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# CRITICAL CHOICES IN A SYSTEM FOR OPTIMIZED DESIGN OF ARBITRARY WAVEFORM TRANSFORMERS

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Traditionally, magnetic component design has been based on power frequency transformers with sinusoidal excitation. However, the movement towards higher density integrated circuits means that reductions in the size of magnetic components must be achieved by operating at higher frequencies, mainly through nonsinusoidal switching circuits. As this trend continues, computing tools are required to carry out designs of magnetic components that also allow evaluation of the high frequency losses in these components. A computer design package is described here that implements a robust transformer design methodology allowing customizable transformer geometries. The concept of a critical frequency is a vital part of this methodology. In addition, the winding choice at high frequencies is optimized to give the most accurate results for the best possible speed. This paper includes a description of the software design processes used and describes the main aspects that were incorporated into the system.

*Keywords*: Transformers; magnetics; computer-aided design; optimization; high frequency; graphical user interfaces.

## 1. Introduction

In the past, the design of magnetic components was largely based on following empirical rules and reading values from design graphs. This was often quite time-consuming, involving a one-way process which had to be repeated from the very beginning if one of the initial parameters, such as the desired output voltage for example, needed to be changed. Also, a number of different catalogues would often have to be referenced, for example wire size tables, data sheets for various cores, and other graphs for the properties of the available core materials. Now that computer-aided design packages are becoming more pervasive, tools can be developed to assist in the design of magnetic components from stored catalogue information, and also to allow evaluation of high frequency effects on the induced losses in these components. The basic design methodology for transformers at both low and high frequencies involves the area product method.[1] However, while an acceptable design results from this methodology, the design is not optimal either in terms of the losses or the size. A new arbitrary waveform transformer design methodology was proposed[2] that is suitable for integration with high frequency winding loss minimization techniques.[3,4]

This paper describes how the methodology has been adapted for use in an application that incorporates both core and winding data previously obtained by consulting catalogues. It emphasizes in particular two critical choices in the design of transformers at various frequencies: whether the critical frequency has been exceeded or not, and if the transformer winding thickness can be optimized for the current specifications. This system not only saves on the time previously required either designing by hand or working with spreadsheets and consulting catalogues, but the accuracy of designs can be improved by avoiding errors commonly encountered when writing on paper or when reading from design graphs. After being guided by the graphical user interface (GUI) system through the various stages, a full design may be prepared along with all of the required core and wire size information.

Initially, an overview of the design process is given, and this will motivate how the transformer system was developed. We will examine the concept of a critical frequency in some detail, followed by a comparison of winding optimization possibilities for implementation in the system. This paper will present a high-level overview of the system with screenshots of the software and test results.

## 2. Transformer Design Process

The basic design process implemented by CAD packages[5,6] includes an idea stage, in which the designer formulates a concept; a calculation stage, where the proposed designs are analyzed; and a judgement stage which will often lead to new concepts being proposed. In a transformer design, application specifications are entered (concept formulation); geometric definitions of transformer cores and windings are made subject to manufacturing details and constraints (design analysis); and predicted performance data — losses, efficiency, temperature rise, etc. — are examined (critical evaluation) as shown in Fig. 1. It may be necessary after judgement to return to the idea or calculation stages to make changes to the design if unsatisfied with the outcome. We will now discuss the two main decision blocks of Fig. 1 in more detail.

### 2.1. *Critical frequency*

The selection of the core is optimized in the transformer methodology[2] to minimize both the core and winding losses. The design can take one of two different paths depending on whether a "critical frequency" is exceeded or not, as represented by the first decision box in the flow chart of Fig. 1. For any transformer application, the critical frequency occurs when a calculated optimum flux density is equal to the saturation flux density as specified by the manufacturer for the core material being used. Above this critical frequency, the total transformer loss can be optimized by setting the flux density equal to the optimum value (which will be less than the saturation value), and the core and winding losses will be approximately equal when

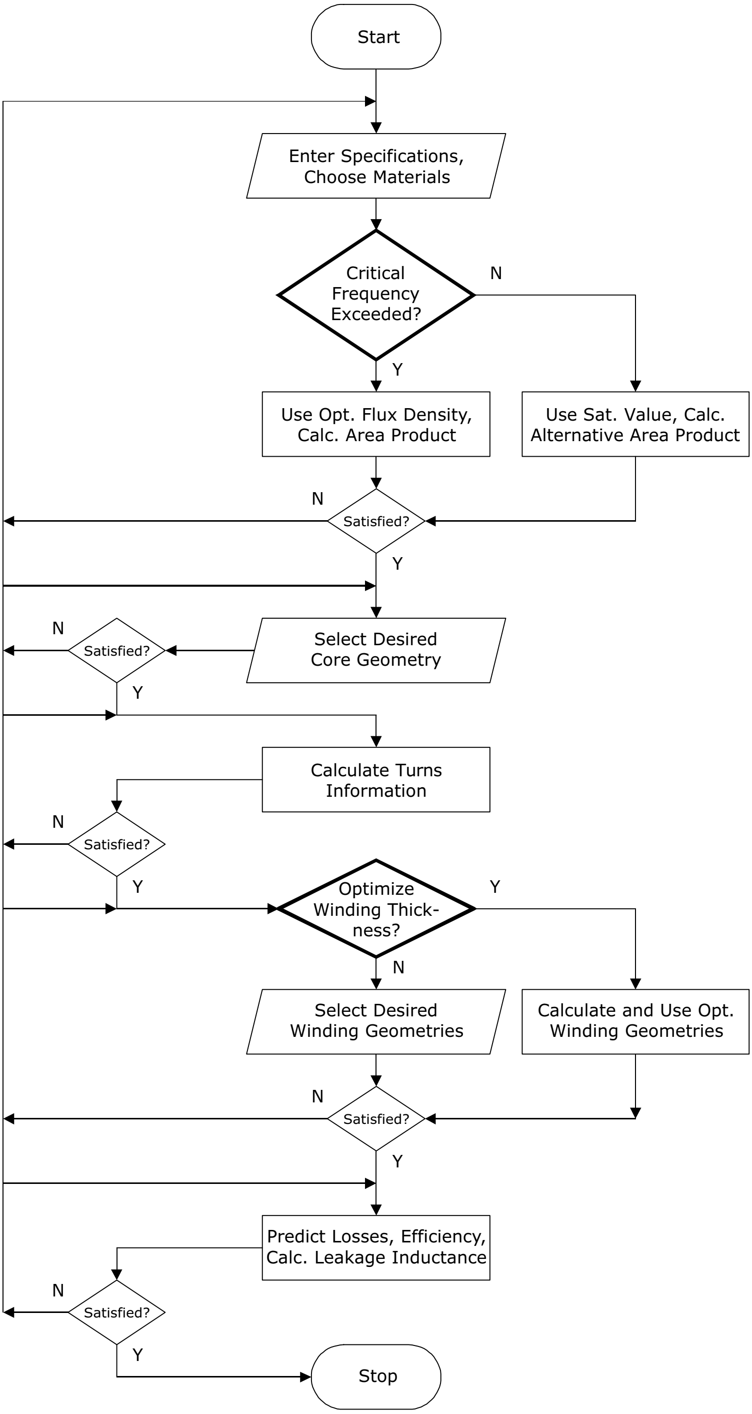
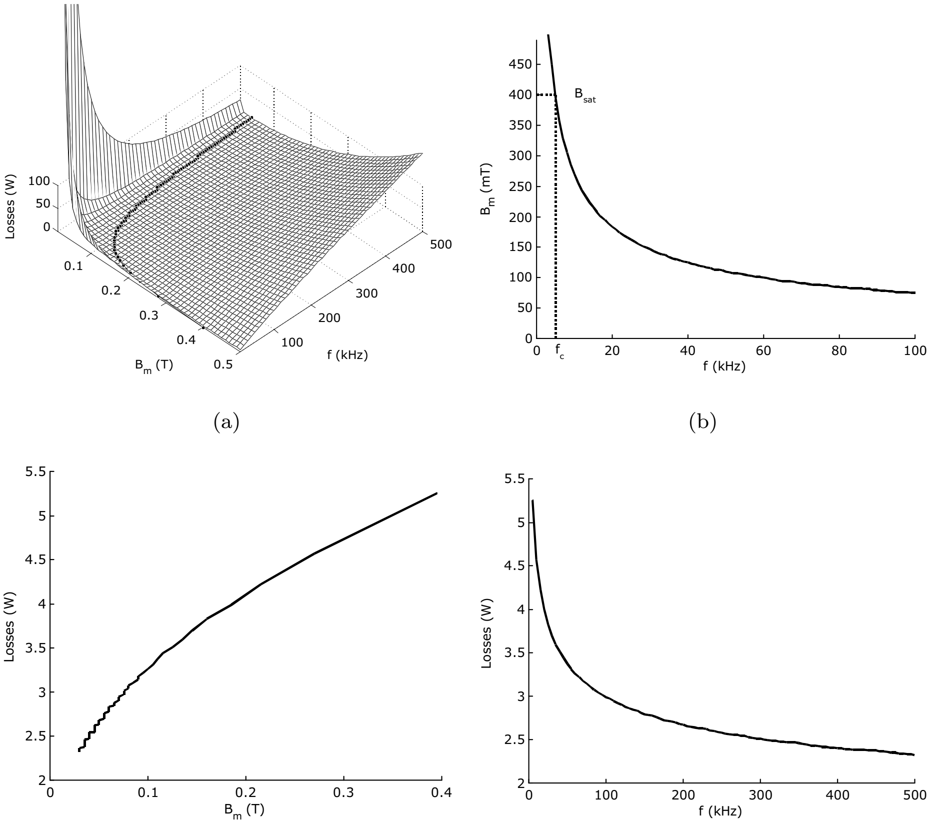


Fig. 1. Flow chart of design steps.



(a) (b)

(c) (d)

Fig. 2. (a) 3D plot of total core and winding losses, (b) the critical frequency, (c) optimum curve as a function of flux density, and (d) optimum curve as a function of frequency.

the appropriate geometry is selected. Below the critical frequency, the throughput of energy is restricted by the limitation that the flux density cannot be greater than the saturation flux density for the core material, and the flux density is set to this saturation value.

A typical 3D total transformer loss curve (winding losses plus core losses) is shown in Fig. 2(a); this has been plotted for a push–pull converter design as tested in Sec. 4. The dark line is the optimum curve, corresponding to the minimum loss points at each frequency. Figure 2(b) is a 2D flux versus frequency plot of this optimum curve, and shows the saturation flux density and corresponding critical frequency.

At low frequencies, the total losses are large at low flux density levels due to the dominance of an inverse squared frequency term in the winding losses. The core loss component accounts for the majority of the total losses at higher frequency and flux density levels. The plot starts at 5 kHz with a corresponding optimum flux

Table 1. Sample optimum points.

| Frequency (kHz) | 4 | 5 | 6 | 10 | 20 | 50 | 100 | 200 | 500 |
|---|---|---|---|---|---|---|---|---|---|
| Opt. flux dens. (mT) | 450 | 397 | 359 | 270 | 184 | 110 | 75 | 51 | 31 |

Table 2. Average error between Fourier analysis and RMS values or regression analysis methods.

| Waveform | sine (%) | Rect. sine (%) | Bipo. sine (%) | Sqr. (%) | Rect. sqr. (%) | Bipo. sqr. (%) | Tria. (%) | Rect. tria. (%) | Bipo. tria. (%) |
|---|---|---|---|---|---|---|---|---|---|
| Fou. — RMS | 0.20 | 1.80 | 2.10 | 3.20 | 6.30 | 4.30 | 1.40 | 2.20 | 2.80 |
| Fou. — Reg. | 0.20 | 1.10 | 0.80 | 1.50 | 2.50 | 1.20 | 0.90 | 1.30 | 0.90 |

density of 0.4 T. This is equal to the saturation flux density of the core material used for this design, and thus marks the critical frequency for this particular case. Total loss values along the optimum line increase with increasing flux density, and decrease with increasing frequency, as shown in Figs. 2(c) and 2(d).

Some sample values from this plot are given in Table 1. It can be seen that the optimum flux density rapidly increases as it approaches the critical frequency. Below the critical frequency of 5 kHz, the saturation value has been exceeded and operation should be limited to 0.4 T.

## 2.2. *Comparison of winding optimizations*

The optimum thickness of a layer in a constant thickness multilayered transformer winding with nonsinusoidal excitation was traditionally found by calculating the Fourier coefficients of the waveform, calculating the AC winding losses at each harmonic frequency component, calculating the total losses for each thickness in a range of values, and reading the optimum layer thickness from a graph of AC winding loss versus layer thickness. Two new methods were presented[3,4] that enable the optimum foil or layer thickness at minimum AC resistance to be found from knowledge of the number of layers, number of harmonics (related to rise time) and duty cycle in any arbitrary periodic current waveform. Variable duty cycle is an integral part of both procedures. The first method,[3] using RMS values of the current waveforms, established a simple and accurate approximation so that optimum thickness formulas can be derived from the AC resistance for arbitrary waveshapes. The second method,[4] using regression analysis, requires that the Fourier coefficients be derived for each new waveform. We will now compare both methods to motivate the method used in our design system.

Table 2 represents sample data for nine waveforms analyzed (normal/rectified/bipolar versions of sine/square/triangle waves) with 40% duty cycle and 4% rise time where applicable. Fourier analysis was carried out over 19 harmonics. The average error between the optimum thicknesses obtained using the Fourier analysis and RMS values or regression analysis methods is calculated over a total number of layers varying from 3 to 10.

Apart from a discrepancy between the optimum thicknesses for the square waves (where an approximation was used to calculate the rise time based on the number of harmonics), the average error between the RMS values method and the Fourier analysis method is slightly higher (1 to 2%) than that between the regression analysis method and the Fourier analysis method.

The advantage of the RMS values method over the regression analysis method is the ease with which optimum thickness formulas can be found and used in a quick design calculation or on paper, since the regression analysis method requires that Fourier coefficients be derived for each new waveshape. However, the optimum thickness formulas derived in the regression analysis method, while more cumbersome due to the presence of harmonic summations, are closer in accuracy to the Fourier analysis method. Also, the harmonic summations are much simpler than those required by the Fourier analysis method, and are quickly solved in a software package. It was therefore decided to use the regression analysis formulas for reasons of higher accuracy while not sacrificing speed.

## 3. Computer Design System

The computer implementation of the proposed methodologies[2–4] is called MaCoDe or Magnetic Component Designer.[7] The Windows-based Visual Basic was chosen as the programming language for MaCoDe as it combines an easy-to-use environment for designing GUI-intensive packages with the power to integrate and distribute the libraries required for opening Access-format relational databases.[8]

During the design process, a user of the system may want to move back to a previous stage of the design to make a change, and then progress from there to facilitate optimization. This allows a cyclic process: one that is not limited to a strict set of steps that must always be carried out from beginning to end each time in a new application (as shown in Fig. 1). From a GUI perspective, the easiest way found to display and navigate through a set of design steps was to represent each one by a folder in a group of folders, each one accessible by clicking on a corresponding named tab. Such a flexible design process allows a variety of changes that a user can make. However, a flow chart showing all the possible design paths becomes much more complicated than that shown in Fig. 1.

Therefore a data flow diagram[9] (DFD) approach was preferable so that the functionality of the various design steps could be shown independently of each other whilst still being able to see the inputs from other steps. Each of the main processes in the top level DFD of Fig. 3 corresponds to one of the design steps. The main processes numbered 1 to 12 in the top level DFD can contain many sub-processes. We will now describe steps 1 and 8, respectively, where the critical frequency is calculated determining the design path that will be taken, and where the user chooses whether to optimize the winding thickness or not.

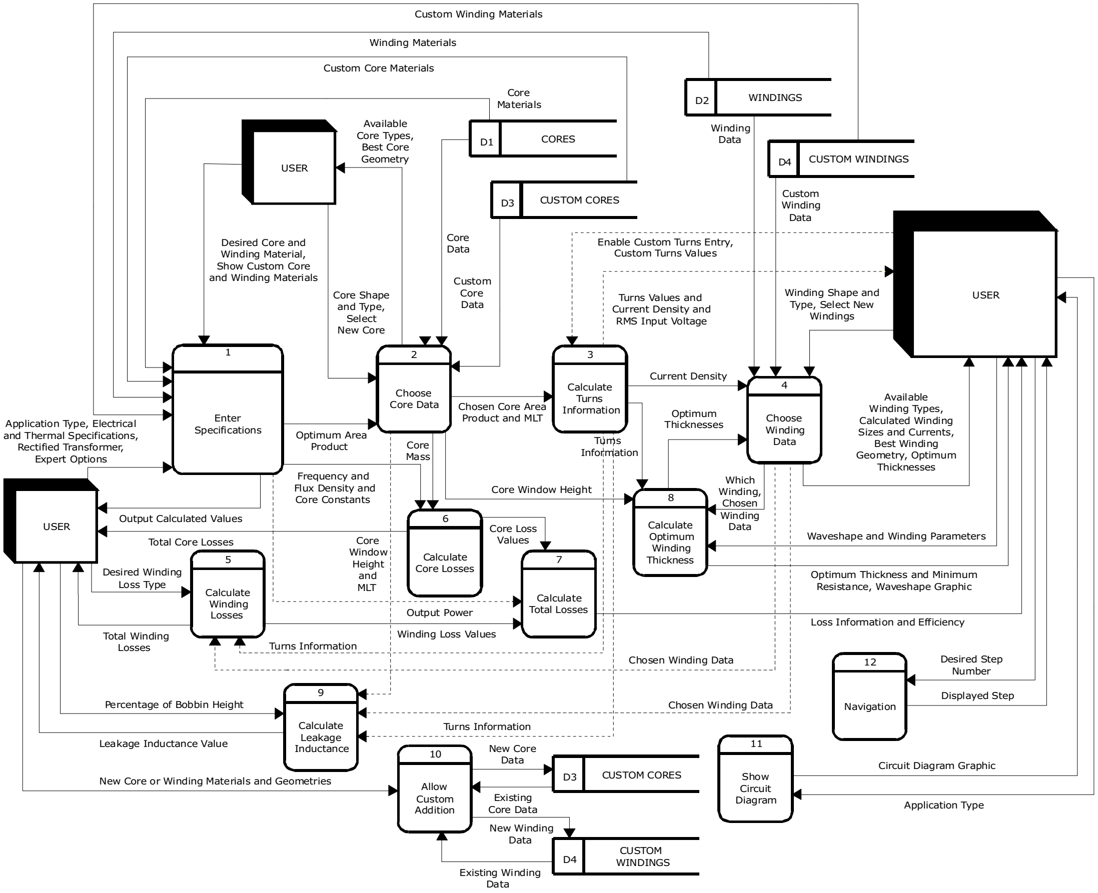


Fig. 3. Top level process DFD 0.

### 3.1. *Enter specifications*

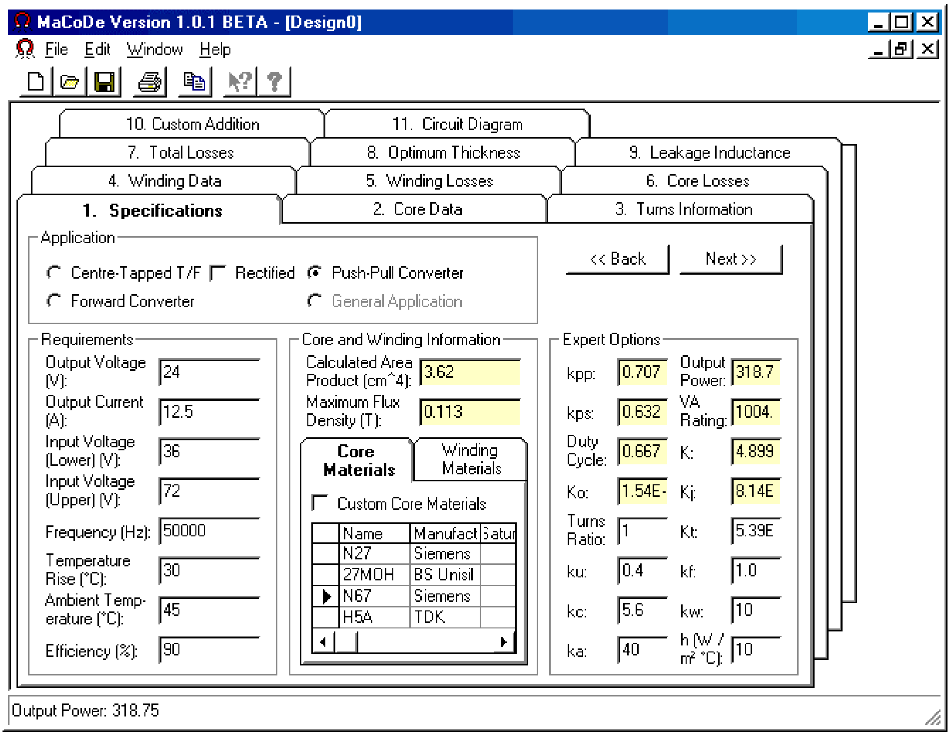
The following sequence of events occurs when a user enters specifications. The user first chooses an application (center-tapped transformer, forward or push–pull converter), enters the specifications (output voltage and current, input voltage range, frequency, temperature rise and ambient, efficiency), and chooses standard or custom core and winding materials. The system then calculates the area product and optimum flux density values. The user may modify "Expert Options" constants and other factors if necessary. The system will recalculate the area product and flux density values as specifications, materials and options are varied. The function to calculate the area product value is a key sub-process in this design step. The input specifications are stored as variables; the output power, waveform and power factors are calculated to yield the VA rating of the design. A number of coefficients are evaluated and the optimum flux density can then be calculated. This flux density is checked against the maximum or saturation flux density, and one of two design paths from the first decision block of Fig. 1 is followed. If the optimum is less than the saturation value, the transformer is operating above the critical frequency and the area product is calculated using a single equation; otherwise the area product is found using a set of Newton–Raphson equations. All calculated results are then displayed to the user.

### 3.2. *Calculate optimum winding thickness*

The aim of this design step is to minimize the effect of AC winding losses, mainly due to the close proximity of windings to each other. By default, the system displays the frequency, duty cycle, rise time (if applicable), number of layers, and current waveform for the primary winding and application under design. The user can choose to override and modify any of these default variables. A different winding or waveform type can also be selected. A sub-process to calculate proximity effects is initially called for the default application values and again subsequent to each user modification. The optimum thickness (normalized to one skin depth at the current frequency) is calculated using the appropriate formulas as derived using the regression analysis method. The minimum AC to DC resistance ratio value is then calculated. A value for the actual optimum thickness in mm is then found using the skin depth value. If the user chooses to use their own thickness value (to fine-tune the resistance ratio), the normalized thickness is set to the value entered by the user, and the resistance ratio and actual thickness in mm are calculated using this value for thickness instead of the calculated optimum thickness value.

## 4. Testing

A number of transformers were built according to geometric definitions obtained from the computer system to ensure that the resulting designs operated within acceptable parameters. For example, a transformer for a push–pull converter application was designed according to the specifications shown in the screenshot of



Application

○ Centre-Tapped T/F ☐ Rectified ● Push-Pull Converter

○ Forward Converter ○ General Application

Requirements

| | |
|---|---|
| Output Voltage (V): | 24 |
| Output Current (A): | 12.5 |
| Input Voltage (Lower) (V): | 36 |
| Input Voltage (Upper) (V): | 72 |
| Frequency (Hz): | 50000 |
| Temperature Rise (°C): | 30 |
| Ambient Temperature (°C): | 45 |
| Efficiency (%): | 90 |

Core and Winding Information

| | |
|---|---|
| Calculated Area Product (cm^4): | 3.62 |
| Maximum Flux Density (T): | 0.113 |

☐ Custom Core Materials

| | Name | Manufact | Satur |
|---|---|---|---|
| | N27 | Siemens | |
| | 27MOH | BS Unisil | |
| ▶ | N67 | Siemens | |
| | H5A | TDK | |

Expert Options

| | | | |
|---|---|---|---|
| kpp: | 0.707 | Output Power: | 318.7 |
| kps: | 0.632 | VA Rating: | 1004. |
| Duty Cycle: | 0.667 | K: | 4.899 |
| Ko: | 1.54E- | Kj: | 8.14E |
| Turns Ratio: | 1 | Kt: | 5.39E |
| ku: | 0.4 | kf: | 1.0 |
| kc: | 5.6 | kw: | 10 |
| ka: | 40 | h (W / m² °C): | 10 |

Output Power: 318.75

Fig. 4. Push–pull converter as designed with system.

Fig. 4. The transformer operates at 50 kHz, with an output power of 318.8 W. The push–pull application specifications also included a maximum temperature rise of 30°C. The calculated optimum flux density of 0.113 T is well below the saturation value of 0.4 T, such that the transformer is operating above the critical frequency.

The converter was constructed and the transformer consisted of an ETD44 core, with six turns of HF120 × 0.10 mm foil for each winding wound on an ETD44V bobbin. The area product value for this core was 4.81 cm.$^4$ Four separate temperature tests were carried out on the push–pull converter transformer for varying lengths of time and different initial transformer temperatures. All tests were carried out for an output voltage of 24 V. In each case, the temperature rise never exceeded the maximum value of 30°C in the initial design specifications for the push–pull converter (the maximum encountered was 27.4°C). The maximum power loss was always just below the predicted total core of the program and winding loss value of 2.456 W (the maximum encountered was 2.404 W).

## 5. Conclusion

A computer-aided design package was presented in this paper which allows the design of transformers with arbitrary waveforms at both low and high frequencies for multiple application types, with particular emphasis on the calculation of the critical frequency to determine a particular design path, and the selection of an optimized winding thickness by the user where appropriate. The Windows-standard GUI allows the user to experiment through try-it-and-see design iterations. As well as incorporated design knowledge, the system allows customizable transformer geometries. Calculation times are negligible, and a fully optimized design can be prepared in minutes once the specifications entry stage has been completed. This software system can be further developed for more transformer applications and can be updated to incorporate inductors and integrated magnetics.

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