fe} = 3.34 cm2
B_{max} = 1.3 T

B = 10^4 / (4.44 x 50 x 1.3 x 3.34)
= 10.5 turns per volt

Primary Turns (Np) = b x Primary voltage

= 10.5 x 230 = 2420 turns

Secondary Turns (Ns) = b x Vrms

= 10.5 x 15.5 = 163

Since the secondary is center tapped , total number of secondary turns

= 163 + 163 = 326

2.3 Calculations of primary and secondary currents (I_P and I_S)

I_P = Primary VA / Primary Voltage = (9.7 / 0.72) / 230
= 0.059 A

$I_S = I_{RMS}$ = 0.312 A = 312 mA

2.4 <u>Selection of appropriate current density</u>

Refer Fig 6 for primary VA = 13.5
Current density = δ = 5.5 A/ mm^2
Chose δ = 4 A/ mm^2 .
This is done because δ values greater than 4 A / mm^2 leads to much thinner wires which are difficult to wind.

2.5 <u>Selection of wire size</u>

δ = 4 A / mm^2
I_P = 59 mA and I_S = 312 mA

Cross sectional area for the primary winding is

= 59 x 10^{-3} / 4 = 15 x 10^{-3} mm^2
A wire with this cross sectional area or higher should be chosen.

Referring to Table 4 , SGW 38 with a cross sectional area of 0.0182 mm^2 is selected for the primary winding and SWG 30 with a cross sectional area of 0.078 mm^2 selected for the secondary winding.

2.5 Check for winding space on the former.

Area required for the primary winding = 0.0182 x 2420 = 44mm^2
Are required for the secondary winding = 0.078x (163+163)
= 25.4 mm^2
Total = 44 = 25.4 = 69.4 mm^2

Assuming a <u>space factor</u> of 0.6 which will give the actual space available for the winding on the former , we get a winding area actually required as
= 69.4 / 0.6 = 116 mm^2 = 1.16 cm^2

The area required for the inter winding insulation and final covering can be considered to be about 20 % to 30 % of the actual area required for the winding.

Area required for insulation $= 1.16 \times 30/100 = 0.35\ mm^2$

Total area (winding + insulation) = $1.16 + 0.35 = 1.51\ cm^2$

This value should be less than or equal to the winding space available in the coil former (the bobbin) .

Referring to Table 2 .

The winding space AW (for a Type 23 bobbin) = $1.85\ cm^2$. Hence the chosen coil former is OK for this design .

If the calculated value is greater than the area available in the bobbin as obtained from Table 2 , the laminations of a superior grade of metal should b eused or the next larger size of core should be used. The core can also be make rectangular and not square instead of using a larger dimension lamination.

<u>Part – III</u>

3.1 Resistance of primary winding (r_P)

R_P = MLT x N_P x resistance per unit length

<u>From Table 2 :</u>

MLT of primary = 5.4 x A
= 5.4 x 1.9 cm
= 10.25 cm
= 10.25×10^{-5} km

From step 2.2 we have N_P = 2420

<u>From Table 4 :</u>

Resistance per unit length for the primary (here SWG 38)
= 942.2 Ω / Km

$r_P = (10.25 \times 10^{-5}) \times 2420 \times 942.2 = 234\ \Omega$

3.2 Resistance of the secondary winding :

R_S = MLT x Ns x Resistance per unit length

<u>From Table 2 :</u>

MLT for the secondary = 7.2 x A
= 7.2 x 1.9 cm
= 12.4 cm
= 12.4×10^{-5} km

N_S = 163

SWG 30 has a resistance of 221 Ω / Km

r_S = (12.4 x 10^{-5}) x 163 x 221 = 4.8 Ω

3.3 Transformer resistance referred to the secondary .

= $r_S + r_P / m^2$ where m = turns ratio = N_P / N_S

N_P / N_S = V prim / V sec = 230 / 15.5 = 14.85

Therefore $r_S + r_P / m^2$ = 4.8 + 234 / (14.85)^2 = 5.86 Ω

3.4 Voltage drop across rectifier at I_{DC} is ≈ 0.7 V (V_D)

3.5 Rectifier resistance (r_R)

I_{DC} = 0.25 A V_D = 0.7 V
r_R = 0.7 / 0.25 = 2.8 ohms

3.6 Total resistance in the secondary circuit (R_S)

This is much greater than the assumed value of RS in step 1.2
Therefore steps (1.3 to 1.6 etc.) affected by this have to be repeated again taking into account the new RS value or r_S and r_P have to be reduced by choosing a higher gauge wire with lower resistance.

(If the calculated value of R_S is less than the assumed value in step 1.2 an external resistance may be added in series with the secondary winding to make up for the assumed value of R_S)

The following calculation shows and example of reducing R_S by reducing r_S .

Part IV : Repeat calculations:

If SWG 28 is chosen for the secondary , from Table 4 we get
Resistance / Km for SWG 28 = 155 Ω

And r_S = (7.2 x 1.9 x 10-5) x 163 x 155 = 3.45 Ω
R_S = 3.45 + 1.06 + 2.8 = 7.31 Ω

The steps affected by the change in value of R_S are given below.

Checking for accommodation of the winding:

2.6 Area for the primary = 44 mm^2
Area for the secondary (SWG 28) = 0.11 x 325 = 35.8 mm^2

Total area for winding = 44 + 35.8 = 79.8 mm^2
Actual area for windings = 79.8 / 0.6 = 133 mm^2

Area for insulations = 133 x 0.3 = 40 mm2
Total Area (winding + insulation) = 133 + 40 = 173 mm^2

This is less than the space available in the Type 23 bobbin so the new wire size can be used.

1.2 R_S = 7.31 and R_S / R_L = 7.31 / 72 = 10.15 %

1.3 From Fig.1 for R_S / R_L = 10.15 % , r_F = 5 %
We have ωCR_L = 12

1.4 C = 12 / (314 x 72) = 530 uF . So the earlier choice of 640uF can still be used. Ripple will go down some more.

1.5 From Fig.3 For R_S / R_L = 10.15 % & ωCR_L = 14.25
$V_{C(DC)}$ / V_M = 73 % , V_M = 18 / 0.73 = 24.7 V

1.6 Vrms = 24.7/2 = 17.4 V

2.1 Type 23 Gr.80 laminations are still being used.
This step will have to be repeated if the lamination grade or step size chosen earlier is changed for the reasons given in section 2.6 .

2.2 b = 10.5 , N_P = 2420
N_S = 10.5 x 17.4 = 183
Total secondary = 183 + 183 .

2.6 Area for (183 + 183) secondary
= 0.11 x 366 = 4 mm^2
Total area = primary area + secondary area = 44+42 = 86 mm^2
Actual area = 86 / 0.6 = 143 mm^2
Area for insulations = 143 x 0.3 = 42 mm^2
Total area for the winding + insulation = 185 mm2 = 1.85 cm^2

3.2 rs = (7.2 x 1.9 x 10^{-5}) x 183 x 155 = 3.88

3.6 RS = 3.88 + 1.06 + 2.8 = 7.74

This is 0.4v more than the previously assumed value of 7.31
The percentage error is 0.4/7.31 = 5.5 %

For practical purposes differences up to 10 % can be accepted.

PART V : Result of the design calculations :

Vrms (sec) = 17.4 V (Part IV , Section 1.6)
I rms (sec) = 312 mA (Part I , Section 1.7)
Sec VA = 10.8 (V rms x I rms x 2)
Pri VA = 10.8 / 0.72 = 15 , I_P = 15 / 230 = 65 mA

Transformer fabrication data:

Lamination type 23 Gr. 80 Square stack.
Bobbin – Square type
Primary - SWG 38 , 2420 turns
Secondary – SWG 28 , 183 + 183 turns

X--X

TABLE-2

Dimensional details for selected types of Transformer laminations

Type No	Tounge width A cm	Effective iron cross sectional area for a square section		Average MLT	Winding Space Aw	No of stamping for a square section
		Grade 80	Grade 51			
		sq. cm	sq. cm	cm	sq. cm	
17	1.27	1.48	1.56	8.2	0.91	36
12A	1.59	2.32	2.44	10.3	1.18	45
23	1.9	3.34	3.52	12.2	1.85	54
45	2.22	4.54	4.79	14.1	2.67	63
15	2.54	5.94	6.26	16	3.75	73
33	2.8	7.21	7.6	17.6	4.56	80
3	3.18	9.27	9.78	20	6.05	89

Note :

1. Thickness of stampings : 0.35 mm

2. Density of laminations : Gr. 80 - 7.55gms / cm^3
Gr. 51 - 7.65 gms / cm^3

3. Stacking factor K 92 % for Gr.80
97 % for Gr.51

4. Effective cross sectional area A_{Fe} = Real cross sectional area x stacking factor
= A_{Re} x k

5. MLT : For the first winding = 5.4 x A
For the second (middle) winding = Average MLT
For the 3rd (last) winding = 7.2 x A

TABLE – 3

Approximate power ratings and efficiency for selected types of Transformer laminations .

Type No	Approximate Power rating at 50 Hz		Approximate primary R	Transformer efficiency (η)	
	Gr.80 @ Bmax	Gr.51 @ Bmax	rp	Gr.80	Gr.51
	1.3 T VA	1.5 T VA	ohms	%	%
17	2.8	3.7	1570	60	65
12A	7	9	514	65	70
23	15	19	226	72	77
45	27	35	120	78	81
15	46	59	60	82	85
33	74	86	30	85	87
3	112	144	9	87	89

Note :

1. Approximate power rating $P = (A_{Fe})^2 \times B\ max$
   A_{Fe} in square centimeters
   Bmax in Tesla

2. Bmax for Gr.80 = 1.3T (4 % Si Steel)

   Bmax for Gr.51 = 1.5T (CRGO)

   Bmax for Dynamo grade = 1.1 T

3. Iron Loss (@ 50 Hz and B max) = 1.76 W/Kg for Gr. 80

   1.11 W/Kg for Gr. 51