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A Novel Method of Design of Choke for a Fluorescent Lamp Using Standard Stampings

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***Abstract:** A fluorescent lamp needs a choke coil which plays role during starting and also as a ballast during normal operation. A fluorescent lamp has high luminous efficiency compared to filament lamps. This is partially offset by the losses occurring in the choke coil. Therefore the choke coil should be designed for minimum possible losses with a look to economic efficiency. Though electronic chokes have appeared recently and they are outpacing older versions due to their various advantages, their life-span is short and they eject objectionable electromagnetic noise. Under the circumstances the economy of the older versions should once again be checked. Though Al-chokes are cheaper, their performance is poor. As such, the copper chokes are better.*

***Keywords:** Fluorescent Tube, Choke Coil, Economic Efficiency, Optimal Design, Starter, Ballast.*

I. INTRODUCTION TO FLUORESCENT LAMP

A fluorescent tube is a low pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light. An electric current in the gas excites mercury vapor which produces short-wave ultraviolet light that then causes a phosphor coating on the inside of the lamp to glow. A fluorescent lamp converts electrical energy into useful light much more efficiently than incandescent lamps. The typical luminous efficacy of fluorescent lighting systems is 50–100 lumens per watt, several times the efficacy of incandescent bulbs with comparable light output.

Fluorescent lamp fixtures are more costly than incandescent lamps because they require a ballast to regulate the current through the lamp, but the lower energy cost typically offsets the higher initial cost. Compact fluorescent lamps are now available in the same popular sizes as incandescent and are used as an energy-saving alternative in homes. Because they contain mercury, many fluorescent lamps are classified as hazardous waste.

II. PRINCIPLE OF OPERATION

The fundamental means for conversion of electrical energy into radiant energy in a fluorescent lamp relies on inelastic scattering of electrons when an incident electron collides with an atom in the gas. The collision is 'inelastic' because a loss of kinetic energy occurs. This higher energy state is unstable, and the atom will emit an ultraviolet photon The UV rays are not visible to the human eye, so they must be converted into visible light. This is done by making use of fluorescence. Ultraviolet photons are absorbed by electrons in the atoms of the lamp's interior fluorescent coating. They in turn emit photons of wavelengths visible to the human eye.

III. CHOKE COIL FOR FLUORESCENT TUBELIGHT

Choke coils are invariably used along with tube lights for two reasons viz.

i) To create a voltage considerably higher than the line voltage by switching action of the starter

ii) To act as a ballast during normal operation and keep the voltage between 100-110 V across the tube. Due to phase difference between the choke voltage and the tube voltage, the choke voltage is usually near to 200 V.

A. Electronic Chokes Vs. Conventional Chokes:

Though electronic chokes are frequently used for fluorescent tube-lights for their low loss, their life-span is quite small. Also they eject objectionable level of electromagnetic waves in the surrounding which is not at all good for health. Earlier chokes using copper as conductor and CRS as core material can be designed for low loss and make it comparable with electronic chokes. The cost is a little on the higher side, but is economically a far better option considering its trouble-free operation and long life. The design methodology using standard E-I stampings, taking the space constraint into consideration, has been taken up. A case-study has been made on a 4-ft tube light with data collected from the laboratory.

Fluorescent lamps are negative differential resistance devices, so as more current flows through them, the electrical resistance of the fluorescent lamp drops, allowing for even more current to flow. Connected directly to a constant-voltage power supply, a fluorescent lamp would rapidly self-destruct due to the uncontrolled current flow. To prevent this, fluorescent lamps must use an auxiliary device, a ballast, to regulate the current flow through the lamp.

The simplest ballast for alternating current (AC) use is an inductor placed in series, consisting of a winding on a laminated magnetic core.

Many different circuits have been used to operate fluorescent lamps. The choice of circuit is based on AC voltage, tube length, initial cost, long term cost, instant versus non-instant starting, temperature ranges and parts availability, etc.

In the conventional circuitry, a choke coil is used in series with the fluorescent tube light for two purposes, which have already been mentioned.

a). To produce a high instantaneous voltage to ignite the tube and

b). To use it as a ballast under steady state.

The luminous efficiency of fluorescent tubes is much higher than that of filament lamps. The efficiency is partly offset due to losses incurring in the choke coil. Therefore, the choke coil has to be designed for low magnetic and electric loss. A low flux-density has to be used to reduce the iron loss, also to limit the operation of the inductor in the linear zone. A low current density has to be used to keep the ohmic losses at a low value. This will obviously increase the selling price of the choke. Higher electric and magnetic loading will reduce the price of the choke but will increase the losses, the temperature rise and reduce the life-span. Therefore a trade-off between the two has to be made to reach optimality condition.

IV. CIRCUIT DIAGRAM FOR MEASUREMENTS OF VOLTAGES, CURRENT AND WATTAGE

The circuit diagram for the fluorescent tube light, equipped with measuring instruments is given below in fig. 1. The schematic circuit diagram and the phasor diagram are also given below in fig. 2a and fig. 2b. Initially no current flows through the tube, only a current flows through the choke and the starter. The starter (bimetallic or glow-type) gives rise to frequent on-off and thus produces a high voltage due to trapped energy in the choke coil.

This instantaneous high voltage breaks down the gap between electrodes and starts the flow of electrons through the tube. The impact of the electrons with the fluorescent coating produces the luminosity. The choke coil acts as a current-limiter during the steady state run.

The phasor diagram shows that there are two components of the source voltage, V_S:

i) Voltage across the tube V_R which is in phase with the current

ii) Voltage across the choke V_C which leads the current by almost 90° - this component is responsible for low p.f. operation of the tube-light.

V. MATHEMATICAL EQUATIONS - THE RATING OF THE CHOKE

Under steady run, the voltage across the tube remains at nearly half of the source voltage or a little less and the voltage across the choke is 85-90% of the source voltage. The combination runs at a lagging p.f. given as:

$$\cos\theta = \frac{V_S^2 + V_R^2 - V_C^2}{2V_S V_R} \qquad 1$$

The normal value is from 0.6-0.7 lagging. The power factor of the choke is given as:

$$\cos\theta = \frac{V_S^2 - V_R^2 - V_C^2}{2V_C V_R} \qquad 2$$

The power factor of the choke is very poor. The rating of the choke coil, $S = V_C I$.

A.K. Shawney has argued that the turns/volt, T_e for design has to be chosen for a rating of $S/2$ as there is a single coil (instead of two coils as in a 2-winding small transformer). The table for $S - T_e$ is given in table-I. It gives an approximate value for T_e, which has to be suitably modified later on in consideration of the space available in the window.

A. Conventional Design Procedure:

After choosing T_e, we have to choose the core material. Low grade CRS is economically compatible. The maximum flux-density B_m should be chosen in consideration of the iron loss and magnetizing AT in the iron parts. The stacking factor may be taken as 0.92-0.95. Then the following quantities are calculated:

$$\phi_m = 1/(4.44\, fT_e)\,;\ A_i = \phi_m / B_m\,;\ A_{gi} = A_i / K_s \qquad 3$$

Where, ϕ_m is the maximum value of the core flux in wb., A_i, A_{gi} are net and gross core area in sq.m. respectively. It has been found through design calculations that a rectangular core is more economic, the depth/width of central limb may be taken as $R = 1.5$ (or varied to get the optimal value). We set $A = \sqrt{A_{gi}/R}$ and make a preliminary choice of E-I stamping by consulting the table, also taking space constraint (i.e. the choke has to be inserted below the tube) into consideration. The table for E-I stampings available in the market is given in table-II.

After choosing the E-I stamping, the window area is calculated as:

$W_w = (B-A)/2 - D$; $H_W = C - 2E$; $A_W = H_W W_W$ 4

Then we choose the conductor material (copper or aluminium) and the current density, δ .The window area must be able to accommodate the conductors or in other words:

$A_w > (N_1 a_1 + N_2 a_2)/K_w$ or $A_w > (N_1 I_1 + N_2 I_2)/(K_w \delta)$ or
$A_w > (V_1 I_1 + V_2 I_2) T_e /(K_w \delta)$ or $A_w > 2 S T_e /(K_w \delta)$ 5

where K_w = window space factor (0.6-0.65 for L.V. winding), a_1/a_2 : C.S. of the primary and secondary conductors.

B. The New Design Procedure:

In the earlier method, the no. of turns has to be changed to accommodate the winding within available space in the window. This is troublesome. In the new method the same table for E-I stampings has been used, but a factor area product has been defined: $A_p = A_{is} A_w$, where A_{is} is the core area of the central limb for square cross-section $(= A^2)$ and $A_w (= (B-A-2D)(C-2E)/4)$ is the window area for E-I stampings.

Now, we find that:

$A_i = \phi / B_m = 1/(4.44 f T_e) = A^2 R K_s = A_{is} R K_s$ where A= width of the central limb and R = rectangularity factor = depth of core/ its width and K_s is the stacking factor .

$A_w = NI/(K_w \delta) = V_c T_e I/(K_w \delta) = S T_e/(K_w \delta)$
$\therefore A_{is} A_w = S/(4.44 f K_w \delta R K_s)$ = area product

Using appropriate values for the design variables, we find out the required area product and then the required size of the standard stamping by consulting table-II.

VI. CHOICE OF SWG AND GAP LENGTH

The exact values of C.S. (copper) and diameter may be obtained by consulting the SWG-chart given in table-III. The addition to diameter due to enameling is small and is taken care of through window space factor.

The choke coil is to be provided with an appropriate air-gap to realize the required inductance. As the choke coil is highly inductive, the required inductive reactance may be taken as: $X_c = V_c / I$. This realized by providing a gap, of length l_g. The formula to be used is given below:

$$Z = \frac{T^2}{(at_i l_i + n_g at_g l_g) T_e}$$, where

at_i = specific at of iron path; l_i = length of iron path
n_g = no. of iron paths; at_g = specific at of air path; l_g = length of air path

VII. CASE STUDIES

Two case-studies have been made, once by the conventional method and then using the new method. The advantage of the new method is obvious.

A. Case Study-1 (Conventional Method):

We shall take up a case-study on a 4-ft. single tube light fitted with copper choke and supplied from a 230 V, 50 Hz. Supply. From measurements, we get:

Source Voltage = 230 V; Voltage across the tube = 110 V; Current drawn = 0.32 A; Power drawn by the tube and choke = 36 W.

$$\therefore p.f. = \frac{36}{230 \times 0.32} = 0.4891 = \cos\phi \therefore \phi = \cos^{-1}(0.4891)$$

$= 60.72^o$. *Now from*

$\cos\phi = \dfrac{V_S^2 + V_R^2 - V_C^2}{2 V_S V_R}$, we get:

$V_C = \sqrt{230^2 + 110^2 - 2 \times 230 \times 110 \times 0.4891} = 200.6$ V

$\therefore$ Rating of the choke, S = 200.6 × 0.32 = 64.2 VA

The choke coil will be designed for: $S/2 =$ 32.1 VA.

A.1. Choice of the Stamping:

For 25 VA, T_e =11.7, for 50 VA, T_e =7.0.

By linear extrapolation:

$$T_e = 11.7 + \frac{7 - 11.7}{50 - 25} \times (32.1 - 25) = 10.36$$

Now we proceed to find out the core size approximately from this value of T_e

$\phi_m = 1/(4.44 \times 50 \times 10.36) = 4.348 \times 10^{-4}$ wb.

We choose CRNOS and a flux-density of B_m = 1.4 Tesla.

$\therefore$ Net iron area, $A_i = \phi_m / B_m = 310$ mm^2. With stacking factor, K_s =0.95,

Gross iron area, $A_{gi} = A_i / K_s$ = 326.3 mm^2. $\therefore$ With rectangularity, $R = 1$, $A = \sqrt{326.3}$ = 18.064 mm.

We choose core no 74, with nearest value of: $A = 11/16\ inch = 17.46$ mm. Therefore width should be: 326.3/17.46=18.68 mm

A.2. Modification of Turns/Volt and the Main Dimensions:

Now we shall check whether the window area can accommodate the winding. With copper conductor and current density 2.8 A/mm^2, the C.S. of the conductor is approximately = 0.32/2.8 = 0.1142 mm^2. We consult the SWG chart and choose SWG no 28 having a C.S of 0.111 mm^2. So the current density increases to: 0.32/0.111= 2.883 A/mm^2.

The width of window for this core, $W_w = (B - A)/2 - D$ = (2.0625-0.6875)/2- 0.34375 = 0.34375 inch = 8.73 mm ; The height of window, $H_w = C - 2E$ = 1.71875- 2 × 0.34375 = 1.03125 inch = 26.19 mm

∴ Window area = 228.7 mm^2. Window space factor is taken as 0.6 ∴ no of conductors that can be accommodated in the window = 228.7 × 06/0.111 = 1236. ∴ Turns/volt has to be reduced to T_e = 1236/200.6 = 6.1615. Further calculations are to be made with this value of T_e. Now,

$$4.44 \times 50 \times 6.1615) = 7.311 \times 10^{-4}\, wb\ ;\ A_i = \phi_m / B_m = 5.222 \times 10^{-4}\, m^2$$

$$A_{gi} = A_i / K_s = 5.497 \times 10^{-4}\, m^2 = 549.7\, mm^2$$

Width of the central limb for the chosen core = 17. 46 mm ∴ Depth of the core= 549.7/17.46 = mm. It give a rectangularity of (31.48/17.46) = 1.8. It is acceptably good. The net size: Height = C = 43.7 mm ; width = B = 52.4 mm ; depth = 31.48+8.73 × 2 = 48.94.

The linear dimensions will increase due to iron casing but the over-all structure can be inserted below the tube.

A.3. Performance Analysis and the Cost:

No of turns = $200.6 \times 6.1625 = 1236$

Mean length of turn= $L_{mt} = 2A(1 + R) + \pi W_w$ = 2 × 17.46(1+1.8) + 3.142 × 8.73 = 125.2 mm = 0.1252 m

Taking resistivity of copper at operating temperature as: $\rho = 0.022\,\Omega / m / mm^2$, the resistance of the coil=

$$R = \frac{\rho L_{mt} N}{a} = \frac{0.022 \times 0.1252 \times 1236}{0.111} = 30.67\ \Omega$$

∴ Copper loss= $I^2 R = 0.32^2 \times 30.67$ = 3.14 W

Volume of copper = $NaL_{mt} \times 10^{-6} = 1236 \times 0.111 \times 0.1252 \times 10^{-6} = 17.177 \times 10^{-6}\, m^3$

Density of copper = 8900 Kg/ m^3

∴ Weight of copper = $8900 \times 17.177 \times 10^{-6}$ = 0.1529 Kg

Taking cost of copper as Rs. 600/- per Kg, the cost of copper = 0.1529 x 600= Rs. 91/70 p

∴ Volume of iron = $(BC - 2W_w H_w) ARK_s$ =

$$(2.0625 \times 1.71875 \times 25.4^2 - 2 \times 8.73 \times 26.19) 17.68 \times 1.8 \times 0.95$$

$$= 55318.9\, mm^3$$

Density of CRS = 7650 Kg/ m^3 ∴ Weight of iron = $55318.9 \times 10^{-9} \times 7650 = 0.423$ Kg

The specific loss/Kg =1.3 W at a flux-density of 1.4 Tesla

∴ Iron loss = 0.423 x 1.3 = 0.55 W

∴ Total loss = 3.14+0.55 = 3.69 W

Taking cost of iron as Rs. 90/- per Kg, the cost of iron = Rs. 38/-

∴ Cost of core and copper comes to Rs. 130/- approximately

Including cost of cover Rs. 20/- and cost of terminals Rs. 8/-, the cost of materials = Rs. 158/-. Including 10% labour charge, the direct cost = Rs. 174/-. Including 20% establishment, the selling cost = Rs. 209/-. With 10% profit the selling price may be fixed at Rs. 230/-

B. Case-Study-2 (New Method):

The same data has been taken for the new method: 4-ft tube light, copper conductor with current density 2.8 A/mm^2. Core material: CRNOS with a flux-density of B_m = 1.4 Tesla. Stacking factor K$_s$= 0.95, Specific losses and costs are same. We take initially, rectangularity factor as 3.0, so that the choke can be easily accommodated below the tube on the casing. The convergence quickly occurs as shown below at stamping no. 12A:

1	19511	17
2	47634	12A

Optimal Core No.= 12A

The parameters and variables are given below:

Voltage across the choke = 230 V
Voltage across the tube = 106 V
Voltage across the choke = 200.7 V
Current drawn by the tube = 0.32 A
Power drawn by the tube = 36 W
Power factor of the tube = 0.4891 lag
Capacity of the choke = 32.11 VA
Maximum flux-density = 1.2 Tesla
Width of central limb = 15.9 mm
Window width = 7.9 mm
Window height = 23.9 mm
Total width = 47.6 mm
Total height = 39.7 mm
Depth of stack = 49 mm
Ratio of depth/ width of central limb = 3.055
No. of air-gaps = 1
Length of air-gap = 0.344 mm
EMF/turn = 0.1954 volts
Turns/volt= 5.1167
SWG No.= 28
Conductor C.S. 0.1110 mm^2
Conductor diam 0.3759 mm
Window space factor = 0.600
Weight of iron = 0.533 Kg
Iron loss = 0.453 W
Copper loss = 4.96 W
Total loss = 5.41 W
Temp. rise = 58.1 ^{o}C
Weight of iron = 0.533 Kg
Cost of iron = Rs. 64/-

Weight of copper =	0.048 Kg.
Cost of copper =	Rs. 29/-
Cost of choke with 30 % overhead =	Rs. 120/-

VII. CONCLUSION

Now-a-days electronic chokes have become much popular. They have low loss and can ignite the tube even at a considerable low voltage. The selling cost of the choke built in with copper conductor and CRS core is a little more than that of its electronic counterpart but its life span is much more. It gives reliable and trouble-free operation for a long time. They do not eject objectionable electromagnetic waves as like their electronic counterparts. Also the voltage profile of our distribution system has mush improved in the recent past. Considering all these merits, use should be made of conventional chokes only, not the electronic one. By suitably designing the choke with standard E-I stampings, the loss can be reduced to level comparable to that of electronic choke. The design procedure has been exemplified in this paper with two case-studies. The normal procedure has been adopted in case-I and the new method has been applied in case-II. The combined copper and iron loss of this choke has been found out to be 3.69 W for case-I which is equal to only 10.25 % of the power drawn by the tube. In case-II, the loss is more: 5.41 W, which is about 15%, but the size and cost both have reduced. The cost is now Rs. 120/- only which is much less than for case-I. The over-all size is also compatible with the holding mechanism of the tube for both the cases- it can be inserted between the tube and the fixture.

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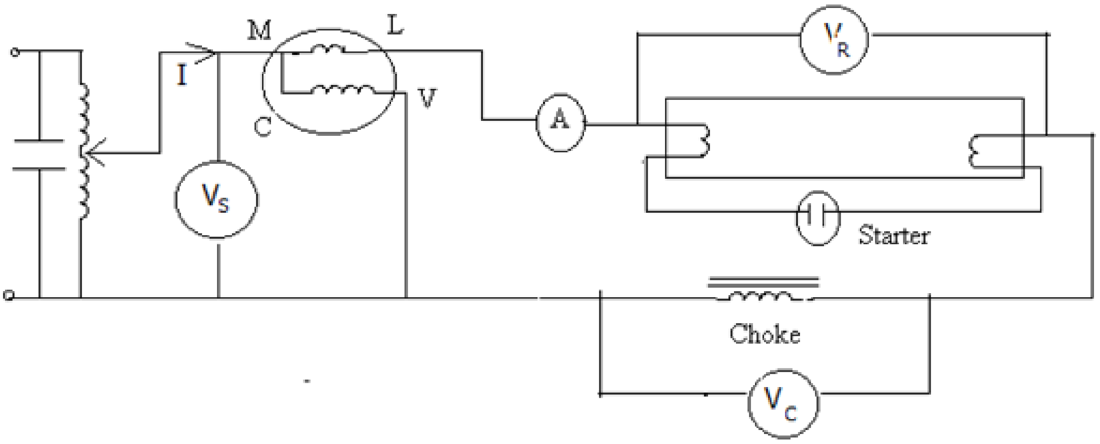

Fig. 1. Circuit Diagram for Measurements on a Flourescent Tubelight

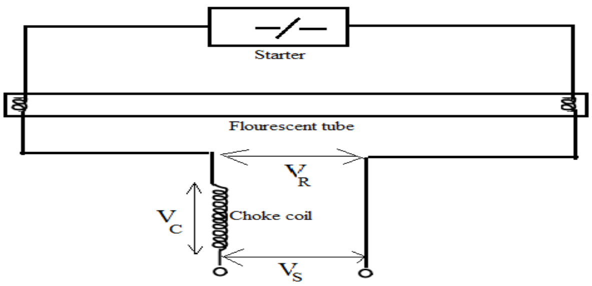

Fig. 2a. Circuit Diagram of a Fluorescent Tubelight

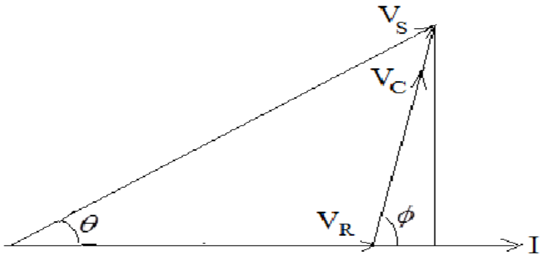

Fig. 2b. Phasor Diagram of Fluorescent Tubelight

X. APPENDIX

Table I. (Table For Turns/Volt For Small Transformers)

VA-Rating	Turns/Volt	VA-Rating	Turns/Volt	VA-Rating	Turns/Volt
10	23.3	75	5.6	300	2.8
15	17.5	100	4.6	400	2.3
20	14.0	150	4.0	500	2.0
25	11.7	200	3.5	750	1.7
50	7.0	250	2.8	1000	1.6

Table II. Dimensions of Standard E-I Stampings (In inch, if mm is Not Mentioned)

Number	A	B	C	D	E	Remarks
17	0.5	1.5	1.25	0.25	0.25	
12A	0.625	1.875	1.5625	0.3125	0.3125	
21	0.625	2.0	2.125	0.3125	0.375	
10/10A	0.625	2.375	2.125	0.375	0.375	
1	0.96875	2.53125	2.25	0.3125	0.3125	
74	0.6875	2.0625	1.71875	0.34375	0.34375	
23	0.75	2.25	1.875	0.375	0.375	
11	0.75	3.0	2.25	0.375	0.375	
11A	0.75	3.0	2.625	0.375	0.375	
2	0.75	3.0	3.0	0.375	0.375	
30	20 mm	60 mm	50 mm	10 mm	10 mm	4 holes 5/32”dia
31	0.875	2.625	2.1875	0.4375	0.4375	
45	0.875	2.625	2.1875	0.4375	0.4375	4 holes 5/32”dia
15	1.0	3.0	2.5	0.5	0.5	4 holes 7/32”dia
44	1.0	3.0	2.5	0.5	0.5	4 holes 7/32”dia
14	1.0	3.3125	2.625	0.53125	0.5	4 holes 7/32”dia
4	1.0	3.8125	3.8125	0.53125	0.5	4 holes 7/32”dia
33	28 mm	84 mm	70 mm	14 mm	14 mm	4 holes 11/64”dia
3	1.25	3.75	3.125	0.625	0.625	4 holes 7/32”dia
13	1.25	4.0	3.5	0.5	0.5	4 holes 7/32”dia
4A	1.3125	4.125	3.4375	0.65625	0.65625	4 holes 3/16”dia
16	1.5	4.5	3.75	0.75	0.75	4 holes 7/32”dia
5	1.5	4.75	3.75	0.75	0.75	4 holes 17/64”dia
6	1.5	5.0	4.5	0.75	0.75	4 holes 9/32”dia
7	2.0	6.0	4.9375	1.0	1.0	4 holes 17/64”dia
43	2.0	6.0	5.0	1.0	1.0	4 holes 17/64”dia
8	2.0	7.25	6.75	1.0	1.0	4 holes 3/8”dia

Table III. SWG-Chart For Wires

SWG Nosq.	AREA mm	DIAM. m	SWG No	AREA sq.mm	DIAM. m	SWG No	AREA sq.mm	DIAM. m
8	12.9717	4.06399	8½	11.7069	3.86078	9	10.5071	3.65760
9½	9.37205	3.45439	10	8.30192	3.25120	10½	7.54186	3.09880
11	6.81824	2.94639	11½	6.13116	2.79400	12	5.48054	2.64160
12½	4.86642	2.48920	13	4.28877	2.33680	13½	3.74761	2.18440
14.0	3.24293	2.03200	14½	2.92674	1.93040	15	2.62677	1.82880
15½	2.34301	1.72720	16	2.07547	1.62560	16½	1.82414	1.52400
17.0	1.58904	1.42240	17½	1.37014	1.32080	18	1.16746	1.21920
18½	0.98099	1.11760	19	0.81073	1.01600	19½	0.73168	0.96520
20	0.65670	0.91440	20½	0.58575	0.86360	21	0.51887	0.81280
21½	0.45604	0.76200	22	0.39726	0.71120	22½	0.34253	0.66040
23	0.29186	0.60960	24	0.24525	0.55880	25	0.20268	0.50800
26	0.16417	0.45720	27	0.13628	0.41655	28	0.11099	0.37592
29	0.09372	0.34544	30	0.07791	0.31496	31	0.06818	0.29463
32	0.05910	0.27431	33	0.05067	0.25400	34	0.04289	0.23369
35	0.03575	0.21335	36	0.02927	0.19305	37	0.02343	0.17272
38	0.01824	0.15239	39	0.01370	0.13207	40	0.01167	0.12190
41	0.00981	0.11176	42	0.00811	0.10162	43	0.00657	0.09146
44	0.00519	0.08129	45	0.00397	0.07110	46	0.00292	0.06097
47	0.00203	0.05084	48	0.00130	0.04068	49	0.00073	0.03049
			50	0.00051	0.02548			

Table- IV: Loss/Specific MMF for CRS

Flux-density, Tesla	Loss, W/Kg	MMF at/m	Flux-density, Tesla	Loss, W/Kg	MMF at/m	Flux-density, Tesla	Loss, W/Kg	MMF at/m
0.8	0.3	50	1.1	0.66	74	1.4	1.3	115
0.9	0.39	57	1.2	0.85	85	1.5	1.55	156
1.0	0.5	65	1.3	1.07	98	1.6	1.95	250