HIGH FREQUENCY WIDEBAND POWER TRANSFORMER DESIGN

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ABSTRACT

The transmission line transformer(TLT) is presented as a viable solution to the problem of high frequency/wide band transformer design for the latest high frequency dc-dc resonant converters. Utilizing transmission line circuit theory, we present the characteristics of the TLT. Turn ratio 2:1 and 3:1 TLT prototypes with isolation were designed and fabricated from microstrip and coaxial cable transmission line. Small signal and power test results point out the advantages of TLT.

I. INTRODUCTION

In recent years, applications of power electronic have been growing fast. In most of applications, the efficiency and the size of the power system are often major concern. In order to achieve high power density and efficiency, the power devices are normally operated at high frequency switching mode. At high frequency, conventional winding transformer limits the performance because interwinding capacitance resonates with the leakage inductance producing oscillatory losses. The core loss also increases as frequency increased. To overcome these problems, one way is to use transmission line transformer(TLT). The TLT provides excellent coupling of the magnetic and electric fields. This ensures a minimum of leakage reactance over the useful frequency range. Between transmission line conductors, the interwinding capacitance is uniformly distributed such as a part of the characteristic impedance Z_o of the line, no resonances will seriously limits upper operating frequency. Unlike in the conventional transformer, performance and characteristics(i.e., voltage, current, and load transformations, etc.)of n:1 TLT are solely a consequence of the interconnection of transmission line segments and are not due to the magnetics of the device. The magnetics' function in a TLT involves minimizing the net current flow in the transmission line segment and does not serve the purpose of power transfer such that the core materials will not have serious effects to TLT performances. The concept of TLT is not new [1], [2], it has been applied to UHF and VHF communications. But, little work has been done in dc-dc high frequency switching mode power supply. One of the major difficulties in TLT is how to isolate input and output without degradation in the transformer performance. In this paper, we provide several design prototypes of TLT which have 2:1 and 3:1 turn ratios with isolation. Experimental results will show advantages of TLT.

II. TLT ANALYSIS

The fundamental transmission line transformer unit, from which the generation of all TLT circuit is achieved, is the 2:1 voltage ratio circuit of Fig.1.

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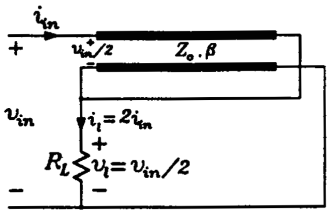

Fig. 1 2:1 TLT

The proper operation of this device, as well as all other TLTs, is based on two assumptions. The first requires that transmission line be kept electrically short, implying that βl be kept small, where $\beta = 2\pi/\lambda$, l is the length of transmission line . The second, if the assumption of perfect transmission line propagation is made, signifying equal and opposite current i_{in} are flowing within the line segments.

Based on the transmission line equations, the exactly responses of TLT circuit can be solved by two ports network analysis. The important characteristics of TLT to be obtained are the voltage transformation ratio n_v, the current transformation ratio n_i, the load transformation ratio n_l^2, the input impedance Z_{in}, and reflection coefficient Γ. Expressions for these quantities are defined in equations (1)-(5).

$$n_v = \frac{V_{in}}{V_l} \tag{1}$$

$$n_i = \frac{i_l}{i_{in}} \tag{2}$$

$$n_l^2 = \frac{V_{in}/i_{in}}{V_l/i_l} = n_v n_i \tag{3}$$

Overall TLT performance is best represented by the load transformation ratio since it incorporates both voltage and current characteristics. Ideally, n_v, n_i and n_l^2 are constants, n:1 turn ratio will give n^2:1 load transfer ratio. In transmission line theory, these quantities vary in magnitude and in phase as a function of frequency(or wavelength), characteristic impedance Z_o and length of transmission line [3],[4]. We define the frequency response of transformer that is value of n_l^2 at different frequency. As design point of view, n_l^2 of a good transformer should have almost constant magnitude and zero phase through wide frequency band. Recognizing V_l/i_l to be the load resistance R_L, input impedance can be written as

$$Z_{in} = \frac{V_{in}}{i_{in}} = n_l^2 R_L \tag{4a}$$

such that n_l^2 can be expressed by

$$n_l^2 = \frac{Z_{in}}{R_L} \tag{4b}$$

With the goal of permitting a simple experimentally verifiable evaluation of TLT performance, a relation between reflection coefficient and input impedance has been derived. In fact, reflection coefficient represents deviation from ideal performance(i.e. n_l^2=const.). The mismatch happened to is that between the input impedance Z_{in}, $n_l^2 R_L$, and a source impedance Z_g. From the transmission line theory, the reflection coefficient at the source is given by

$$\Gamma = \frac{Z_{in} - Z_g}{Z_{in} + Z_g} = |\Gamma| e^{j\theta} \tag{5}$$

If $\Gamma = 0$, it represents a perfect transformation which means no insertion loss. In terms of S-parameters expression, the reflection coefficient Γ equals to S_{11}, solving equation (5),

$$Z_{in} = Z_g \frac{1 + |S_{11}| e^{j\theta}}{1 - |S_{11}| e^{j\theta}} \tag{6}$$

S_{11} can be directly measured from HP Network Analyzer/S-parameter test set. Substituting Z_{in} into equation (4b), the frequency response of TLT will be obtained.

III. SMALL SIGNAL TEST RESULTS

Several 2:1 and 3:1 prototype TLT transformers have been designed and assembled as detailed in Table 1. Device A and B are made by TDK LP core wound by microstrip transmission line shown in Fig. 2, consisting of two narrow

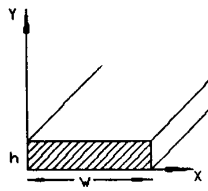

Fig.2 Microstrip Transmission Line

ribbon copper which width is W separated by dielectric substrate which height is h. The shape ratio W/h and dielectric coefficient ϵ_r determine the characteristic impedance Z_o of transmission line. In microstrip transmission line, most field lines in the dielectric region concentrated between two strip and some fraction in the air region above the substrate. For this reason, the microstrip line can not support pure TEM wave. In most practical applications, however, the dielectric substrate is electrically very thin($h < \lambda$), so the field is quasi-TEM wave. In quasi-TEM wave, the phase velocity and propagation constant can be expressed as

$$v_p = \frac{c}{\sqrt{\epsilon_e}} \tag{7}$$

$$\beta = k_o \sqrt{\epsilon_e} \tag{8}$$

where k_o is wave number in free space, ϵ_e is the effective dielectric constant of the microstrip line. The effective dielectric constant satisfies the relation

$$1 < \epsilon_e < \epsilon_r$$

and is dependent on the substrate thickness h and conductor width W [5]. We select Thermal-H-10 material manufactured by Acme Division as dielectric substrate which dielectric constant ϵ_r is 3.7. The effective dielectric constant of microstrip line is given approximately by

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12h/W}} \tag{9}$$

Given the dimensions of the microstrip line, the characteristic impedance Z_o can be calculated as

$$Z_o = \begin{cases} \dfrac{60}{\sqrt{\epsilon_e}} \ln\left(\dfrac{8h}{W} + \dfrac{W}{4h}\right) \\ \dfrac{120\pi}{\sqrt{\epsilon_e}[W/h + 1.393 + 0.667\ln(W/h + 1.444]} \end{cases} \tag{10}$$

For a given characteristic impedance Z_o and dielectric constant ϵ_r, the W/h ratio can be found as

$$\frac{W}{h} = \begin{cases} \dfrac{8e^A}{e^{2A} - 2} & for W/h < 2 \\ \dfrac{120\pi}{\sqrt{\epsilon_e}[W/h + 1.393 + 0.667\ln(W/h + 1.44} \end{cases} \tag{11}$$

where
$$A = \frac{Z_o}{60} \sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(0.23 + \frac{0.11}{\epsilon_r}\right)$$
$$B = \frac{377\pi}{2Z_o\sqrt{\epsilon_r}}.$$

Device C and D are made by pot core, C is wound by RG-174 coaxial cable, and D is wound by microstrip line. Photographs of the assembled device A and C are shown in Figs. 3-4.

With the use of the HP test set, all of the prototype transformers were submitted to an input impedance test and short circuit test. The equivalent circuit of short circuit is shown in Fig. 5. The Z_{in} test will give the frequency

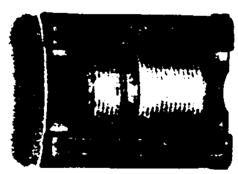

Fig.3 Assembled transformer, Device A

Fig.4 Assembled transformer, Device C

DEVICE	TURN RATIO	CORE SPECIFICATIONS	WINDING SPECIFICATIONS
A	2:1	LP32/13; PC40; TDK μ_i=3000	Cu. STRIP, W/h=20.4, Z_o=9.6Ω, 6 TURNS
B	3:1	LP32/13; PC40; TDK μ_i=3000	Cu. STRIP, W/h=20.4, Z_o=9.6Ω,, 8T/1S, 4T/2S
C	2:1	J43019UG,MAGNETICS μ_i=5000	Cu. STRIP, W/h=13.8, Z_o=14.2Ω, 6 TURNS
D	2:1	J43019UG,MAGNETICS μ_i=5000	RG-174 COAX. CABLE, 5 TURNS

Table 1. Transformer Specifications

response of the transformers. Since S-parameter test set has 50Ω port, load resistance R_L was set to 12.5Ω and 5.6Ω for the 2:1 and 3:1 devices. The short circuit test will give the leakage inductance L_l and total copper loss r_c. Figs. 6-9 give the frequency response of each device. Table 2 lists L_l and r_c of each transformer at 1MHZ. Fig.6 and 8 show the device A and C have operation bandwidth from 100KHZ to 10MHZ. They also have small leakage inductance and copper resistance.

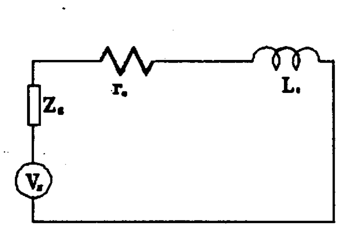

Fig.5 Equivalent Circuit of Short Circuit

These devices can be applied into the most dc-dc switching mode power converters.

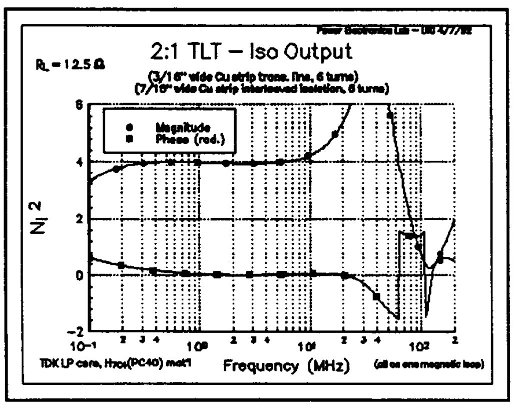

Fig.6 Frequency Response of Device A

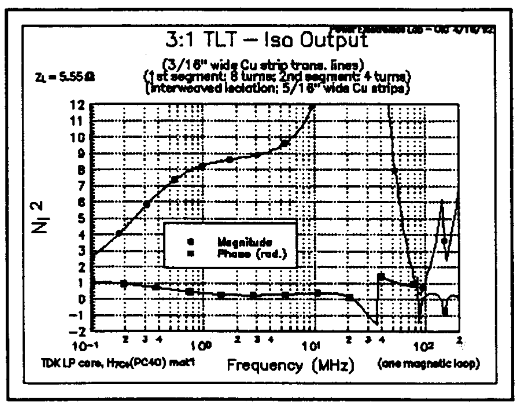

Fig.7 Frequency Response of Device B

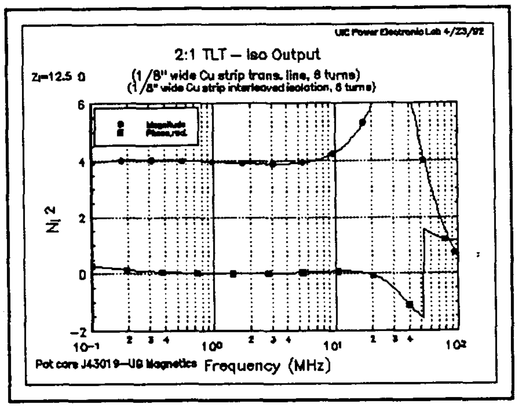

Fig.8 Frequency Response of Device C

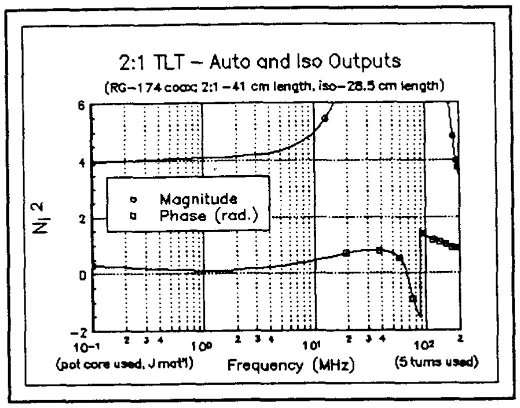

Fig.9 Frequency Response of Device D

DEVICE	A	B	C	D
L_l(nH)	370	600	390	400
$r_c(\Omega)$	0.24	0.35	0.37	0.60

Table 2. Leakage Inductance and Copper Resistance of Each Device

IV. POWER TEST RESULTS.

The transformers were power tested with an open loop shown in Fig. 10. The input voltage is sine wave signal which rms value is 84 volt. Ideally, R_m is infinity, the voltage V_{in} and current i_{in} are 90 degree out of phase, the core loss is zero. In practice, R_m has certain value such that V_{in} and i_{in} have a phase angle γ between 0 and $\pi/2$. The core loss will given by

$$P_l = V_{in} I_{in} \cos\theta \qquad (12)$$

Table 3. lists power loss of each transformer at 1MHZ. Device A and C have small power losses such that they should have high efficiencies.

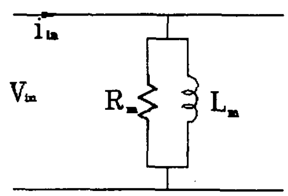

Fig.10 Equivalent Circuit of Open Loop

DEVICE	A	B	C	D
POWER LOSS(Watt)	0.7	1.1	0.9	1.2

Table 3. Power Loss at 1MHZ of Each Device

V. CONCLUSION

In this paper the prototype transmission line transformer has been designed and tested. The experimental results show the advantages of TLT such as wide bandwidth, small leakage inductance and power loss. Unlike the conventional transformer, the TLT is expected to yield better performance as the frequency of operation is increased. With its inherently compact microstrip line layout design, the TLT can fulfill the power transformer miniaturization sought after. TLT can also be applied to the planar transformer design. The shortage of the TLT is more completed to make isolation and multiple outputs.

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