

# Application and Analysis of Adjustable Profile High Frequency Switchmode Transformer Having a U-Shaped Winding Structure

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**Abstract**—This paper introduces a newly developed high frequency switchmode transformer consisting of a U-shaped winding and a multiple toroidal magnetic core element structure. The new transformer with adjustable profile structure exhibits a utilization of the core area which is better than a planar core but worse than a pot core. The coupling efficiency of the transformer is much higher than a planar core structure. The numerical results for the flux density and eddy current density have been compared with those of a planar and pot core transformer structure. The maximum normalized eddy current density of the new structure is 50% less than a pot core or a planar core. The experimental results at low current excitation indicate that the copper loss is lower at high frequency (10 MHz) when using the new winding structure. The core loss is primarily due to hysteresis and increases significantly if a MnZn based material such as TDK PC40 is used at frequencies above 2MHz.

**Index Terms**— Transformer, eddy-current, flux density, copper and core losses, leakage and magnetizing impedances

## I. INTRODUCTION

High frequency (HF) transformers play an important role in most HF switching power supplies. Unfortunately they are not commercially available in a wide range of shapes and sizes due to constraints imposed by material properties and manufacturing processes. The materials of choice at high frequencies include powder cores, MnZn ferrites and NiZn ferrites. The design of transformers for use at high frequencies is also problematic due to difficulties in establishing numerical values for leakage inductance, inter and intra winding capacitance, skin and proximity effect losses and core losses.

A high frequency transformer with a U-shaped winding and multiple toroidal core element structure has been used in radio transmitters as a RF transformer for more than two decades. It was introduced into power electronics in the early 1990's [1] and has since gained greater acceptance in a

number of DC/DC converter applications [2]. This type of transformer exhibits many advantages in high frequency applications such as high power density, high efficiency, low leakage inductance, adjustable profile and low EMI.

This paper presents a newly developed adjustable U-shaped winding transformer with multiple toroidal core element structure. The frequency-dependent magnetizing impedance and leakage impedance are determined experimentally. Finally the distribution of magnetic flux and eddy current in the magnetic core and windings are determined numerically.

## II. CONFIGURATION OF U-SHAPED WINDING STRUCTURE

A adjustable U-shaped winding transformer consists of a small diameter U-shaped meandering copper tube with several high- $\mu$  toroidal cores placed around the copper tube. The ends of the tube are soldered onto the printed circuit board as shown in Fig.1. The U-shaped copper tube represents a one turn primary winding. An insulated copper wire is passed through the tube and serves as the secondary winding of the transformer. The number of turns to be used depends on the desired transformation ratio. The basic consideration of the copper tube thickness is the wall thickness of the outer tube is selected to have the optimum thickness for the highest nominal operating frequency. The diameter is then increased in order to decrease the current density and to increase the heat removal surface area. Multiple wire or litz wire should be used for the inner winding so as to reduce the impact of skin effect.

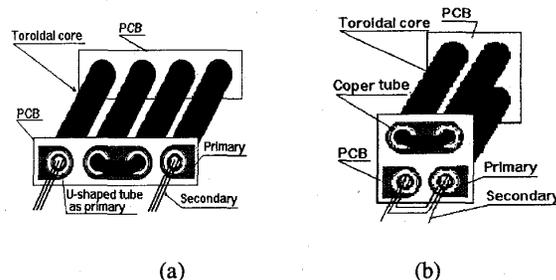


Fig. 1. Configuration of adjustable U-shaped winding transformer with multiple toroidal core element. (a) Horizontally extended structure, (b) Vertically extended structure with lower leakage flux.

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### III. VOLTAGE RATIO AND IMPEDANCE CHARACTERISTICS

Fig. 2 shows the voltage ratio of input voltage  $V_1$  and output voltage  $V_2$  versus frequency. The result indicates that the voltage ratio equals the turn ratio 1:1 and is almost constant over the frequency range of interest due to the good magnetic coupling. The coupling efficiency of the transformer is much higher than a planar core structure. At much higher frequencies, the voltage ratio is influenced by parasitic winding capacitances.

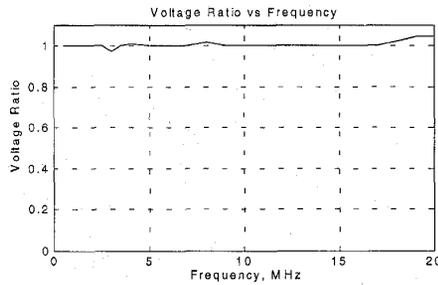


Fig.2 Voltage ratio  $V_1/V_2$  versus frequency.

The copper losses and core losses of a TDK PC40 high-frequency toroidal magnetic core were experimentally investigated under small signal conditions. The leakage inductance  $L_1$  and resistance  $R_1$  were obtained by using a short circuit test. The magnetising inductance  $L_m$  and magnetizing branch equivalent core loss resistance  $R_m$  were obtained by using an open circuit test. All results were obtained using a HP4285A (75KHz-30MHz) precision LCR meter. The results are shown in Table I.

The experimental results indicate a frequency independent leakage inductance  $L_1$  over the frequency range 100KHz to 2 MHz. The winding resistance  $R_1$  is also almost frequency independent. The experimental results also show that the magnetizing inductance  $L_m$ , related to permeability  $\mu$ , and

TABLE I  
LEAKAGE AND MAGNETIZING IMPEDANCE CHARACTERISTICS

Freq. (MHz)	$L_1$ (nH)	$R_1$ ( $\Omega$ )	$L_m$ ( $\mu$ H)	$R_m$ ( $\Omega$ )
0.1	223.50	0.037	23.03	0.110
0.2	220.40	0.040	23.50	0.359
0.3	218.90	0.043	23.87	0.789
0.4	216.00	0.047	24.49	1.580
0.5	213.70	0.052	25.38	3.180
0.6	212.40	0.057	26.53	6.550
0.7	211.45	0.061	27.78	13.400
0.8	210.60	0.065	28.76	25.480
0.9	209.92	0.069	29.08	42.530
1.0	209.19	0.072	28.84	62.840
1.5	207.40	0.087	21.74	176.928
2.0	206.44	0.102	12.90	252.850

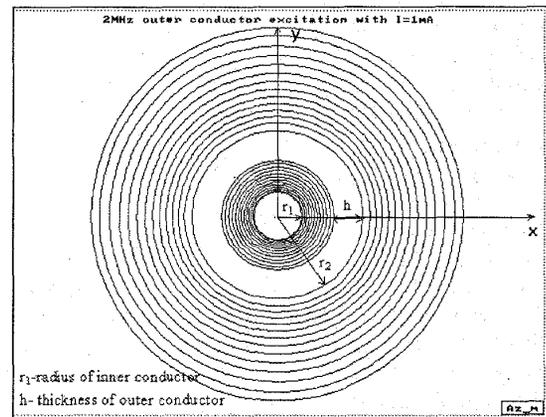
the resistance  $R_m$ , related to the hysteresis core losses, change significantly with frequency. The equivalent circuit magnetizing impedance can be obtained by using the following formulas:

$$L_M = \frac{R_m^2 + \omega^2 L_m}{\omega^2 L_m} \quad (1)$$

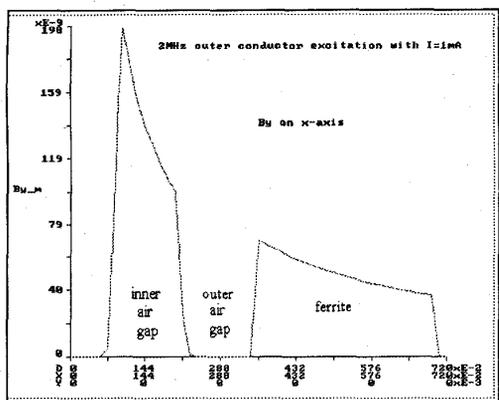
$$R_{fe} = \frac{R_m^2 + \omega^2 L_m}{R_m} \quad (2)$$

### IV. NUMERICAL ANALYSIS OF MAGNETIC FLUX AND EDDY CURRENT DISTRIBUTION

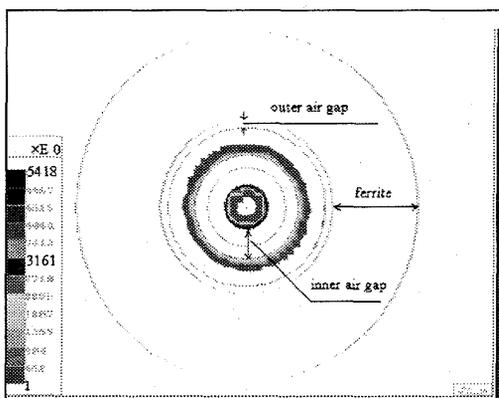
Fig. 3 shows the computer simulation results for the flux density in the core and eddy-current density distribution in the windings under open-circuit conditions for second winding, when ignoring the impact of end winding effects. The operating condition results in the worst case for core loss. The simulation results were obtained by using the commercial software package [3]. The flux density distribution  $B_y$  along x axis shown in Fig. 3 (b) results in a core area utilization which is better than a planar core but worse than a pot core [4]. Fig.3 (c) shows that the eddy current is distributed on the inside surface of the primary winding and the outside surface of the secondary winding. The asymmetric distribution is a consequence of the proximity effect. The asymmetry distribution can be reduced and hence copper losses reduced by increasing the diameter of the outer tube (primary winding), by leaving the thickness of the outer wall unchanged and by using litz wire for the secondary winding.



(a)



(b)



(c)

Fig. 3. Magnetic field distribution with excitation on outer tube winding,  $r_1 = 0.9\text{mm}$ ,  $h = 1.1\text{mm}$ ,  $r_2 = 3.2\text{mm}$ , TDK-PC40 (T14x3.5x7) ferrite, (a) Flux distribution, (b) Flux density  $B_y$  along X axis, (c) Eddy-current distribution.

## V. COMPARISON OF EDDY-CURRENT LOSSES

The flux density and eddy current distribution for the U-shaped transformer have been compared with those of a pot core and planar core transformers [4]. Fig.4 shows the comparison of maximum eddy current density for the following three types of transformers: MET U-shaped primary winding and litz wire secondary with multiple toroidal core element structure; PCT I pot core with separated primary and secondary winding structure; PCT II pot core with twisted primary and secondary winding structure; PST I planar magnetic core with meander type winding structure and PST II planar magnetic core with spiral winding structure. The maximum normalized eddy current distribution of the new structure is 50% less than that of a pot core or a planar core. Consequently its losses at higher frequencies should be lower than the planar or pot core structure.

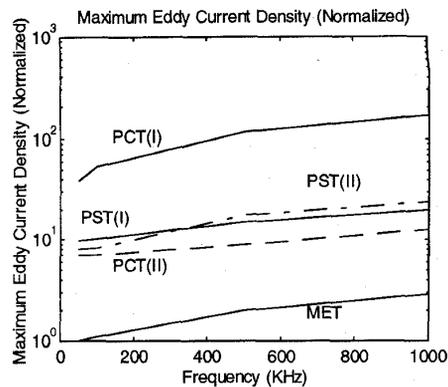


Fig. 4. Comparisons of normalized eddy-current density.

## VI. CONCLUSIONS

The paper presented a newly developed adjustable profile U-shaped winding transformer with multiple toroidal core element structure. The experimental and numerical results have demonstrated the following advantages at high operating frequencies: low copper losses, low leakage impedance, high power density, high magnetic coupling. The new design should also be less costly to manufacture and has an adjustable profile. A boundary element method was used to investigate the magnetic flux density distribution in the transformer core and eddy current distribution in the windings. These distributions can be optimized by using a litz wire secondary and a large diameter concentric hollow tubular primary winding. Future work will concentrate on further optimizing the design of the magnetic system subject to constraints imposed by the heat transfer properties of the core material and surrounding environment. Also, EMI generated at the winding terminals, shielding effects of the tube winding, coupling between primary and secondary windings and winding end loss effects will be investigated.

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