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How to Design a Sophisticated 200 watt to 600 watt Brick dc-to-dc Power Converter

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Abstract

Typically, high current density (12.7 mm x 61.0 mm x 116.8 mm) brick dc-to-dc converters require high frequency switching, complex topologies, and sophisticated circuit designs. This article presents a simple, reliable, and cost effective design of brick-size dc-to-dc converters that can achieve a power density of up to 6.6 watts/cm^3 (over 36 watts/in.^{3}) at 600 watt level. Efficiency can be as high as 90%. Due to a technological break-through in the solution of the transformer leakage inductance problem, a simple push-pull pulse-width-modulated topology can be used. The result is a simple and highly reliable dc-to-dc converter with superior thermal characteristics as well as high current output capability.

1. Introduction

A design can be considered sophisticated when it can meet demanding specifications, can be manufactured economically in large quantities, and has high reliability.

High power density is normally obtained by raising the switching frequency so as to reduce the size of magnetic and filter components. This attempt is, however, thawed by the leakage inductance associated with the power transformer. This is a significant limitation of high frequency power converters. To permit high frequency switching, this problem must be alleviated.

One method of reducing the leakage inductance is to reduce the number of turns on the windings. With off-line converters, the turns ratio can be as high as 16 : 1, or higher. That means the minimum number of primary turns must be at least 16. Leakage inductance is directly proportional to the square of the number of turns. The turns ratio thus sets, for conventional transformers, the limit of the level of leakage reduction, even if a single secondary turn is used.

Resonant topologies have been adopted by many designers primarily to overcome this problem, but in the process, inherited a whole new set of problems peculiar to that particular topology.

It is apparent that if the leakage inductance can be substantially reduced, the switching frequency can be raised further to bring about further miniaturization and higher power density.

The solution lies in configuring the transformer to yield less leakage, reducing the number of turns (primary and secondary), and obtaining higher current density. One such transformer configuration is the Flat Transformer.

2. The Flat Transformer

The flat transformer [1] is a magnetic structure comprising a number of elements, N_e. Each of these elements 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 N_p turns, the transformation ratio is $N_p \times N_e : 1$. This means that if the number of elements N_e are increased, the number of primary turns N_p can be reduced. This also means that *a single primary turn* is feasible.

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.

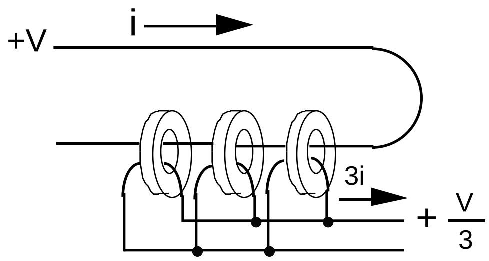

Figure 1. Flat Transformer with Transformation Ratio of 3 : 1

Higher transformation ratios may be obtained by using more than one primary turn. Hence, 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 is shown below):

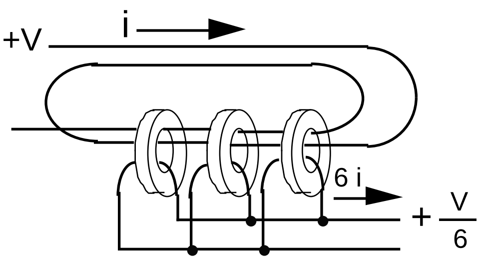

Figure 2. Flat Transformer with 3 Elements and Transformation Ratio of 6 : 1

Due to the distributed secondary windings, current-sharing is automatically accomplished, and rectifiers of lower current rating can be used for each output winding. The total output current is the sum of the current from all the secondary outputs. Thus the current rating of the transformer is dependent only on the number of elements used without affecting the profile of the transformer.

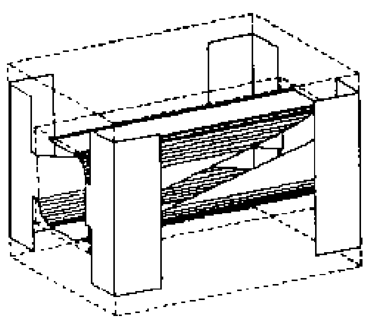

Fig. 3. Constructional Details of One Ferrite Block

The Flat Transformer is comprised of ferrite blocks. The constructional details of one block are shown in Figure 3. The core blocks are made of a special ferrite material. Each core block has a core area of 0.34 cm^2 and a core volume of 1 cm^3. The height and width of the core block are both 10.2 mm. (0.4”). The length of the core block is 13.67 mm. (0.538”).

A two single-turn secondary winding is inserted into each block to incorporate the output winding with a centre-tap. This secondary winding design succeeds in eliminating the labor normally required of fabricating a tapped secondary winding. The conductors bonded into each block are rated for 30 amps.

Virtually perfect coupling between winding and core is accomplished by bonding each turn to the inside surface of the block. The conductor or turn follows a 180° helical path such that the turn connects from one outside corner diagonally to the opposite outside corner.

Four ferrite blocks are used to make up the power transformer in the current design. This core-block arrangement permits *modularity* in transformer construction never before possible with conventional transformer technology, and is one of the chief contributing factors in achieving high power and high *current* density.

3. Configuring a Transformer to Meet Class F Requirement

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

$$R = \rho \frac{\ell}{A} \tag{1}$$

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 characterised 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.,

$$\alpha = \frac{R_t - R_o}{R_o t} \tag{2}$$

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

$$R_t = R_o(1 + \alpha t) \tag{3}$$

The value of α is a characteristic of the conductor material, 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.

Material (at 20°C)	Resistivity (ρ) (Ohm - meters)	Temp. Coeff. α (Ohms / Ohm/°C)
Aluminum	2.83×10^{-8}	.0039
Copper, annealed	1.724×10^{-8}	.00393
Copper, hard - drawn	1.77×10^{-8}	.00382
German Silver (18% Ni)	33×10^{-8}	.0004
Iron	9×10^{-8}	.005
Lead	22×10^{-8}	.0041
Nickel	7.8×10^{-8}	.006
Silver (99.98% pure)	1.64×10^{-8}	.0038
Tin	11.5×10^{-8}	.0042

Table 1. Resistivities ρ of Selected Conductor Materials
(Values taken from Smithsonian Physical Tables).

To configure a transformer to meet Class F requirement, an experiment was performed with direct current passing through a single turn of a #30 A.W.G. The actual wire chosen is the regular wire used for wire-wrap applications in digital circuits with Kynar insulation. The reason for this choice is because the #30 A.W.G. wire has approximately 100 circular mils in cross section. The test is performed with the wire inserted into a loose-fit teflon sleeve. The design of this experiment is aimed at the thermal characteristics of the transformer when wound with such a *sleeved* wire. By performing such an experiment, two conditions are identified: (i) Better thermal condition can be expected when the wire is not sleeved; and (ii) Themal condition is verified when used with sleeve for isolation requirement.

From Table 1, 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, an increase of another 100°C yields 123°C, which is just a few degrees below 130°C (Class F) requirements.

The combination of sleeve and wire was inserted into a ferrite block. The current level was adjusted from 0 ampere upwards to obtain a 40% resistance increase (corresponds to 100°C rise in temperature) in the wire. After a thermal stabilisation period of not less than 2 hours, this current was found to be 6 amperes.

This result corresponds to a current density of*16.6667 circular mils/ampere* (60 mA/circular mil). On this basis, it was decided that the current density of *50 circular mils/ampere* or 20 mA/circular mil (3 times the wire cross section area) is very *conservative* for windings with a small number of (less than 5) turns. And even at this conservative current density, it is still 7 times denser than the conventional transformer. However, since the amount of current is reduced to 1/3 of the tested value, the temperature rise is also expected to be reduced.

These results demonstrated a far superior current density as compared with the conventional technology, which normally requires 350 circular mils/ampere.

4. Low Leakage Inductance

To provide some insight into the order of magnitude of the leakage inductance, the results of a previous article [2] shows that the leakage inductance for 10 ferrite blocks (5 modules at 2 blocks per module) with a 3-turn primary winding yields 0.18 µH, or 4 nH/2-block module. The following formula provides a means for calculating leakage inductance for other configurations:

$$L_p = L_{\text{mod}} \times N_e \times N_p^2 \quad (4)$$

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:

$$0.18\mu H = L_{\text{mod}} \times 5 \times 3^2 \quad (5)$$

Therefore,

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

From these results, it can be seen that the leakage inductance for 4 blocks will be insignificant, especially when compared with conventional transformer technology.

5. Choice of Topology

As the leakage inductance problem is brought under control, the switching frequency can be raised, and the magnetic component sizes reduced. Simple topologies can be used in place of resonant topologies. For a reliable design, it is essential to keep the circuit simple. To accomplish this, the simple push-pull topology is selected for the task at hand. A whole family of converters can be designed based on this topology.

The design procedure for the push-pull dc-to-dc converter is well-known. The description provided below will highlight only the important aspects pertinent to an example design. Let the output voltage be 3.3 volts at 50 amps. Let the input voltage be 48 volts nominal (36 volts minimum, and 72 volts maximum)

The transformation ratio (or 'turns' ratio for conventional understanding) is first calculated based on the steady state transfer function of the circuit, given by

$$\frac{V_o}{V_i} = nD \quad (5)$$

where n is the transformation ratio equivalent to the ratio of number of secondary turns N_s divided by the number of primary turns N_p, or

$$n = \frac{N_s}{N_p} \qquad (6)$$

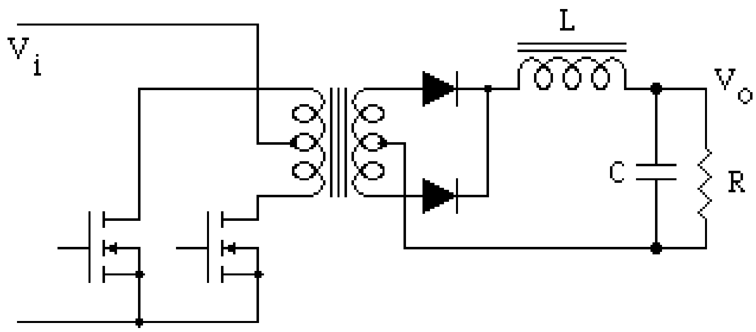

Fig. 4. Basic Push-Pull Converter Topology

For a maximum duty ratio of 80% over one cycle, and allow a forward voltage drop V_F of 1 volt for the output rectifiers, the transformation ratio can be calculated:

$$\frac{V_o + V_F}{V_i} = 0.8n\text{, or } \frac{V_o + V_F}{0.8V_{i\,\min}} = n = \frac{3.3+1}{0.8 \times 36} = 0.149\text{, or } \frac{1}{n} = 6.6977$$

Rounding it off to $\frac{1}{n} = 6$ gives the low duty ratio at high line, $D_L = \frac{V_o + V_F}{nV_{i\,\max}}$,

or $D_L = \frac{3.3+1}{\frac{1}{6} \times 72} = 0.358$ for both switches, yielding $D_L = 0.179$ for each switch.

Similarly, the high duty ratio is: $D_H = 0.358$ for each switch.

The volt-second supported by each side of the primary winding is $V_{i\,\max} D_L$ for one switch, and the number of primary turns is given by

$$N_p = \frac{V_{i\,\max} D_L \times 10^4}{KfBA_c} \qquad (7)$$

$$= \frac{72 \times 0.179 \times 10^4}{4 \times 3 \times 10^5 \times 0.1 \times 0.34} = 3.16 \text{ for one ferrite block.}$$

This means that for 4 ferrite blocks, the number of primary turns can be reduced to 1, with margin to spare. Also, previous results [2] have shown that each block is capable of delivering 75 watts at a transformer efficiency of 99.67%, thus rendering this design capable of delivering 300 watts, conservatively.

For a transformation ratio of 6 to 1, a new half-turn technique (patent pending) is introduced. This is possible and non-detrimental to the flat transformer because of its characteristically symmetrical and low-leakage structure. Thus 3 turns can be wound through the 4-core blocks and tapped at the $1\frac{1}{2}$ turn point, satisfying the ratio of 6 : 1. Based on these adjustments, the resultant flux density is

$$B = \frac{V_{i\,\max} D_L \times 10^4}{N_p KfA_c} = \frac{72 \times 0.179 \times 10^4}{1.5 \times 4 \times 3 \times 10^5 \times 0.34 \times 4} = .0526 \text{ tesla.} \qquad (8)$$

6. Summary and Conclusions

It has been shown that a simple pulse-width-modulated topology can be used to design a high *current* density power converter when the leakage inductance of the power transformer is minimized to an insignificant level. Low profile is also accomplished by using the *flat transformer* technology.

The enhancement on the design is multifold: (i) Permits high frequency switching; (ii) High current and high power density; (iii) Distributed thermal structure; (iv) Modularity; (v) Low profile; (vi) Built-in current-sharing characteristics; (vii) High dielectric isolation; and (viii) Superior shock and vibration characteristics.

The flat transformer now ranks first in current density in the brick-type converter arena.

References:

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8. Demonstration kits are available from: Flat Transformer Technology Corporation, 240 Briggs Avenue; Costa Mesa, California 92626, U.S.A. Telephone: (714) 850 7320, Facsimile: (714) 850 7321.