RJ 9536 (83542) October 5, 1993
Computer Science

Research Report

A LONG, THIN, FLEXIBLE TRANSFORMER

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ABSTRACT The design and construction of a transformer thin and flexible enough to resemble and be used as a powercord is described and analyzed. Unlike earlier designs, the transformer design presented in this article has an efficiency and flux linkage that rivals those of standard transformer designs. The powercord transformer consists of a series of toroidal magnetic cores which are stacked into a long string of short magnetic circuits. This transformer can be designed to function at arbitrarily low or high frequencies; in particular, power-line frequencies (50 or 60 Hz.) are possible. This design can, with minor modifications, be used to produce a powercord inductor as well. A manufacturing process is also presented that uses this unique design to produce transformers more easily than is conventionally possible. Because transformers are ubiquitous in electrical devices, this design has the potential to replace the bulky box-shaped transformers in hundreds of products and can be used to address practical problems of product size, weight balance, and heat generation.

Introduction

Virtually every electrically-powered device in use today relies upon a transformer, whether it be for impedance matching, for AC voltage conversion, or for isolation in an off-line power supply. Despite this reliance upon transformers, however, their design has traditionally been subject to several severe limitations. The standard approach to building a transformer is to wind several coils of wires about a single core. Although many different core shapes are in common usage (E-shaped armatures, toroids, cup cores, etc.), the resulting transformer is generally box-shaped and rigid.

Such traditional transformers suffer from several problems. First, transformers frequently dictate the size and shape of devices which contain them, especially for small and/or portable devices such as electric razors, modems, and notebook computers. In many cases, the transformer and other power supply components are placed within a cumbersome box at the end of the device's power cord. Users of such devices must remember to carry around the special power supply box and cord if they wish to use the device. Additionally, the power supply box often blocks other electrical outlets when it is plugged into the wall. Second, box-type transformers used to power devices generate heat and can become uncomfortably, even dangerously, warm. In certain cases, the box-transformer must be expanded in size and weight (making it even more cumbersome) so that it can dissipate the required quantity of heat. Finally, traditional methods of transformer manufacture are inherently difficult and expensive because of the complex mechanical operations involved in coil winding.

This article presents a solution to these problems by demonstrating the first design of a practical transformer that is sufficiently small and flexible to resemble and to function as an electrical powercord (see Figure 1). Although powercord transformers have been considered by others, previous designs are too inefficient or have too little flux linkage to function successfully, especially at low power-line frequencies [1,2]. This design can, by eliminating the secondary wiring, be used to design thin, flexible inductors as well.

Powercord transformers are promising for future electric design because they are inherently less cumbersome than traditional transformers. In addition, heat dissipation in a powercord transformer is significantly better than in a box-shaped transformer because heat is created all along the length of the cord rather than being concentrated at one point. The powercord transformer also has a relatively large surface area from which to radiate heat. Finally, a possible alternative to conventional manufacturing methods is presented for the powercord transformer design.

Basic Design and Analysis

The basic design of the powercord transformer is shown in Figure 2. The powercord transformer consists of a stack of thin-walled toroids of magnetic material with primary and secondary coils running through the stack. When the transformer is operated, these toroids act as the magnetic circuits of the device. This design constructs a transformer which consists of many individual transformers in series, with overall properties equal to a combination of the properties of the individual toroids.

Since each individual magnetic circuit is short and toroidal, virtually all of the magnetic flux is predictably contained within the magnetic material. The high degree of flux containment results in extremely low flux leakage between primary and secondary in the transformer, in high inductance, and in high efficiency. Since the diameter of each toroid is small, the resulting powercord transformer is thin. In addition, by leaving space between the toroid cores, one can ensure that any required bending of the powercord transformer occurs between cores and neither bends nor damages any delicate core material. The core material can be further protected by covering the powercord transformer in a casing that is either thicker or somewhat stiffer around each core.

Ultimately, the properties of a transformer are dominated by the inherent properties of the magnetic materials that comprise it. A transformer must be designed so that, when it operates, its magnetic core material does not saturate. The most magnetically "stressful" operating condition (i.e., when core saturation is most likely to occur) for a practical transformer occurs when its secondary circuit is open. Interestingly, for ideal transformers, each operating condition is equally stressful because the magnetizing forces from the primary and secondary currents cancel each other within the core material of the transformer, leaving only self-inductive current in the primary to cause possible saturation in the core [3].

The significant current that must be considered is the self-inductive current in the primary. If the transformer is subject to a sinusoidal RMS voltage V, then the magnitude (i.e., the peak value) of the resulting self-inductive sinusoidal current in the primary can be calculated from

$$I = \frac{V\sqrt{2}}{\omega L}, \tag{1}$$

where I (Amperes) is the magnitude of the sinusoidal current; ω (rad/sec), equal to $2\pi f$, is the angular frequency at which the transformer is operated; and L (henries) is the self-inductance of the primary side of the transformer.

The magnetizing force, H (oersteds), induced by a current I (Amperes) in toroidally-wound wires is

$$H = \frac{N_1 I}{500r}, \tag{2}$$

where N_1 is the number of wire turns in the toroid (in this case, the number of turns in the primary side of the powercord transformer), and r (meters) is the radius of the given position within the toroid. Combining equations (1) and (2), the self-inductive sinusoidal current within the transformer's primary induces a magnetizing force within the core material that is given by

$$H = \frac{N_1 V \sqrt{2}}{500 r \omega L}. \tag{3}$$

The maximum magnetizing force within each toroid is experienced at $r=a$, the inner radius (meters) of each toroidal core:

$$H_m = \frac{N_1 V \sqrt{2}}{500 a \omega L}. \tag{4}$$

In designing the powercord transformer, one must ensure that H_m does not exceed the magnetizing force required to saturate the magnetic material from which the toroidal cores have been formed. Different magnetic materials have inherently different values for the magnetizing force which will cause saturation. These values are usually a function of the composition, construction, and annealing of the magnetic material as well as the frequency at which the transformer is run.

Continuing the analysis, in the case of the powercord transformer the self-inductance of the primary side of the transformer is the sum of the individual self-inductances of the individual toroids. This justifiable approximation ignores the very small inductance contribution from the air portions of the powercord transformer. Since the inductance of a toroid is well-known in the literature, it can be shown that the inductance of the primary in this multicore transformer is correctly given by

$$L = \left(2\text{x}10^{-7}\right)\mu\left(N_1\right)^2 nh \ln\left(\tfrac{b}{a}\right) , \tag{5}$$

where L (henries) is the primary self-inductance, μ (unitless) is the relative permeability of the core material, N_1 is (as before) the number of wire turns in the primary, n is the number of small toroidal cores, h (meters) is the height of each toroidal core, a (meters) is the inner radius of each toroidal core, and b (meters) is the outer radius of each toroidal core.

Combining equations (4) and (5) results in the design equation for the powercord transformer. The maximum tolerable RMS primary voltage per primary turn (so that the magnetic material does not saturate) can be calculated from

$$\frac{V}{N_1} = \left(\tfrac{\sqrt{2}}{2}\text{x}10^{-4}\right) H_m \omega \mu n h a \ln\left(\tfrac{b}{a}\right) . \tag{6}$$

Equation (6) allows computation of the required number of toroidal cores required for a given core material, transformer geometry, operational frequency, and RMS input voltage. It shows that if nh (the sum of the heights of the toroidal cores) is lengthened, then the number of wire turns is reduced for a given input voltage. In other words, this design is optimized for a long and thin powercord transformer.

The powercord transformer's efficiency and flux-linkage between primary and secondary are both extremely high and rival those of transformers of conventional designs. The sole disadvantage with this design is that the resistance of the transformer's coils is increased compared with conventional designs due to the lengthening of the transformer's wire coils.

Implementation

This design has been studied and tested. A 3 feet long, .25 inch diameter flexible powercord transformer prototype was constructed in accordance with this design (see Figure 3 for photograph). The prototype contains 47 toroidal cores, each of which is .5 inch high. Individual toroidal cores are separated by .25 inch. The cores were constructed from tape-wound, 2 mil (.002 inch) thick 50% nickel-iron alloy (Square Orthonol®) with $\mu_{max} \approx 150{,}000$ and $H_m \approx .2$ oersteds [4]. The prototype functions as expected (60 Hz., 8.3 V RMS input, 7:1 step-down transformer), and demonstrates the feasibility of a 60 Hz. 120 V RMS powercord transformer.

This prototype was constructed for demonstration purposes with scotch tape holding together orthonol toroids over varnished monofilamental primary wire and polyethylene-insulated secondary wire. Although it has been squashed and bent, it has continued to function for a year with only a slight degradation in its properties. The design appears remarkably robust.

Manufacturing Considerations

Traditional transformer manufacture is inherently difficult and generally requires relatively complex mechanical winding shuttles [5]. Although this powercord transformer design can be manufactured by such a standard approach (i.e., coiling wires through a stack of toroids), its design suggests an alternate approach (see Figure 4). First stack the toroid cores. Then thread a bundle of primary and secondary wires through the center of the stack. Finally, lay corresponding wires the length of the stack and connect internal and external wires so as to create the requisite coil circuits. Such a process could possibly be automated by creating custom connectors for the end of each stack. This approach might be easier for manufacturing, and can be extended to transformers (or an inductor) with arbitrarily many primary and secondary circuits.

Conclusion

The powercord transformer design presented in this article was originally developed in order to shrink notebook computer power supplies by placing the power supply transformer within the power-line cord. Its advantages, however, might extend beyond this application and include flexible placement in products, ease of heat dissipation, and decentralized weight for product balance. Line cord transformers could be used to replace the standard, bulky, box-type transformer in hundreds of products. Prime candidates for this switch include shavers, modems, and any other product which plugs a transformer in a box into the wall outlet. There currently exist no other alternate solutions that eliminate the transformer in a box used by these products.

Acknowledgments

The authors would like to thank Bob Kelley for his indispensable effort and insight in developing the powercord transformer.

References

[1] U.S. Patent No. 2,436,742 issued to Bussy on 02/48.

[2] S. Hayano, Y. Nakajima, H. Saotome, and Y. Saito. "A New Type High Frequency Transformer," IEEE Trans. Magn., Vol. 27, No. 6, pp. 5205-7, Nov. 1991.

[3] Vincent Del Toro, Electromechanical Devices for Energy Conversion and Control Systems (Prentice-Hall, Inc., Englewood Cliffs, N. J. 1968), p. 68.

[4] Square Orthonol® is manufactured by Magnetics, A Division of Spang & Company, P. O. Box 391, Butler, Pennsylvania 16003. Telephone (412) 282-8282.

[5] William M. Flanagan, Handbook of Transformer Applications (McGraw-Hill Book Company, New York, 1968), p. 7.32.

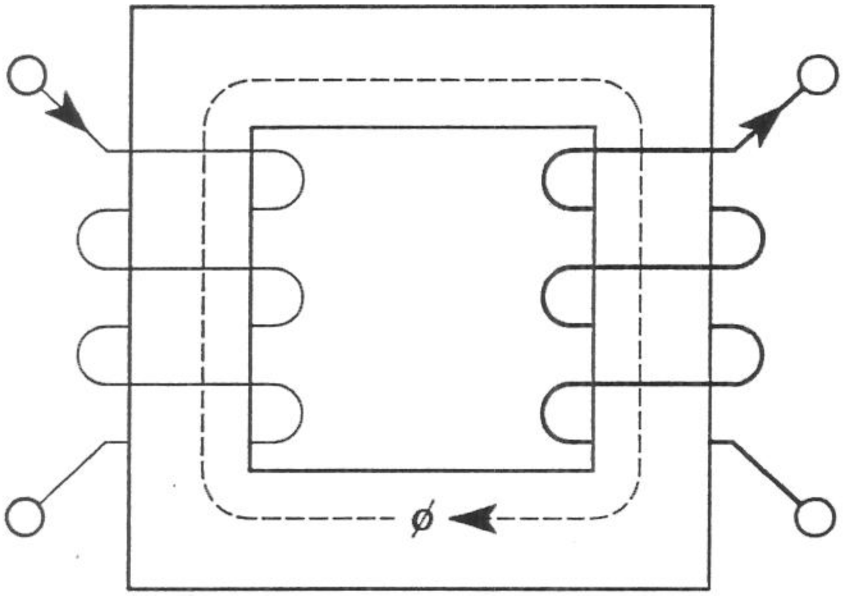

Figure 1a. Traditional box-shaped transformer topology.

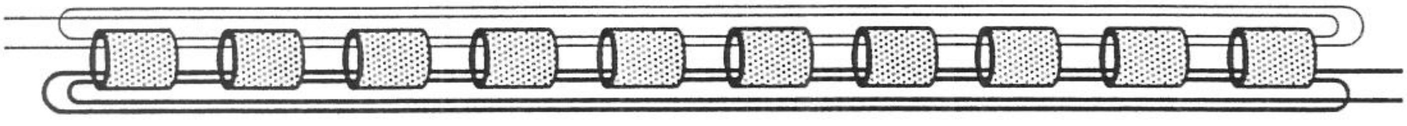

Figure 1b. New powercord transformer topology.

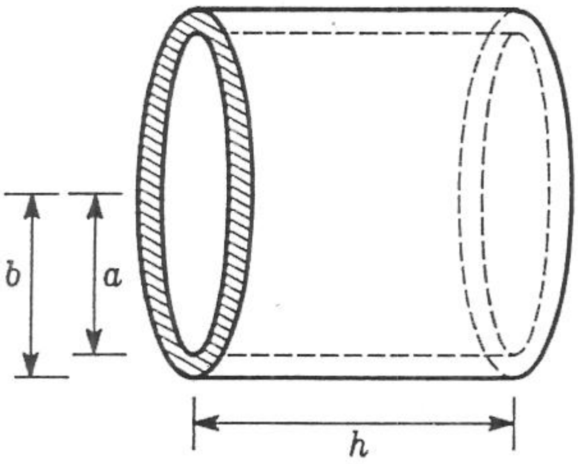

Figure 2a. A large-scale view of a single toroidal core, showing ***a,*** the inner radius; ***b,*** the outer radius; and ***h,*** the height.

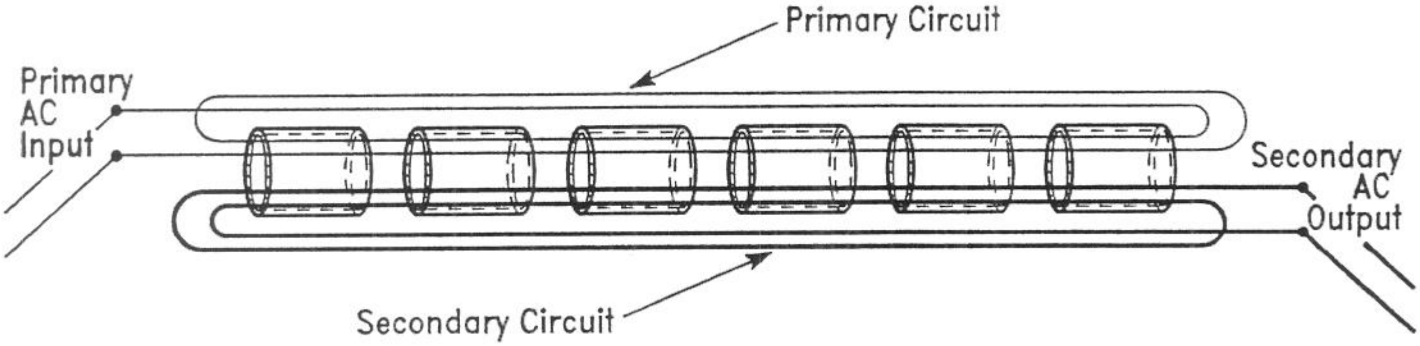

Figure 2b. Wire coiling diagram for the powercord transformer. The input-output voltage properties of the transformer can be controlled by varying the ratio of the number of primary turns to the number of secondary turns.

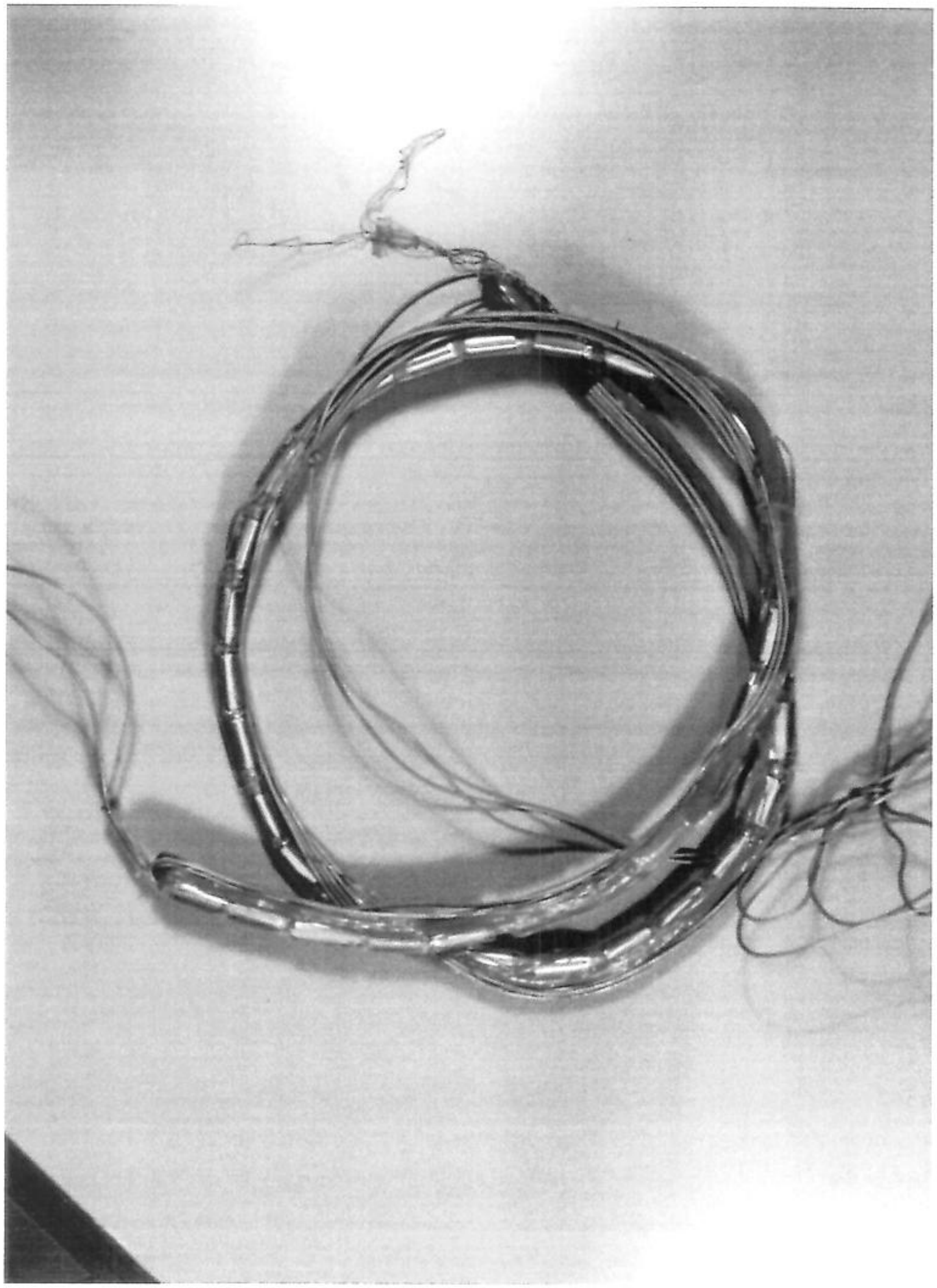

Figure 3. A photograph of the prototype powercord transformer described in the text. It contains 47 toroidal cores connected in series to form a long (3 feet), thin (.25 inch), flexible 7:1 step-down transformer capable of handling 8.3 V RMS input at 60 Hz. Powercord transformers that can be connected directly to line voltage should be possible.

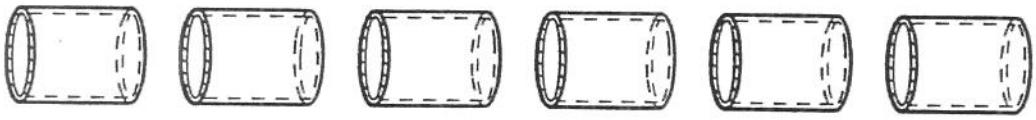

Figure 4a. A simplified manufacturing process for the powercord transformer. For simplicity, only a single wire coil has been shown, but this process extends to arbitrarily many coils. First, stack the toroid cores.

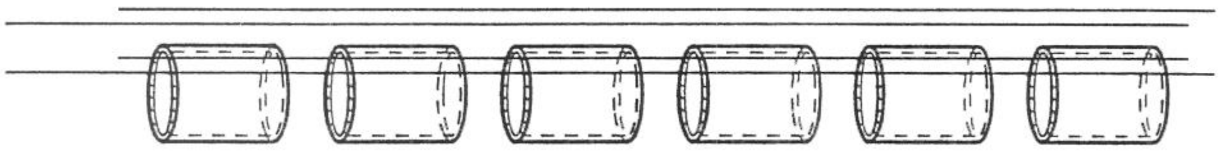

Figure 4b. Second, thread a bundle of primary and secondary wires through the center of the stack. Also lay corresponding wires the length of the toroid stack.

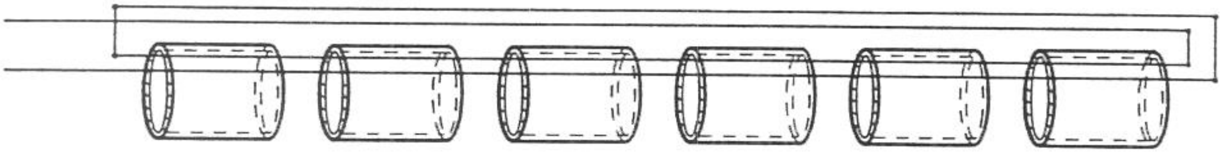

Figure 4c. Finally, connect internal and external wires to create the transformer coil circuits.