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Discrete Design Optimization of Small Open Type Dry Transformers

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Abstract

Transformers of small ratings have a wide field of application. They are generally designed and fabricated using standard stampings available in the market. The design is made according to guidelines given in text-books. But such guidelines do not yield a cost-optimal solution. It may even fail to give a feasible solution if design variables are not properly chosen. This paper presents a method to get the cost-optimal solution subject to usual design constraints. The line of approach is completely different from that given in the standard text-books. Computer programs have been developed for finding out the cost-optimal design using standard stampings and case studies have been made on its basis.

Keywords: *Optimal design, small transformer, standard stampings*

Symbols and abbreviations

S	Rating, VA
V_1, V_2	Primary and secondary voltage, V
I_1, I_2	Primary and secondary current, A
B_m	Maximum value of flux-density, Tesla
δ	Current density, A/sq. mm
K_s, K_w	Stacking factor, window space factor
A, B, C, D, E	Dimensions of E-I stamping
H_w, W_w, R_w	Window height, width, height/width ratio
d_s	Stack depth
R (= d_s/A)	Stack depth ratio
T_e	No. of turns/volt
T_1, T_2	No. of turns of the primary and secondary
a_1, a_2	C.S. of the primary and secondary conductors, sq. mm.
CT	Total cost of the transformer inclusive of overheads, Rs.
η	Efficiency, %
VR	Voltage regulation, %
TR	Temperature rise, ^oC
I_o	No load current, %

1. Introduction

For job production, small transformers are normally designed with standard laminations available in the market, mostly using standard E-I laminations. Other options are standard T-U and E-E stampings. For mass production, a factory may opt for non-standard laminations, which has to be punched by the factory itself for achieving greater economy. The available text-book methods do not give an optimal solution and sometimes may even fail to give a feasible solution if the design variables are chosen freely [1]. This is unfortunate as in long past (1967) O.W. Anderson emphasized on optimal design of electrical machines [2] and M. Ramamoorty

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advanced his treatise on computer-aided design of electrical equipment [3]. That the available methods are inadequate will be clear from the algorithm for design of small transformers given by A.K. Sawhney [1], as given below:

Step 1: Input specifications - S, V_1, V_2, f, taps, if any.
Step 2: Choose design variables - B_m, δ, R; Fix up constants K_s, K_w
Step 3: Find T_e from Table 1 [4]
Step 4: Find $A_i = 1/(4.44 \times T_e.\ f.\ B_m)$; $A_{gi} = A_i/K_s$
Step 5: Find $A' = (A_{gi}/R)^{1/2}$
Step 6: Choose a standard stamping having 'A' just above A', from Table 2 [4]
Step 7: Find $I_1 = S/(V_1.\eta)$; $I_2 = S/V_2$; $a_1 = I_1/\delta$; $a_2 = I_2/\delta$
Step 8: Find the corresponding values of SWG nos. and the modified C.S. a_1 and a_2
Step 9: Find $A_w = (C - E)/(B – A - 2.D)/2$
Step 10: Find $K_w = (a_1 T_1 + a_2 T_2)/A_w$
[Check whether there is a shortfall or a surplus- the shortfall makes the design unfeasible and the surplus makes it uneconomic.]
Step 11: * If the design is unfeasible or uneconomic then change the value of T_e. Go to step 4 else to step 12
Step 12: Make performance calculations
Step 13: Give print out
Step 14: Stop
Step 15: End

Table 1. (Turns/volt for small transformers) [1]

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 2. (Dimensions of standard E-I stampings available in the market) [1]

Core no.	A	B	C	D	E	H_w	A_w	A_i	A_p
17	12.7	38.1	31.8	6.35	6.35	19.0	121	161	19511
12A	15.9	47.6	39.7	7.9	7.9	23.8	189	252	47634
74	17.5	52.4	43.7	8.7	8.7	26.2	229	305	69741
23	19.0	57.2	47.6	9.5	9.5	28.6	272	363	98774
30	20.0	60.0	50.0	10.0	10.0	30.0	300	400	120019
45	22.2	66.7	60.3	11.0	11.0	38.4	431	494	212932
15	25.4	76.2	63.5	12.7	12.7	38.1	484	645	312174
33	28.0	84.0	70.0	14.0	14.0	42.0	589	783	461083
3	31.8	95.3	79.4	17.1	17.1	45.1	658	1008	663775
4A	33.3	104.8	87.3	16.7	16.7	54.0	1028	1111	1142757
16	38.1	114.3	95.3	19.0	19.0	57.2	1089	1452	1580379
5	38.1	120.7	95.3	19.0	18.0	57.2	1270	1452	1843775
6	38.1	127.0	114.3	19.0	19.0	76.2	1935	1452	2809562
7	50.8	152.4	125.4	25.4	19.0	74.6	1895	2581	4890719
43	50.8	152.4	127.0	25.4	25.4	76.2	1935	2581	4994776
8	50.8	184.2	171.5	25.4	25.4	120.7	4980	2581	12851140

(All dimensions are converted into mm)

The step 11 (marked with asterisk) has been added to make the design feasible and economical. It is absent in the original book. Even after this modification, this algorithm has the inherent weakness. It does not have any comments from the computed values of the performance variables into the program. Hence, no change can be made if the value of some performance variables is found unsatisfactory. To obviate this difficulty and to reach a cost-optimal solution, a new computer-based design methodology has been developed which takes care of the design constraints judiciously chosen or imposed by the customer.

2. The New Design Methodology

The attempt to use computer for the design of a transformer was reported by S.B. Williams et al as early as in 1956. W. A. Sharpley et al used digital computer to design a power transformer in 1958. The concept of optimality and the means to reach the same was shown by O.W. Anderson in 1967 [2]. Computer-aided design of electrical equipment has been discussed in details in a treatise by M. Ramamoorty who has also given the concept of optimality [3]. However, none of these references shows appropriate method for optimal design of small transformers, particularly using standard E-I stampings.

In the new method to be discussed in the following paragraphs, a quantity area product for E-I stampings has been defined which is the product of the window area and the gross iron area of a square core. The data-file for the standard E-I stampings has been equipped with the area-product for each standard core no. (table - 2) [1]. The required area-product for a small transformer of given specifications is found out in the following manner:

Turns/volt, $T_e = I/(4.44 \times f.\ \phi) = 1/(4.44 \times f.\ B_m.\ A_{gi}.\ K_s)$ (1)

For E-I stampings with a stack depth ratio R, the gross iron area is given as:

$A_{gi} = A.\ d_s = A_2.\ R$ (2)

The window area is given as:

$A_w = (N_1.\ I_1 + N_2.\ I_2)/(K_w.\ \delta) = T_e\ (V_1.I_1 + V_2.I_2)/\ (K_w.\ \delta)$ (3)

Equations (i), (ii) and (iii) yields :

$A_w\ .A_{gi} = S/\ (2.22 \times f.\ B_m\ .\ K_s\ .\ K_w.\ \delta) = A_p.\ R$
Or, $A_p = S/\ (2.22 \times f.\ B_m\ .\ K_s\ .\ K_w.\ \delta.\ R)$ (4)

For standard E-I stampings the area product is given by the expression:

$A_p = A_2\ (C - E).(B – A - 2.D)/2$ (5)

The value of A_p obtained from equation (iv) is compared with those in the data-file sequentially for choosing the standard stamping required for the specific design problem, with rectangularity factor varying between 1.0 to 3.0. The procedure generates a number of solutions. The most economic one is accept provided. it does not violate any of the design constraints.

The following design variables have been set in from the experience of the designer:

- Max. flux density in the core = 1.1 to 1.15 Tesla
- Max. current density in the conductor = 2.7 to 2.8 A/sq. mm

The following design constraints have been set in:

- TR ≤ TR-max, for the class of insulation chosen (E) TR-max = 70 ^oC
- VR ≤ VR-max (normally set at 5%)
- $\eta \geq \eta$-min (0.9 to 0.95 for small transformers)
- $I_o \leq I_o$-max (normally 2 to 3%)

The algorithm for optimal solution is given below:

Step 1: Input specifications- S, V_1, V_2, f, tap-settings
Step 2: Set values of constants K_s, K_w Initialize stack depth ratio R = 3
Step 3: Set the design constraints VR-max, TR-max, η-min, I_o-max
Step 4: Set the values of design variables: B_m, δ; mincost = high value
Step 5: Find out the primary and secondary currents and the C.S. of conductors
Step 6: Open the SWG file and find out the SWG numbers
Step 7: Open the core loss file and find out the specific core loss
Step 8: Open the magnetizing AT file and find out the specific AT

Step 9: While R≥ 1
Step 10: Find A_p as per equation (iv)
Step 11: Open data-file for E-I stampings and store the data in array
Step 12: Search sequentially for the next higher value of A_p and choose the core no.
Step 13: Find out dimensions of the core and the coil
Step 14 : Find out the cost inclusive of overheads
Step 15: Make performance computations- TR, VR, η, I_o etc. If any of the design constraints are violated then step 18
Step 16: If the cost ≥ mincost then step18
Step 17: Store the core no., dimensions of core and coil, performance variables and the cost
Step 18: End
Step 19: Print specifications, elements & total cost and the values of variables performance
Step 20: Stop
Step 21: End

3. Case Studies

Case-studies have been made for a 500 VA, 230/115 V, 50 Hz. Single phase transformer using E-I stampings, and using standard stampings available in the market. The design constraints have been set at:
VR-max = 5%; TR-max = 70 ^oC with class E insulation; η-min = 0.92; I_o-max = 2%

The print-outs are given below:

- VA-rating of the transformer = 500
- Primary voltage in volts = 230
- Secondary voltage in volts = 115
- Maximum flux-density chosen = 1.1 Tesla
- Current density chosen = 2.7 A/mm^2
- Specific cost of CRS core = Rs. 150/-
- Specific cost of copper = Rs. 480/-
- Area product (reqired) in mm^4 = 2900231

The possible choices of standard cores are given below:

Core no.	Rectangularity	Cost in Rs.
16	2.752724	2384/-
5	2.359478	2325/-
6	1.548407	2392/-
7	0.889511	2443/-

From the above, the core for most economic design has been chosen.

The core and conductors:

Core no.= 5
Width of central limb in mm = 38.1
Window width in mm = 22.3
Window height in mm = 57.3
Total width in mm = 120.7
Total height in mm = 95.3
Depth of stack in mm = 89.9
Ratio of depth/ width of central limb = 2.36
EMF/turn in volts = 0.7695
Turns/volt = 1.2996
No. of primary turns = 298

No. of additional primary turns for taps = 15
Total primary turns = 313
No. of secondary turns = 149
No. of additional secondary turns for taps = 0
Total secondary turns = 149
Primary current in A = 2.4155
Secondary current in A = 4.3478
Primary SWG no.= 18½
Secondary SWG no.= 16½
Primary conductor C.S. in mm^2 = 0.981
Secondary conductor C.S. in mm^2 = 1.824
Primary conductor diameter in mm = 1.118
Secondary conductor diameter in mm = 1.524
Window space factor = 0.453

Performance variables:
Iron loss in Watts = 6.725
Copper loss in Watts = 25.06
Percent iron loss = 1.345
Percent copper loss = 5.011
Total percent loss = 6.356
Efficiency at full load and at 0.8 lagging pf = 0.9264
Temperature rise = 51.6 ^{o}C
Iron loss current in A = 0.02924
Magnetising current in A = 0.0201
No load current in A = 0.0355
Percent no load current = 1.47
Base impedance (referred to primary) = 105.8 Ω
Leakage reactance (referred to primary) = 187.3 Ω
% resistance = 5.011
% reactance = 1.770
% impedance = 5.314
% Regulation at full load and pf 0.8 lag = 5.071

Weight and cost:
Weight of iron in Kg = 5.661
Cost of iron = Rs. 849/-
Weight of copper in Kg = 1.691
Cost of copper = Rs. 811/-
Total weight of iron and conductor in Kg = 7.351
Total cost of iron and conductor = Rs.1661/-
Cost of transformer with 40% overhead = Rs. 2325/-

It is found from the print-outs that there are four numbers of feasible solution while stack depth ratio is varied between 0.8 to 2.8 and the cost-optimal solution is obtained for core no. 5.

4. Conclusion

There are a large scale application of small one-phase transformers e.g. in battery chargers, inverters and several other domestic and industrial appliances. So they must be designed cost-effectively. The design methodology suggested by Dymkov [4] or Sawhney [1] is inadequate in the sense that it fails to give a cost-optimal solution and may even fail to give a feasible solution provided the design variables are freely chosen. Also there is no feedback from the values of performance variables in the process. There is as such no check against their unsatisfactory values. Though authors like Sharpley et al, Ramamoorty etc. have dealt with computer-aided design and its optimization, they have given no outline for design of small transformers using standard stampings. Therefore, the need for developing a computer program for this specific case was strongly felt. The program developed has been tested for transformers ranging in ratings from a few VA to KVA and has been found to be satisfactory.

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