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Flat Transformers for Low Voltage, High Current, High Frequency Power Converters

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Abstract: The flat transformer is a magnetic structure comprising a number of elements, N_e, each of which can be identified as an individual transformer by itself. These elements are arranged to obtain a transformation ratio (an equivalent turns ratio) of $1 : \frac{1}{N_e}$, or $N_e : 1$, with a single turn secondary winding. With a primary having a number of turns N_p, the transformation ratio is $N_p \times N_e : 1$.

The flat transformer is particularly well asuited to low profile, low output voltage, high current applications for high frequency switched-mode power conversion applications. It has extremely low leakage inductance, high magnetization inductance, excellent coupling, very low temperature rise, and is easily insulated for high dielectric requirements with no appreciable degradation in performance.

Now commercially available, the FLAT TRANSFORMER AND INDUCTOR MODULES have very low profile. These modules can exceed most high density high power converter performance expectations.

Fundamental Concepts

In a low output voltage high frequency conventional transformer, the output winding is usually configured to have a single turn. If the transformer has a turns ratio of n to 1, then the primary winding will have n turns. The number of primary turns cannot be less than n, by design.

In the flat transformer [1], the magnetic structure is comprised of many ferrite cores. The ferrite cores can be arranged in groups or elements of 1 to n in number. That is to say, 1 or more ferrite cores can be a “group” or “element” by itself; and the complete transformer is built with more than one of these “elements.”

Turns ratios are usually referred to a single core. When a group of cores are used, the resulting *equivalent* turns ratio is not reflected in individual cores, but rather is a reflection of the **transformation ratio** of the whole. Based on this principle, a single primary turn is feasible with the flat transformer.

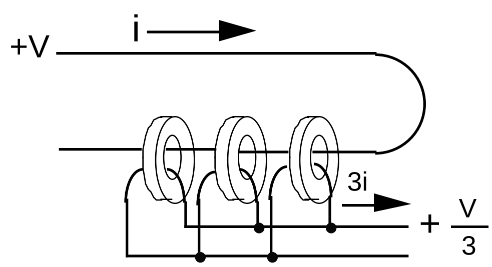


Figure 1. Flat Transformer with Transformation Ratio of 3 : 1

In the most basic arrangement of the flat transformer, a single turn is used for the primary as well as the secondary; and the transformation ratio of this flat transformer is now determined by the number of elements, N_e.

Higher transformation ratios may be obtained by using more than one primary turn. The transformation ratio of the flat transformer is determined by the product of the number of elements, N_e, and the number of primary turns, N_p:

Transformation Ratio = ($N_e \times N_p$) to 1 (N_p=2, shown below)

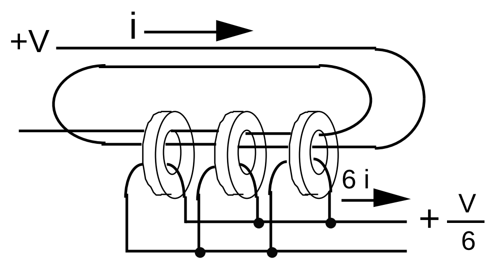


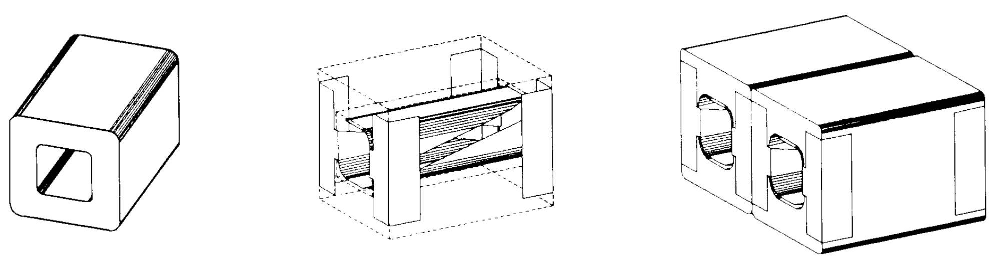
Figure 2. Flat Transformer with 3 Elements and Transformation Ratio of 6 : 1

Flat Transformer-Inductor Module Design

This module is optimized for bridge or half-bridge converters providing a 5-volt output with a single secondary turn, and operates at a switching frequency of 250 kHz (500 kHz output ripple). Each module can have a power delivery capacity of 150 watts.

The transformer part of this module is made up of two rectangular ferrite blocks with a square hole at the center. See Figure 3(a). An additional block, with a total of three blocks, is added to the combination to perform the function of the inductor.

Two single-turn secondary windings are inserted in each block to incorporate the output winding with a center-tap. Each turn is bonded to the inside surface of the block, and follows a 180° helical path such that the turn connects from one outside corner diagonally to the other outside corner. See Figure 3(b). The two blocks are arranged to have the secondary winding of one block connected in series with the adjacent block. The connections to the secondary windings are located at the corners of the blocks as shown in Figure 3(c).



(a) (b) (c)

Figure 3. (a) Single Core Block, (b) Core Block with Helical Windings, and (c) Two Blocks Connected Together.

This secondary winding design succeeds in eliminating the labor normally required of fabricating a tapped secondary winding.

The module is connected directly to a TO-247 dual rectifier package as shown in Figure 4. Since the inductor is on the tap side, which is the negative side, the cathodes of the rectifiers are connected directly to the output terminals.

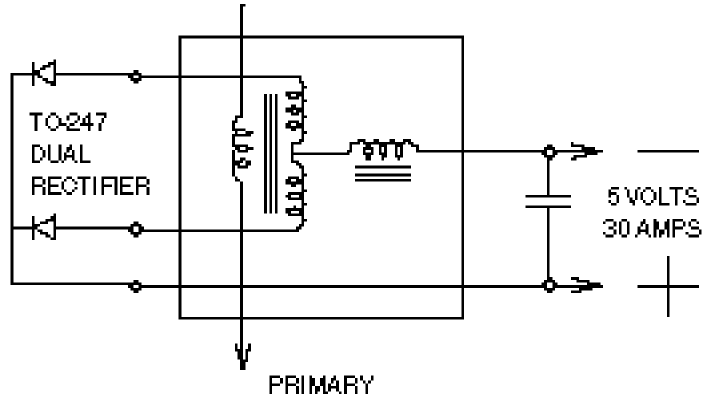


Figure 4. Electrical Layout of Flat Transformer Module

Figure 5 shows a single flat transformer module complete with top and bottom plates (which form the output terminals) and output rectifiers. The total height of the module is 11.7 mm. (0.46"). This arrangement permits **modularity** in transformer construction never before possible, and is one of the chief contributing factors in achieving high power density.

Direct current power is the product of voltage and current. A smaller transformer core helps to reduce the size of the transformer. The true contrubution in achieving high power density must rely on the ability of this transformer to provide **high current density** also. High current density is the second most important contribution of the flat transformer. More about this later.

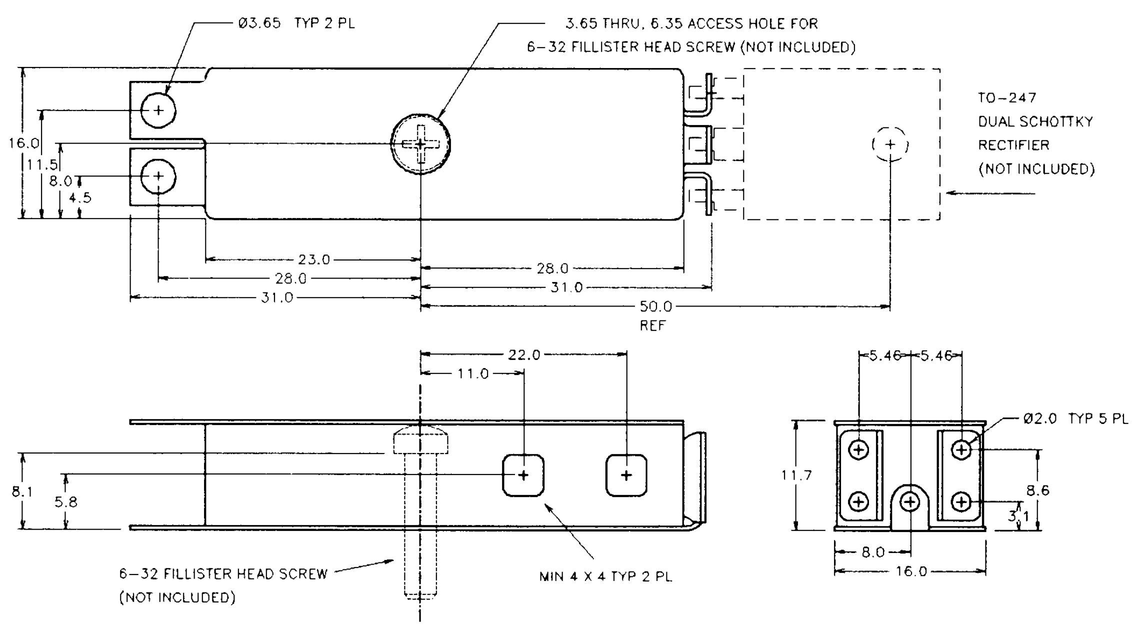


Figure 5. Complete Assembly of One Flat Transformer Module

Specifications and Related Experimental Details:

The core blocks are made of **MN-8CX** (Ceramic Magnetics, Inc.) material.

Each core block has a core area of 0.34 cm^2 and a core volume of 1 cm^3.

The **height** of the core block is 10.2 mm. (**0.4”**), which is also the same as the width. The length of the core block is 13.67 mm. (0.538”).

Since each module is comprised of two blocks, the module core area (for the transformer part) is **0.68 cm^2**, the magnetic path length is **2.8 cm.**, and the module core volume is **2 cm^3**.

The inductance is **10 µH/module/turn^2**; i.e., the multiplying factor is N^2, where N is the number of turns.

Example: If there are 4 turns wound on the module, the inductance will be

4^2 X 10 µH = 160 µH.

Due to the close proximity of the windings and core layout, the maximum leakage inductance per module is only 4 nH. This leakage inductance was measured using 5 modules with the rectifier terminals shorted by a copper strap, and a three turn primary winding. The measured (leakage) inductance for 5 modules with 3 primary turns was 0.18 µH

Since the primary inductance is given by the inductance of the module times the number of modules times the square of the number of primary turns, or, mathematically,

$$L_p = L_{mod} \times N_e \times N_p^2$$

where L_p is the primary inductance, L_{mod} is the inductance of 1 turn through 1 module (2 blocks), N_e is the number of modules, and N_p^2 is the square of the number of primary turns. This formula gives the primary inductance when measured with the secondary open-circuited; and will give the leakage inductance, when measured with secondary shorted.

For a 5-module half-bridge flat transformer with 3 primary turns, the following substitutions can be made:

$$0.18\mu H = L_{mod} \times 5 \times 3^2$$

Therefore,

$$L_{mod} = \frac{0.18\mu H}{5 \times 3^2} = \frac{180nH}{45} = 4nH$$

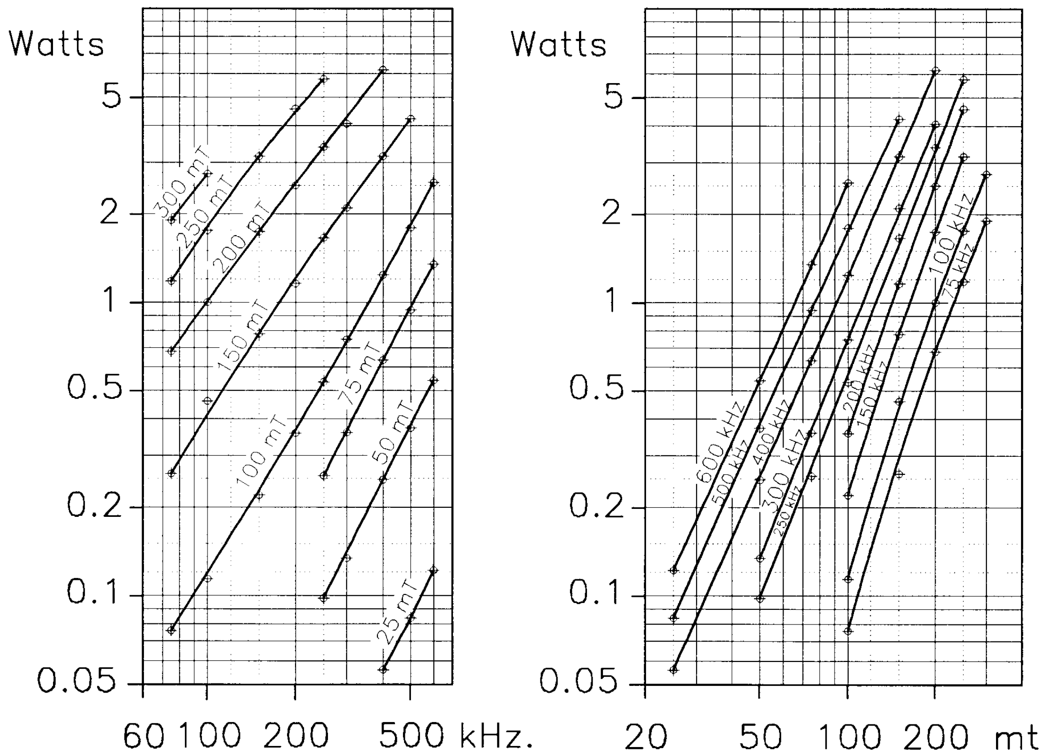
The inductor section is comprised of a 3-turn winding with an inductance of 2.7 µH (min.) at 20 Amps., and 2.0 µH (min.) at 30 Amps.

The core loss characteristics (per module) relating flux density to operating frequency are shown in Figure 6.

A typical 5-module demonstration circuit designed for a 750-Watt half-bridge converter with a flux density of 75 mT has a total (for all 5 modules) loss of approximately 1.25 Watts. If the same loss is assumed for the windings, which would be extremely conservative, the total transformer loss will be 2.5 Watts. Based on these numbers, the transformation efficiency is,

$$\text{Efficiency } \eta = \frac{P_o}{P_i} \times 100\% = \frac{P_o}{P_o + P_L} \times 100\%$$

where P_o is output power, P_i is input power, and P_L is total transformer loss.



(a) (b)

Figure 6. Transformer Section: (a) Relating Frequency to Power Loss, and (b) Relating Flux Density to Power Loss; per module

Hence, $\text{Efficiency } \eta = \dfrac{750}{750 + 2.5} \times 100\% = 99.67\%.$

Achieving High Power Density with High Current Density

This is the greatest electrical difference between a flat matrix transformer and a conventional transformer. Though the physical differences are obvious, the electrical differences are quite subtle, and remains unclear until a closer examination is made.

For any homogeneous conductor of uniform cross section, the resistance of the conductor depends on the length, the area of the cross section, the temperature, and the material of which it is composed. The resistance varies directly with the length and inversely with the area of cross section. The resistance of a conductor can be formulated as

$$R = \rho \frac{\ell}{A}$$

where R is the resistance, ρ is the resistivity (which depends on the temperature) of the material, ℓ is the length of the conductor, and A is the area of cross section normal to the direction of the current flowing in the conductor.

For pure metals the resistance increases with the temperature. In this case, the change in resistance with respect to the change of temperature is very close to a linear function, and can be characterized by a *temperature coefficient* α. **The temperature coefficient for that material is**

defined as being that fraction of the resistance at 0°C by which its resistance changes for each Celsius degree change in temperature, i.e.,

$$\alpha = \frac{R_t - R_o}{R_o t}$$

Material	ρ (Ohm -meters at 20°C)
Aluminum	2.83×10^{-8}
Copper, annealed	1.724×10^{-8}
Copper, hard -drawn	1.77×10^{-8}
German Silver (18% Ni)	33×10^{-8}
Gold, pure drawn	2.4×10^{-8}
Iron, cast	9×10^{-8}
Lead	22×10^{-8}
Mercury	96×10^{-8}
Nickel	7.8×10^{-8}
Platinum	10×10^{-8}
Silver (99.98% pure)	1.64×10^{-8}
Tin	11.5×10^{-8}

Table 1. Resistivities ρ of Selected Conductor Materials[1]

[1]Values taken from Smithsonian Physical Tables.

Where R_t is the resistance of the conductor at t°C, and R_o is the resistance of the conductor at 0°C. Rearranging the above expression yields

$$R_t = R_o(1 + \alpha t)$$

The value of α is a characteristic of the material of the conductor, and the temperature range considered is *positive* when the resistance increases as the temperature is raised (e.g., pure metals), but is *negative* for non-metals for which resistance decreases with a temperature rise.

From Table 2, the temperature coefficient of copper is approximately 0.4%/°C. Therefore, a 40% increase in resistance corresponds to a temperature rise of 100°C. From a room temperature of 23°C, add another 100°C gives 123°C, which is just a few degrees below 130°C (Class F) requirements.

An experiment was performed with direct current passing through a single turn of a #30 A.W.G. (the normal wire used for wire-wrap applications in digital circuits with approximately 100 circular mils in cross section, Kynar insulation) inserted into a loose fit teflon sleeve. The combination of sleeve and wire was inserted into a ferrite block. The current level was adjusted from 0 ampere upwards to obtain a resistance increase in the wire by 40% (100°C rise). After a period of no less than 2 hours stabilization, this current was found to be 6 amperes.

Material (at 20°C)	Temperature Coeff. α (Ohms/Ohm/°C)
Aluminum	.0039
Copper, annealed	.00393
Copper, hard -drawn	.00382
German Silver (18% Ni)	.0004
Iron	.005
Lead	.0041
Mercury	.00089
Molydenum	.0034
Nickel	.006
Platinum	.003
Silver (99.98% pure)	.0038
Tin	.0042

Table 2. Temperature Coefficients of Resistance of Selected Conductor Materials

This result corresponds to **16.6667 circular mils/ampere**. On this basis, it was decided that the current density of **50 circular mils/ampere** (3 times the wire cross section area) **is very conservative** for windings with a small (less than 5) number of turns.

In consideration of the conventional transformer design practice, the following table is reproduced from McLyman [2] to identify the current density used in these designs:

Core Type	Losses	K_j (25°C)	K_j (50°C)	(x)	K_s	K_w	K_v
Pot Core	$P_{cu} = P_{fe}$	433	632	–0.17	33.8	48.0	14.5
Powder Core	P_{cu} P_{fe}	403	590	–0.12	32.5	58.8	13.1
Laminations	$P_{cu} = P_{fe}$	366	534	–0.12	41.3	68.2	19.7
C -Core	$P_{cu} = P_{fe}$	323	468	–0.14	39.2	66.6	17.9
Single -Coil	P_{cu} P_{fe}	395	569	–0.14	44.5	76.6	25.6
Tape - Wound	$P_{cu} = P_{fe}$	250	365	–0.13	50.9	82.3	25.0

$J = K_j A_p^{(x)}$ $\quad A_t = K_s A_p^{0.5}$ $\quad W_t = K_w A_p^{0.75}$ $\quad V_{ol} = K_v A_p^{0.75}$

Table 3. Relationships Between Core Loss, Core Geometry, and Current Density in Conventional Transformer Design Considerations.

From Table 3, the powder core losses are used for comparison, based on its core geometry similar to that of a regular toroidal core, which is the closest approximation to the cores used for the current flat transformer design. This table was developed using curve fitting technique, based on manufacturers' data.

In an example of a half-bridge transformer design [8], the current density J was calculated as 559 amps./cm^2. The core used was a PQ core. The current density of 559 amps./cm^2 is the same as 5.59 amps./mm^2, or 5.59 amps./1973 circular mils. This is the same as 2.833249 mA/circular mil, or **352.9517 circular mils/amp. (conventional transformer design)**. Comparing this number with the **conservative flat matrix transformer design of 50 circular mils/amp**., and the **experimental matrix current density of 16.67 circular mils/amp**.

The above results can be tabulated in a table as shown in Table 4:

Transformer	Current Density (Circular Mils/Amp.)	Circuit
Conventional	353	Half -Bridge
Flat Matrix (Conservative)	50	Half -Bridge
Flat Matrix (Experimental)	16.67	Half - Bridge

Table 4. Current Density Comparison with Conventional Transformer Design

Based on these findings, the modules were designed and optimized for low voltage high current applications. This same design philosophy can be applied to design smaller and/or larger modules to accommodate other output voltages and output power levels.

Type of Transformer	Volts/Turn/Module	Waveform	%Duty	Primary Voltage
Conventional	5	Sine	–	V_{in}
Push-Pull	10	PWM	50	V_{in}
Half - Bridge	20	PWM	50	$\frac{1}{2} V_{in}$
Full-Bridge	10	PWM	50	V_{in}
Forward	10	PWM	45	V_{in}

Table 5. Optimized Flat Matrix Transformer Module Design.

Summary and Conclusions

A detailed description of the design philosophy of the flat matrix transformer module has been given. The experimental results show that the current density of this type of transformer is, conservatively, higher than the conventional transformer by a factor of at least 5.

It appears that the **key to high power density** is not just pushing up the switching frequency, but is also important to have good thermal characteristics as well as high current density.

The flat matrix transformer has **modularity**, which permit power level flexibility and superior thermal characteristics.

Due to the low probable number of primary turns, the **current density** of the transformer can be increased dramatically beyond the capability of any conventional designs.

The advantage of this transformer has been well documented previously [1, 3, 4, 5, 6, 8], and will only be summarized here. The main points are: (i) High efficiency, (ii) High power density, (iii) Low profile, (iv) Simple construction, (v) Low leakage inductance, (vi) High current density, (vii) Modularity and design flexibility, (viii) Distributed heat concentration, (ix) Resistant to shock and vibration, (x) High dielectric isolation, and (xi) Current sharing.

The maximum potential of this transformer has yet to be explored and discovered.

References:

1. Edward Herbert, "Design and Application of Matrix Transformers and Symmetrical Converters," a tutorial presented at the *High Frequency Power Conversion Conference '90*, Santa Clara, CA, May 11, 1990.
2. C. W. T. McLyman, *Transformer and Inductor Design Handbook*, Second Edition, Marcel Dekker, Inc., New York, New York, 1988.
3. James Ley Lau, et al, "Flat Transformers -- For Low Voltage, High Current, High Frequency Power Converters," *Coil Winding, Insulation & Electrical Manufacturing '96*, June 4-6, 1996, Berlin, Germany.
4. K. Kit Sum, et al, "Novel Low Profile Matrix Transformers for High Density Power Conversion," *PowerConversion and Intelligent Motion*, September, 1988.
5. K. Kit Sum, et al, "A High Density Power Converter Utilizing A Novel Matrix Transformer," Best Paper Award, *SATECH 88 Conference*, October 3-6, 1988, Dearborn, Michigan, U.S.A.
6. K. Kit Sum, "Design and Application of Matrix Transformers," paper presented at the *High Frequency Power Conversion Conference '90*, Santa Clara, CA, May, 1990.
7. K. Kit Sum and B. Carsten, "Trends in High Frequency Power Conversion," paper presented at the *High Frequency Power Conversion Conference*, San Diego, May 1988.
8. C. W. T. McLyman, *Designing Magnetic Components for High Frequency dc-dc Converters*, KG Magnetics, Inc., San Marino, California, 1993; Example #302, page 79.
9. U. S. Patent Nos: 4,665,357; 4,845,606; 4,942,353 and/or 5,093,646. Others pending.