The Matrix Transformer — A New Way to Use Ferrites

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INTRODUCTION

This article describes the matrix transformer technology suitable for the implementation of low profile, high power density, and high frequency power converters. Comprised of multiple toroidal cores, the matrix transformer is arranged in groups or elements which constitute the "turns ratio." The realization of a single primary turn resulting in low leakage inductance is illustrated. The application of this transformer configuration to all known topologies is outlined.

THE CONVENTIONAL POWER TRANSFORMER

High leakage inductance is one of the well-known problems in modern power transformers. In today's shrinking power converters, high profile designs and hot spot temperatures at the center of the core are two of the nightmares faced by design engineers.

To reduce core loss, the flux density is considerably iterated at high operating frequencies. For a given output current, the transformer wire window must be large enough to accommodate reasonably low loss windings in order to be efficient. These limitations pose considerable problems in the miniaturization of the power converter.

Another common problem is that the single-turn secondary winding (for a 5-V output) does not permit accurate turns ratio for other outputs requiring voltages such as 12 volts, 18 volts, etc.

Based on experience in the design of the conventional transformer, it is apparent that it would be highly

An alternative ferrite configuration offers new options in transformer design.

desirable to have single-turn secondary winding as well as single-turn primary winding.

THE MATRIX TRANSFORMER

With the matrix transformer, a single primary turn is possible, and multiple single-secondary-turn combinations can also be made. The result is a low profile, low leakage inductance, high power density power transformer configuration with distributed thermal properties not found in conventional transformer designs.

The single-turn primary winding is accomplished by a novel arrangement of toroidal cores into groups or elements, thus resulting in a substantial reduction in leakage inductance. The characteristics of this transformer configuration make it highly suited to low profile, high power density, pulse-width-modulated and resonant power converter implementation.

MATRIX TRANSFORMER CONSTRUCTION

The matrix transformer is constructed with many toroidal cores or groups of toroidal cores. For analytical purposes, group or an element is defined as the smallest part having an identifiable structure as a transformer. For a transformer with a single-turn primary winding, the number of elements is analogous to the conventional transformer turns ratio, i.e., if there are *n* elements in the transformer, the effective turns ratio will be n : 1 or 2n : 1 depending on the transformer configuration.

The conceptual details of this transformer can be described systematically by a series of illustrations. (Figures 1 to 4.) Figure 1 shows a toroidal transformer with a single primary turn and a single secondary turn (turns ratio of 1:1). The concept of implementing a transformer with more than one core is illustrated in Figure 2. For Figures 1, 2 and 3, the number of elements is a direct reflection of the turns ratio. Figure 3 depicts a matrix transformer with the secondary windings connected in phase and in parallel. There is only one turn on the primary, but by the physical arrangement of the cores and the windings, a step-down ratio of 2:1 is accomplished.

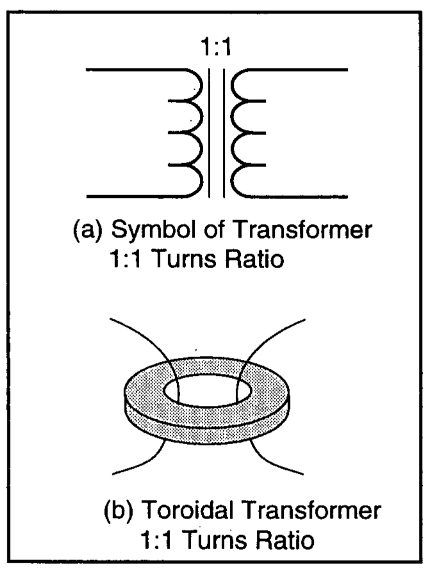

Figure 1. *Symbolic and Pictorial Representation of Transformer.*

*See Advertisement on Page 117.

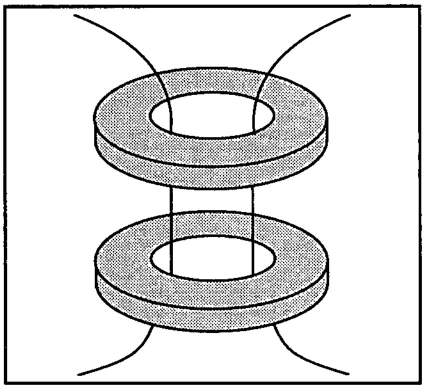

Figure 2. *Pictorial Representation of Transformer with More Than One Toroid, 1:1 Turns Ratio.*

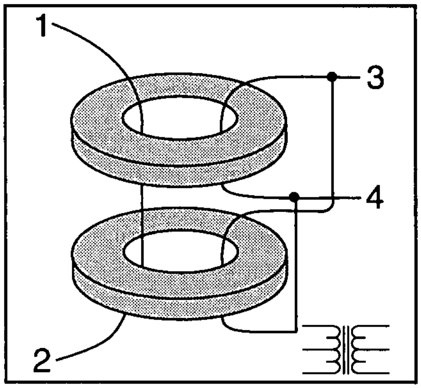

Figure 3. *Matrix Transformer, 2:1 Turns Ratio.*

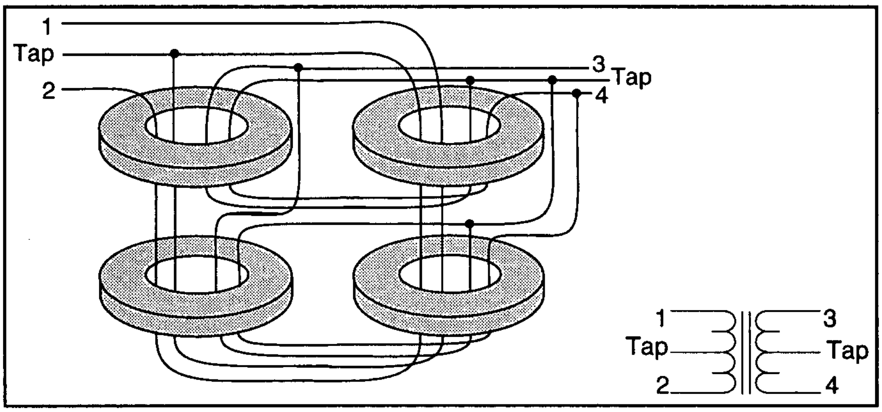

Figure 4. *Center-tapped Matrix Transformer, 2:1 Turns Ratio.*

The physical configuration of a center-tapped matrix transformer is shown in Figure 4. In this configuration, the number of elements provides the equivalent of the conventional transformer turns ratio of n:2 where n is the number of elements. If more core area is required for a given design, a number of cores can be used in place of each of the four toroids shown in Figure 4. Due to the distributed layout of this transformer, the following unusual characteristics are noted:

- Short thermal paths — since the magnetic cores are no longer concentrated as one lumped core, the thermal paths of many smaller cores (as compared with one large core) are naturally much shorter
- No single hot spot temperature — the normal single hot spot of a lumped transformer does not exist here since there are many cores to take the burden of power transfer
- Higher current and flux density — since heat dissipation is distributed among many cores and single turns of wire

In addition to these features, the matrix transformer is, by design, of very low profile and highly suited for high power density power processor synthesis.

DESIGN PHILOSOPHY

The matrix transformer is, in essence, an extension of the concept of fractional turn transformer implementation with multiple cores. However, this method of implementation is more elegant because the fractional turns of the conventional transformer are replaced with full turns in the matrix transformer. Common to all transformers, the primary to secondary voltage ratio is the same as the equivalent turns ratio. The primary to secondary current ratio is the inverse of the equivalent turns ratio. The net ampere turns in each element of this transformer is zero, and the voltage is equal across all parallel paths. Because the current in any winding is directly proportional to the turns ratio, and the turns ratio within any element is 1:1, resulting in equal currents, the physical properties of this transformer configuration permit the primary and secondary windings to be made with the same size wires, in spite of current step-up or step-down (ignoring the effect of magnetizing current).

At high operating frequencies (above 100 kHz), the use of Litz wire is not necessarily beneficial in spite of the skin effect. This is because the reduced cross-sectional area of the Litz wire occupying a given window area is less effective for heat transfer.

An important feature of this transformer is its low leakage characteristics. Because the leakage inductance associated with a transformer is proportional to the square of the number of turns, a single primary turn transformer is obviously better than a transformer with a multi-turn primary winding. For off-line converters, the leakage inductance of the single-turn primary transformer is theoretically 13^2 or 169 times better than that of the 13-turn primary winding counterpart.

With a single primary turn, the wire size can be reduced to match the loss of the conventional transformer primary (which has 13 turns, with longer wire length) while maintaining the same overall copper loss properties. This indicates that the traditional approach of balancing core loss and copper loss is not necessarily optimum for this new transformer configuration.

Switching frequency is intuitively chosen for the feasibility of obtaining a single-turn primary winding for a given set of cores. To qualify this statement, it would be instructive to consider which one of the design parameters is the most desirable. If a low profile is the most important

Continued on page 115

goal, then the outer diameter of the core can be selected first. The number of cores required can then be estimated, based on the space allowed for the transformer.

According to Faraday's law of induction, the transformer is designed to support an input voltage. For pulse-width-modulated transformers, the input volt-second is of interest:

$$V_i Dt = 4BAn_cN \times 10^{-4}$$

where
V_i = input voltage in volts
D = duty ratio
B = flux density, tesla
A_C = total core area (n_cA_c), cm^2
N = number of primary turns
t = period of the switching frequency, seconds
A_c = core area of one toroidal core, cm^2
n_c = number of toroidal cores used

The flux density is chosen for a pre-determined loss figure. The core loss per unit volume is obtained from the manufacturer's core data, and can be minimized by increasing the ratio of core area A_c to core volume vol_c. The maximum ratio of A_c/vol_c occurs when the ratio of the total height of n_c toroidal cores to the inside diameter of the core is maximum. The rationale is similar to the preference for using a long slender core in the conventional transformer. Here, the single long slender core is simulated by a string of many "short" toroids. However, by the same reasoning, a string of more slender toroids (with identical cross-sectional area A_c) is preferred. A long slender core has a higher surface area to volume ratio and heat dissipation is improved.

APPLICATION TO POWER CONVERTERS

The matrix transformer is applicable to all known power converter topologies. The configuration depicted in Figure 3 is suitable for use in the buck-derived forward converter as well as the isolated flyback (buck-boost-derived) converter. In the case of the flyback converter application, powder toroidal cores of controlled permeability should be used in place of the pure ferrite toroids. For the push-pull converter, the configuration shown in Figure 4 is applicable. The configuration shown in Figure 5 is suitable for both the half-bridge and the full-bridge converters.

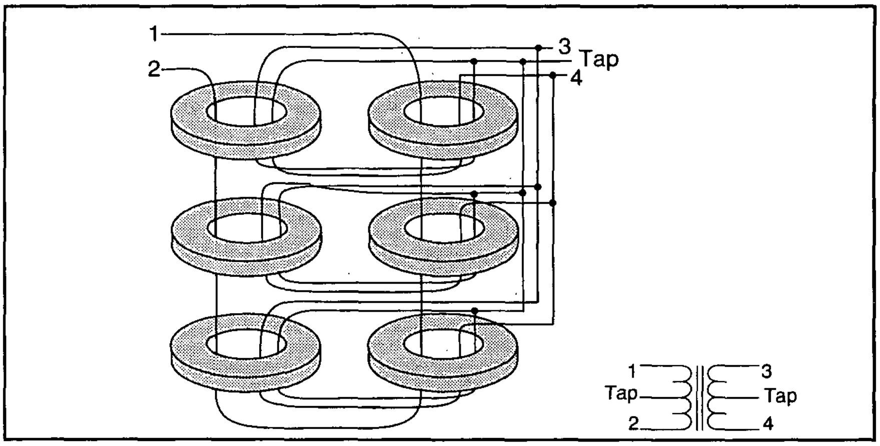

Figure 5. *Matrix Transformer with Tapped Secondary, 3:1 Turns Ratio.*

Note that an option exists here to allow the designer to connect all secondary windings in phase and in parallel with one set of output rectifiers. With more even heat distribution, the secondary windings may be connected to separate sets of output rectifiers with the outputs of all rectifier circuits connected in parallel. (The current will divide exactly and equally.)

SUMMARY AND CONCLUSIONS

Several novel low profile matrix transformer configurations for high density power conversions have been described. The matrix transformer demonstrated the following significant qualities:

- Easy thermal management due to the distributed nature of core and output winding arrangements
- High current density in windings without undue increase of power loss due to shorter turn length and lower turns count
- Single-turn primary that is feasible and practical
- Accurate turns ratios that are feasible
- Ability to isolate to meet agency approvals
- Low leakage inductance and excellent coupling by design
- Low mechanical profile permitting high density packaging
- Absence of single hot spot in transformer
- Excellent shock and vibration characteristics due to distributed mass

Multiple secondary windings can be paralleled in phase prior to rectification using either one or many sets of output rectifiers for heat distribution, and can be paralleled at the output with no concern for problems with current sharing.

The above qualities indicate that this matrix transformer configuration represents an important advancement toward improving the performance of the conventional power transformer. The technology of the matrix transformer is just evolving. Future efforts will be directed towards its application to dc-to-dc and off-line power converters and special power conversion topologies.

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