

An Algorithm For Designing an Inductor-Transformer of a Flyback Converter With Optimal Copper/Core loss Ratio

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ABSTRACT

Flyback converters are becoming more and more popular due to their simplicity and the few number of components that they require. One of the main challenges that face the design of flyback converters is the design of the transformer which is vital to the operation of the converter. The transformer stores energy when the electronic switch is ON and transfers this energy through the secondary side when the switch is OFF. Hence it's more a case of two coupled inductors rather than the conventional transformer action.

This research presents an algorithm to design the inductor-transformer of a flyback converter. The essential equations for inductor-transformer are presented, calculations of primary and secondary winding specifications is also carried out. The algorithm adopts a method of optimizing the design by considering an optimal copper/core loss ratio. Several common cores configuration are considered and results for each type is presented. Numerical values such as optimum CU and core losses, efficiency, air gap length, number of turns on both sides for each type of core is illustrated . Change of switching frequency and its effect on optimal efficiency and air gap length is carried out using two configurations only. Results show that some of the proposed cores have high optimal efficiency, reasonable weight and satisfactory performance. The proposed algorithm can be utilized for continuous and discontinuous modes of operation for a flyback converter.

نسبه مثالية لخسارة النحاس\الحديد

خوارزمية لتصميم ملف المحول

لقد بحثنا في أكثر فأكثر بسبب بسطتها وقلّة عدد المكونات التي تظلمها.
إحدى التحديات الرئيسية التي تواجه تصميم محول الارتداد العكسي هو تصميم المحولة التي تعتبر الجزء الحيوي
في عمل هذا المحول. حيث
عندما يكون المفتاح الإلكتروني في حالة التوصيل ويحول

هذه الطاقة إلى الجانب الثاني عندها يكون المفتح في حالة لا ظفء. لذلك يعمل هذا المحول كملفين متواشجين وليس كمحول التقليدي.

يقدم هذا البحث خوارزمية لتصميم محول الارتداد العكسي حيث تم تقديم المعادلات الضرورية لهذا الملف. كذلك تقوم الخوارزمية بحسابات المواصفات للملفين الابتدائي و الثانوي. الخوارزمية تتبنى طريقة لتحسين التصميم بحساب نسبة مثالية لخسارة النحاس إلى خسارة الحديد. بينها. تمت دراسة تأثير تغير تردد التقطيع على الكفاءة المثالية وطول الفجوة الهوائية لنموذجين فقط. تبين النتائج بان بعض الأشكال المقترحة لقلب الملف لها كفاءة مثالية عالية ووزن معقول وأداء عالي. الخوارزمية المقترحة يمكن أن تستخدم لعمل محول الارتداد العكسي .

1.INTRODUCTION

Characterized by their low cost and simplicity flyback converters are becoming more popular in medium power applications. Two main factors control the design and operation of these converters the first, is the control circuit that produces the pulses (modulation techniques) for the static electric switch and the second is transformer design.

The inductor-transformer for these converters play a major role during the ON period of the switch and during the OFF period. Energy handling capacity is a decisive factor in the performance behavior of these converters, therefore the design of the inductor- transformer is an active part of the overall design of the converter. Reference (Basak A. et al 1994) presented a core losses approach to design transformer, finite elements model was suggested to compute flux density and eventually losses distribution in a transformer. (Riath.T.Al-Jubory 2007) suggest an algorithm for designing a three phase core type distribution transformers. The algorithm adopts many criterion such as optimum core/copper loss ratio to find the optimum design. While (Rubaii A.1994) presented an algorithm for single phase conventional transformer design for classroom use, the research presented particulars of core and coils for transformer.

In this research an algorithm is suggested to design an inductor-transformer for a flyback converter. The algorithm uses various core configurations to find the optimum one for this transformer. The optimum core is selected based on the optimum core/copper loss ratio. Coil particulars for both sides of the transformer are determined.

2-BASIC DESIGN OF TRANSFORMER

The principle behind flyback converters is based on energy storage. The inductor stores energy during the on period and discharges this energy to the load during the off period, fig.1 shows the circuit for this converter. Two distinct modes of operation are possible in this case, discontinuous and continuous modes. In the discontinuous mode all energy stored in the inductor is transferred to an output capacitor and eventually the load. This will result in a smaller inductor size but stresses out both the capacitor and the electronic switching device. In the continuous mode not all the energy is transferred to the capacitor and load before another charging period starts. Fig. 1,(a) and (b) shows the B-H loop for each mode of operation (Colonel Wm.T Mclyman 2004),.

The design of an inductor-transformer for an isolated buck-boost converter is generally divided into categories, design of core and determination of particulars for primary and secondary windings. In the DCM, the loop is larger and hence high core losses compared to CCM.

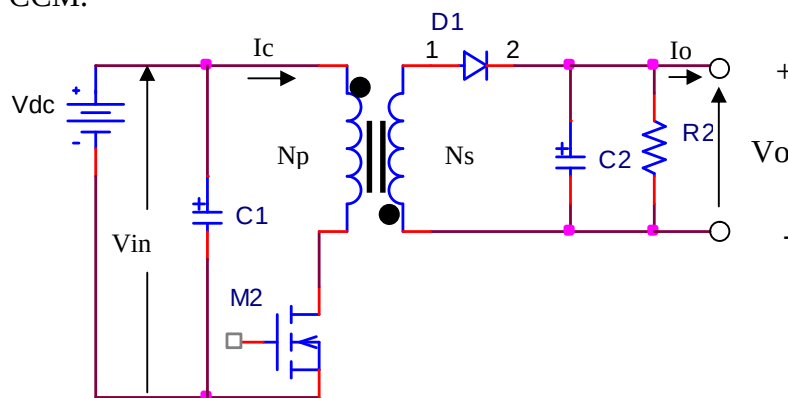


Fig. 1, flyback Converter(isolated buck-boost converter)

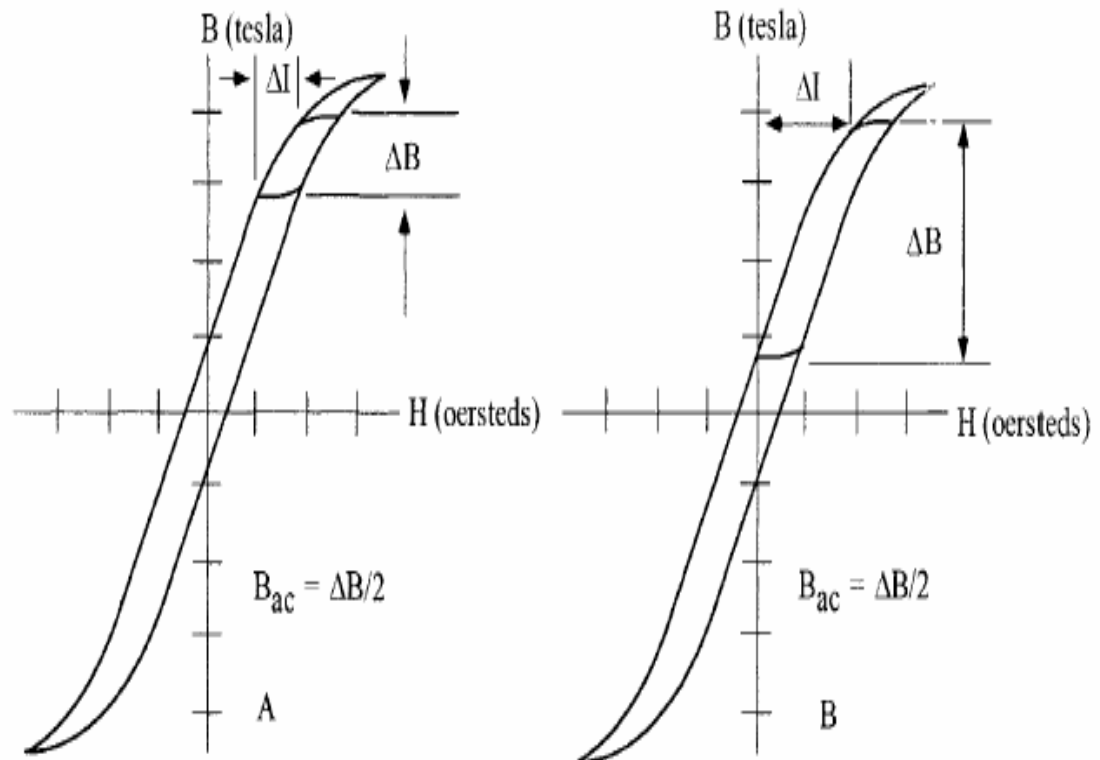


Fig. 2, BH loop for Both (A) Continuous Mode and (B) Discontinues mode (Alex Vanden Bossche et al 2005).

2-1 Core Design of Inductor-transformer of a Flyback Converter

Two main types of core may be used, powder magnetic cores which require distributed air gaps and ferrite or laminated cores in which the air gap is discrete. The core used in this research is ferrite core with a calculated air gap length. Of course these ferrite material has a low reluctance path to transfer energy from air gap to winding.

Beside the core material, shape is one of the important consideration the designer should take into account. One of the key factors in core shape is the window configuration typically a wider window will make the winding breath maximum and minimize the number of layers. The ac resistance and eventually the corresponding copper losses will also be reduced. Leakage inductance can also be minimized by a wider window configuration hence easing the stress on the switch. The following core types EC, ETD and LP cores are all E-E (these letters refer to the shape of these cores)

core shapes with large, wide windows and can be a suitable choice for a flyback converter.

To start designing of the core, we can first calculate the secondary load power (Colonel Wm.T Mclyman 2004):-

$$P_{o(Max)} = I_o V_o \quad (1)$$

Hence for a flyback converter with efficiency (η) the input maximum current:-

$$I_{in(Max)} = \frac{P_{o(Max)}}{V_{in(min)} \eta} \quad (2)$$

$$\text{Hence } V_{in(min)} = V_{in} - (\Delta v \times V_{in}) \quad (3)$$

The primary peak current for the converter:-

$$I_{P(PK)} = \frac{2P_{o(Max)} T}{\eta V_{in(min)} \text{ton}} \quad (4)$$

Also the primary r.m.s. current:-

$$I_{P(r.m.s.)} = I_{P(PK)} \sqrt{\frac{\text{ton}}{3T}} \quad (5)$$

The maximum input power is given by:-

$$P_{in(Max)} = \frac{P_{o(Max)}}{\eta} \quad (6)$$

And the equivalent input resistance as seen from the primary side is:-

$$R_{in(equ)} = \frac{(V_{in(Min)})^2}{P_{in(Max)}} \quad (7)$$

Accordingly the inductance for primary side is given by:-

$$L = \frac{R_{in(equ)} T D_{Max}^2}{2} \quad (8)$$

Next we can calculate the energy-handling capability:-

$$E_n = \frac{L I_{P(PK)}^2}{2} \quad (9)$$

The electrical condition loading is given by:-

$$K_e = 0.145 P_o B_m^2 \times 10^{-4} \quad (10)$$

Hence we can find the core geometry produce (Area product times length),

$$K_g = \frac{E_n^2}{K_e \alpha} \text{ cm}^5 \quad (11)$$

Based on the value of K_g we can select the core for this inductor-transformer. For each core the specifications are known such as permeability, magnetic path length, mean length turn, window area ,----etc.

The current density required,

$$J = \frac{2E_n \times 10^4}{B_m A_p K_u} \text{ (A/cm}^2\text{)} \quad (12)$$

Now, to calculate the number of turns on the primary side of the inductor-transformer as follows:-

$$\text{Window area of primary} = W_a/2 \quad (13)$$

$$\text{Then, } N_p = \frac{K_u W_{ap}}{S_{np} \times A} \quad (14)$$

Then the required length of air gap in the inductor is calculated as:-

$$lg = \frac{0.4 \pi N_p^2 A_c (1 \times 10^{-8})}{L} - \frac{MPL}{\mu_r} \quad (15)$$

Here in this analysis the fringing factor for flux is considered unity.

2.2 Winding Specifications for Inductor-Transformer of Flyback Converter

Since both primary and secondary currents are known and so as the current density then area of primary winding is (Colonel Wm.T Mclyman 2004),

$$A_{pw} = \frac{I_{p(r.m.s.)}}{J} \text{ cm}^2 \quad (16)$$

The required number of strands for the primary side is given by:-

$$S_{np} = \frac{A_{pw}}{A} \quad (17)$$

The most popular gauges that can be used are shown in table 1 (Colonel Wm.T Mclyman 2004)

Then the resistivity is given by:-

$$\rho_p = \frac{\rho_{\Omega/\text{cm}}}{S_{np}} \quad (18)$$

Finally the primary winding resistance can be calculated as,

$$R_p = MLT (N_p) \rho_p \times 10^{-6} \quad (19)$$

Hence the primary Cu losses are ,

$$P_p = I_p^2 R_p \quad (20)$$

To calculate the turn ratio for the inductor-transformer,

$$n = \frac{V_{in}}{V_o} \times \frac{D_{max}}{1 - D_{max}} \text{ turns} \quad (21)$$

At the same time, the turn ratio can utilized to calculate secondary number of turns,

$$n = \frac{N_p}{N_s} \quad (22)$$

$$\therefore N_s = \frac{N_p}{n} \quad (23)$$

Moving to secondary quantities:-

The secondary peak current is given by:-

$$I_{s(pk)} = \frac{2I_o}{(1 - D_{Max} - D_w)} \quad (24)$$

And the r.m.s. current of the secondary side is:-

$$I_{s(r.m.s.)} = I_{s(pk)} \sqrt{\frac{(1 - D_{Max} - D_w)}{3}} \quad (25)$$

Also the cross sectional area of secondary winding wire,

$$A_{sw} = \frac{I_{s(r.m.s.)}}{J} \quad (26)$$

And the number of strands for secondary winding is given by:-

$$S_{ns} = \frac{A_{sw}}{A} \quad (27)$$

The resistivity for the wire of secondary side is:-

$$\rho_s = \frac{\rho_{\Omega/cm}}{S_{ns}} \quad (28)$$

The secondary resistance is:-

$$R_s = MLT (N_s) (\rho_s) \quad (29)$$

The corresponding Cu losses are:-

$$P_s = I_{s(r.m.s.)}^2 R_s \quad (30)$$

Then the total Cu losses for the inductor-transformer is given by:-

$$P_{cu}=P_p+P_s \quad (31)$$

The final stage is the calculation of the iron losses for the used core, the ac flux density is given by:-

$$B_{ac} = \frac{0.4 \pi N_p \left(\frac{I_{p(PK)}}{2} \right) (1 \times 10^{-4})}{lg + \left(\frac{MPL}{\mu_r} \right)} \quad (32)$$

Hence the watts per Kg for the core material is:-

$$W_k = 4.855 (1 \times 10^{-5}) (f_s)^{1.63} (B_{ac})^{2.62} \text{ w/Kg} \quad (33)$$

Hence the total losses of the core is given by:-

$$P_c = W_k \times W_{tfe} \quad (34)$$

Hence total losses for the converter is given by:-

$$P_{tot}=P_c+P_{cu} \quad (35)$$

The efficiency for the designed inductor-transformer is given by:-

$$\eta = \frac{P_o}{P_o + P_{tot}} \times 100\% \quad (36)$$

Table 1, wire selection (Colonel Wm.T Mclyman 2004)

Wire AWG	Bare area	Area I_{ns}	$\rho\Omega/\text{cm}$
#26	0.00128	0.00163	1345
#27	0.001021	0.001313	1687
#28	0.0008046	0.0010515	2142

3- DESIGNING WITH OPTIMUM CORE TO COPPER LOSS RATIO

Nearly all magnetic components design require a compromise between maximum flux density and core losses on one side and copper losses on the other side. This compromise can lead to an efficiency which may attain maximum value. This maximum efficiency could occur any where from half to full load conditions. Hence it's logical that the designed inductor-transformer for the flyback converter should be checked to observe wheather it's close or far away from optimal values with respect to losses and efficiency. One thing which should be mentioned here is that the optimization process is discrete, in the sense that it depends on several other factors

such as core shapes, material, number of turnsetc. Here the core losses and copper losses are calculated first then it is possible to find the optimum values for these losses and hence optimum ratio then, in general case, the core losses mainly depend on the frequency and on the peak induction level (Alex Vanden Bossche et al 2005):-

$$P_c = K f_s^a B^\beta \quad (37)$$

The total Cu losses for flyback converter

$$P_{cu} = P_p + P_s \quad (38)$$

For the flyback inductor-transformer the optimum core losses $P_{c,opt}$ and copper losses $P_{cu,opt}$. When increasing the number of turns by a factor of ϵ , the induction flux B in the core is decreased by a factor of ϵ because the flux linkage is kept constant, that is the induction is proportional to ϵ^{-1} . Thus, considering equation (37), the core losses are inversely proportional to ϵ^β (Alex Vanden Bossche et al 2005):-

$$\therefore P_c = P_{c,opt} \epsilon^{-\beta} \quad (39)$$

The copper losses can be represented as a function of their optimal value and ϵ as:-

$$P_{cu} = P_{cu,opt} \epsilon^\gamma \quad (40)$$

Combing eq.(40) and (39) we can write,

$$P_{tot} = (P_c / \epsilon^\beta) + P_{cu,opt} \epsilon^\gamma \quad (41)$$

For optimal design, the total losses P_{tot} should be minimum for ϵ^{-1}

$$\frac{d P_{tot}}{d \epsilon} = 0 \quad (42)$$

$$\frac{d}{d \epsilon} (P_{fe} + P_{cu}) = 0 \quad (43)$$

$$\therefore \frac{P_{c,opt}}{P_{cu,opt}} = \frac{\gamma}{\beta} \epsilon^{\gamma+\beta} \quad (44)$$

Compared to the total losses, the optimal core and copper losses in the general case is (Alex Vanden Bossche et al 2005):-

$$P_{c,opt} = \frac{\gamma}{\gamma + \beta} P_{tot} \quad (45)$$

$$P_{cu,opt} = \frac{\beta}{\gamma + \beta} P_{tot} \quad (46)$$

Hence dividing eq. (45) by eq. (46) gives,

$$\frac{P_{c,opt}}{P_{cu,opt}} = \frac{\gamma}{\beta} \quad (47)$$

For constant copper value $\gamma=2$ (Alex Vanden Bossche et al 2005).

Hence we can calculate $P_{c,opt}$ and $P_{cu,opt}$ using equations (45) and (46).

The efficiency corresponding to optimal core/copper loss ratio can be calculated as:-

$$\eta_{opt} = \frac{P_o}{P_o + P_{cu,opt} + P_{c,opt}} \quad (48)$$

4- THE PROPOSED ALGORITHM

The proposed algorithm presents the design of an inductor-transformer for a flyback converter. The algorithm deals with core design first then moves to winding specifications. For each design an optimum value for core and copper losses and hence the efficiency corresponding to these optimum value are determined. The algorithm employees several core configurations to the design and the most optimum one is selected. During the design phase switching frequencies of 20 kHz, 50 kHz, 100 kHz and 200 kHz are considered for two specific core configurations.

Fig. 3 shows the flow chart for the proposed algorithm.

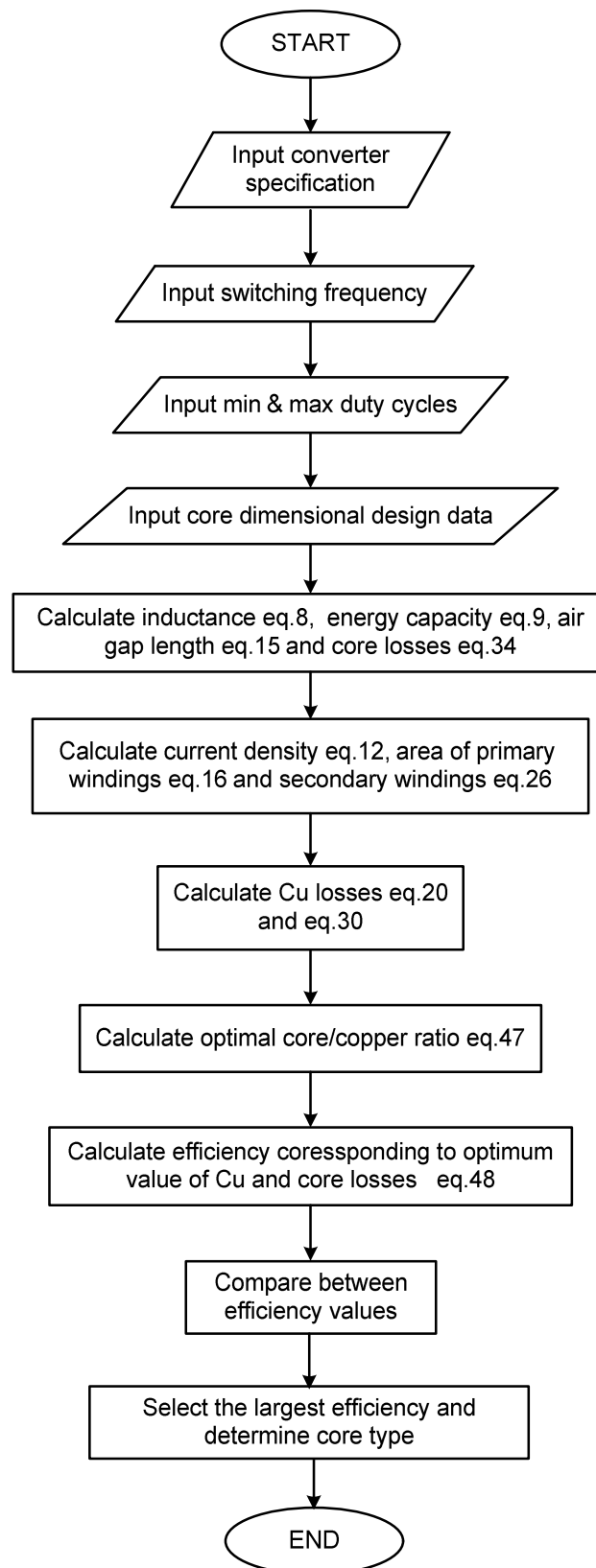
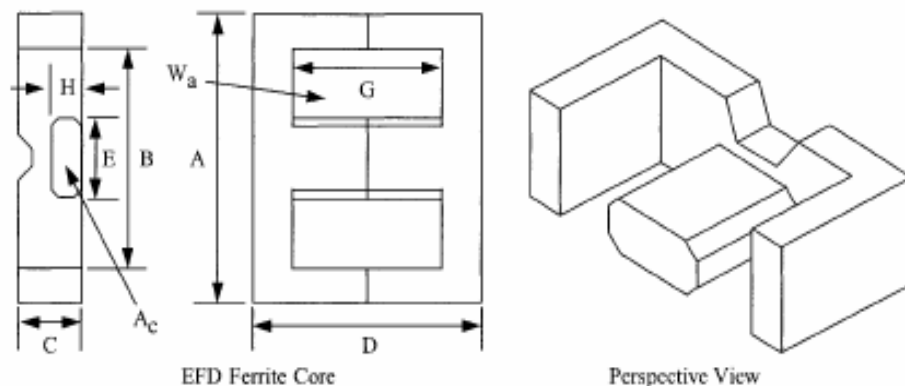


Fig. 3, Flow chart of proposed algorithm

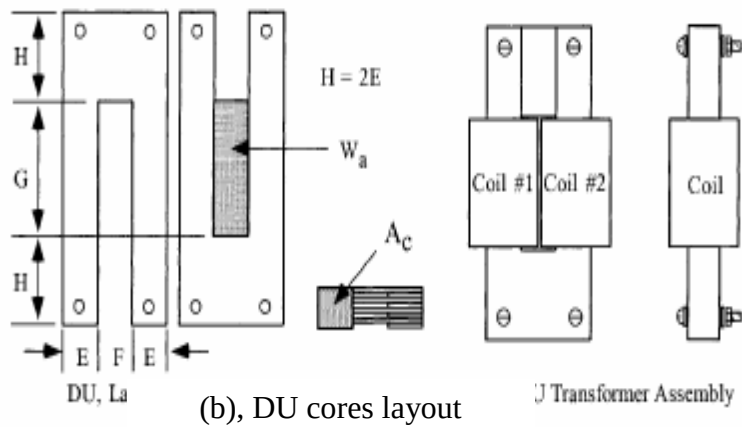
5- RESULTS

The proposed algorithm is implemented using MAT LAB 7.0. The algorithm is tested with the core configurations shown in fig 4. Each core has its own dimensional design data (Colonel Wm.T Mclyman 2004). For each core configuration, the algorithm calculates, energy handling capability, number of strands for primary and secondary sides of the inductor-transformer, number of turns, optimum values of core and copper losses and optimum efficiency. In this work the value of γ is 2, this so because the cross section of the wire is constant. The value of β is 2 so that the ratio γ/β is unity. Therefore in this case optimum (maximum) efficiency occurs when core losses equal copper losses in the converter. Table 2 shows results for a switching frequency of 100 kHz with converter specifications shown in appendix 1.

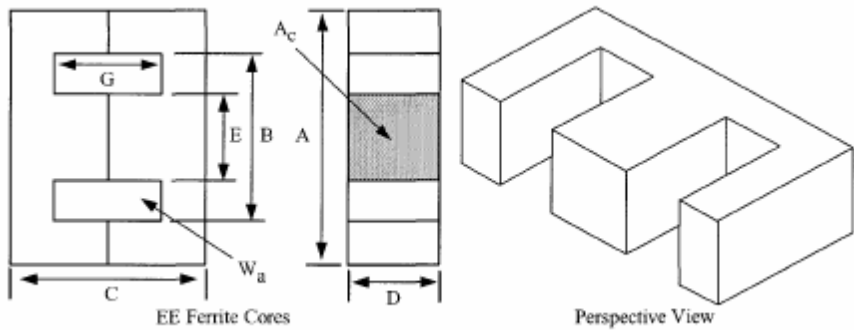
To examine the effect of switching frequency on optimal efficiency and air gap length, fig.5,(a) shows this effect with optimal efficiency while fig.5,(b) illustrates change of frequency with air gap length for core configuration EE2425. Fig 6 shows these changes for core configuration EFD20. It's concluded that increasing the frequency reduces the size of capacitance of the converter, primary and secondary inductances hence size of the converter is reduced. However losses increase and the efficiency decrease. In this work its concluded that for EE2425 the efficiency begins decreasing as switching frequency approximately cross the 50 kHz border. While for EFD20 cores the efficiency decreases at approximately 75 kHz. For EFD20 the drop in optimum efficiency is relatively small compared to EE2425 cores.



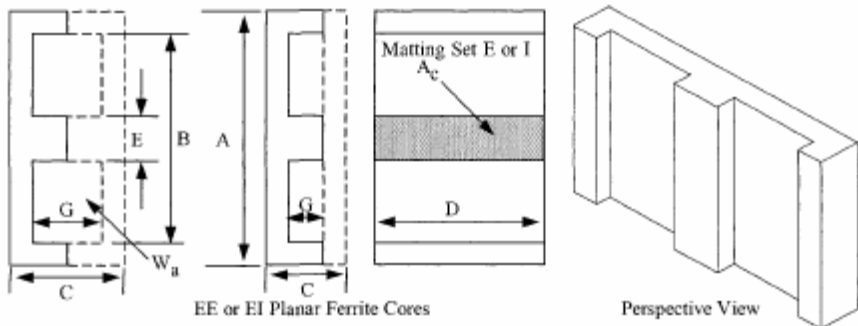
(a), EFD cores layout



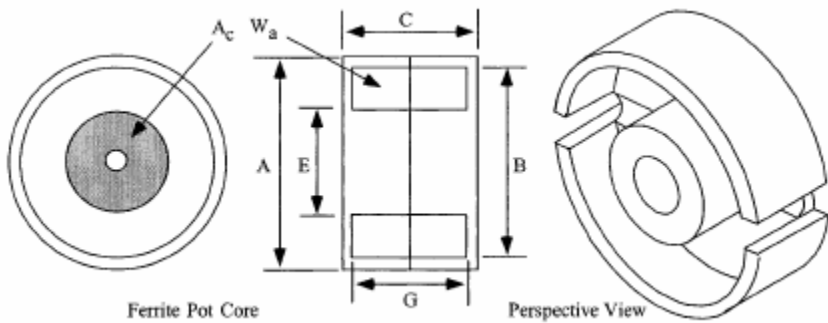
(b), DU cores layout



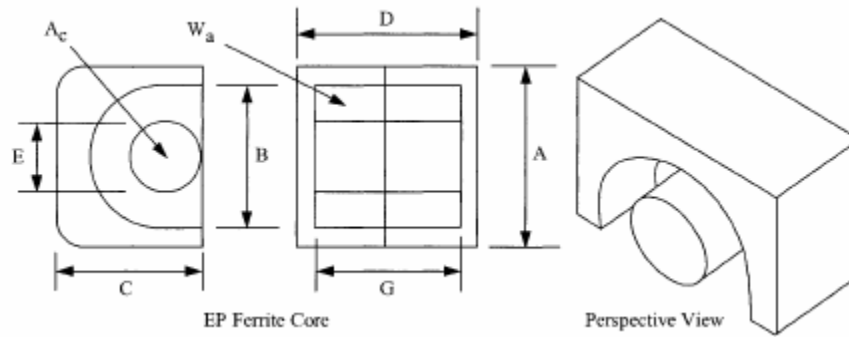
(c), EE cores layout



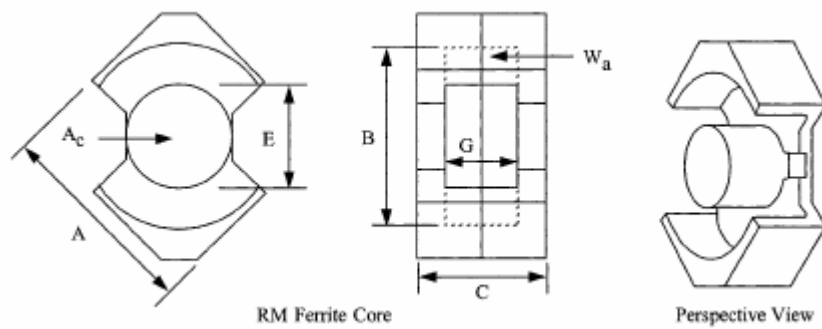
(d), EI PLANNAR cores layout



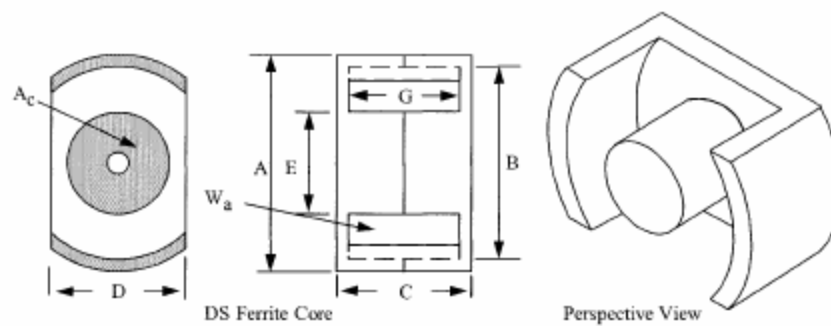
(e), PC cores layout



(f), EP cores layout



(g), RM cores layout

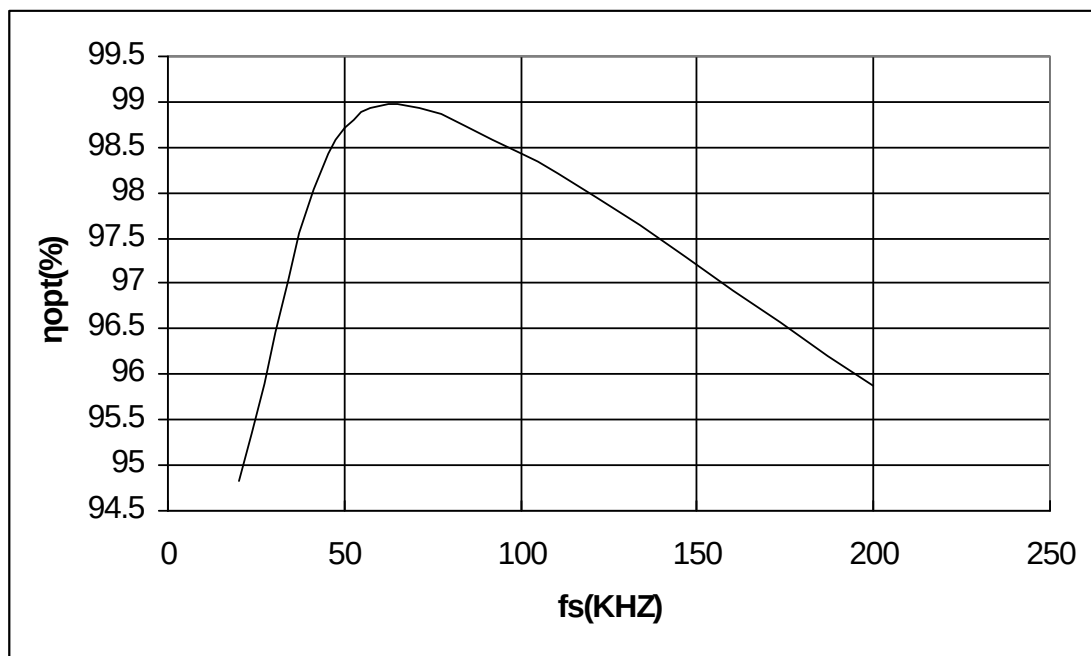


(h), DS cores layout

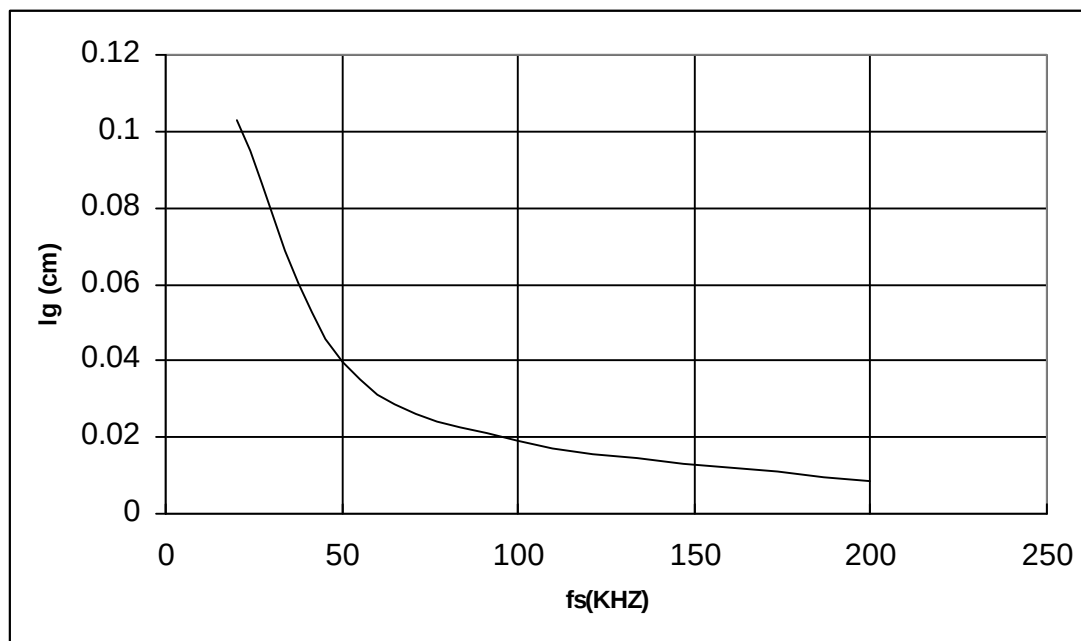
Fig. 4, Different core layouts used in proposed algorithm (Alex Vanden Bossche et al 2005)

Table2 Results from algorithm for various cores (L=35 μ h)

No.	Core Type	Energy handling capacity (W.S)	P _{cu,opt} (w)	P _{c,opt} (w)	Efficiency (%)	Air gap Length (cm)	N _p	N _s	S _{np}	S _{ns}
1	DU18	133	0.1579	0.1205	97.73	0.0344	27	5	4	17
2	EE2425	133	0.1081	0.0825	98.43	0.019	15	3	6	24
3	EI42216(Planar)	133	0.1231	0.094	98.22	0.009	7	2	3	10
4	EFD20	133	0.0961	0.0734	98.607	0.0242	19	4	3	12
5	EE43208 (Planar)	133	0.259	0.1977	96.33	0.0046	5	1	14	57
6	PC41811	133	0.0982	0.0749	98.578	0.0177	14	3	2	9
7	EP17	133	0.1414	0.108	97.96	0.0226	17	3	2	8
8	RM6	133	0.0852	0.06511	98.763	0.0208	16	3	2	7
9	RM8/ILP	133	0.1178	0.0899	98.2986	0.0133	11	2	3	11
10	DS42318	133	0.1463	0.117	97.8959	0.018	14	3	4	18

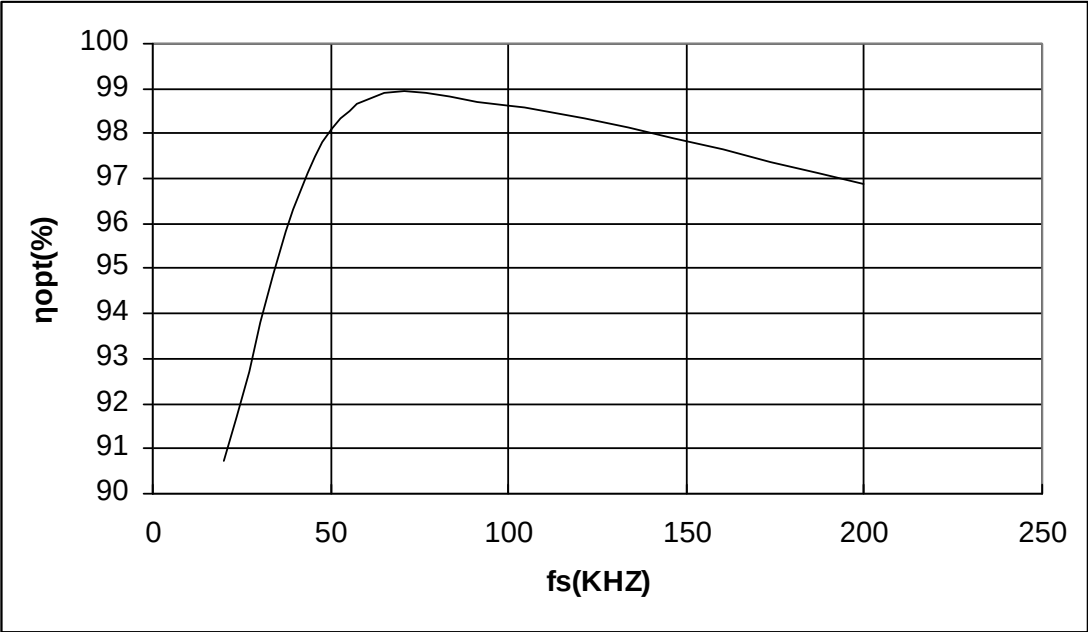


(a)

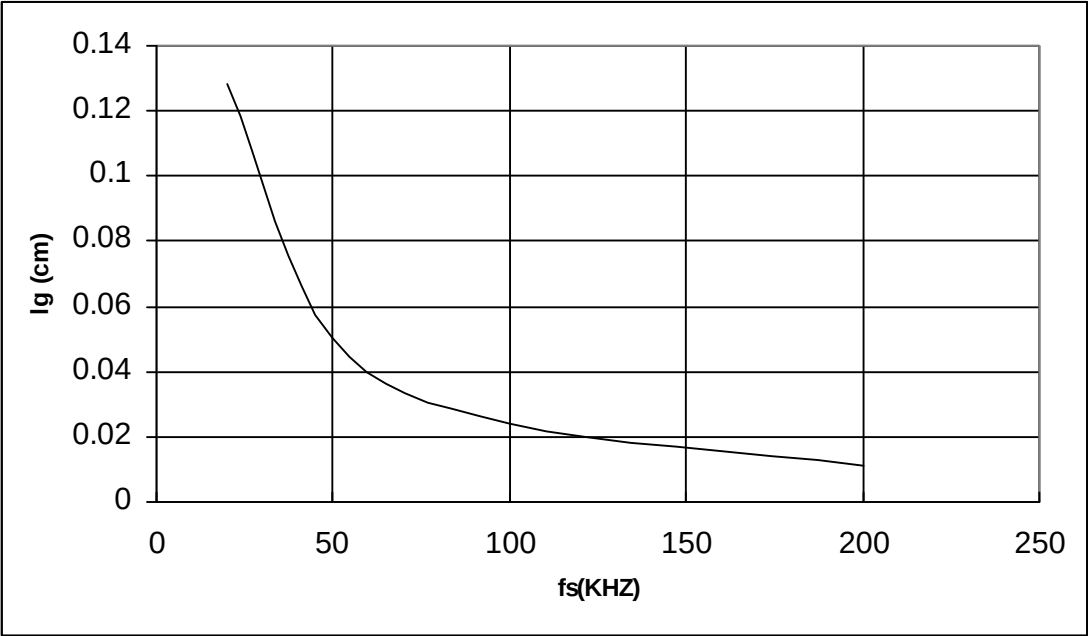


(b)

Fig.5, Effect of change of frequency for EE2425 cores



(a)



(b)

Fig.6, Effect of frequency change for EFD20 cores

6- CONCLUSION

From the results shown, the following conclusion can be made:-

1. An algorithm is presented to design inductor-transformer of a flyback converter.
2. Several core configurations are tested and some of these cores show high efficiency and satisfactory performance.
3. For two types of core configuration EE2425 and EFD20 change of switching frequency from 20kHz, 50kHz, 100kHz and 200kHz, the performance parameters and optimal efficiency is high making these types of cores common for such frequencies.
4. The proposed algorithm is suitable for industrial applications where design of flyback converter is required.

Appendix 1

Specification of flyback converter (Colonel Wm.T Mclyman 2004):

Input voltage =28v

Percentage change in input voltage =14 %

Output voltage =5v

Full load output current =2A

Maximum input voltage =32v

Minimum input voltage =24v

Maximum ripple current =20% of maximum output current

Window utilization factor = 0.29

Desired duty cycle =0.5 at 32v

Switching frequency = 100kHz

Regulation of converter =1.0%

Minimum duty cycle (dwell duty cycle) =0.1

References:

Alex Vanden Bossche and Vencislav Cekov Valchev, (2005), Inductor and Transformer for power electronics, Taylor & Francis group, CRC press.

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List of Symbols

A: bare area for AWG number.

a: is the switching frequency exponent.

Ac: iron cross-sectional area (cm²).

A_{pw}: cross sectional area of primary winding.

A_{sw}: cross sectional area of secondary winding.

At: surface area of core (cm²).

B: induction peak value of the AC waveform.

B_{ac} : ac flux density.

B_m : maximum flux density.

D_{Max} : maximum duty cycle of converter.

D_w : dwell duty cycle.

E_n : energy handling capability (w.s)

f_s : is the switching frequency.

$I_{in(Max)}$: input maximum current.

I_o : full load output current from flyback converter.

$I_{p(pk)}$: peak primary current.

$I_{s(pk)}$: peak secondary current.

$I_{s(r.m.s.)}$: r.m.s. secondary current.

K: is the core loss coefficient, $K=F(f_s, B, T)$

K_e : electrical condition.

K_g : core geometry (cm^5).

K_u : utilization factor.

n: turn ratio.

N_p : number of turns on primary side.

P_c : core losses.

P_{cu} : total Cu losses of the inductor transformer.

$P_{o(Max)}$: maximum output power.

P_p : primary Cu losses.

P_s : secondary Cu losses.

P_{tot} : total losses of designed converter.

S_{np} : number of strands for primary side.

S_{ns} : number of strands for secondary side.

T: Period (on time of switch +off time of switch)

t_{on} : the "ON period" time of the electric switch.

$V_{in(Min)}$: minimum input voltage.

V_{in} : input voltage.

V_o : output voltage.

W_a : window area (cm^2).

W_k : watts per Kg losses of core material.

W_{tcu} : copper weight (grams).

W_{tfe} : core weight (grams).

α : converter regulation.

β : core losses exponent.

γ : is the coefficient, the value of which is in the range of 1-3.

Δv : Percentage change in input voltage (deviation).

η : converter efficiency.

μ_r : core relative permeability.

ρ_p : resistivity of wire for primary winding.

ρ_s : resistivity of wire for secondary side.

$\rho_{\Omega/\text{cm}}$: resistivity of wire corresponding to AWG number.

Abbreviations:-

A_p : area product.

AWG: American wire gauge.

CCM:- continuous conduction mode.

DCM:- discontinuous conduction mode.

MLT: mean length turn.

MPL: magnetic path length.