A Computer-Aided Graphic Design Tool for Minimum Weight Inductors in Switching Converters

by

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(ABSTRACT)

A computer-aided design procedure has been developed to determine the minimum weight design solutions, for singly wound EE- and EI-cored inductors that perform the functions of energy storage and transfer in switching DC-DC power converters. Three converter topologies, namely the Buck, the Boost, and the Buck/Boost have been considered in implementing the closed form Lagrange Multiplier-based solution to the design problem.

A notable feature is the interactive use of design graphs to facilitate a trade-off study between the weight of the inductor, the total losses in the inductor and the peak current stress in the switching transistor and diode. Thus useful insight is obtained by bringing aspects of converter design into view. Practical core and magnetic material data from manufacturer's catalogs can be specified and the design optimized for the minimal weight.

Acknowledgements

I wish to dedicate this work to my parents, , whose love and encouragement is a deep and strong force in my life; and to my brother , my sister and her family, who have done so much, so lightly.

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1.0 Introduction

1.1 Thesis Objectives

A comprehensive, graphic, computer-aided design procedure has been developed for minimum weight singly wound inductors that can perform the functions of energy storage and transfer in DC-DC switching power converters. Three basic converter configurations: the buck, boost and buck/boost converter circuits, have been considered. The Lagrangian multiplier solution obtained in closed-form [1] has been implemented to achieve an optimum design with minimum weight as the objective.

Design optimization of power electronic components and converters has been the focus of much research attention. The establishing of design graphs to aid in the design of inductors for switching converters was developed by Chin, Chen, and Lee [2]. Such a procedure helps make trade-offs between such factors as core weight, peak switch current and the total inductor losses. However, the use of these graphs is not very appealing since some of the graphs are frequency specific and further, many new parameters and normalizing factors are introduced, demanding the user to labor with them in order to obtain useful results. The technique presented here overcomes these drawbacks by using an interactive computer-aided graphic design procedure which is easy to use and provides useful design insight. The program provides the detailed magnetics design of the inductor as given by the Lagrange multiplier solution in [1] and further, practical core information can be incorporated making the design procedure very realistic.

A key feature of the design tool presented here is the insight provided in terms of the inductor weight, the total power loss in the inductor, and the maximum current stress in the switch. The user has freedom to prioritize these parameters, make trade-offs and then obtain a practical design that best matches the objectives.

In developing this interactive, computer-aided, design procedure, emphasis has been placed on a user-friendly, user-guided approach. The engineer is able to scroll through design curves, perform trade-offs, and quickly arrive at an optimal design solution. This forms the basis for making practical choices from the commercial catalogs, see the deviations from the optimum design, if any, and subsequently minimize such deviations iteratively. Thus, the software makes readily available a powerful design procedure to any power electronics design engineer. Presented here is the software package developed together with a number of design examples that demonstrate the procedure and its capabilities.

In Chapter One, following an introductory discussion, the design problem and the scope of the current effort is presented.

Chapter Two further examines the design problem, the approach to the solution and presents the context in which the Lagrange Multiplier Technique can be applied, its mathematical formulation and the analytical solutions of [1].

Chapter Three outlines the structure of the program developed to perform the design task. It details the program components and their various functions.

In Chapter Four the results from the program and the information derived from the design graphs are presented. Design solutions for the inductor, for each of the Buck, Boost and Buck/Boost converter topologies are discussed.

Chapter Five is a discussion of the conclusions made and suggestions for future research.

Appendix A is intended to serve as a User's Guide to the software package.

1.2 The Design Problem

In a switching DC-DC converter, the energy storage inductor is the heaviest component. Reducing its size and weight is a definite means to streamline the size and bulk of the entire converter itself. Knowing the converter specifications like operating voltages, power levels and switching frequency as well as device current ratings, the quest is to design the energy storage inductor such that:

- the inductor has the lowest weight possible,
- does not suffer excessive core and winding losses, and lastly,
- current stress ratings on the transistor and diode are lowered to the extent possible.

Having defined the problem and advanced towards arriving at the solution methodology [3,2] the next task would be to ensure that the algorithm can be made practical, easy to use and provide useful design insight. Such a task would necessarily form the complement to the strategy developed.

The interactive graphical design procedure presented here has been developed on the IBM-PC AT; it constitutes a capable design tool contributing to the effort in power electronic component design optimization. The procedure allows:

1. Rapid trade-off study between inductor weight, total inductor losses and switch current stress.

2. Comparison study between a practically realizable design and the theoretical optimal design solution.

3. Design freedom to perform trade-offs and iteratively optimize the practical design.

2.0 Switching Converter Inductor Design Optimization

2.1 Design Considerations

Switching DC-DC power converters essentially transfer power from a DC source to a load in a switching mode that enables the control of power transfer. Accomplishing this requires the use of semiconductor switches (typically a bipolar transistor or a MOSFET device is used), freewheeling diodes and network elements such as resistors, inductors, and capacitors.

The configuration of the network elements, the diode, and the switch results in different converter topologies each of which have unique characteristics. However, there are two topologies that can be considered functionally basic, namely, the Buck and the Boost converters that realize voltage step-down and voltage step-up functions respectively. The Buck/Boost topology combines these two features using an inductor as the energy storage and transfer mechanism while the Cuk converter represents another such combination using

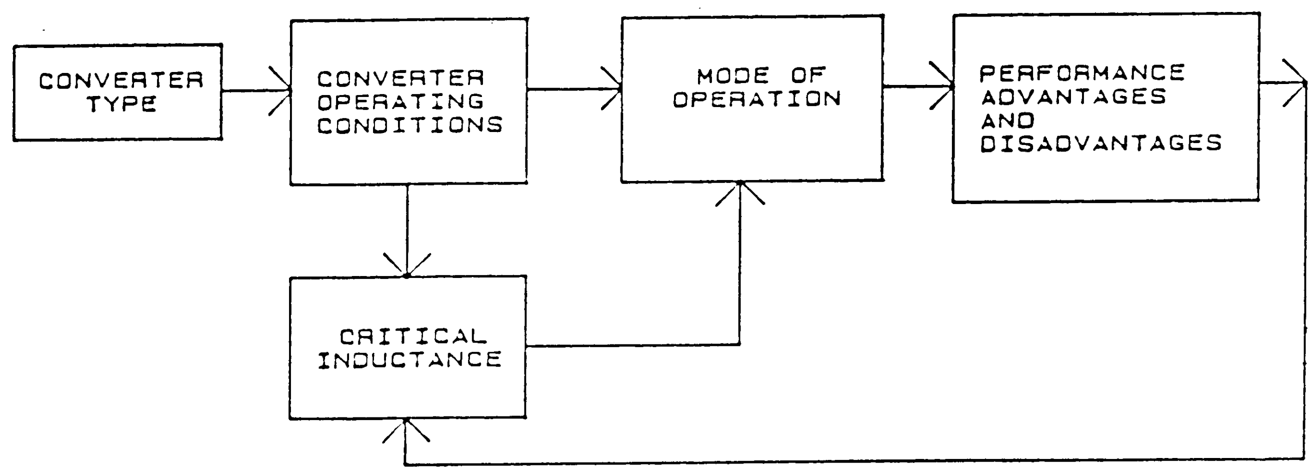


Figure 1. The Inductor in a Switching DC-DC Converter

a capacitor for energy storage and transfer. In general, DC-DC converters use an inductor to perform the functions of energy storage, transfer, and current waveform smoothing.

Conventional design of the energy-storage inductor requires several iterations of trial-and-error as well as the good intuition of a designer before a satisfactory design is obtained. It further lacks the ability to provide design insight in a quick and efficient manner, thereby making design optimization a difficult task.

In this thesis, based on the results of references [1, 2, 3, and 4], a comprehensive design procedure has been developed in a computer-based environment. Figure (1) indicates the key role played by the inductor in the converter performance as a whole.

The converter type and the operating conditions, determine the value of the critical inductance necessary to maintain continuous current flow in the inductor. This condition represents the Continuous Conduction Mode (CCM) of the converter. When the inductance is much greater than the critical value, the converter is said to operate in deep CCM. If the inductance is smaller than the critical value, current flow falls to zero for a finite period of time, resulting in a condition known as the Discontinuous Conduction Mode (DCM) of the converter.

Each operating mode of the converter profoundly affects the performance of the converter and must be kept in view by the designer [8]. The inductance chosen affects how far into any mode, CCM or DCM, that the converter is placed for a given set of operating conditions.

Figure (2) shows in block diagram form, the design approach presented in this thesis. The inductance is chosen based on the desired conduction mode and the value of the critical inductance. Having chosen the inductance the core is picked and the number of turns of wire designed. This requires conforming to the constraints of saturation flux density and the available window area as detailed in Section 2.3.1. Thus the resulting inductor weight and losses can be determined. The current stress in the switch and diode depends upon the

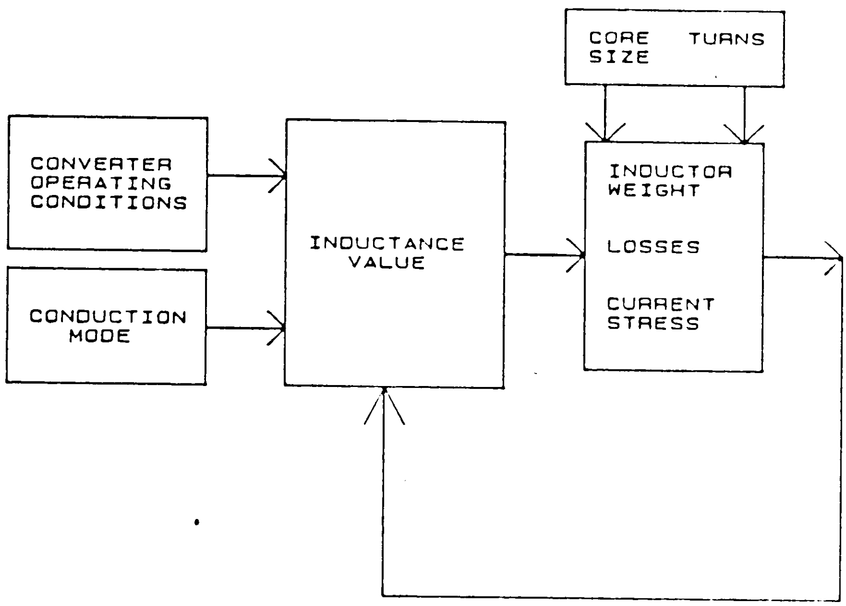


Figure 2. Inductor Design Approach

inductance and the converter operating conditions, and is evaluated. A trade-off study is made between these parameters and the design cycle iterated with other available cores, in order to determine the best practical design.

Incorporated into this design cycle is the minimum weight design solution derived in reference [1], information about the corresponding inductor losses and, the resulting current stress in the switch and diode. The designer can use this information to realize a practical design that closely matches the optimum solution.

2.2 Switching Converter Relationships

The Buck, the Boost, and the Buck/Boost converter topologies are considered in the discussion that follows. In figure (3) are the circuit diagrams, and labeled are the quantities of interest. Assumed in the derivations is that the output capacitor C is infinitely large and consequently the output ripple voltage is negligibly small. In forming the loss model, the AC component of the total rms current is assumed to be very small relative to the DC component, and the increase in winding resistance due to the Skin and Proximity effects to result in a negligibly small loss component. Given the converter operating conditions such as:

V_{IMAX} - maximum input voltage

V_{IMIN} - minimum input voltage

V_O - output voltage

V_Q - transistor forward voltage drop

V_D - diode forward voltage drop

P_{OMAX} - maximum output power

P_{OMIN} - minimum output power

Frequency

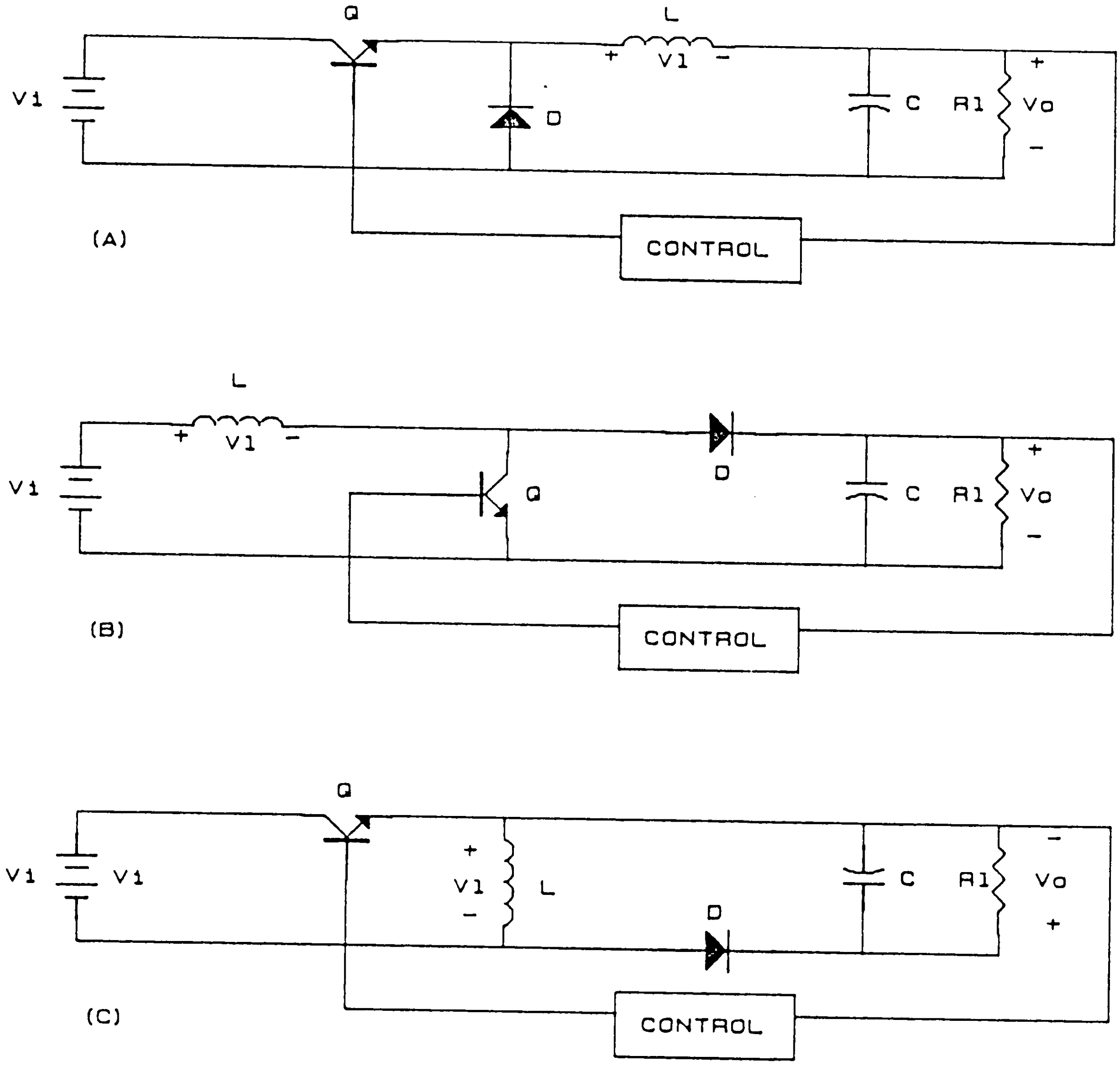
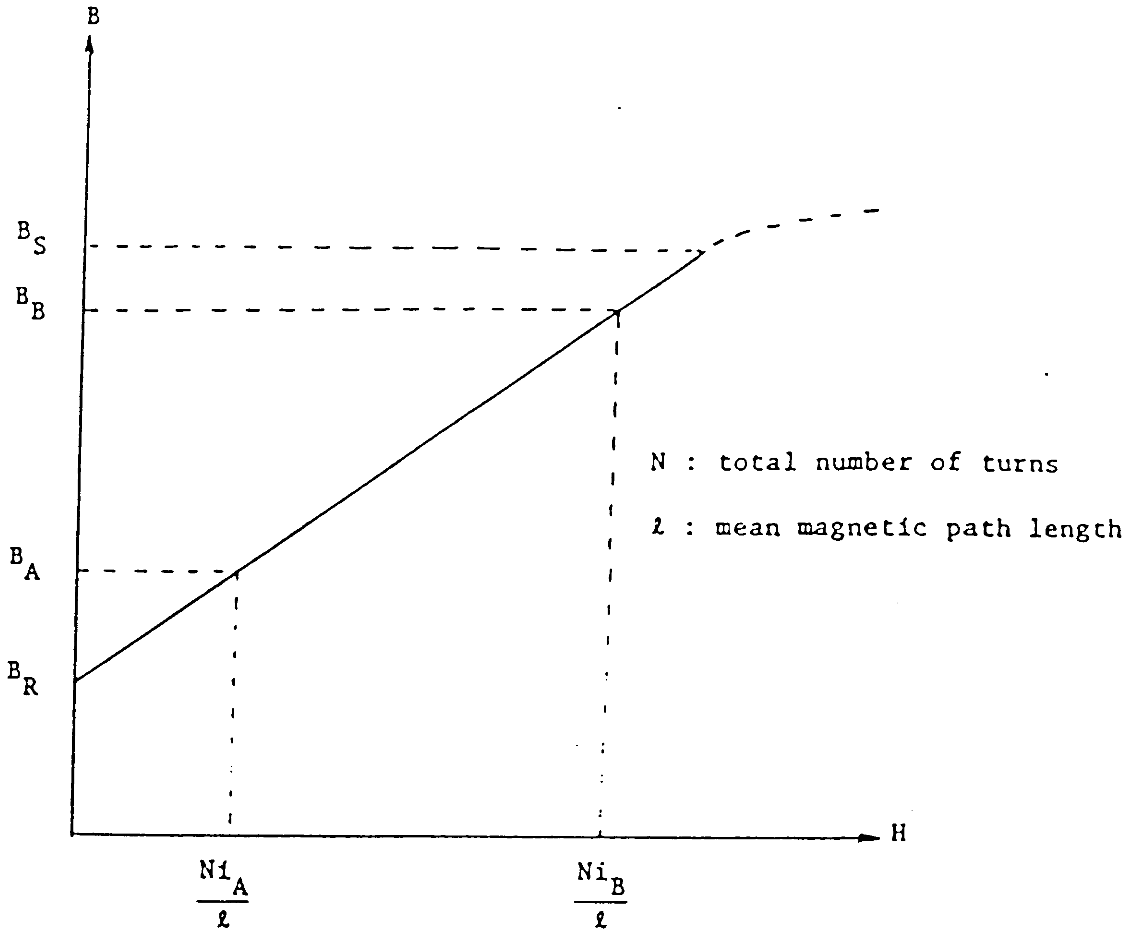


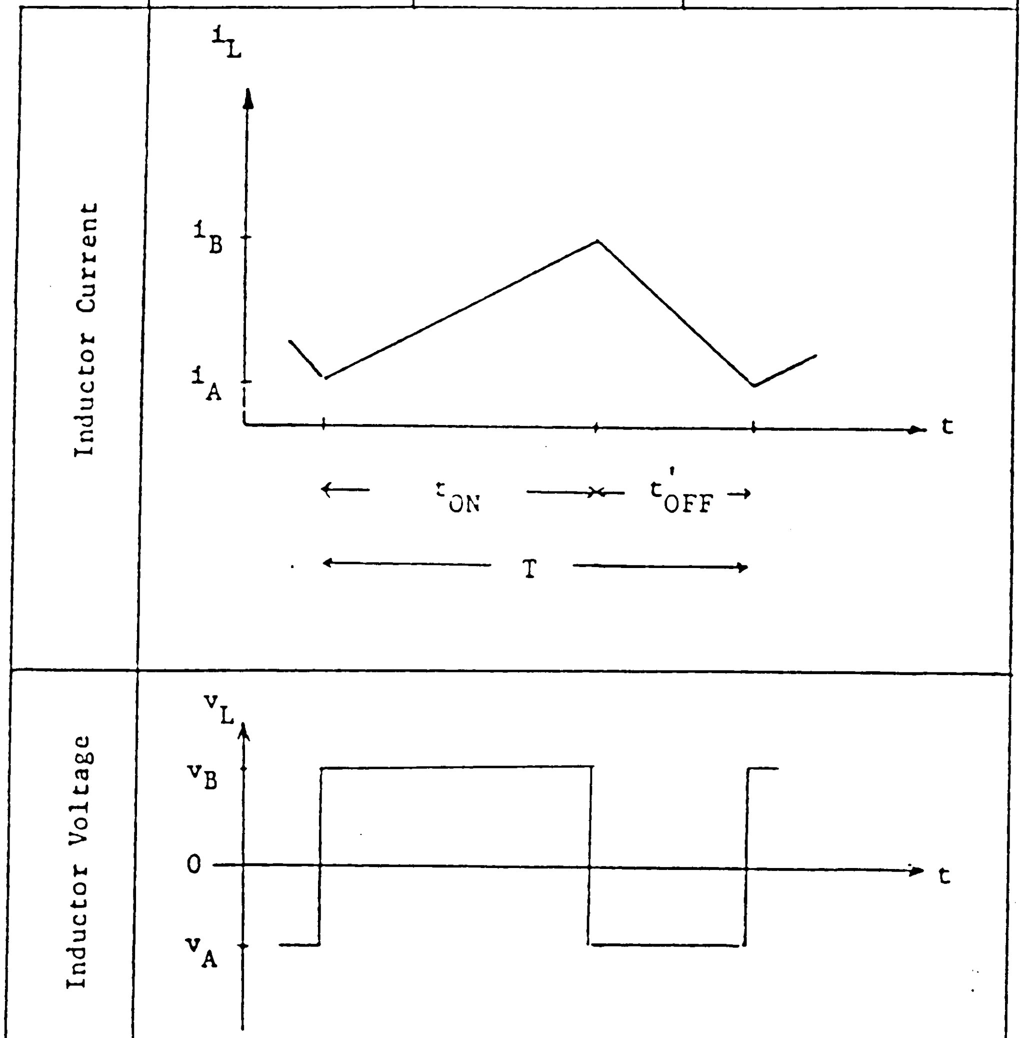
Figure 3. Converter topologies: (a) Buck (b) Boost (c) Buck/Boost



Symbol	Definition
A	Core cross-section area
B_A	Minimum value of core flux density excursion
B_B	Maximum value of core flux density excursion
$B_{A,min}$	Lowest possible value of B_A
$B_{B,max}$	Highest possible value of B_B
B_R	Residual flux density
B_S	Maximum allowable flux density in the core
N	Total number of turns

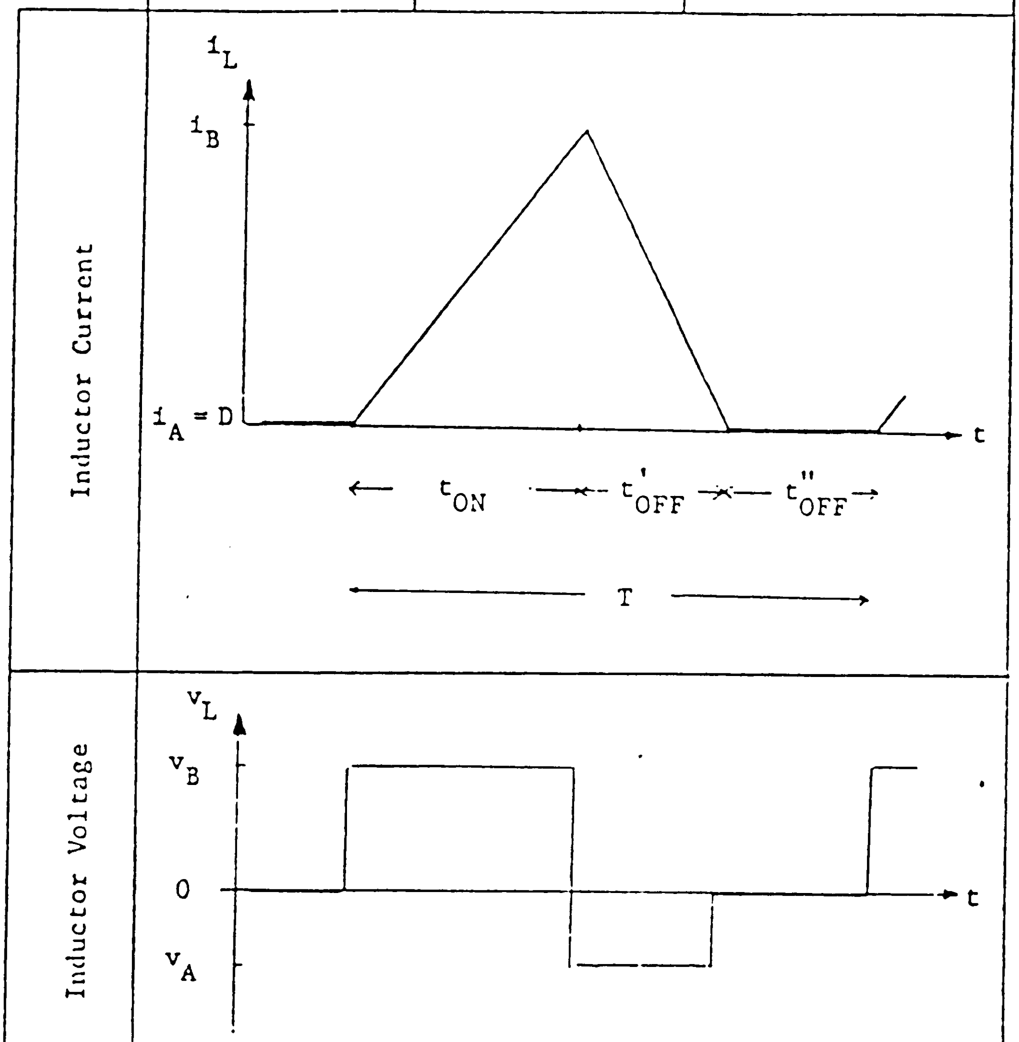
Figure 4. Magnetic Core Characteristics

	Buck	Boost	Buck-Boost



	Buck	Boost	Buck-Boost
$v_A =$	$-(V_O+V_D)$	$-(V_O+V_D-V_I)$	$-(V_O+V_D)$
$v_B =$	$V_I-V_O-V_Q$	V_I-V_Q	V_I-V_Q

Figure 5. Inductor Current and Voltage Waveforms: Continuous Conduction Mode



	Buck	Boost	Buck-Boost
v_A =	$-(V_O+V_D)$	$-(V_O+V_D-V_I)$	$-(V_O+V_D)$
v_B =	$V_I-V_O-V_Q$	V_I-V_Q	V_I-V_Q

Figure 6. Inductor Current and Voltage Waveforms: Discontinuous Conduction Mode

and knowing the maximum current stress the semiconductor devices can tolerate, we wish to design the minimum weight EE- or EI-core inductor.

Figure (4) shows typical magnetic core characteristics, and the range of flux densities over which the core is operated. In reference [3], the values of P_O and V_I required to result in converter operation such that $B_{B,max}$ and $B_{A,min}$ occur have been evaluated, and are used here.

Figures (5) and (6) show waveforms of the inductor current in the Continuous Conduction Mode (CCM) and the Discontinuous Conduction Mode (DCM) respectively. For each switching interval, the critical value of inductance required to maintain the inductor in continuous conduction can be determined [3,1]. Figures (3) through (6) are reproduced from reference [1]. For the three converters considered we have:

Buck Converter:

$$L_{crit} = \frac{TV_O(V_{IMAX} - V_O - V_Q)(V_O + V_D)}{2P_{OMAX}(V_{IMAX} + V_D - V_Q)}$$

Boost converter:

$$L_{crit} = \frac{TV_O(V_{IMIN} - V_Q)^2(V_O + V_D - V_{IMIN})}{2P_{OMAX}(V_O + V_D - V_Q)^2}$$

Buck/Boost converter:

$$L_{crit} = \frac{TV_O(V_{IMIN} - V_Q)^2(V_O + V_D)}{2P_{OMAX}(V_{IMIN} + V_O + V_D - V_Q)^2}$$

The magnetic core of the inductor must be operated without allowing saturation to occur since we wish to ensure its inductive properties are retained. If B_A and B_B are the minimum and maximum values of the core flux density excursion, these parameters as well as the flux swing, can be expressed as a function of the converter operating conditions and the magnetics parameters [3,1].

The maximum value as well as the rms value of the current in the transistor or diode can be expressed as functions of the inductance and the converter operating conditions [3,1]. These quantities are uniquely defined for each converter and the particular mode in which it may be operating.

Using the above quantities and applying the Lagrange Multiplier technique to the EE- or the EI-core problem, closed-form solutions to the core design geometry can be arrived at as derived in [1]. The core and winding losses can be modeled as shown in Section 2.3.2. The peak current stress is then determined and together with the optimal core weight and the corresponding losses, three important design parameters are now available to us.

If minimum weight is the overriding concern, then that inductance which results in the least weight is picked. This information is used to determine the complete core geometry and magnetics design parameters. Such a design is the optimal design by weight, and must be implemented to realize it. Typically, the total power loss in the inductor and the peak switch current are important parameters, keeping in view the design of the converter and the selection of semiconductor devices. The characteristic profiles are used to perform a trade-off between these parameters and subsequently choose the inductance. The corresponding core to achieve minimum weight is determined using the Lagrange Multiplier solution.

These procedures are examined in the following sections.

2.3 Lagrange Multiplier Technique

An objective function, $f(X, K)$ is to be minimized subject to the design constraints:

$$g_i(X, K, r) = 0, \quad i = 1, 2, ... j \qquad [1]$$

where $X=(x_1,....., x_n)$ are the variables to be determined,

K's are known design constants,

r's are requirements the optimal design must meet.

The Lagrangian function, F is formed as

$$F = f + \sum_{i=1}^{j} h_i g_i \qquad [2]$$

where h_i's are the Lagrangian Multipliers.

The partials of F with respect to the parameters x's are formed and set to zero for the extremal value:

$$\frac{\partial F}{\partial x_k} = \frac{\partial f}{\partial x_k} + \sum_{i=1}^{j} h_i \frac{\partial g_i}{\partial x_k} = 0, \quad k = 1, 2, ...n \qquad [3]$$

Equations [1] and [3] form (j+n) equations in (j+n) unknowns, which are, x_1 through x_n and h_1 through h_j .

These equations are used to solve for the design variables x_1 through x_n.

2.3.1 EE- and EI-core Design Solutions

The core models and their dimensions are indicated in Figure (7).

The design problem is formulated so that the Lagrange Multiplier technique can be applied.

Given known constants:

A_C , the copper wire size

B_S , maximum allowable flux density

D_I , the core iron density

D_C , the copper winding density

F_C , the winding pitch factor

F_W , the window fill factor

The design requirements:

L , the inductance

I_P , the peak transistor current.

The design constraints G_i (X, K, r) are:

1. Saturation flux density constraint

$$B_S N A - L I_P = 0$$

2. Window area constraint

$$\frac{N A_C}{F_W} - G D = 0$$

N is the number of turns of copper wire

G, F, C, and D are the core dimensions

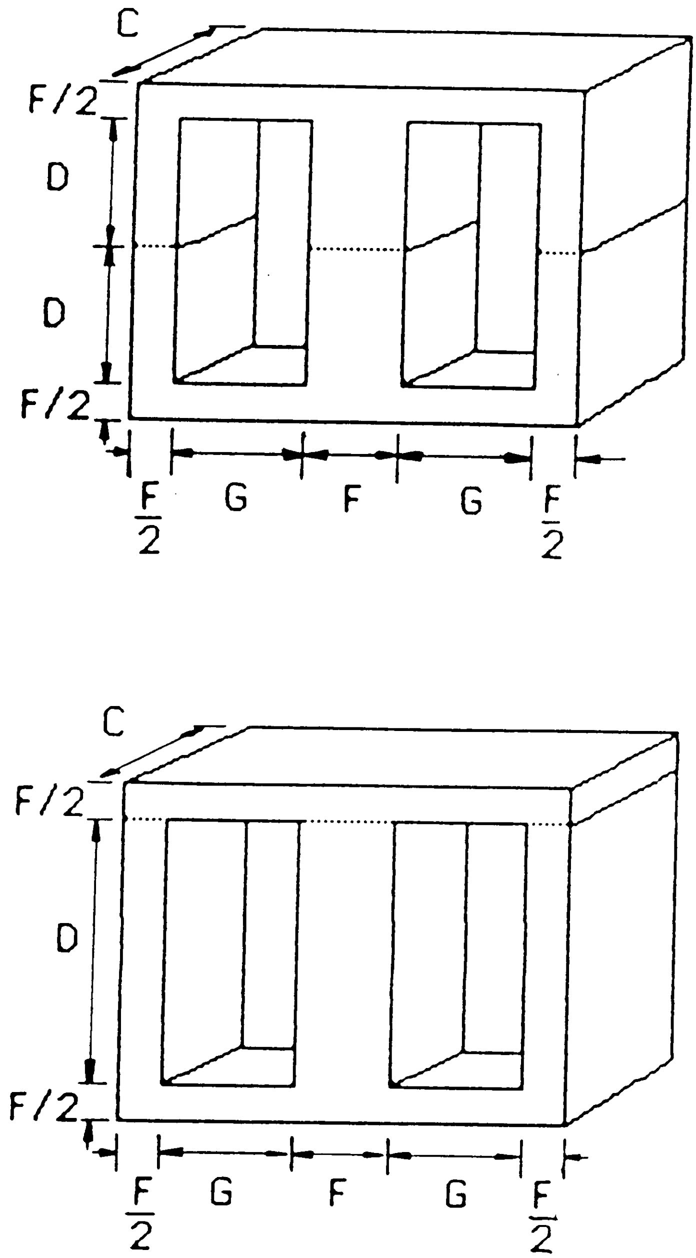


Figure 7. EE-and EI-core models

A is the cross sectional area of the core center-leg

The design variables to be determined are:

G, F, and N

The Objective Function is the Inductor Weight sought to be minimized:

$$W_t = \text{Core Weight} + \text{Copper Winding Weight}$$

$$W_t = 2D_iK_1F^2(F+G+D) + D_C(MLT)A_CN$$

where MLT is the mean length per turn of wire,

$$MLT = 2F_C(D + F)$$

The Lagrange Multiplier Technique can now be used to obtain closed form solutions for the variables as in [1]:

$$G = (L\, I_P A_C)^{0.25} S^{0.5}$$

$$F = \frac{(L\, I_P A_C)^{0.25}}{(K_1 K_2 F_W B_S S)^{0.5}}$$

$$N = \frac{K_2 F_W S (L\, I_P A_C)^{0.5}}{A_C}$$

This allows us to express the minimal weight of an inductor as:

$$W_t = K \times (L\, I_P A_C)^{0.75}$$

where I_P is a function of inductance and converter operating conditions

$$I_P = f(L, T, V_O, V_I, V_Q, V_D, P_O)$$

and where

$$K = f(B_S, K_1, K_2, F_C, F_W, D_i, D_C, S)$$

$$S = f(D_i, D_C, F_C, F_W, K_1, K_2, B_S)$$

Thus the core geometry can be solved for analytically, the solution representing the dimensions of a core optimized for minimum weight [4,1].

2.3.2 Core loss model and Wire size

The core loss model uses:

- Ferroxcube 3C8 ferrite core characteristics
- Statistical Analysis System curve fitting technique to determine alpha, m, and n parameters of the core loss equation

In CCM the core loss is given by

$$P = \alpha \bullet \text{core volume} \bullet (\Delta B)^m \bullet (\text{frequency})^n$$

and in DCM by

$$P = \alpha \bullet \text{core volume} \bullet (\Delta B)^m \bullet \left[\frac{\text{frequency}}{\left[\frac{t_{ON} + t'_{OFF}}{T} \right]} \right]^n \bullet \left[\frac{t_{ON} + t'_{OFF}}{T} \right]$$

α = 1.06, m = 2.50, n = 1.32 are the values determined for all frequencies from ΔB = 0.2 to 0.4 Tesla, the range in which most ferrite cores are operated.

Copper losses are determined as

$$\text{Cu loss} = I_{rms}^2 \times R_{dc}$$

where I_{rms} is the rms current and R_{dc} is the dc winding resistance. As mentioned earlier, it is assumed that the AC component of the total rms current is so small such that any increase in winding resistance due to Skin and Proximity effects does not result in any significant increase in the copper losses.

Wire size: The wire size A_C is determined based on the computation of 1000 circular mils per ampere,

$$A_C = K_C \times I_{rms}$$

where $K_C = 3.99 \times 10^{-7}$ m² per Amp, and

$$I_{rms} = f(L, T, V_I, V_O, V_Q, V_D)$$

Thus the optimal design solution for the minimum weight core, the corresponding total inductor losses and the maximum current in the switching transistor and diode have been determined. This knowledge allows comparison with a core that may be picked from a design catalog and any deviation from optimal core parameters can be rapidly evaluated using the design procedure.

3.0 Software Organization

3.1 Program Environment

The package is called INDOPT, an inductor design optimization tool for switching DC-DC power converters. Together with the main program two data files are required which are supplied to the user along with the code. These are the SPECS.INP and the CONTROL.INP files. Converter operating conditions and other parameters are specified to INDOPT via the SPECS.INP file. Certain control parameters used by INDOPT are read from the CONTROL.INP file. Appendix A discusses the structure of these two data files in detail.

Figure (8) shows the flow of computation within the package.

- Design specs and control parameters are provided to INDOPT at the start.
- The program determines the minimum weight optimal solution as well as the characteristic profiles of weight, losses and current stress.
- The user supplies practical core information.

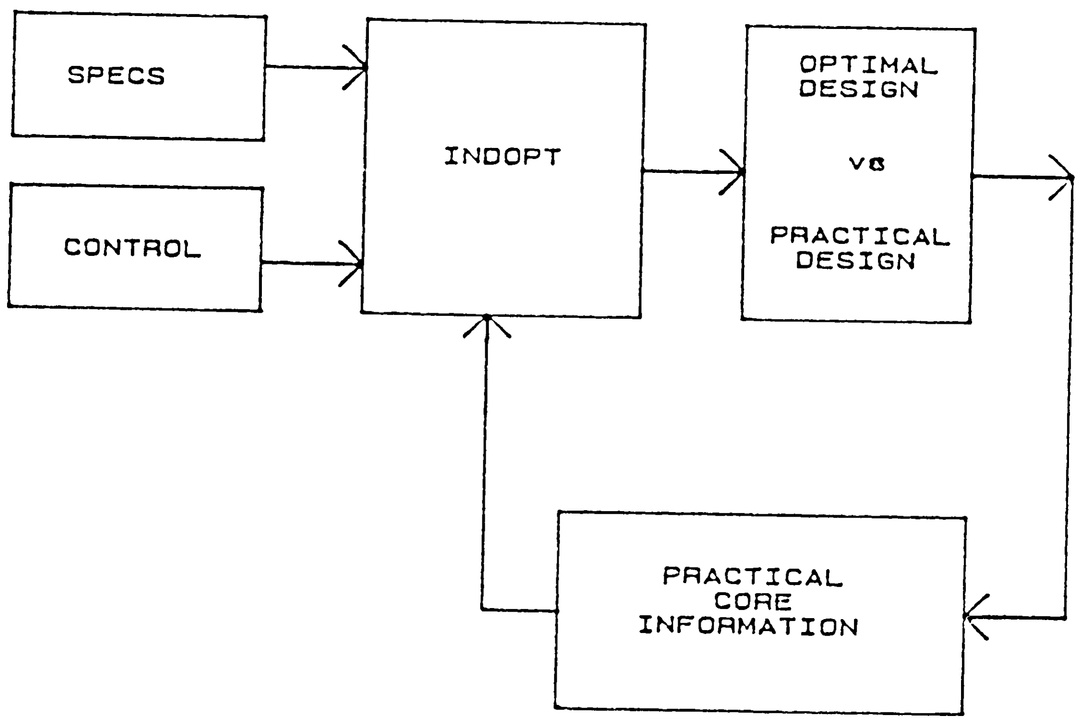


Figure 8. Operation of INDOPT

- The optimal design with the given core is determined and comparative profiles of weight, loss, and current stress between the two designs are provided.

- The design procedure is iterated until an acceptable inductance and core are fixed.

3.2 Subroutines and their Functions

The function of the main program is primarily managerial. Figure (9) is a flowchart of the program's operation. Memory requirements as specified in [7] are first initialized. Subsequently, various subroutines are called to perform the tasks of design, data I/O, and the graphics routine interface.

There are sixteen subroutines in all, listed by name below, and their functions described in the sections that follow.

1. Subroutine INLIZE

2. Subroutine MINWT

3. Subroutine IPEAK

4. Subroutine LOSS

5. Subroutine DESIGN

6. Subroutine FIXDES

7. Subroutine NEWWL

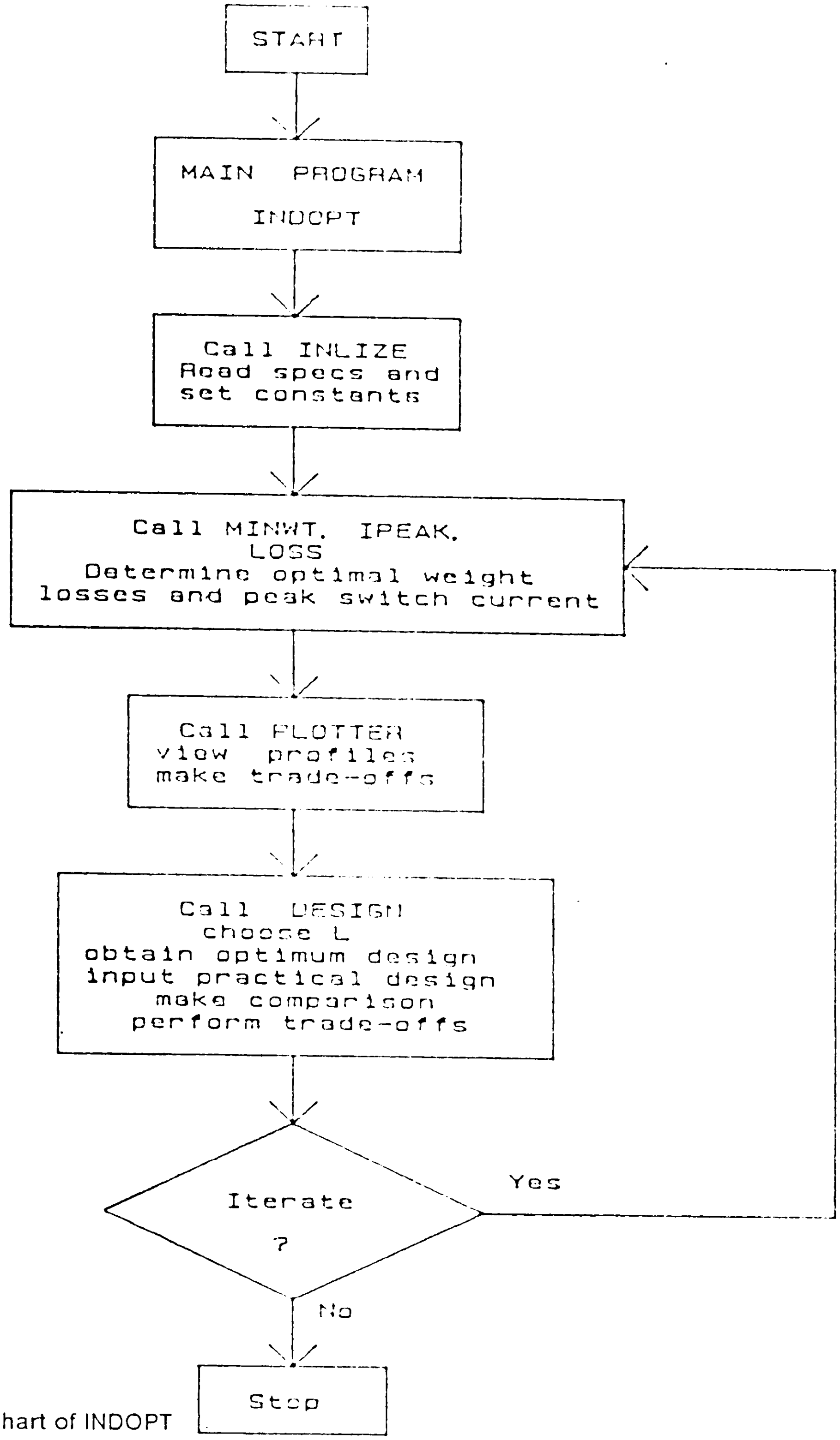


Figure 9. Flowchart of INDOPT

8. Subroutine REDO

9. Subroutine GETCMP

10. Subroutine FNDCMP

11. Subroutine WRTCMP

12. Subroutine INSERT

13. Subroutine PLOTTER

14. Subroutine PLTWT

15. Subroutine PLTLOSS

16. Subroutine PLTIPK

3.2.1 Subroutine INLIZE

This routine performs certain critical functions of housekeeping. It acts as the first level of user interface when the program is initiated, calls GETCMP and returns to the main program the converter specs and design constants.

3.2.2 Subroutines MINWT, IPEAK, and LOSS

These routines implement the Lagrange Multiplier solutions for the weight of the optimal core and inductor total losses and computes the peak current through the transistor. They write into data files MINWAYT.DAT, IPEAK.DAT, and LOSS.DAT respectively. This data is used to generate the corresponding plots that can be viewed at the monitor or routed to a plotter.

3.2.3 Subroutines DESIGN and FIXDES

In DESIGN the inductor core parameters of interest are computed. Figure (10) outlines the tasks accomplished by this routine as well as indicates the subroutines invoked in turn. The calculations represent the optimized design values as determined by the Lagrange Multiplier method. The user is prompted to supply practical core information so that further optimization can be performed in FIXDES and a comparison with the optimal design can be made.

3.2.4 Subroutines NEWWL and REDO

NEWWL is invoked by FIXDES to compute the weight of the inductor and its losses, given the core data by the user. The weight and loss models discussed in Chapter 2 are implemented.

Data is written into NEWWAYT.DAT and NEWLOSS.DAT for use by the plotting routines to generate the comparative profiles.

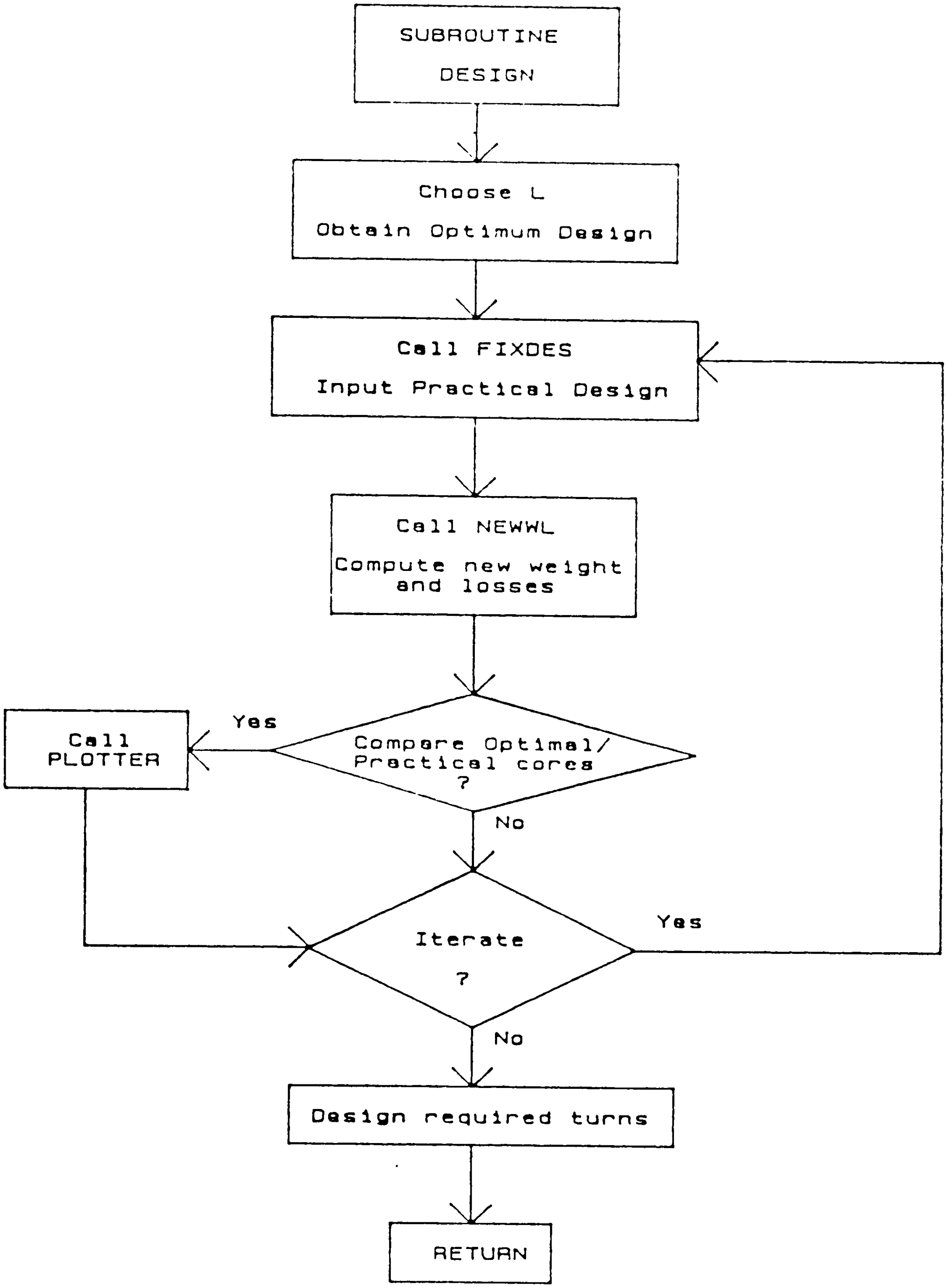


Figure 10. Flowchart of Subroutine DESIGN

Subroutine REDO is an interface routine that loops the design procedure ensuring the correct parameters are passed back to subroutine DESIGN, thereby allowing the program to operate in an iterative manner.

3.2.5 Subroutines GETCMP, FNDCMP, WRTCMP, and INSERT

These routines are invoked to handle I/O, to read from the SPECS.INP file the converter operating conditions and design data. GETCMP calls FNDCMP for every component item to be read from SPECS.INP. If FNDCMP is unable to locate an item, it prompts the user for the value of the item and writes into the SPECS.INP file. The writing into SPECS.INP is performed by the WRTCMP routine, when invoked by the FNDCMP routine.

Subroutine INSERT is called by WRTCMP to write into the i'th position of the data file, both the component name and value.

3.2.6 Subroutines PLOTTER, PLTWT, PLTLOSS, and PLTIPK

The PLOTTER routine manages the generation of weight, loss and peak current profiles. It calls the PLTWT, PLTLOSS, and the PLTIPK routines and performs user interfacing functions.

PLTWT generates the Inductor weight versus Inductance profiles, PLTLOSS generate the Inductor total Losses versus Inductance profiles, and PLTIPK generates the Peak Switch Current versus Inductance profile. All these routines call library functions from the IBM PC Plotting System Library.

4.0 Design Examples

In this Chapter three design examples are presented, with actual program runs being performed for each of the Buck, Boost, and Buck/Boost converters.

While the design of an inductor having minimum weight is our primary objective, the total inductor losses as well as the current stress in the semiconductor devices are also sought to be minimized. Thus the scope of minimum weight inductor design is broadened to mean: designing an inductor that has the least possible weight, results in an acceptable current peak through the semiconductor devices, and has low core and copper losses.

The design procedure presented here realizes these objectives by providing the user with complete freedom to weigh each of the criteria, iterate with practical cores from manufacturer's catalogs, and arrive at a practical design using the optimal design as the target.

4.1 Example 1: Buck Converter

Problem: To design an EI-cored inductor for a converter operating at 40 kHz. The converter specifications are:

$V_{IMAX} = 25V$, $V_{IMIN} = 22V$, $V_O = 20V$, $P_{OMAX} = 40W$

$B_S = 0.35 Tesla$, $F_W = 0.25$, $V_Q = 1.0V$, $V_D = 1.0V$

Solution procedure: The given specs are entered into the SPECS.INP file, the other design constants changed if necessary. The format of this file is shown in Appendix A. File CONTROL.INP remains unaltered.

The program is run following the procedure detailed in Appendix A. The user is told:

The critical inductance is: 0.21E-04 Henries

In response to the prompts the user can see the design graphs for the optimal inductor weight, its total losses and the peak transistor current plotted against inductance, as shown in figures (11), (12), and (13) respectively.

It is clear that if minimum weight is the sole criterion, an inductance of 10 μH will result in the least weight. The program can be used to determine the core geometry, the wire size, and the number of turns required for this inductance. However, since low losses and reduced peak current stress are also desired, the profiles are viewed to identify an inductance that can meet these three requirements.

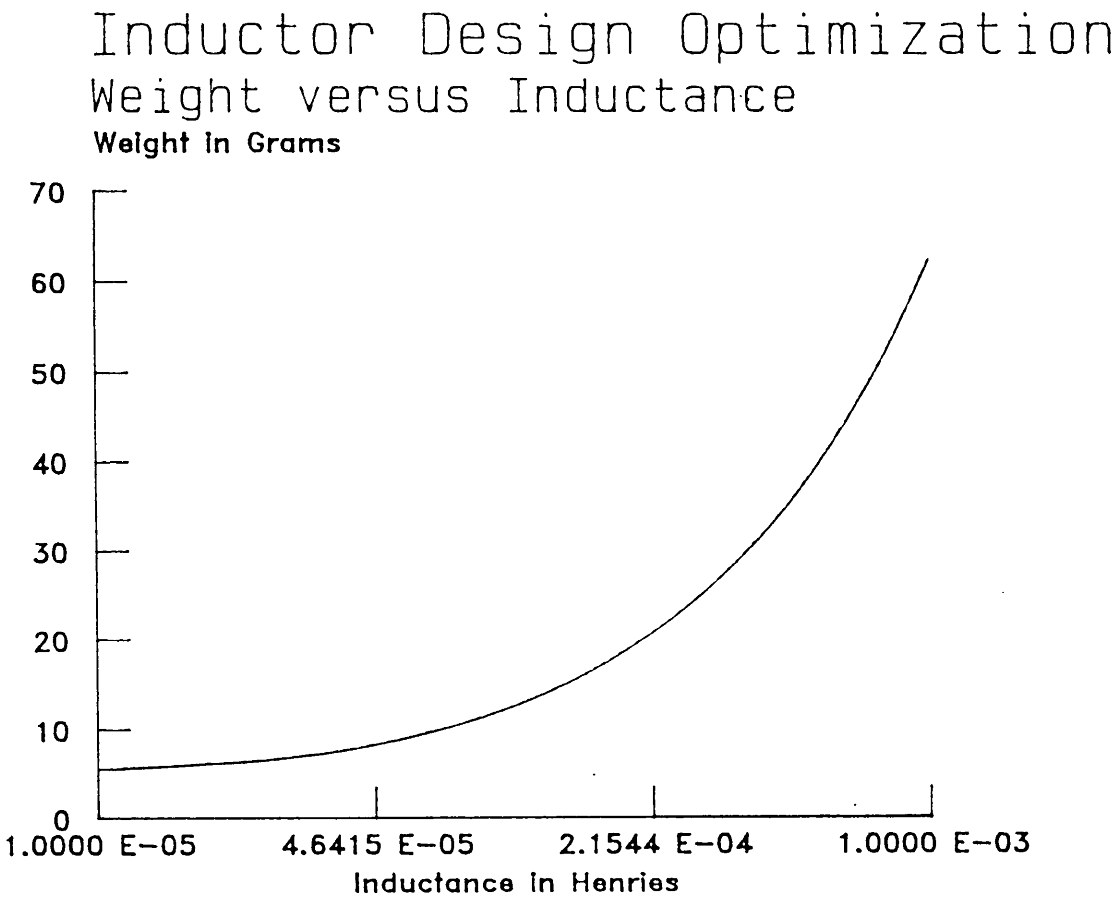


Figure 11. Buck converter: Optimal Core Weight vs Inductance

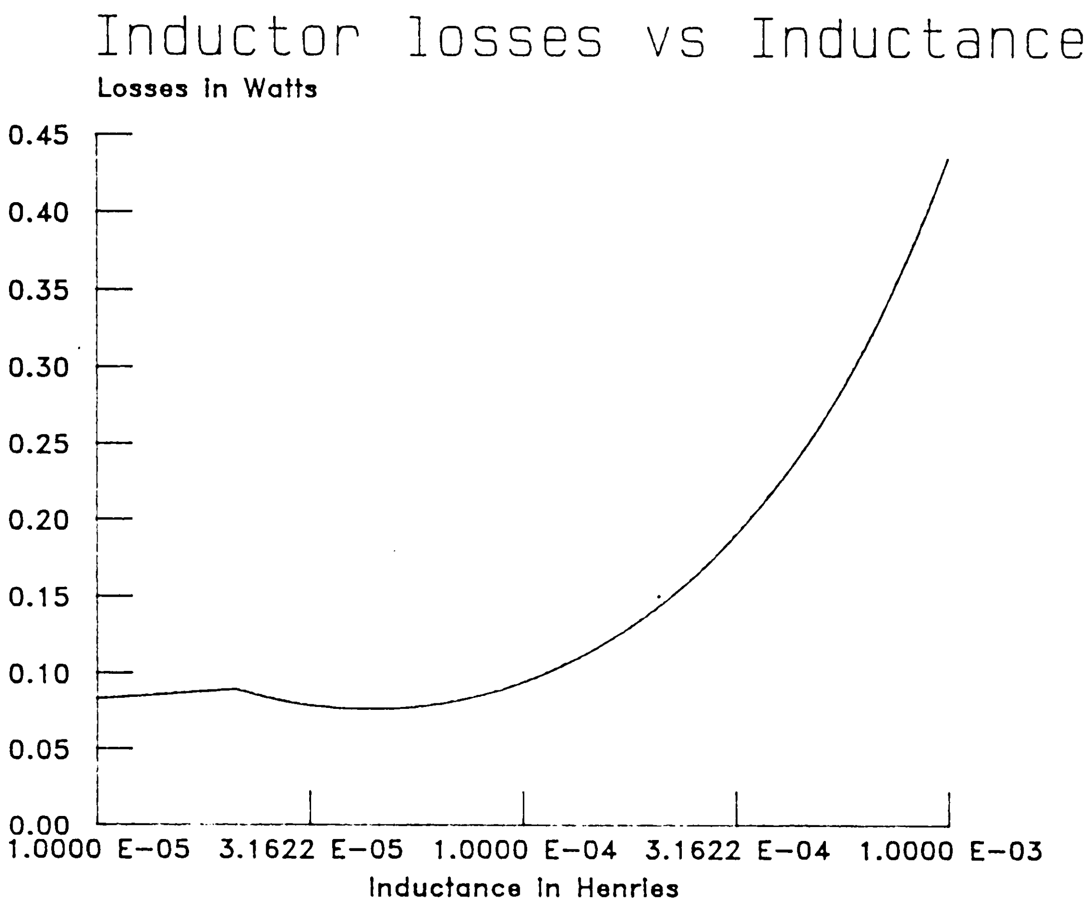


Figure 12. Buck Converter: Optimal Core Losses vs Inductance

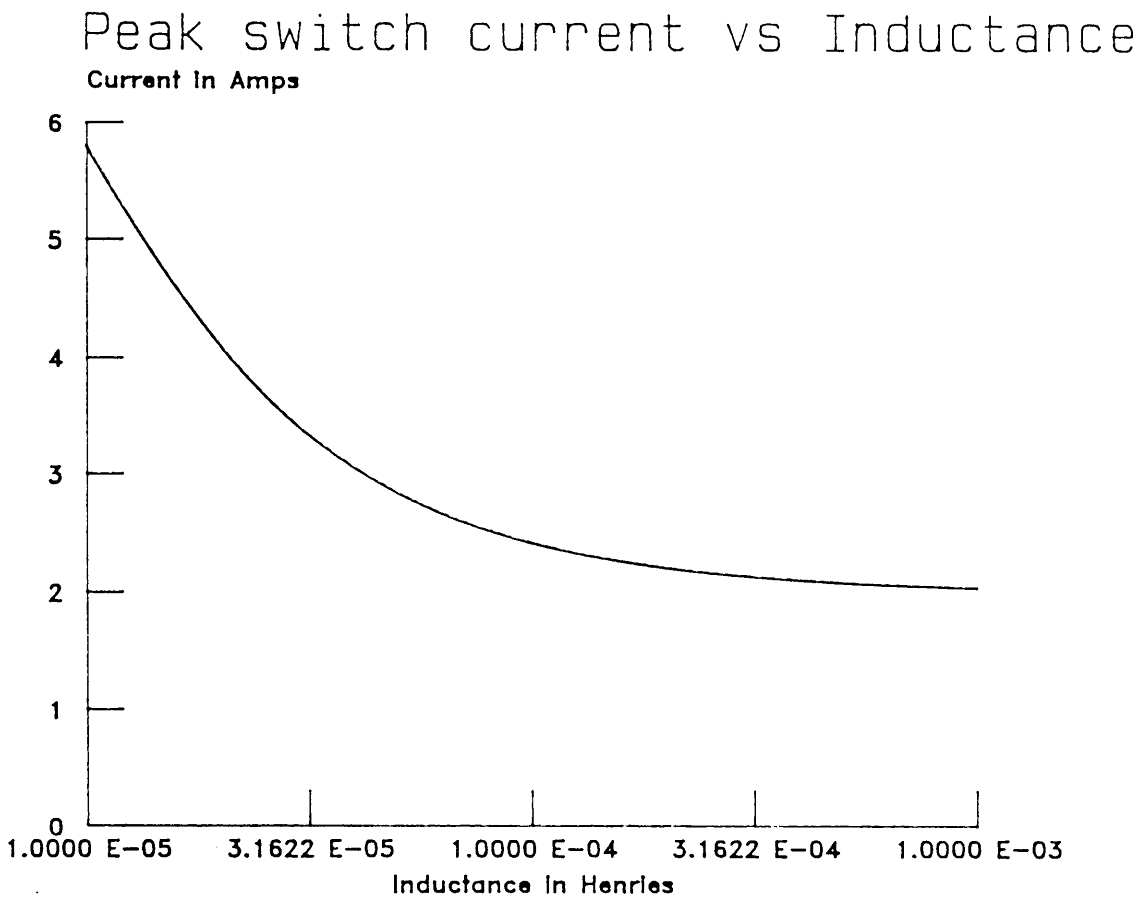


Figure 13. Buck Converter: Peak Switch Current vs Inductance

We identify 50 μH as the inductance at which the

- weight is quite low, and
- losses are a minimum

However, the peak current stress is high compared to the current levels that occur at higher inductances. This can be viewed as the penalty paid while gaining favorable weight and loss characteristics. Such a trade-off is precisely what was mentioned earlier. The user is free to choose that inductance which results in satisfactory weight, loss, and current characteristics.

Upon providing the inductance chosen in response to the prompts, the program designs the E-core required for this inductance, and determines the required gauge of wire and turns. The design is:

Wire size	=	0.82E+00	square mm
Number of turns	=	26	
Window width, G	=	8.10	mm
Leg length, D	=	10.5	mm
Center leg width, F	=	3.95	mm
Core thickness, C	=	3.95	mm

The next task before the user is to choose a core that dimensionally matches this optimal design. Given a particular choice of cores available to the user from a commercial catalog an exact match is quite unlikely. Thus the user must select a core that closely matches the suggested design. In seeking this match, two factors come into play:

1. The available window area for a particular selection of core

2. The center leg cross-sectional area of the core chosen

The core picked from the catalog must have available a window area at least that suggested by the optimal design, in order that the turns of wire be accommodated. This requisite could be relaxed if the core selected has a center leg area greater than that suggested as per the optimal design. In such a case, fewer turns than the design value could achieve the desired inductance. The core that must be avoided would therefore be one having both smaller window area as well as smaller center leg cross-sectional area, with reference to the optimum design suggested by the program.

While keeping these considerations in mind would help realize a practical design close to the optimal, the program is capable of handling any deviations from the suggested guidelines. For any choice of core the user is told the inductance that can be achieved with it, and further, the characteristic curves of the core chosen can be viewed, compared to the optimal case, and design iterations repeated if necessary.

From the Magnetics core catalog, the core #44011-EC is picked and its geometry entered in response to the prompts.

G =	8.66	mm
D =	10.26	mm
F =	10.69	mm
C =	10.69	mm

This core is chosen because it matches the window area suggested by the optimal design very closely, being slightly greater. It may be noted however that the center leg cross-sectional area is much greater than that of the optimal core. Thus, it can be expected that this core would weigh more than the optimal core, owing to its larger volume and hence have greater losses. Further, for the same number of turns of copper of a given gauge, higher inductances can be achieved with this core owing to its larger cross-sectional area compared to the optimal core.

The program determines the turns that must be wound to achieve minimum weight with this core, as well as informs the user of the upper bound on the number turns to be used, if a combination of air-gap and turns is preferred. The following information is provided:

Upper limit on the number of turns for this core = 27

(based on window area)

Lower limit on the number of turns for this core = 4

(based on non-saturation of core)

Minimal weight with this core = 37.25 grams

The characteristic curves can be viewed now to compare the practical choice versus the optimal core as shown in figures (14), (15), and (16). The peak current curve is the same as in figure (13) since the maximum current that flows through the transistor or diode depends only on the inductance and the converter operating conditions, and is therefore independent of the core chosen.

As was expected, figure (14) reveals that the core chosen is heavier than the optimal core and the weight increases monotonically with inductance. This is due to the fact that given a particular core, larger inductances can be achieved by winding more turns of wire, which directly leads to increased weight.

The loss profiles of the optimal design compared to the fixed core reveals an interesting characteristic. At low inductances the converter operates in DCM where the current peaks are high leading to a high rms current value. Consequently the flux swing is higher in DCM

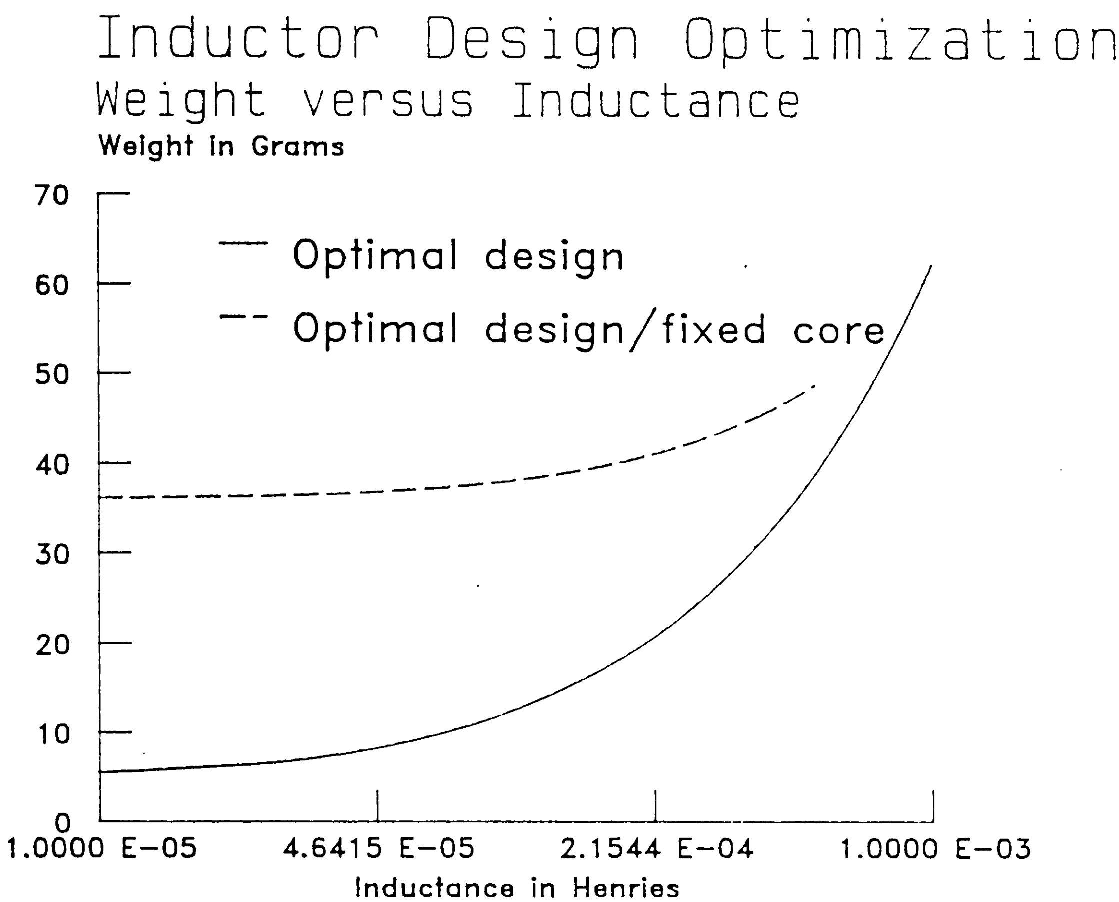


Figure 14. Buck converter: Optimal and Practical Core Weight Profiles

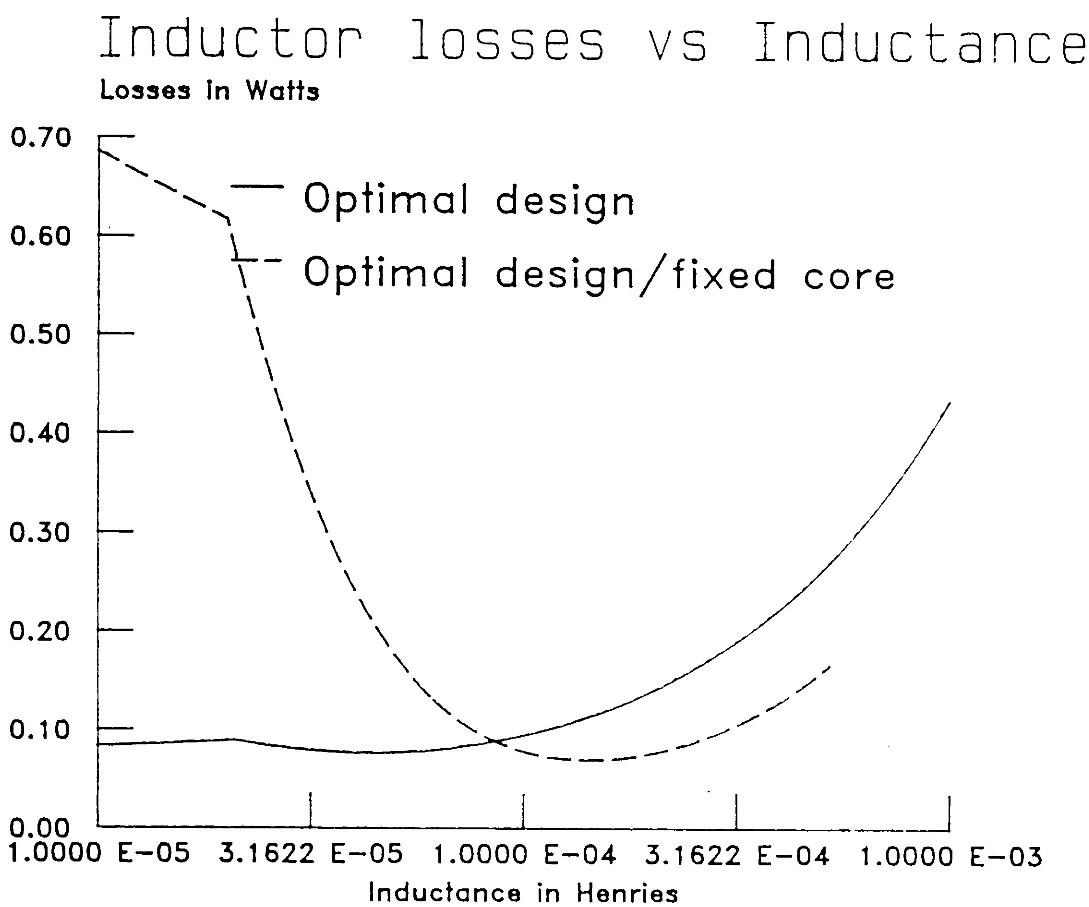


Figure 15. Buck Converter: Optimal and Practical Core Loss Profiles

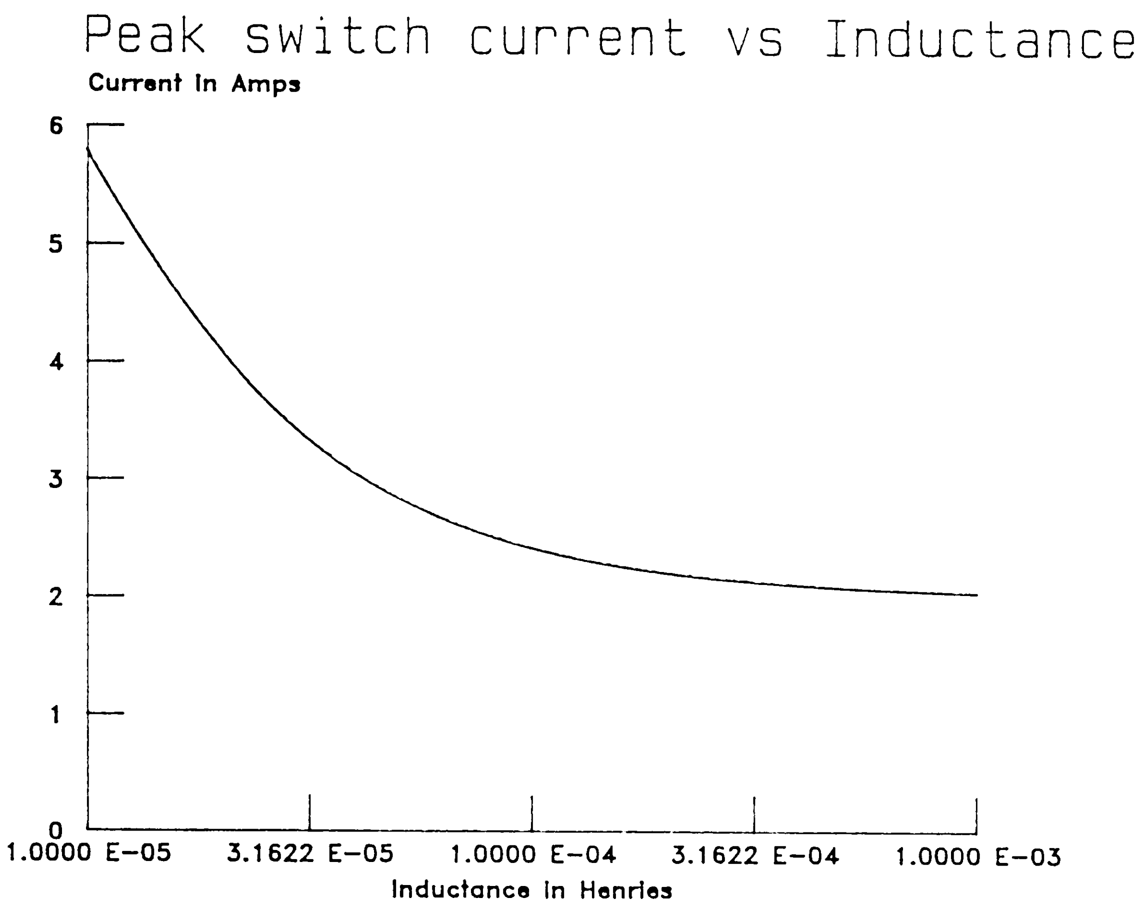


Figure 16. Buck Converter: Peak Switch Current vs Inductance

than in CCM. The combined effect of this and the larger core volume, is that the total inductor losses are high at low inductances.

At inductances greater than 21 μH, the converter enters CCM where the flux swing is much smaller than in DCM, since the ripple current is smaller now. At higher inductances, the converter is placed in deep CCM where the ripple current is still smaller. Thus core losses fall off rapidly at higher inductances. With a fixed core, higher inductances are achieved by using more turns of copper wire. Thus, the copper losses increase with inductance. At lower inductances the core losses dominate the winding losses which are small. The combination of core and copper loss characteristics therefore result in a U-shaped curve as can be seen in figure (15).

It can also be observed that the loss characteristic for the optimal core runs above that for the fixed core at higher inductances. This is due to the fact that the optimal design (where weight is minimized) uses a core having the least possible volume and a full window resulting from the maximum number of turns that can be accommodated. With the fixed core, we have the least number of turns wound on a large core in order to realize a particular inductance. Thus the copper losses for the optimal case would be greater than the case with a fixed core, specially at higher inductances where more turns of wire are required, causing the profile for the optimal core overtake that of the fixed core.

It is seen that for this core, inductances about 125 μH would be the preferred operating point. Here the loss curve bottoms out while the weight increase is not too significant over that at 50 μH. Further, the higher inductance results in a smaller peak current of 2.3A while the peak current at 50 μH is 2.9A.

Iterating through the program again, with 125 μH as the desired inductance the optimal core design is first obtained. Choosing the core #44011-EC once again, the turns that can be used is designed:

Upper limit on the number of turns for this core = 28

(based on window area)

Lower limit on the number of turns for this core = 7

(based on non-saturation of core)

Minimal weight with this core = 38.71 grams

The design procedure is now concluded. An I-piece is chosen to match the E-core selected.

4.2 Example 2: Buck/Boost Converter

Problem: To design an EI-cored inductor for a Buck/Boost converter operating at 40 kHz. The converter specifications are the same as in Example 1.

Solution procedure: As before, INDOPT is run with the choice of converter being the Buck/Boost. The design graphs can be scrolled through, and are shown in figures (17), (18), and (19).

The program determines the critical inductance to be: 32.8 μH

Now, an inductance has to be picked and the inductor designed for the minimal weight, keeping in view the total core and copper losses as well as the current stress in the switch. Using the loss profile of figure (18) and the peak current profile of figure (19), an inductance of 75 μH can be identified to result in the least losses and place the converter operation sufficiently deep in CCM where the maximum current profile has begun to level off.

This value is entered into the computer in response to the prompts. The optimal inductor is designed:

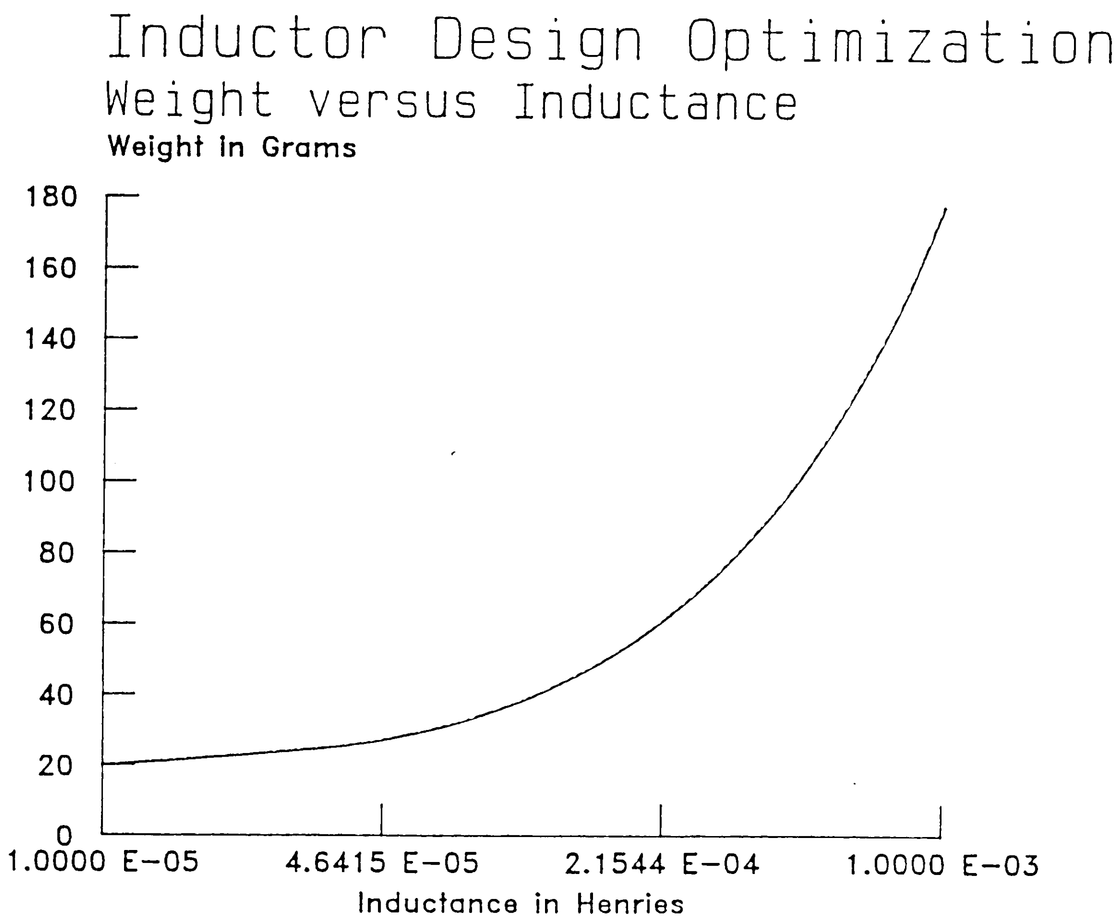


Figure 17. Buck/Boost Converter: Optimal Core Weight vs Inductance

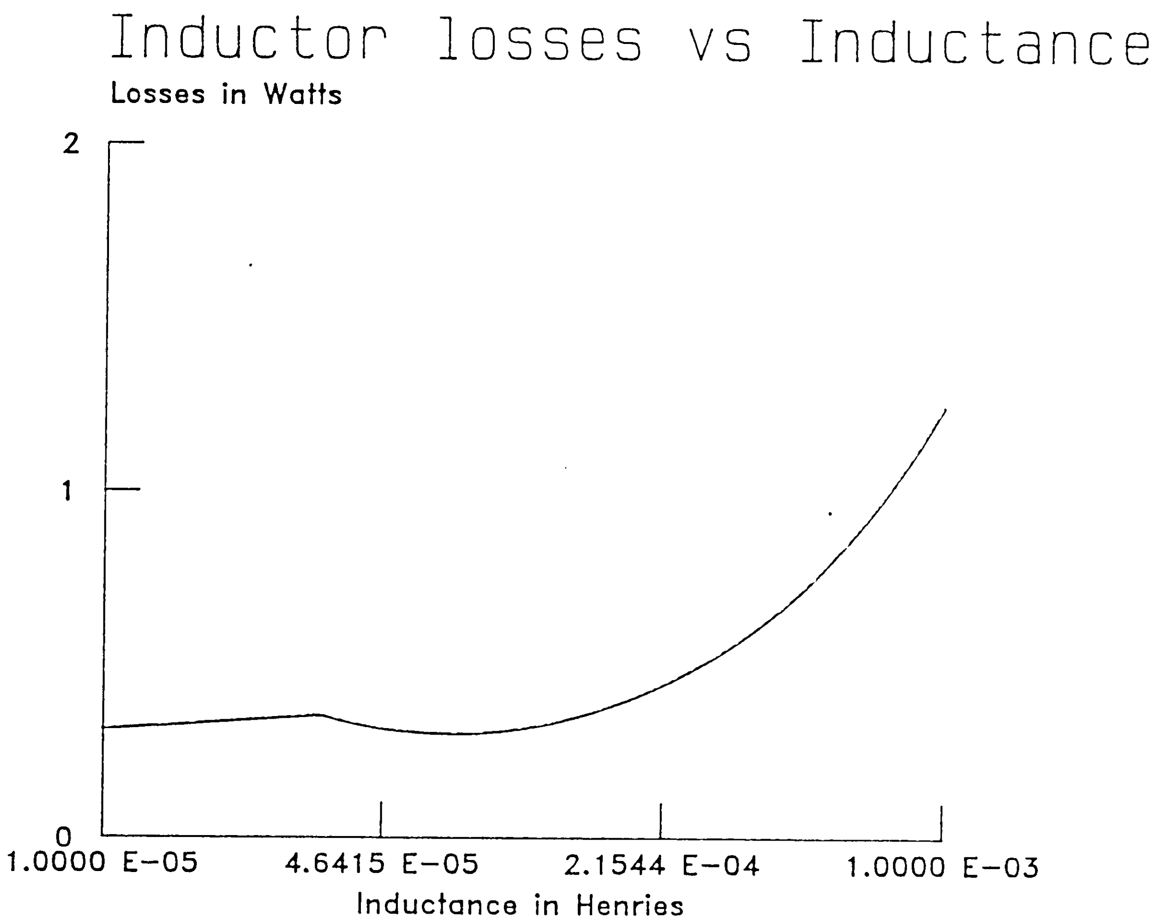


Figure 18. Buck/Boost Converter: Optimal Core Losses vs Inductance

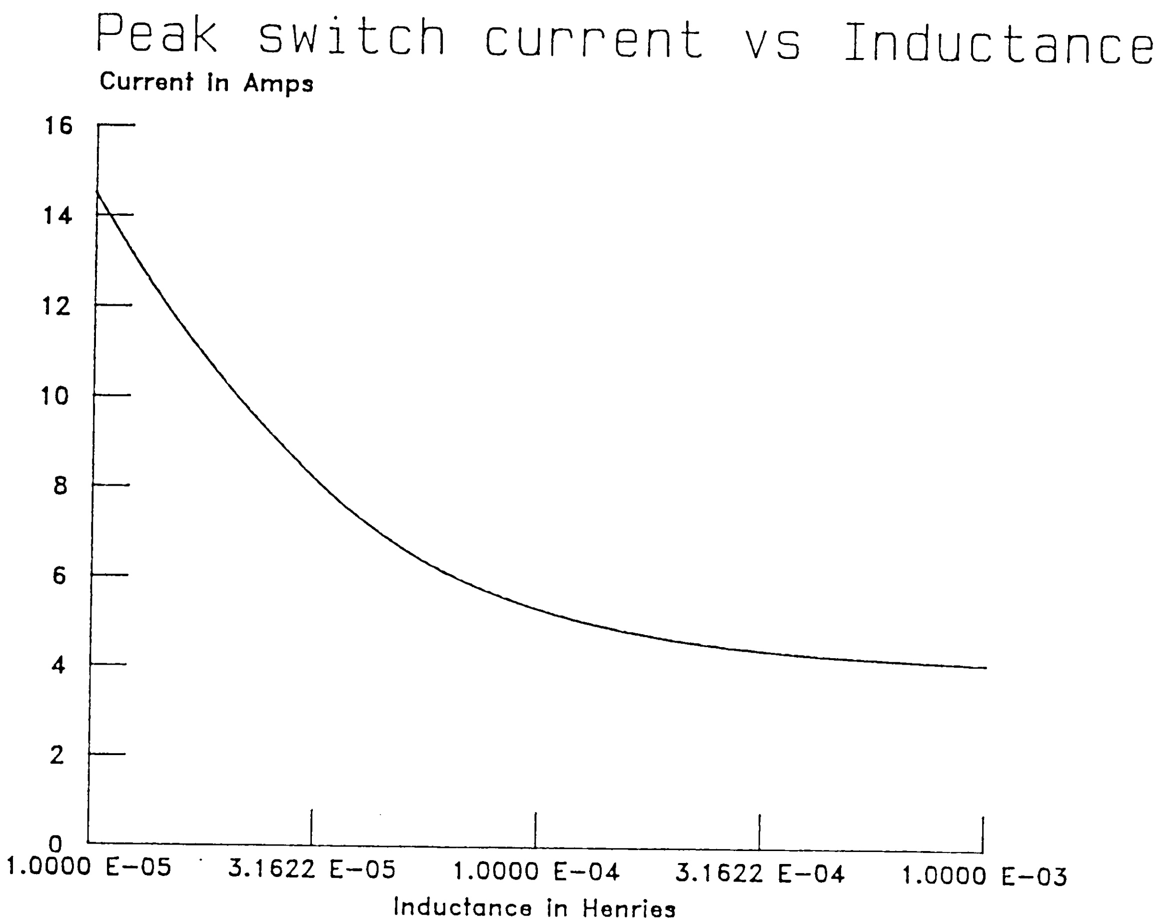


Figure 19. Buck/Boost Converter: Peak Switch Current vs Inductance

Wire size	=	0.16E+01	square mm
Number of turns	=	32	
Window width, G	=	12.73	mm
Leg length, D	=	16.54	mm
Center leg width, F	=	6.21	mm
Core thickness, C	=	6.21	mm

The core #45528-EC is picked. This has a window area approaching that of the optimal though smaller, while its center leg area is much bigger than that of the optimal core. Its dimensions are:

G =	10.7	mm
D =	18.8	mm
C =	20.6	mm
F =	16.8	mm

The number of turns to be used with this core to achieve an inductance of 75 μH is determined. The upper limit on turns is determined by the available window area with the core chosen. The lower limit is determined by the number of turns required to keep the core from saturating. A suitable number of turns is selected between this range so that the core is operated below saturation. These turns will determine the air-gap to be introduced according to the classical relationship:

$$l_g = \frac{\mu \times N^2 \times A}{L}$$

where l_g is the length of the air-gap, μ is the effective permeability of the core material, N the number of turns, A the cross-sectional area of the core center leg, and L the inductance. The program computes the following:

Upper limit on the number of turns for this core = 31

(based on window area)

Lower limit on the number of turns for this core = 4

(based on non-saturation of core)

The minimal weight obtained with this core is determined to be 173.88 grams. The available window area will restrict the inductance that can be achieved with this core. The maximum inductance possible is determined to be 954.55 μH. The comparative profiles can be viewed in figures (20), (21), and (22).

This core is seen to deviate widely from the optimal core profiles of weight and losses, though around 200 μH the losses are similar. However, at this operating point the weight is much more than that predicted for the optimal core.

The design procedure is repeated for 75 μH choosing a different core and performing the trade-offs once again. In this iteration core #44020-EC is chosen and its dimensions entered in response to the prompts.

G =	9.54	mm
D =	15.16	mm
C =	15.4	mm
F =	11.8	mm

As before the program determines the following information:

Upper limit on the number of turns for this core = 22

(based on window area)

Lower limit on the number of turns for this core = 7

(based on non-saturation of core)

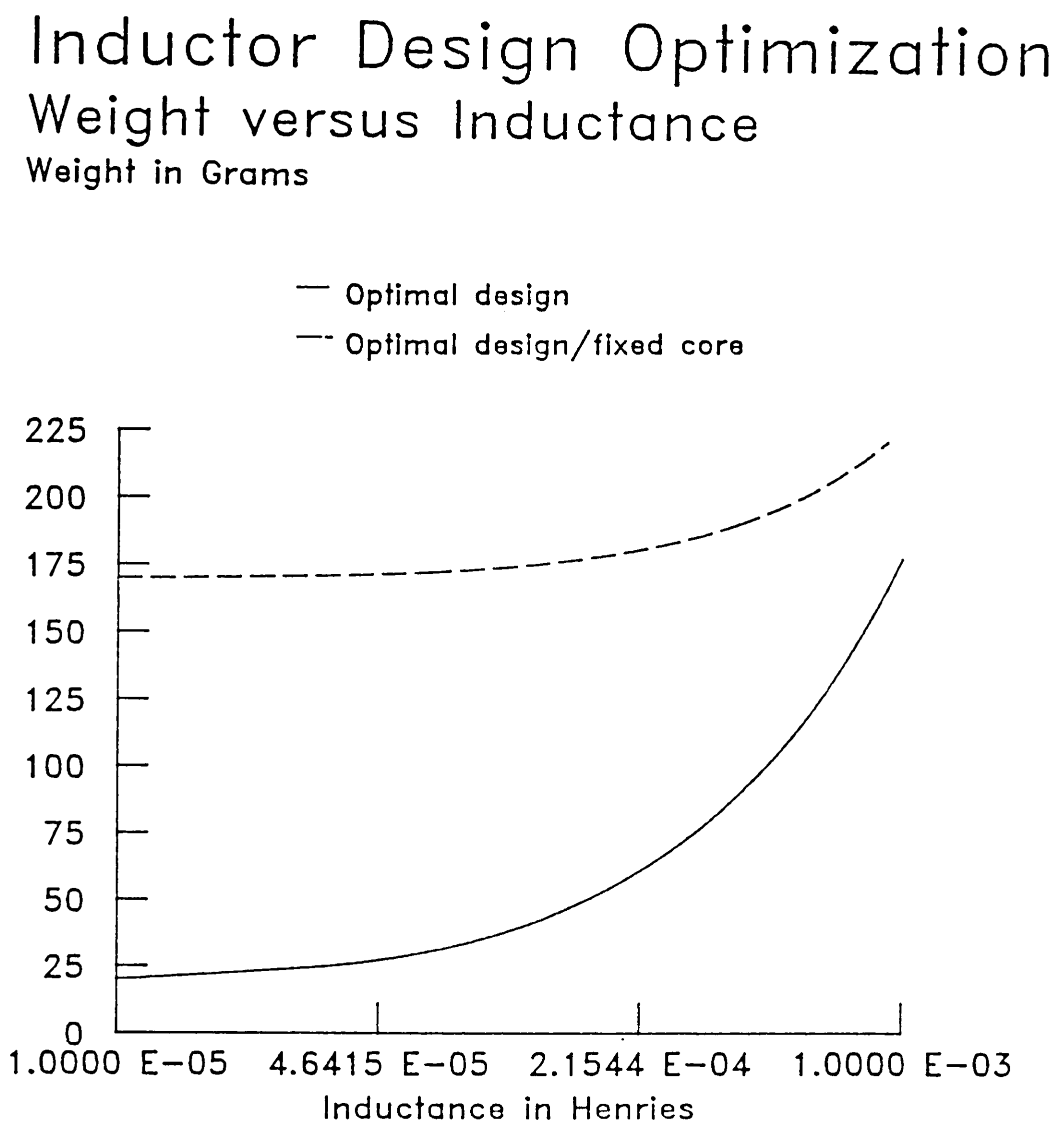


Figure 20. Buck/Boost converter: Optimal and Practical Core Weight Profiles

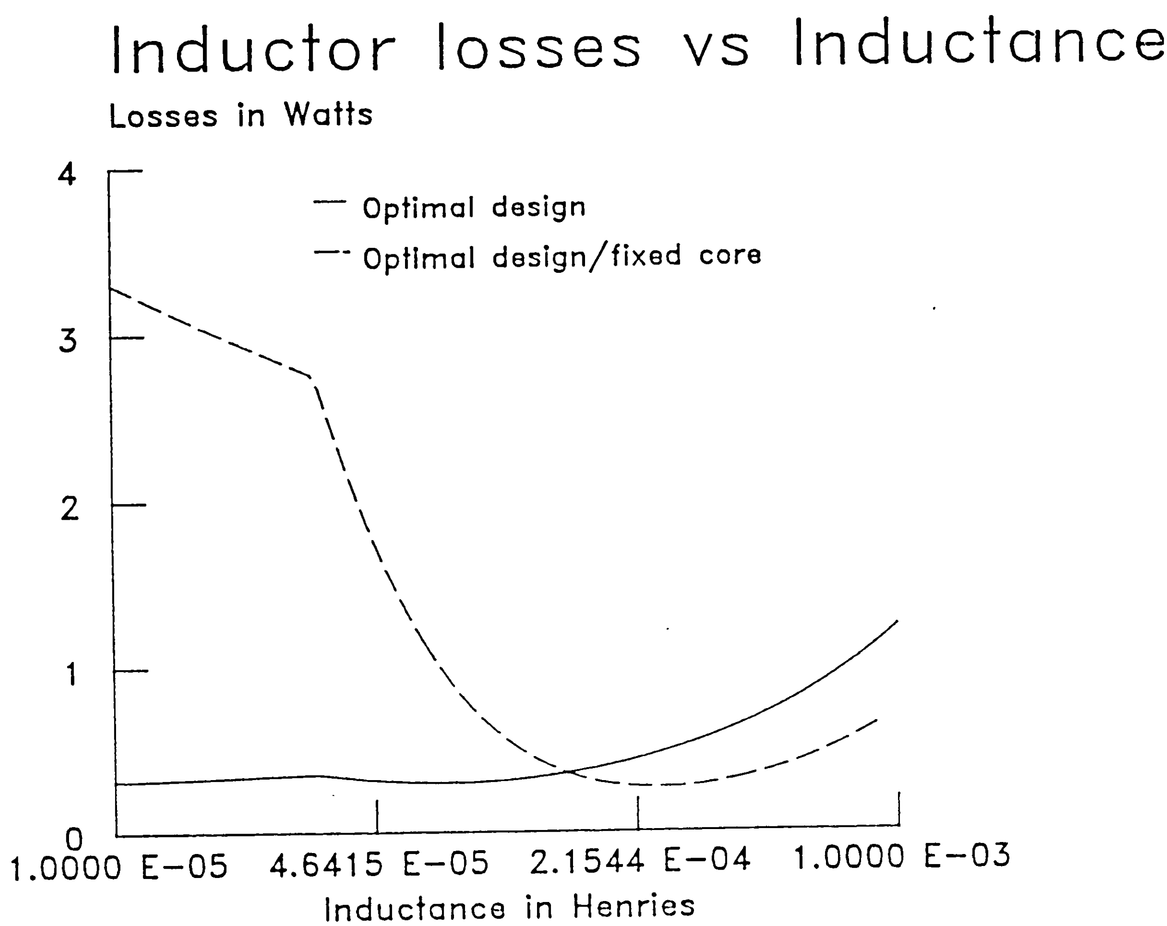


Figure 21. Buck/Boost Converter: Optimal and Practical Core Loss Profiles

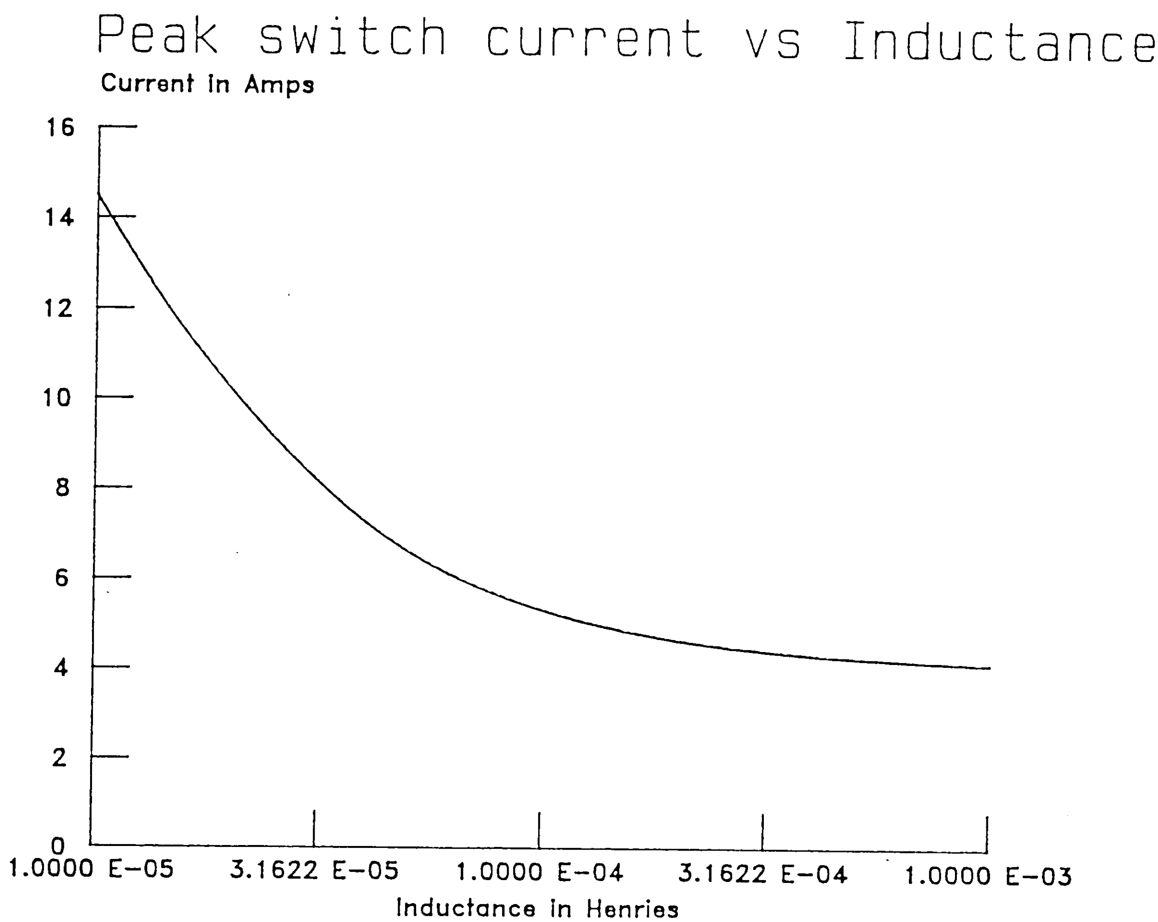


Figure 22. Buck/Boost Converter: Peak Switch Current vs Inductance

Minimal weight with this core = 78.19 grams

The maximum inductance that can be achieved with this core is determined to be 327.46 μH. Figures (23) and (24) show the new characteristics with this core compared to the optimal core. The peak current profile remains the same as in figure (22).

We can observe that this inductor weighs less than the previously designed inductor. Using the turns determined above, an inductance of 75 μH can be wound and this is determined to weigh 78.2 grams.

It can also be seen from figure (24) that the least inductor losses occur at about 200 μH and correspondingly the maximum current stress is smaller than that at 75 μH. If these considerations are of significant importance, then at the expense of obtaining a heavier inductor an inductance of 200 μH is wound.

For purposes of demonstration, this iteration is performed. 200 μH is specified to the program and the core #44020-EC picked. The turns range that applies is determined by the program as:

Upper limit on the number of turns for this core = 23
(based on window area)
Lower limit on the number of turns for this core = 15
(based on non-saturation of core)

Minimal weight with this core = 88.19 grams

The least possible weight with this design is computed to be 88.2 grams which is 10 grams more than the weight of the 75 μH inductor. The freedom to perform such trade-offs is allowed the user and further iterations made if necessary. Having obtained designs for both the 75

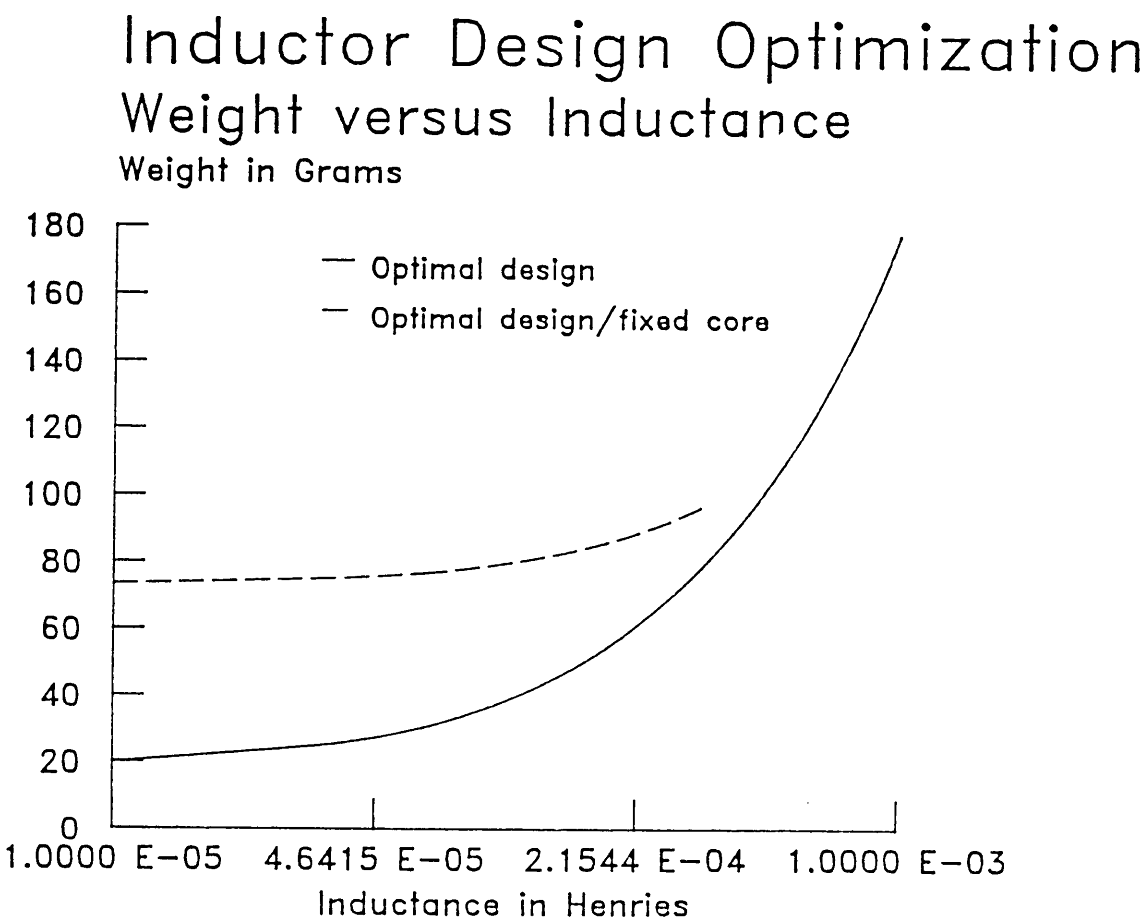


Figure 23. Buck/Boost converter: Optimal and Practical Core Weight Profiles

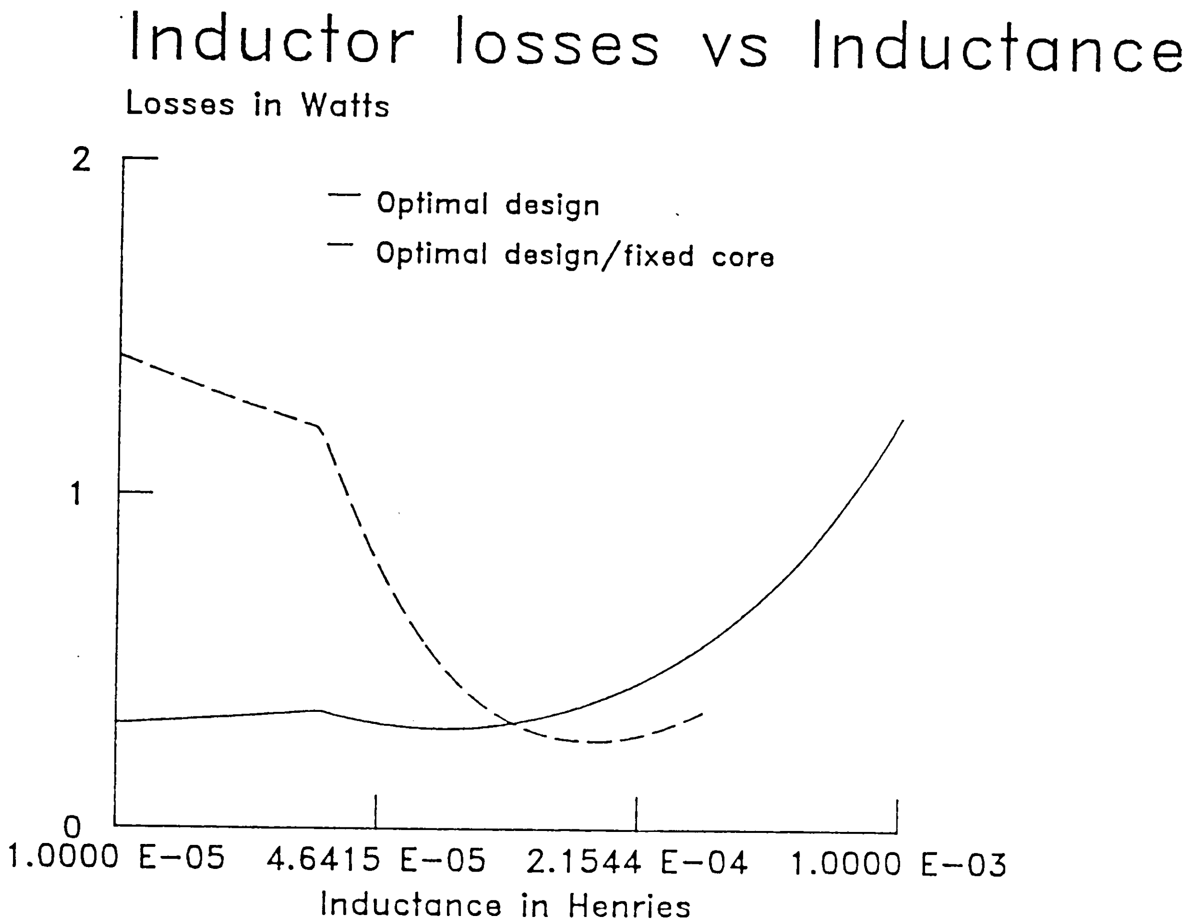


Figure 24. Buck/Boost Converter: Optimal and Practical Core Loss Profiles

μH and the 200μH inductor given the core #44020-EC, the design procedure is concluded. An I-piece is appropriately chosen.

4.3 Example 3: Boost Converter

Problem: To design an EE-cored inductor for a Boost converter operating at 40 kHz. The converter specifications are:

$V_{IMAX} = 30V$, $V_{IMIN} = 25V$, $V_O = 40V$, $P_{OMAX} = 40W$

$B_S = 0.35 Tesla$, $F_W = 0.25$, $V_Q = 1.0V$, $V_D = 1.0V$

Solution procedure: The converter specs are entered into the SPECS.INP file as outlined in Appendix A. The program INDOPT is run and the user responds to prompts to obtain the characteristic profiles as shown in figures (25), (26), and (27).

From the curves an inductance of 150 μH can be identified as a good choice since:

- the losses bottom out here
- the peak current stress is low

However, there is an increase in weight at higher inductances which must be kept in view. Upon entering this value, the program computes the optimal core design parameters:

Wire size	=	0.69E+00	square mm
Number of turns	=	46	
Window width, G	=	9.86	mm

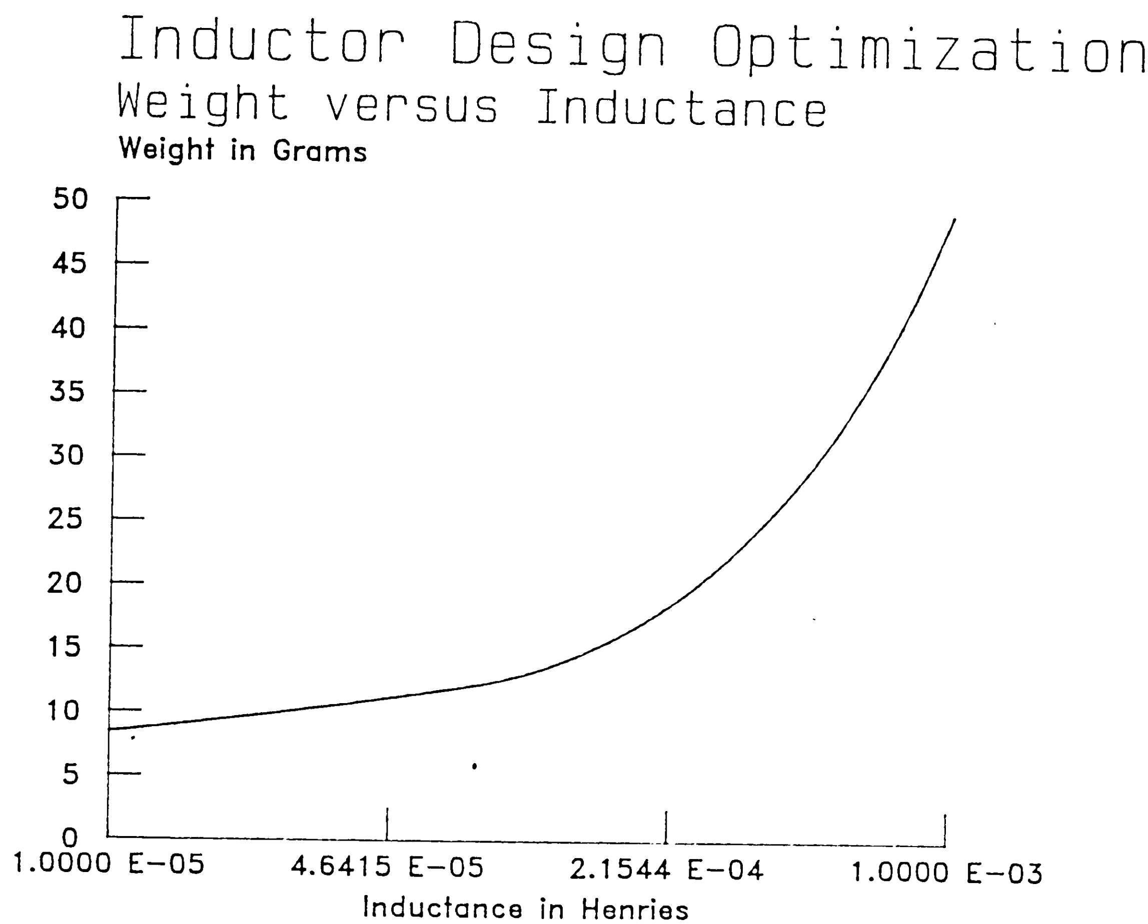


Figure 25. Boost Converter: Optimal Core Weight vs Inductance

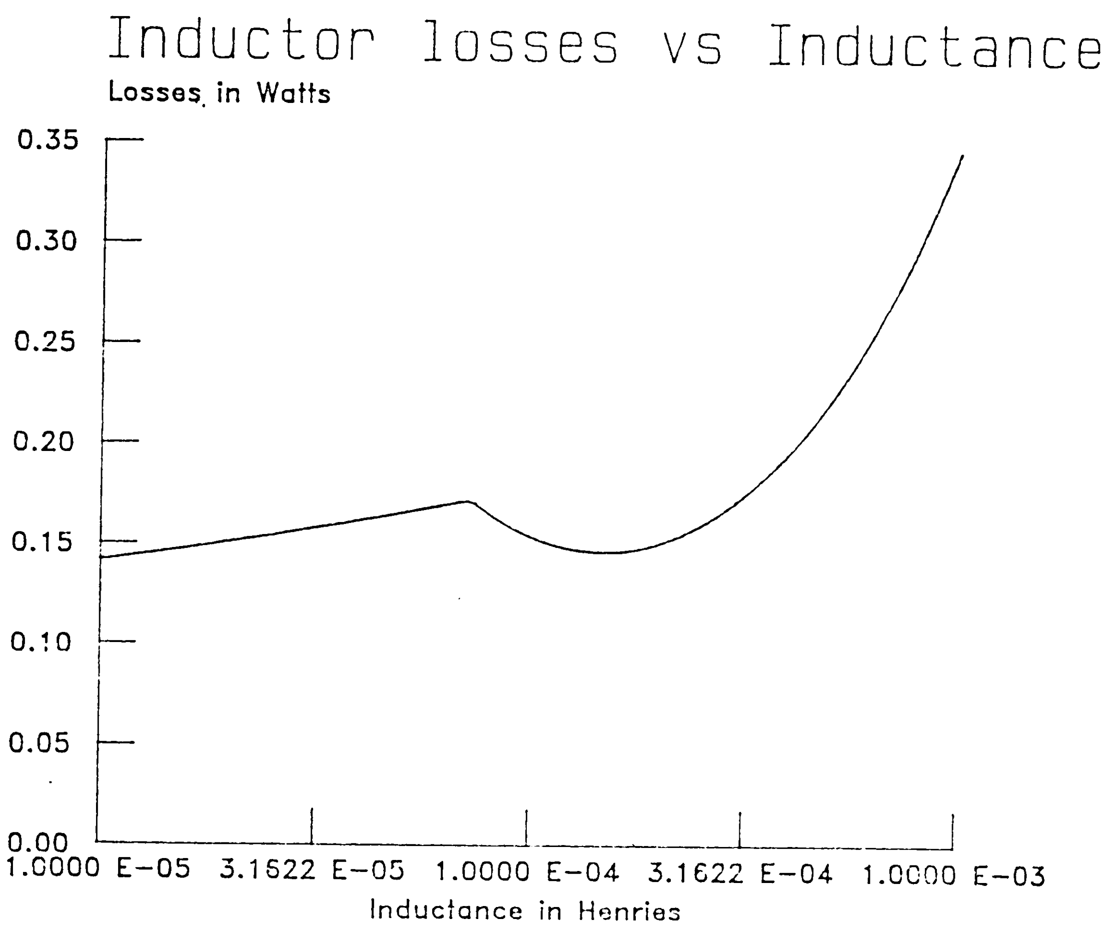


Figure 26. Boost Converter: Optimal Core Losses vs Inductance

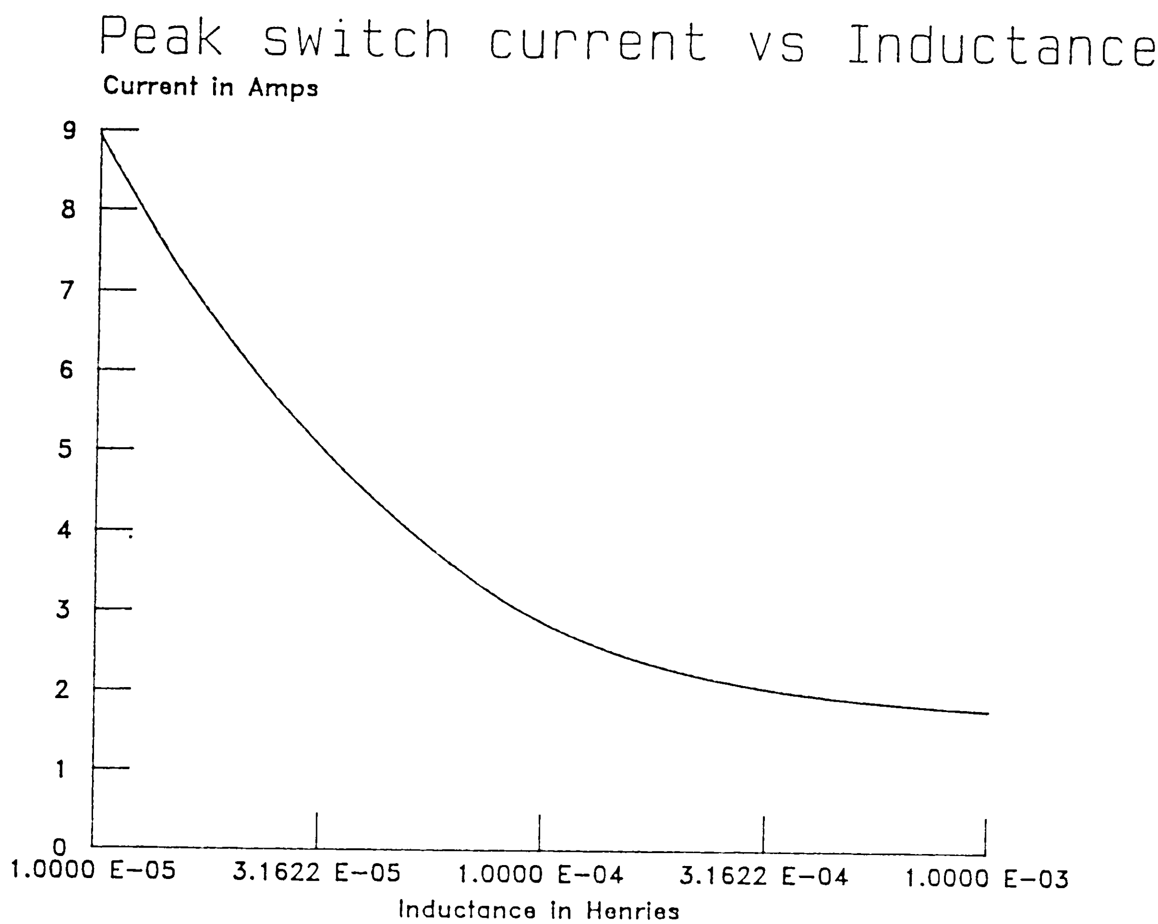


Figure 27. Boost Converter: Peak Switch Current vs Inductance

Leg length, D	=	6.41	mm
Center leg width, F	=	4.81	mm
Core thickness, C	=	4.81	mm

From the commercial catalog a core must be chosen such that its window area and its cross-sectional area are both no smaller than the optimal design. The core part #43007-EC is picked, which has a window slightly larger than that suggested, though its center leg cross-sectional area is greater than that of the optimal design.

Its dimensions are:

G =	6.46	mm
D =	10.01	mm
C =	7.06	mm
F =	6.96	mm

The new profiles can be viewed and are shown on figures (28) and (29). The current profile is the same as in figure (27).

It is seen that the choice of core compares very well with the optimal core. The weight profile tends to that of the optimal while the loss curve indicates that at 150 μH the losses are low also approaching that in the optimal core. The peak current stress is 2.5 A and is helpful in determining the device ratings.

Further design information is now provided:

Upper limit on the number of turns for this core = 47

(based on window area)

Lower limit on the number of turns for this core = 22

(based on non-saturation of core)

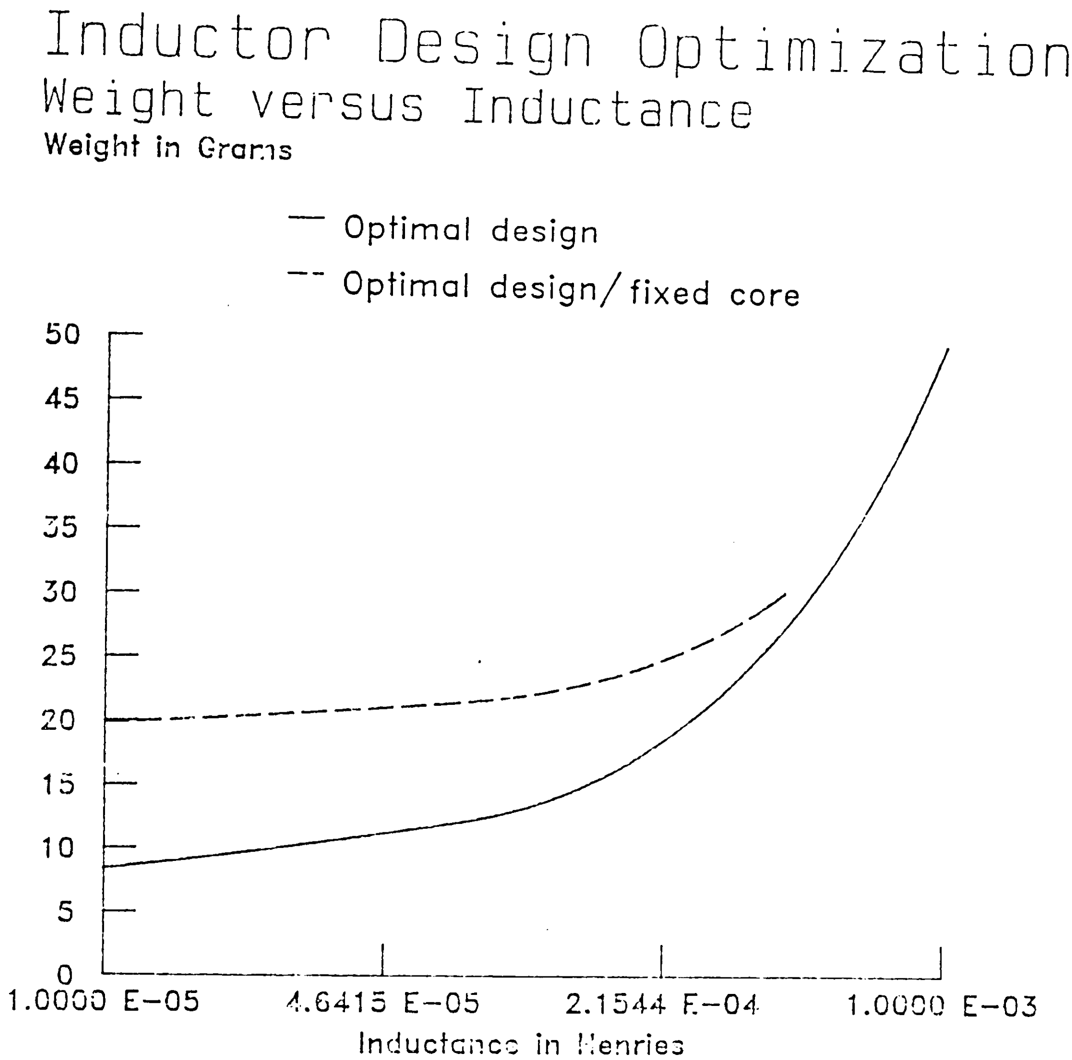


Figure 28. Boost converter: Optimal and Practical Core Weight Profiles

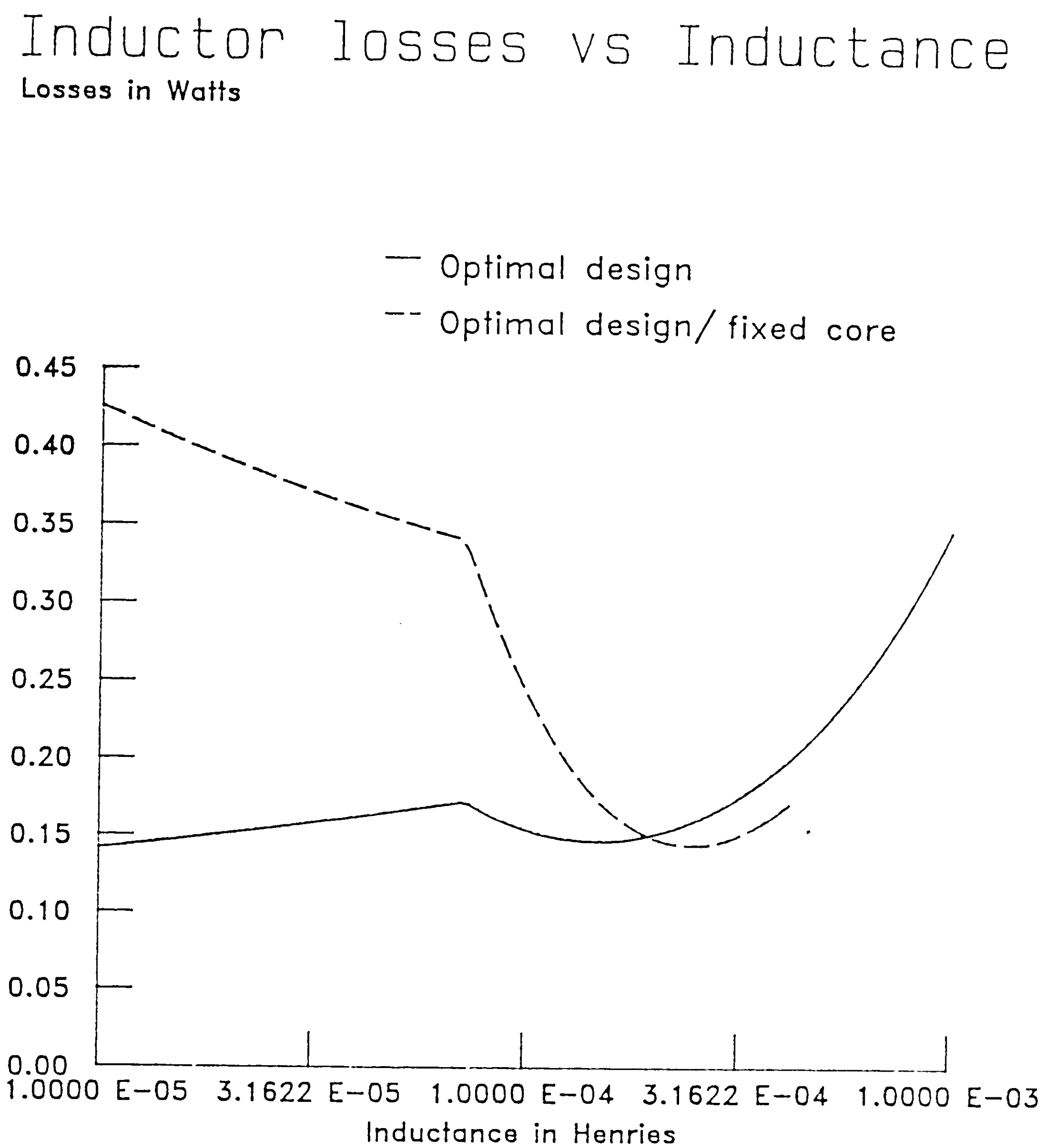


Figure 29. Boost Converter: Optimal and Practical Core Loss Profiles

Minimal weight with this core = 23.34 grams

Inductances of 432.88 microhenries or
larger cannot be wound on this core

Using the turns range suggested, a particular number of turns is to be picked by the user and the core air-gap determined. The minimum weight at 150 μH is determined to be 23.34 grams and since the core size is fixed, the maximum inductance that can be achieved is determined to be 432.88 μH.

Another E-core is chosen to complete the EE-core design. Having obtained the design for an inductance of 150 μH using the core #43007-EC, the procedure using INDOPT is completed.

5.0 Conclusions

An interactive, computer-aided graphical design procedure for EE- and EI-cored inductors used in switching DC-DC converters has been developed and presented. The software has been developed on the IBM-PC AT to function as a useful and portable design tool. The Buck, Boost, and the Buck/Boost converter topologies have been implemented in this procedure and the respective design examples presented.

The Lagrange Multiplier analytical solution [1] for the minimum weight inductor has been incorporated and the new tasks accomplished by this program is the optimization of practical designs for the minimum weight and the ability to obtain useful design insight rapidly. Design freedom to pick any commercially available core and perform comparative trade-offs is allowed. A key feature of this interactive procedure is that the weight of the inductor, the total core and copper losses, and the maximum current stress in the semiconductor devices can be considered and a trade-off performed in the process of determining the inductance and optimizing its magnetics design.

Thus an inductor with minimum weight can be designed for three switching DC-DC converter topologies, the procedure incorporating the dynamic aspects unique to each converter, and allowing the optimization of practical designs.

5.1.1 Future Work

Three converter topologies namely, the Buck, Boost and the Buck/Boost types have been considered and EE/EI-cored inductor designs are realizable with this package. Given the large family of derived converters, it is possible to reduce them to one of these basic configurations and optimize the design of the inductive element. Future effort could be directed to allow the user input complex converter topologies directly, and the program capable of performing the reduction, optimization, and rescaling to the original converter.

Other commonly used cores like pot-cores could be incorporated into the scope of this design procedure in order that the package be made more versatile. Modeling of winding losses could include high frequency effects and the effect of the operating frequency on the design are others aspect that would provide useful insight.

In this effort the analytical solutions using the Lagrange Multiplier were implemented. Comparing this approach with numerical optimization techniques like ALAG (Augmented Lagrangian), or even combining them if possible, could be the direction of future research. This could further refine design techniques in the effort to develop capable optimization tools for Power Electronics components and systems.

References

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2. S. A. Chin, D. Y. Chen, and F. C. Lee, "Optimization of the Energy Storage Inductors for DC-DC Converters", *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-19, no. 2, March 1983.

3. D. Y. Chen, H. A. Owen, Jr., and T. G. Wilson, "Computer-Aided Design and Graphics Applied to the Study of Inductor-Energy-Storage DC-to-DC Electronic Power Converters", *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-9, no. 4, July 1973.

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8. Rudolf P. Severns, Gordon E. Bloom,*Modern DC-to-DC Switchmode Power Converter Circuits*, Van Nostrand Reinhold Company, New York, 1985.

9. E. C. Snelling, *Soft Ferrites - Properties and Applications*, The Chemical Rubber Company Press, 18901 Cranwood Parkway, Cleveland, Ohio 44128, 1969.

Appendix A. User's Guide to INDOPT

The following discussion is intended to serve as a stand-alone guide to running and using INDOPT, a comprehensive, graphic, interactive computer-aided design tool to design minimum weight EE- and EI-core inductors used in switching power converters.

The User's Guide is organized as follows:

1. Computer Environment

2. Procedure and Operation

3. Design Example

A.1 Computer Environment

A.1.1 Software Setup

The program INDOPT has been written in FORTRAN and developed to run on the IBM Personal Computer AT using the IBM PC Professional FORTRAN Compiler, Version 1.0, © IBM Corp. 1984, and the IBM PC Plotting System, Version 1.0, © IBM Corp. 1984.

The IBM PC Professional Fortran compiler is based on the American National Standard Programming Language FORTRAN/77(ANSI X3.9-1978) but contains several IBM extensions. Reference [5] provides more information on this subject. Use of this compiler requires the IBM PC DOS, Version 2.1 or later and the IBM PC Linker, Version 2.3 or later, to link the programs so developed.

To use the Plotting System, the IBM PC Plotting System Library and the IBM Virtual Device Interface software are required. Device drivers as appropriate to the system on which the applications program is being run must be loaded. The DOS and the Linker versions required are the same as mentioned before. In developing INDOPT, the library routines pertaining to the IBM PC Professional FORTRAN Compiler were incorporated.

A.1.2 Machine Requirements

Currently the software runs on an IBM PC-AT equipped with a 20MB hard disk, 1MB memory, and two 1.2MB diskette drives. The graphics output devices the software writes to are: an IBM PC 320x200 four color medium resolution monitor and a HP 7475A six pen color plotter.

Corresponding to these graphics devices, the VDIDY004.SYS and the VDIPLSIX.SYS device drivers are loaded into memory when the system is initialized. INDOPT uses approximately 30KB of memory during a program run. It requires that a math coprocessor compatible with the system be installed. A serial port is used to communicate with the hardcopy graphics device.

Appropriate to the location where this program is being run, the device driver libraries that match the monitor and plotter must be initialized [7].

A.2 Procedure and Operation

A.2.1 Steps before running INDOPT

INDOPT requires two data files in the course of a run. These are called:

1. SPECS.INP

2. CONTROL.INP

The file SPECS.INP is to be used to specify the converter operating conditions, the magnetic material constants, material densities, copper resistivity, core aspect ratios and device voltage drops. Shown below is a typical data file.

File: SPECS.INP

```
19 0 0 0
30.0000000E+00 VIMAX          Maximum input voltage
```

25.0000000E+00 VIMIN	Minimum input voltage
40.0000000E+00 VO	Output voltage
1.00000000E+00 VQ	Transistor forward voltage drop
1.00000000E+00 VD	Diode forward voltage drop
40.0000000E+00 POMAX	Maximum output power
20.0000000E+03 FREQ	Switching frequency
0.35000000E+00 BS	Maximum allowable core flux density
8.90000000E+03 DC	Copper winding density
5.20000000E+03 DI	Core iron density
1.65000000E+00 FC	Winding pitch factor
0.25000000E+00 FW	Window fill factor
1.00000000E+00 K1	Core thickness/Tongue width
1.30000000E+00 K2	Core window height/Window width
3.99000000E-07 KC	Wire size proportionality constant
0.17240000E-07 RO	Copper resistivity
2.50000000E+00 EM	Core material parameter
1.32000000E+00 EN	Core material parameter

Data is read in the format (E14.7,1X,A10). Line one contains a parameter which tells the subroutine FNDCMP the number of values to be read in all. While many of the comments against the numbers listed above are self explanatory, it must be mentioned that KC is a constant used in determining the copper wire size to be used, EM and EN are parameters used in the core loss model of Section 2.3.2. [1]. In particular, the ferrite 3C8 has been used here. If other core materials are used then the EM and EN values are correspondingly altered.

The CONTROL.INP file is used to provide the program with certain parameters that affect the plot characteristics. Information that is passed on refers to

1. Inductance range for viewing plots

2. Number of points plotted

File: CONTROL.INP

```
  10.0E-06   1000.0E-06
100
```

Line one has values that form the upper and lower bounds on the inductance values over which the various characteristic curves are plotted. These numbers can be altered by the user if necessary. Line two tells the program the number of data points to be evaluated. This setting may not be altered.

A.2.2 Running the Program

The procedure discussed here refers to the version of INDOPT resident on the IBM PC AT at the Computational Laboratory of the Virginia Power Electronics Center.

1. Boot the IBM PC-AT to the C: drive

2. In response to the C> prompt, type
   CD RAM \ GRAFIKS <Enter>

3. To specify the converter operating conditions or to change any of the default parameters, the SPECS.INP file must be edited. This can be done by using the PCX Editor program resident in the sub-directory. Type
   PCX SPECS.INP <Enter>
   The file is opened and changes, if any, made. To close the file, hit <Enter> to position the cursor in the command line once again and type

FILE <Enter>

The changes have now been recorded. This procedure can be repeated with the CONTROL.INP file to alter the inductance range if necessary.

4. Ensure the C: \ RAM \ GRAFIKS> prompt returns to the screen. Now type

   INDOPT <Enter>

The program will now run and prompt the user to make a selection amongst the converter topologies. The design procedure is initiated thereafter in an interactive manner. Other prompts will then follow.

Halting Execution: To stop the execution of the program at any point, press the CNTRL and BREAK keys simultaneously. Execution is halted immediately.

Display Environment: After exiting the INDOPT program the display device must be reset using the DOS MODE command appropriate for the display. In its current location on the IBM PC-AT discussed here, type

RES <Enter>

This will restore the display environment and the cursor will become visible if not present.

A.3 Design Example

Discussed here is a complete program run with the various prompts and responses. Computer prompts are shown in bold type.

In this example an EE-cored inductor is optimally designed based on given specifications. The user then chooses a core from a design catalog, determines its effect on the weight and loss, performs trade-offs and iterates till an acceptable design is obtained.

Problem: Design an EE-core inductor, given converter specifications as below. Find the inductor's minimum weight, the peak transistor current, and the total inductor power loss for a Buck/Boost converter operated at a switching frequency of 40 kHz.

Specs:

$B_S = 0.35$, $F_W = 0.25$, $V_{I,max} = 30V$, $V_{I,min} = 25V$, $V_O = 40V$, $V_Q = 1V$, $V_D = 1V$, $P_{O,max} = 40W$

The specs are entered into the data file SPECS.INP; the various design constants remain the same as shown in the data file before. The CONTROL.INP file can be modified, if we wish to change the inductance sweep range.

In response to the C: \ RAM \ GRAFIKS> prompt, type

INDOPT <Enter>

The welcome message flashes on to the screen and the user is prompted to make a choice of the converter type. Once this is made, the converter specs appear on the screen and execution continues. Shown below are excerpts of what actually appears on the monitor.

Buck/Boost converter inductor design

The critical inductance is: 0.70 E-04 Henries

Execution suspended: Please press Enter to view graphs..

Now the user is prompted to view the characteristic profiles of the Optimal Inductor Weight versus Inductance, the Total Inductor Losses versus Inductance, and the Peak Switch Current versus Inductance.

Upon pressing <Enter> the user can scroll through these curves to identify the inductance that would result in

- the lowest total inductor losses
- the least device current stress

Having identified an inductance, the Weight versus Inductance profile provides an estimate of the lowest possible weight of the inductor. Upon specifying the inductance, the detailed design of the inductor to achieve minimum weight is performed by the program. This design is the Lagrange Multiplier optimal solution. These characteristic curves are shown in figures (30), (31), and (32).

From the curves we can identify 150 μH to be the inductance which would result in the least losses and allow a small peak current stress in the transistor switch and diode. These features are desirable, so we would like to design the minimum weight inductor having an inductance of 150 μH.

The dimensions of this optimal core is determined by the program and is the Lagrange Multiplier solution to the design problem. The user is prompted further.

Are you designing an EI or an EE core?

Enter 1 if EI core or 2 if EE core

Select the type of core to be designed. Upon entering the appropriate number, 2, in this case, operation continues.

This is an EE core design.....

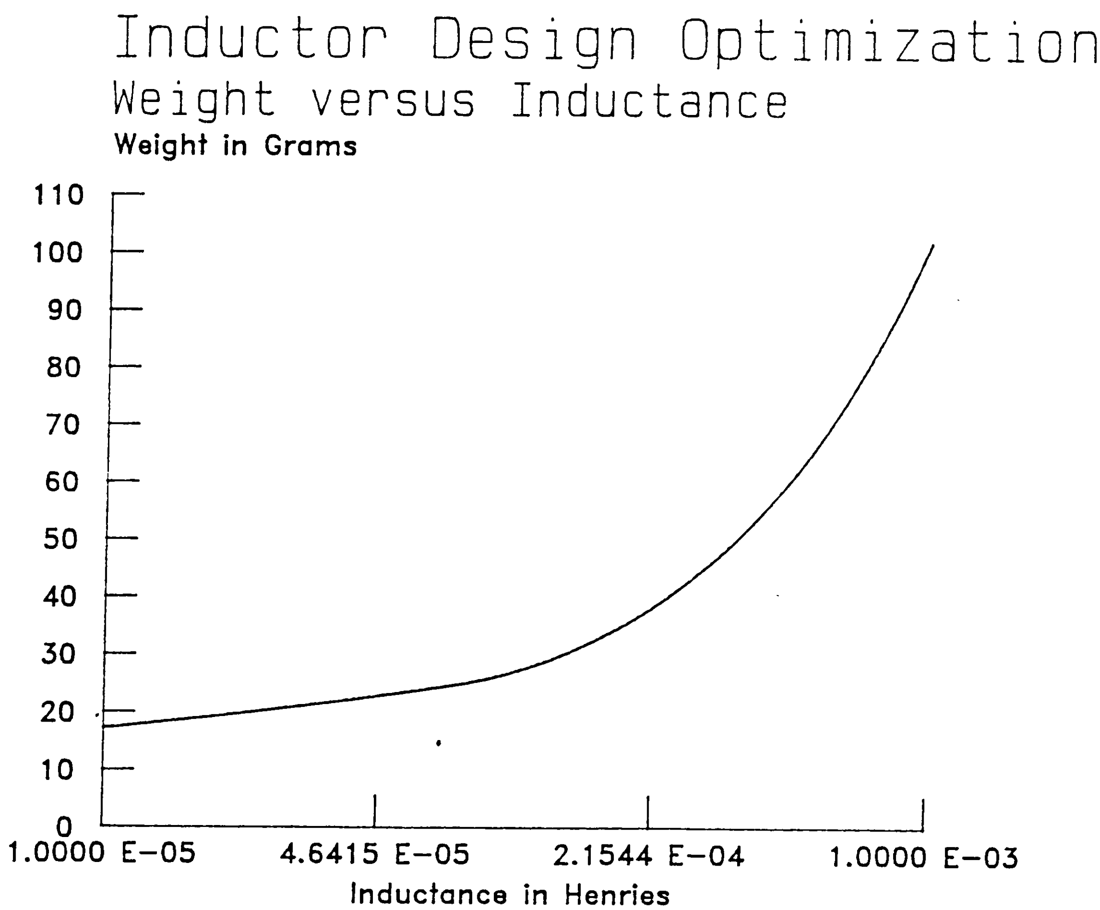

Figure 30. Buck/Boost Converter. Optimal Core Weight vs. Inductance

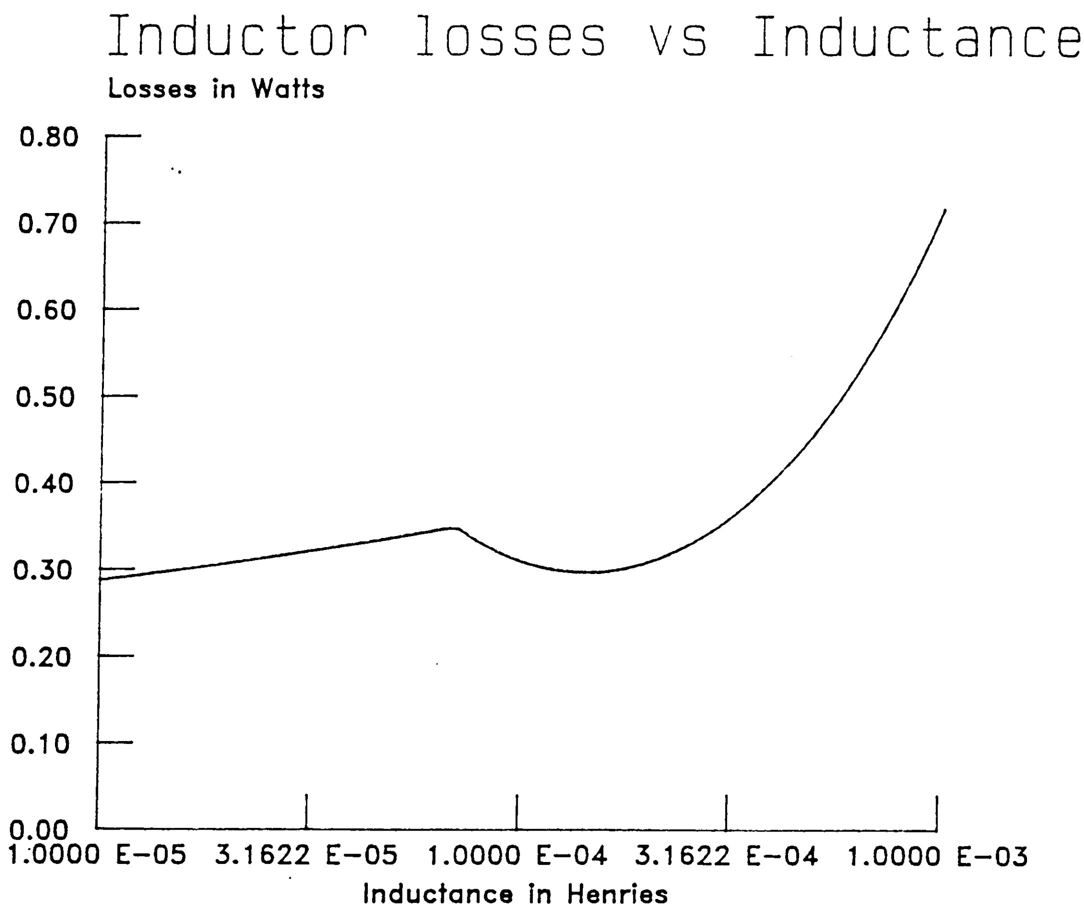

Figure 31. Buck/Boost Converter. Total Inductor Losses vs. Inductance

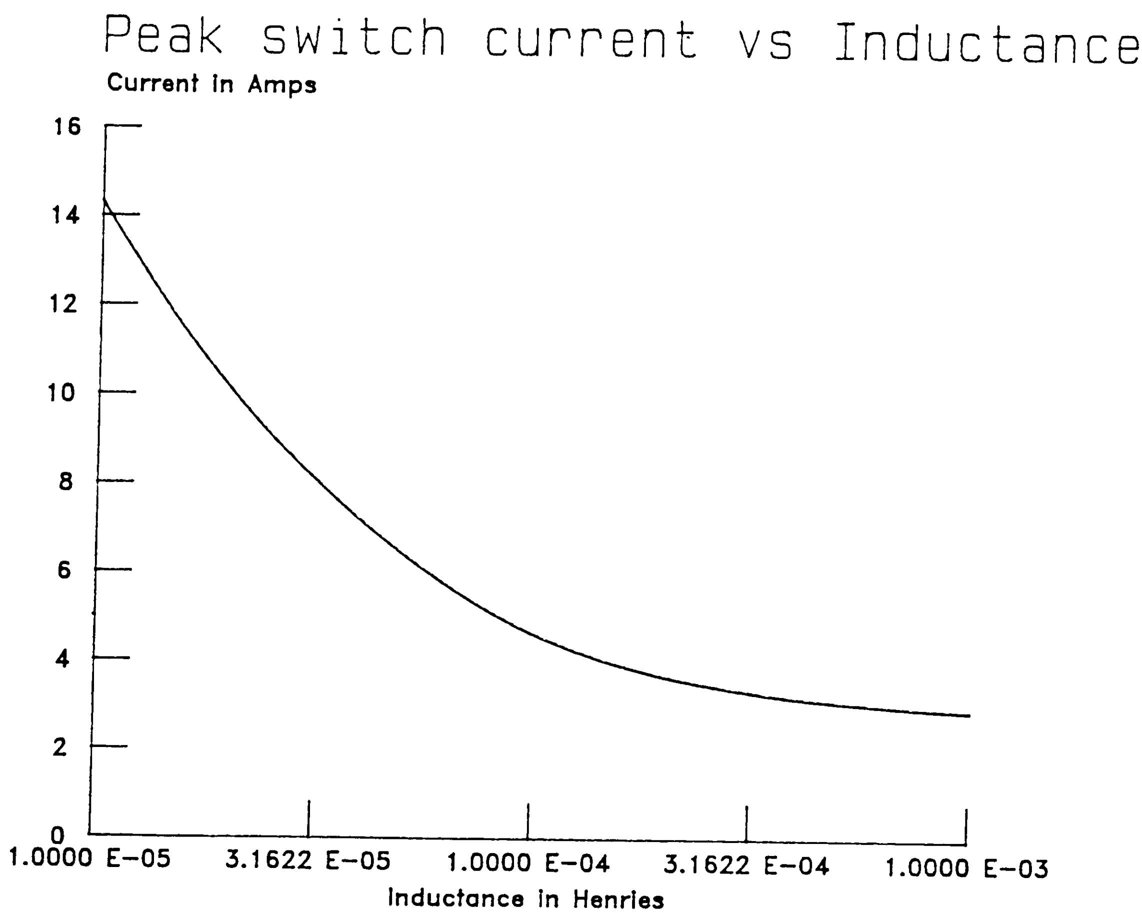

Figure 32. Buck/Boost Converter. Peak Transistor Current vs. Inductance

Enter value of inductance in microhenries.

Enter the value of inductance for which the minimum weight core is to be designed. For this problem 150 μH is the value, so enter 150 in response to the prompts. The following information is determined, as operation continues.....

Inductance L = 150.00 microhenries

Peak transistor current	=	**3.97**	**amps**
Inductor weight	=	**31.86**	**grams**
Power loss	=	**0.300**	**watts**
Wire size	=	**0.11E+01**	**square mm**
Number of turns	=	**46**	
Window width, G	=	**12.53**	**mm**
Leg length, D	=	**8.14**	**mm**
Center leg width, F	=	**6.11**	**mm**
Core thickness, C	=	**6.11**	**mm**

Do you wish to fix the core dimensions ? Enter Y for Yes or N for No.

The optimal core weight and design details are computed and presented as above. Further, the peak transistor current and the total inductor losses at this inductance are indicated.

From a catalog select an E-core that has a window area and center leg cross-sectional area at least as big as the design. While one of these two areas may be smaller than the design, in no event can the core picked have both window and core cross-sectional areas smaller than the optimal design, if the specified inductance is to be achieved. Using information from a Magnetics Catalog, part #45021-EC is picked and the core dimensions entered in response to the prompts.

Enter value for window width G in mm

G = 10.10 mm

Enter value for leg length D in mm

D = 12.75 mm

Enter value for core thickness C in mm

C = 14.60 mm

Enter value for center leg width F in mm

F = 14.60 mm

Given the chosen core, the following information is determined.....

Upper limit on the number of turns for this core = 58

(based on window area)

Lower limit on the number of turns for this core = 8

(based on non-saturation of core)

Minimal weight with this core = 118.96 grams

The above range of turns corresponds to the wire size already determined. A combination of air gap and turns must be chosen by the designer to achieve the desired inductance. The inductor's minimal weight with this core now depends only on the number of turns. This weight has been computed using the lower limit.

Do you wish to see the new characteristics with this core?

Enter Y for Yes or N for No.

Y

The critical inductance is: 0.70 E-04 Henries

Given the core, the weight would vary if the inductance were changed. The profile of the least possible weight versus inductance can be plotted and compared to that of the optimal core, shown in figure (33). Also, the total inductor losses can be compared to that of the optimal core, shown in figure (34). A profile of the peak transistor current versus inductance is also plotted in figure (35). These curves are used to perform trade-offs between the parameters of minimal weight, total inductor losses, and the maximum current in the switch.

The critical inductance is determined and presented, allowing the designer to be aware of the mode in which the converter would operate for a particular choice of inductance.

On the following pages are the graphs used in the design process.

Do you wish to repeat the design procedure ? Enter Y for Yes or N for No.

Y

The critical inductance is determined to be 70 μH which would imply that using a smaller inductor would result in operating the converter in the discontinuous conduction mode. From the characteristics it can be seen that inductances about 300 μH result in fewer losses and lower peak current stress though the inductor weight is slightly higher than that corresponding to 150 μH.

Consequently, it appears that a bigger inductance may be a better choice. However, we can defer specifying another value until our choice of the E-core results in a close-to-optimal characteristic.

It is apparent that the particular choice of core is very heavy and for inductances below 215 μH, the losses are much greater than those of the optimal core. We choose to iterate with new cores picked from the catalog.

Now the design procedure is initiated once again........

Are you designing an EI or an EE core?

Enter 1 if EI core or 2 if EE core

This is an EE core design.....

Enter value of inductance in microhenries.

Inductance = 150.00 microhenries

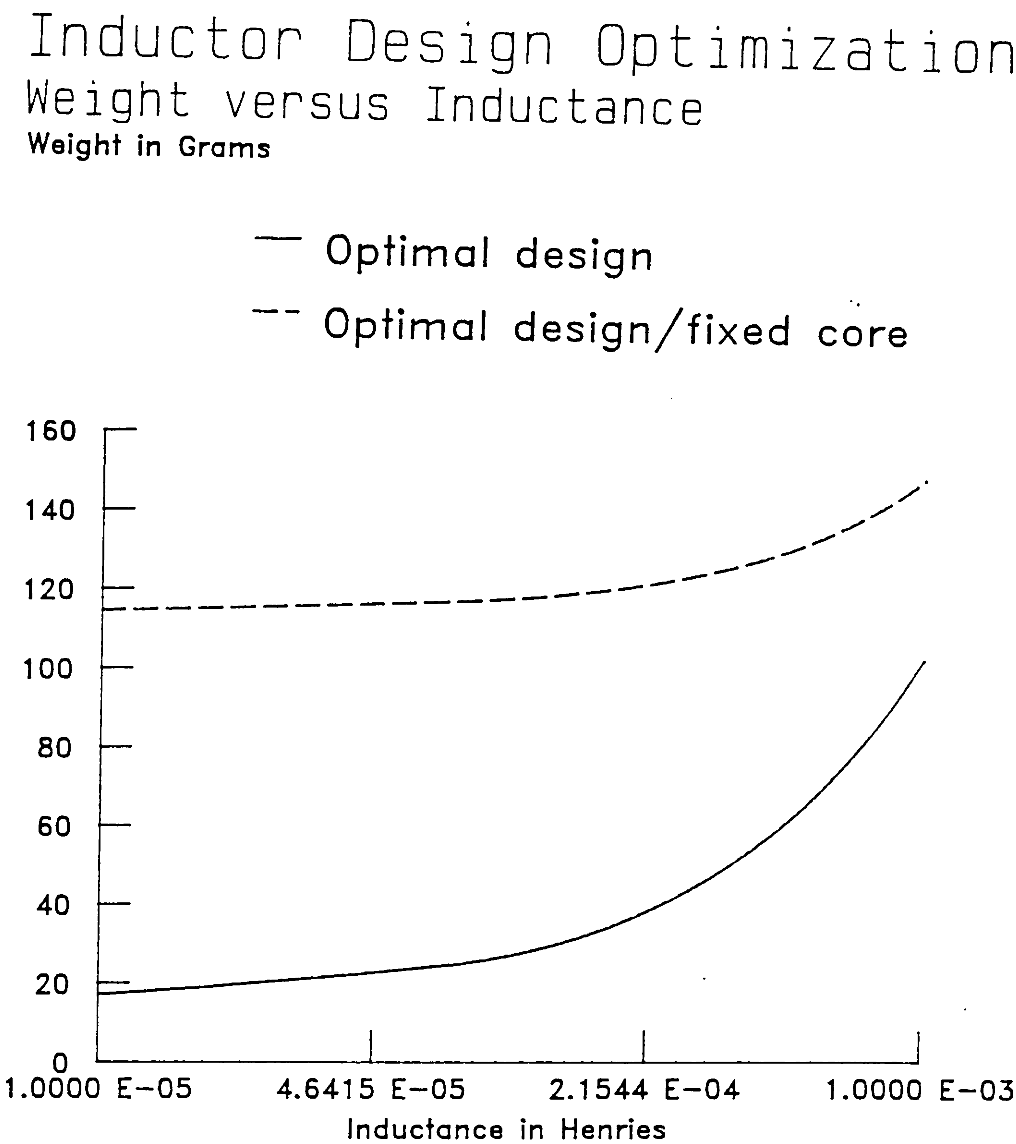

Figure 33. Buck/Boost Converter. Optimal and Practical Core Weight Profiles

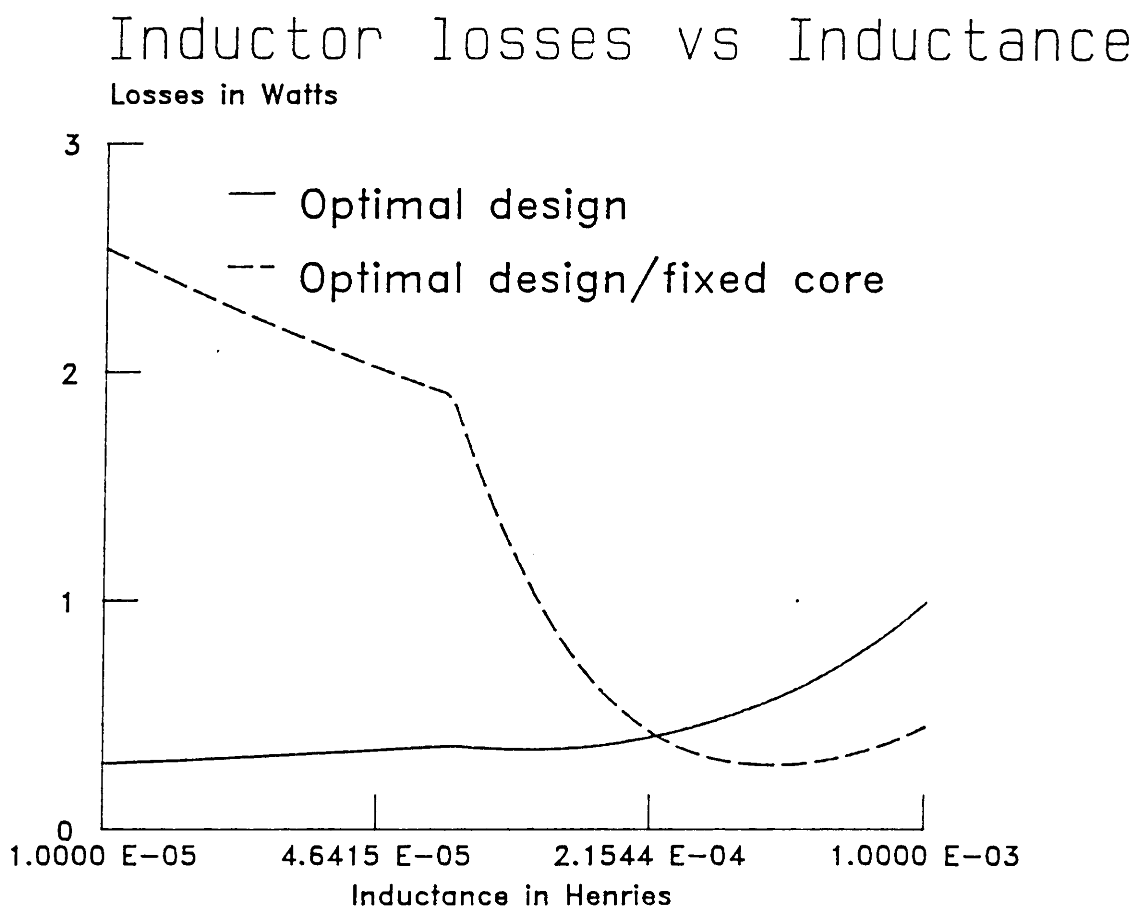

Figure 34. Buck/Boost Converter. Optimal and Practical Core Loss Profiles

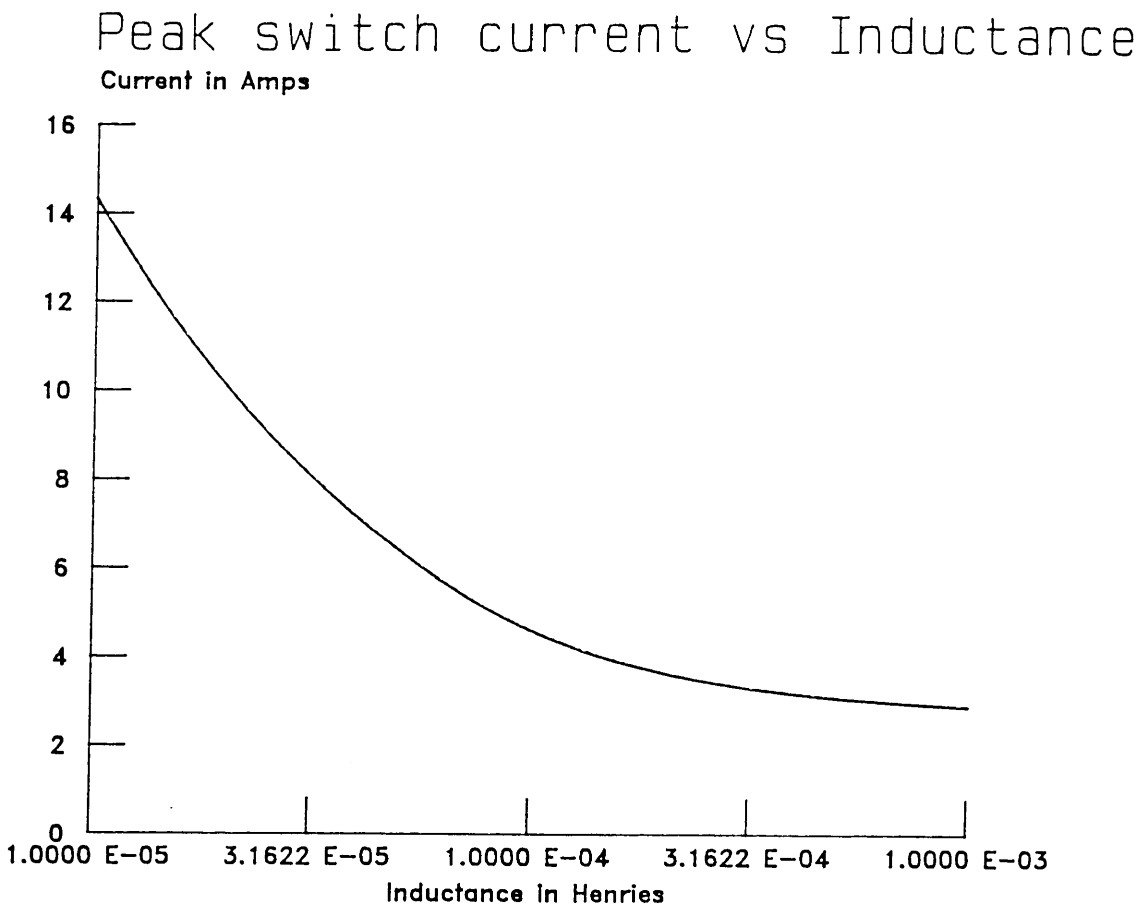

Figure 35. Buck/Boost Converter. Peak Transistor Current vs. Inductance

Peak transistor current	=	3.97	amps
Inductor weight	=	31.86	grams
Power loss	=	0.30	watts
Wire size	=	0.11E+01	square mm
Number of turns	=	46	
Window width, G	=	12.53	mm
Leg length, D	=	8.14	mm
Center leg width, F	=	6.11	mm
Core thickness, C	=	6.11	mm

Do you wish to fix the core dimensions ? Enter Y for Yes or N for No.

We pick an E-core, part #45015-EC which is smaller than that chosen during the previous pass, but having a window area close to that of the optimal core. Notice that this core has a center leg area much bigger than that of the optimal core designed by the program. This could allow us to wind the desired inductance using fewer turns than that required using the optimal core.

Enter value for window width G in mm

G = 11.78 mm

Enter value for leg length D in mm

D = 8.15 mm

Enter value for core thickness C in mm

C = 13.20 mm

Enter value for center leg width F in mm

F = 12.60 mm

Upper limit on the number of turns for this core = 43

(based on window area)

Lower limit on the number of turns for this core = 10

(based on non-saturation of core)

Minimal weight with this core = 78.85 grams

Do you wish to see the new characteristics with this core?

Enter Y for Yes or N for No.

Y

It is clear that this core results in a much lesser weight than what was obtainable in the previous iteration. The new characteristic curves can be viewed again. They are shown in figures (36) and (37).

While the core weight and the losses are functions of core geometry, the maximum current depends solely on the converter specs. Thus, the peak current versus inductance profile seen earlier in figure (35) remains valid.

The smaller window with this core will limit the inductance that can be achieved. This information is computed and displayed.

Inductances of 911.16 microhenries or

larger cannot be wound on this core

We repeat the design procedure picking other cores and comparing their characteristic profiles with the intention of choosing one that is most satisfactory with respect to the parameters of weight, loss, and peak current stress.

In the next iteration core part #43007-EC is picked. Its dimensions are:

G = 6.46 mm

D = 10.01 mm

C = 7.06 mm

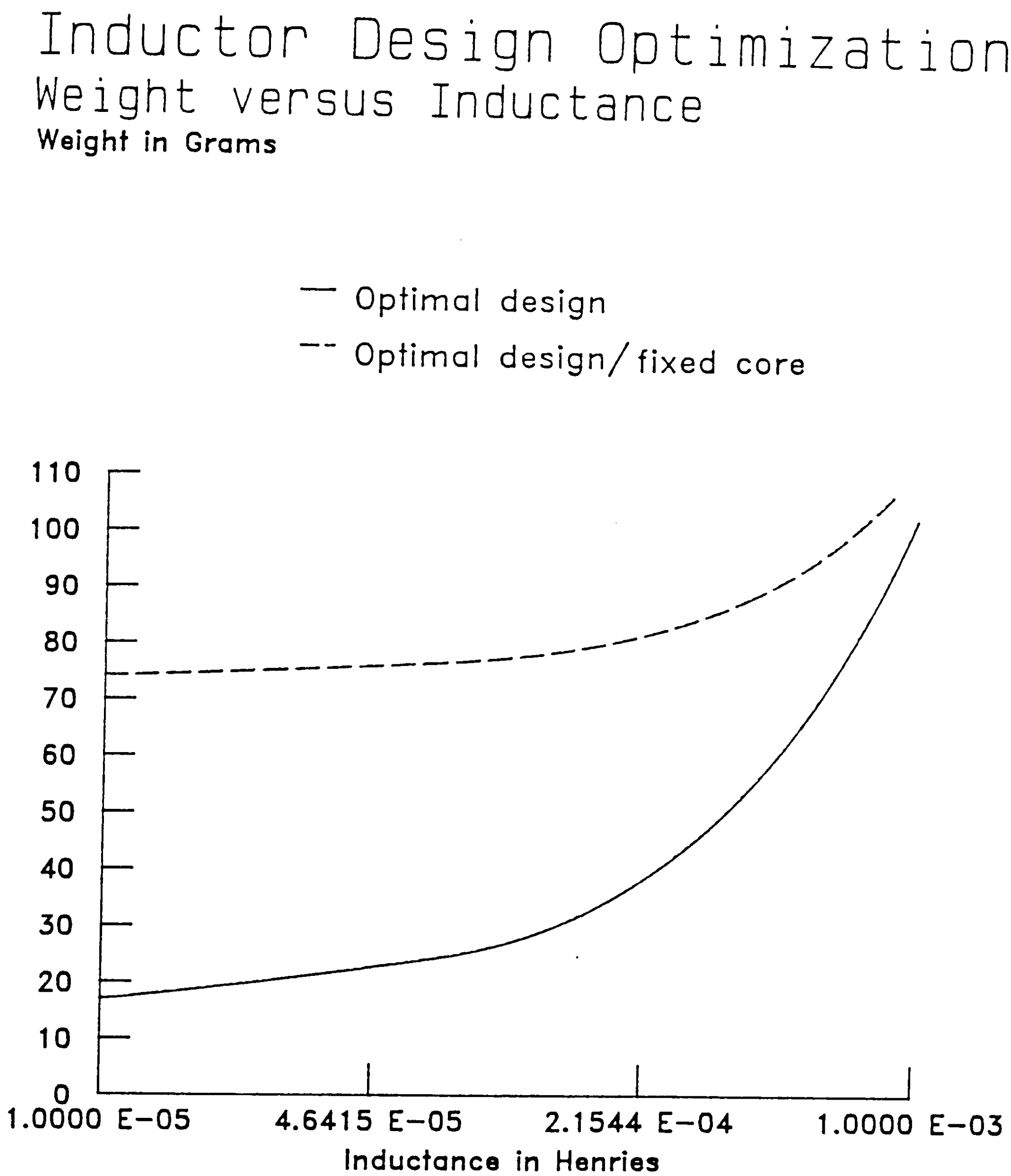

Figure 36. Buck/Boost Converter. Optimal and Practical Core Weight Profiles

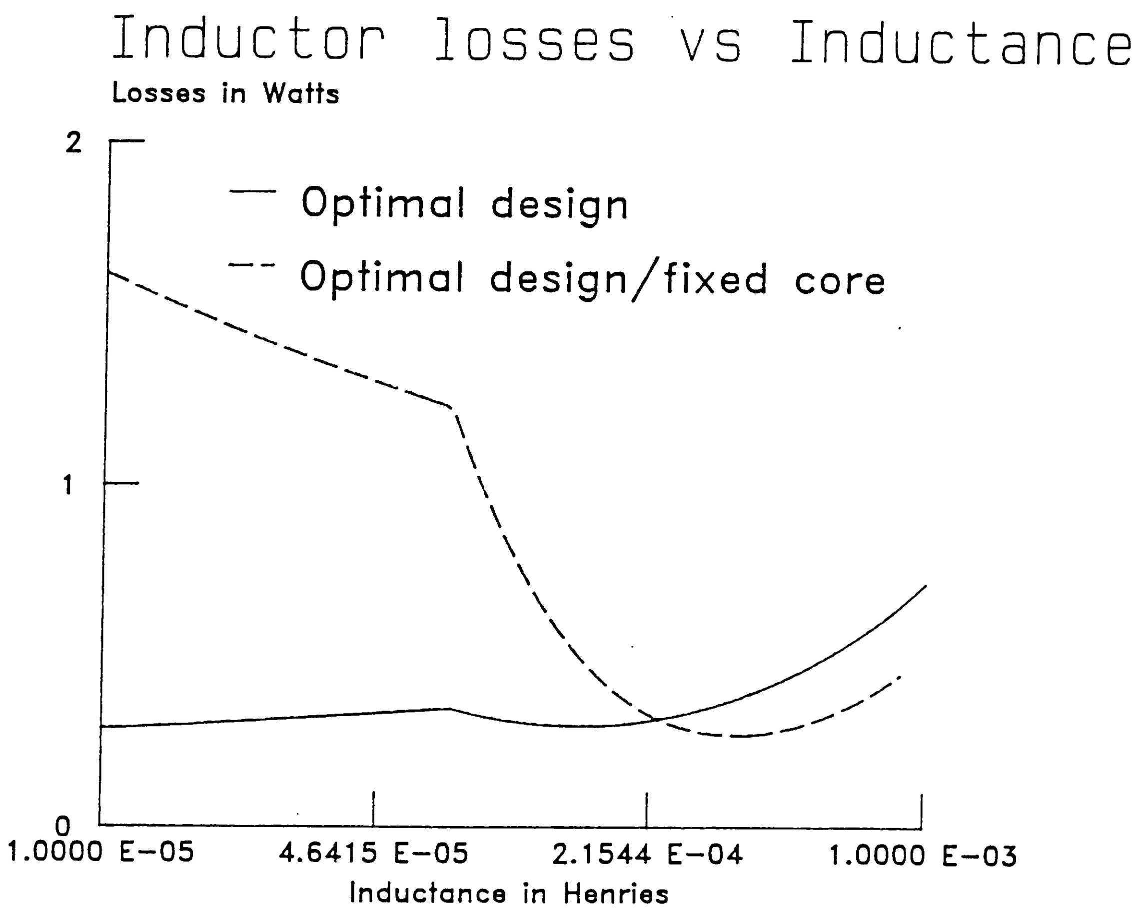

Figure 37. Buck/Boost Converter. Optimal and Practical Core Loss Profiles

$F = 6.96$ mm

The program determines the turns that can be used to achieve 150 μH using the wire gauge determined above.

Upper limit on the number of turns for this core = 29

(based on window area)

Lower limit on the number of turns for this core = 35

(based on non-saturation of core)

It can be seen the turns needed are conflicting, each requirement arising from meeting the window area and the non-saturation constraints respectively. The following message appears on the screen:

This core cannot be used for the desired value of inductance.

The upper limit on the turns is determined based on the available window area. The lower limit is arrived at by not allowing the core to saturate. For the core chosen it is apparent that these two constraints are conflicting and therefore, the desired inductance cannot be obtained. However, it may still be possible to wind another inductance with this core. This information is provided to the user.

Viewing the weight and loss profiles in figures (38) and (39) can help perform design trade-offs.

Do you wish to see the new characteristics with this core?

Enter Y for Yes or N for No.

Y

The design graphs can be seen on the pages that follow.

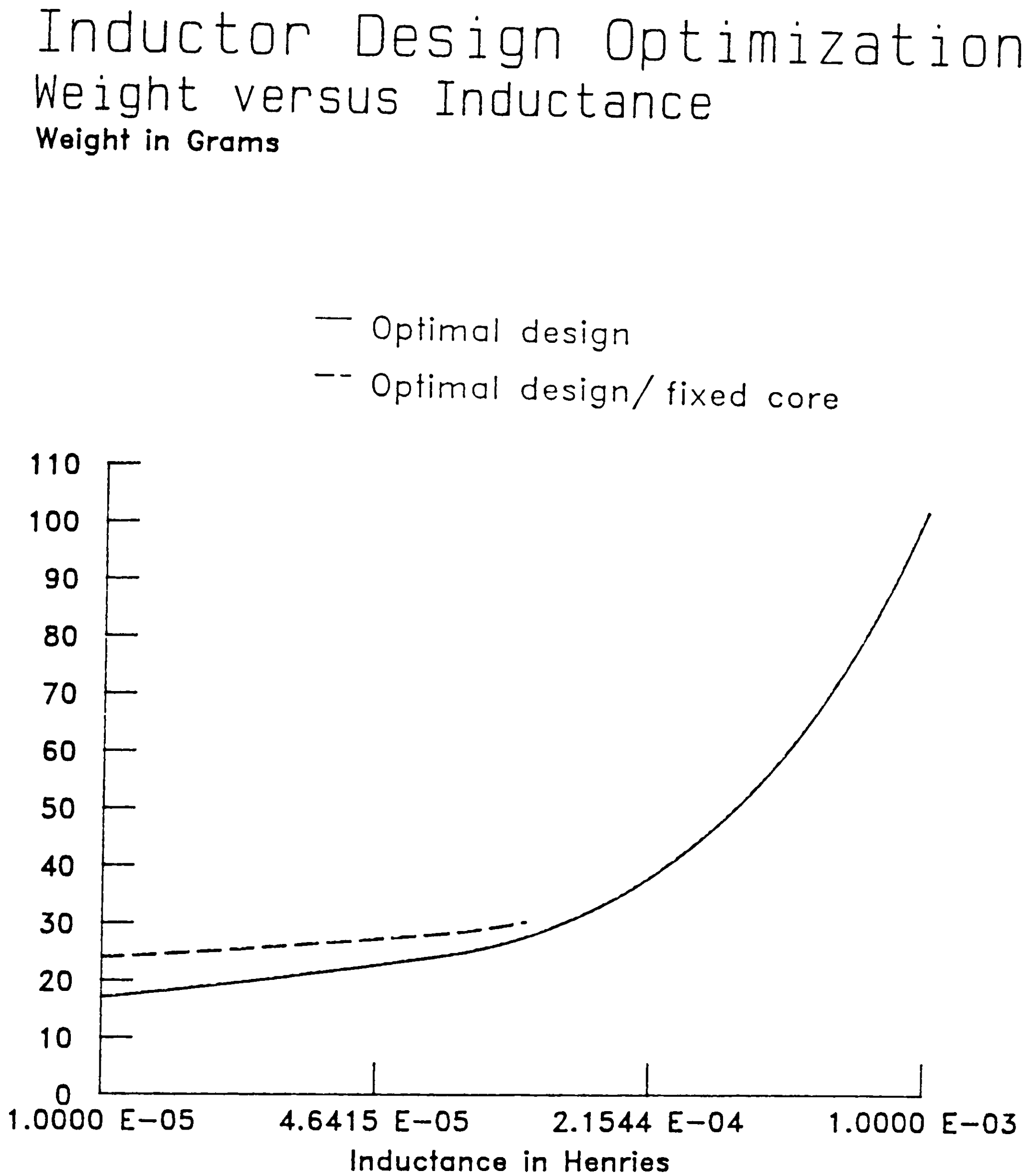

Figure 38. Buck/Boost Converter. Optimal and Practical Core Weight Profiles

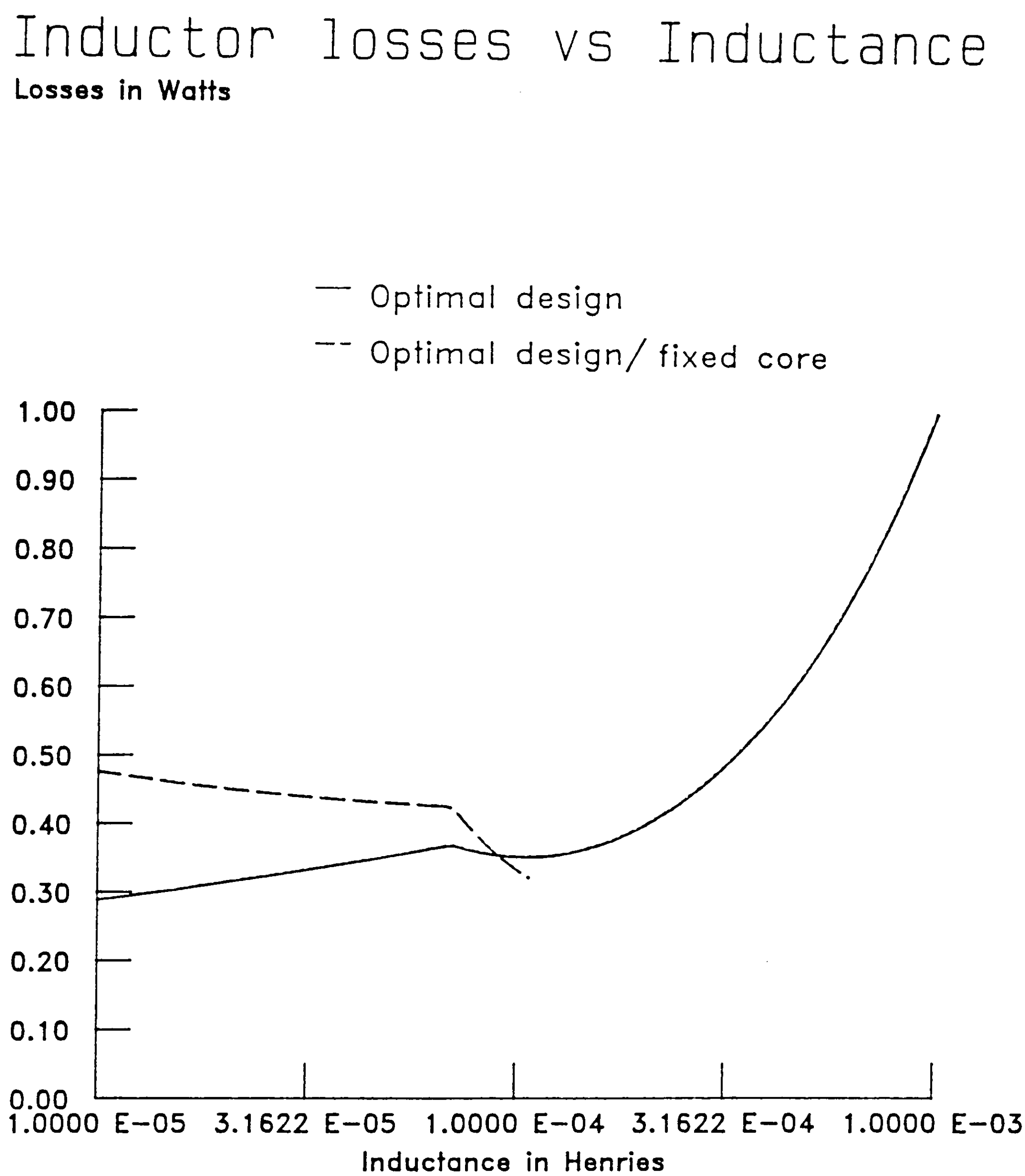

Figure 39. Buck/Boost Converter. Optimal and Practical Core Loss Profiles

The characteristics reveal the range of inductances that can be achieved with a given core and the corresponding minimal weight. The chosen core during this iteration is much smaller than the earlier one; consequently, it weighs less and the losses are fewer. Further, the small size limits the inductance that can be achieved with this core.

Information about the inductances that can be obtained is now presented...

Inductances of 112.33 microhenries or

larger cannot be wound on this core

Do you wish to repeat the design procedure ?

Enter Y for Yes or N for No.

Y

Another design iteration is now initiated. This time core #44011-EC is picked. Its dimensions are:

G = 8.66 mm

D = 10.26 mm

C = 10.69 mm

F = 10.69 mm

For the inductance of 150 μH the optimal design is computed and the new core dimensions are entered. As before the upper and lower limits on the turns are determined.

Upper limit on turns = 40

Lower limit on turns = 15

Minimal weight with this core = 57.92 grams

For the core chosen, the deviation from optimum weight is seen to be higher than the previous iteration. The loss profile indicates that the total inductor losses are minimal at a higher inductance of about 300 μH. However, if a higher inductance is chosen, the corresponding weight would increase.

These trade-offs can be made by viewing the new weight and loss profiles shown on the following pages. The curves are plotted in figures (40) and (41).

More design information is now presented:

Inductances of 546.23 microhenries or

larger cannot be wound on this core

From these profiles we can conclude that the previous choice of core resulted in low weight and losses, both parameters being very desirable. We can go back to choose core part #43007-EC and an inductance of 100 μH which results in the most favorable weight and loss features, while ensuring a small peak current stress.

This iteration is initiated now. The user responses are similar to what has been detailed above, the inductance value chosen to be 100 μH.

Enter value of inductance in microhenries.

Inductance L = 100.00 microhenries

Peak transistor current	=	**4.601**	**amps**
Inductor weight	=	**27.065**	**grams**
Power loss	=	**0.309**	**watts**
Wire size	=	**0.12E+01**	**square mm**
Number of turns	=	**40**	
Window width, G	=	**11.863**	**mm**
Leg length, D	=	**7.711**	**mm**

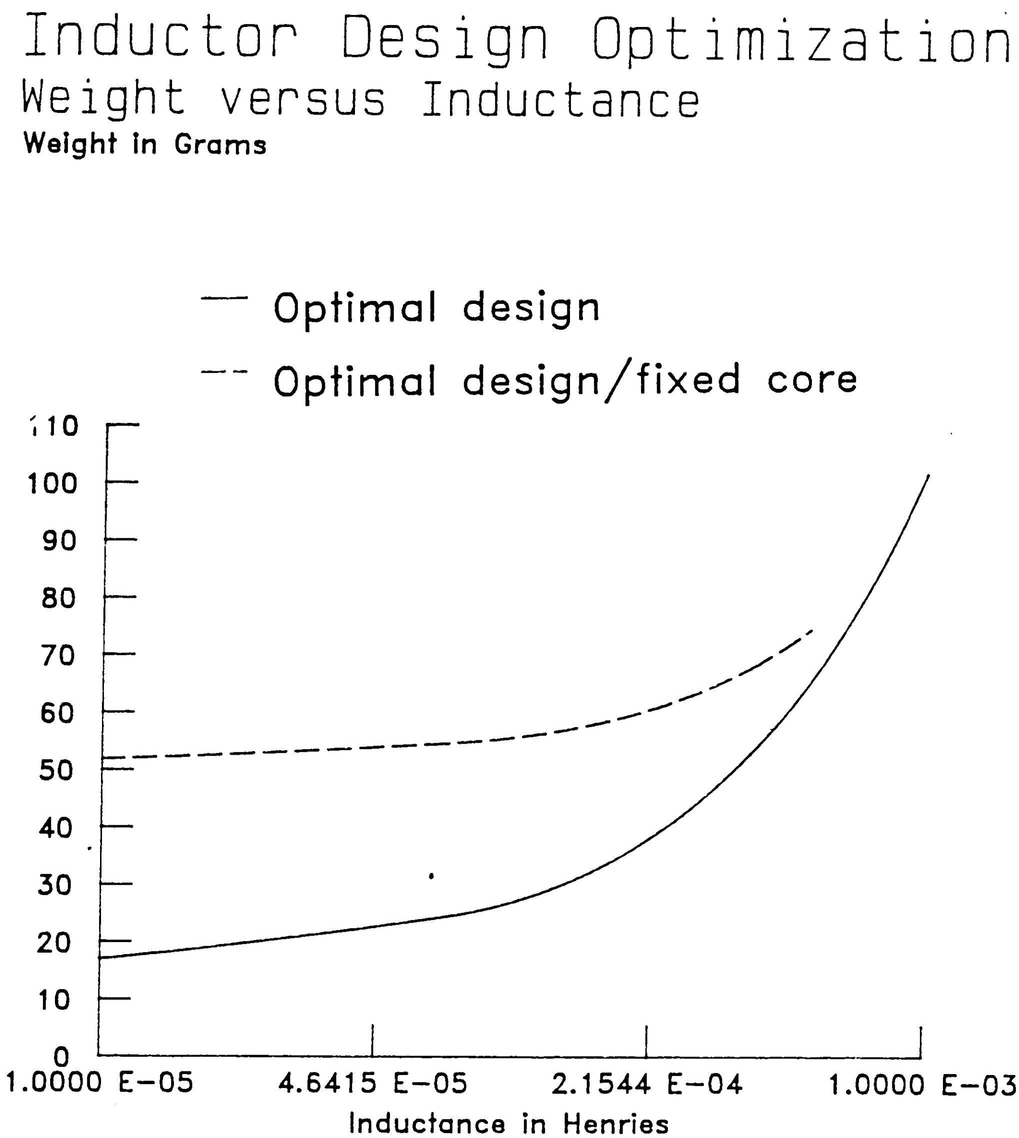

Figure 40. Buck/Boost Converter. Optimal and Practical Core Weight Profiles

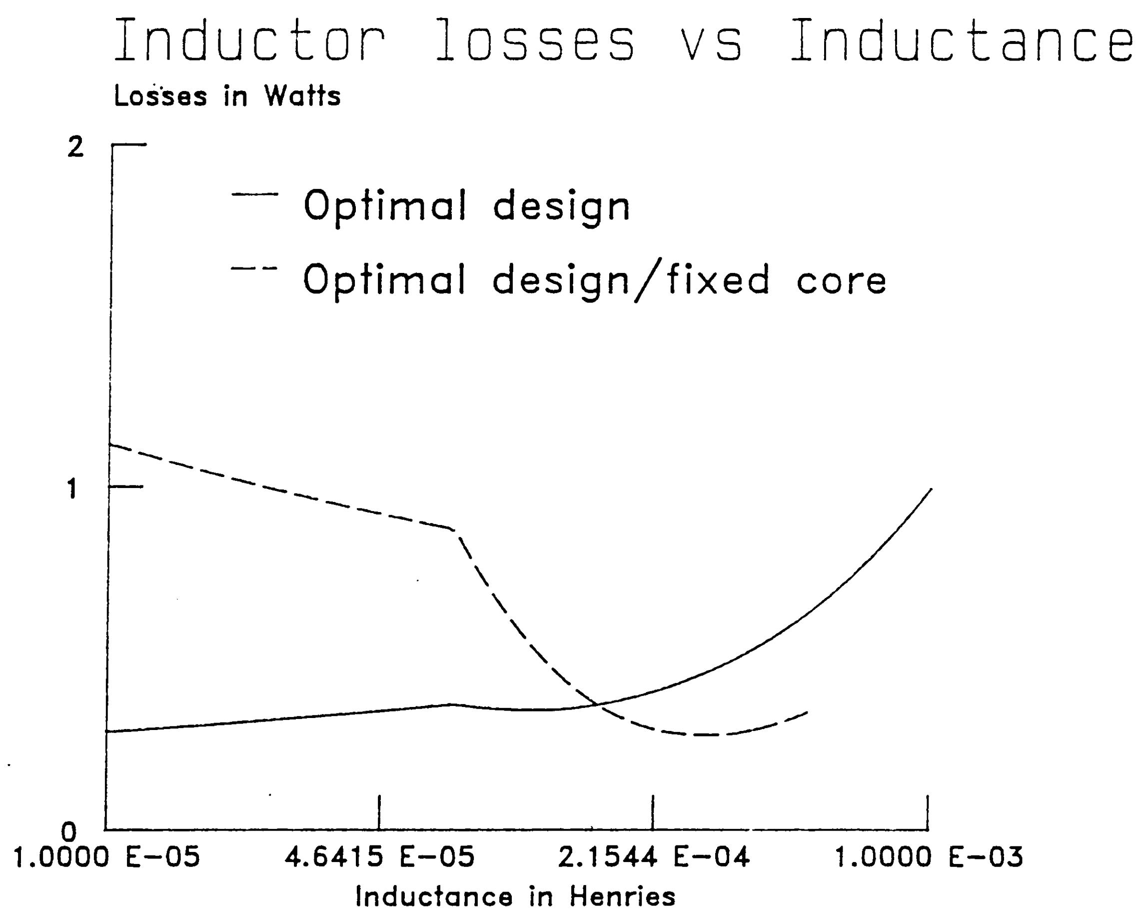

Figure 41. Buck/Boost Converter. Optimal and Practical Core Loss Profiles

Center leg width, F = 5.787 mm

Core thickness, C = 5.787 mm

The core dimensions are specified in response to the prompts from the program. The messages on the monitor are shown below.

Enter value for window width G in mm

G = 6.46 mm

Enter value for leg length D in mm

D = 10.01 mm

Enter value for core thickness C in mm

C = 7.06 mm

Enter value for center leg width F in mm

F = 6.96 mm

Upper limit on the number of turns for this core = 28

Lower limit on the number of turns for this core = 27

Minimal weight with this core = 30.04 grams

Do you wish to see the new characteristics with this core?

Enter Y for Yes or N for No.

N

Inductances of 112.33 microhenries or

larger cannot be wound on this core

Do you wish to repeat the design procedure ?

Enter Y for Yes or N for No.

N

For the turns of wire determined above, the length of the air-gap is calculated. The other identical E-core is picked and the design implemented to realize this EE-cored inductor.

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