RESPONSE CHARACTERISTICS OF A TRANSMISSION LINE BASED TRANSFORMER

Akira Homma*

Division of Quantum Energy, Faculty of Engineering, Hokkaido University,
North 13, West 8, Kita-ku, Sapporo 060-8628, Japan

Abstract

Response characteristics of a transmission line based transformer were studied to take into account signals that inevitably appear in the space outside of the transmission lines. A prototype of the transformer, using semi-rigid co-axial cables, was constructed and tested to confirm the results of the theory. Good agreement was obtained between the theory and experiments in the 5 MHz to 3 GHz frequency range. A 3 dB bandwidth of this transformer was also obtained from about 20 MHz to 1 GHz.

1 INTRODUCTION

Transmission line based transformers (TLBT) have been widely used in fields requiring high-speed high-power pulse techniques such as in linear accelerator technology. However, only a little attention has been paid to the frequency response characteristics. [1][2] In general, the frequency response is one of the most important characteristics when transformers are actually used. This paper describes a theoretical approach to study frequency response characteristics of a TLBT.

Based on the principles of operation TLBT can be classified into two types. One, a transmission line (normally co-axial cables) wound around a magnetic core such as ferrite or other magnetic material. A large inductance can be made between input and output so that the transformer achieves high inductive isolation for transient voltage changes between input and output. However, even though an inversion of the signal is possible, dc isolation of input and output is impossible. The other type of TLBT uses one conductor of the transmission line as the primary winding and the other conductor as the secondary winding or vice versa. A TLBT of this type can invert the signals and isolation of the dc potential of input and output is possible. [3][4] The operational principle of this second type is similar to an ordinary transformer. The TLBT considered in this article belongs to the latter type.

2 OPERATIONAL PRINCIPLE

As shown in Fig. 1, the transformer is composed of two co-axial lines, 1 and 2, with the same path length and impedance, Z/2. The inner and outer conductors of the co-axial lines correspond to the primary and secondary windings of an ordinary transformer, which can isolate the dc potential of the input and output. In the figure, the solid arrows show the direction of the electric lines of force for signals propagated inside the co-axial lines. The input signal transmitted by the coaxial line with impedance Z divides into lines 1 and 2 each with impedances of Z/2 (at the junction **S**). From here the signals travel in the lines and join at junction **J** where the signal is reconstructed as the output and transmitted to the co-axial line with impedance Z. A small part of the signal leaks from the junction of the co-axial lines at **J**. The signal is termed ‘the coil-mode signal’, and is illustrated by the broken arrows in the figure. The coil-mode signal travels in the space formed by the outer conductors of the co-axial lines 1 and 2, and this space is termed the ’coil-mode line’. The signal is reflected at the short-circuited end **S**, where the polarity is inverted and the signal returns to junction **J**. Then a part of the signal is reflected and reenters the coil-mode line again, and the other part of the signal is transmitted as the output. Thus the round trip of the coil-mode signal described above is repeated. The coil-mode signal can be seen as an electromagnetic field stored inside the space of the coil-mode line.

The output voltage of the TLBT at any instant is determined by the sum of all the incident waves at junction **J**. The following analysis assumes the coil-mode line to be a lossless ideal transmission line with impedance αZ where the signal is transmitted by the fundamental electromagnetic mode with constant propagation time. The coil-mode impedance was determined with the characteristic impedance of a parallel wire-line in air.

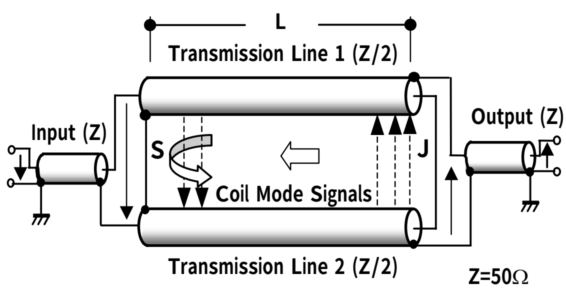

Fig.1. The basis of the structure of the TLBT.

* homma@qe.eng.hokudai.ac.jp

3 RESPONSE FUNCTIONS

The unit impulse response function was determined first. By considering multiple reflection of the voltage wave in the coil-mode line, the unit impulse response of the TLBT is readily obtained from the total of the voltage wave incidence in the output terminal. The detailed procedure for deducing the response was reported previously. [3][4] When an impulse signal is applied to the input terminal at time t=0, the resulting impulse response is given as

$$h(t)=\frac{2\alpha}{1+2\alpha}\left\{\delta(t)\;-\;\frac{2}{1+2\alpha}\sum_{n=1}^{\infty}\left(\frac{2\alpha-1}{1+2\alpha}\right)^{n-1}\;\delta(t-nT)\right\} \quad (1)$$

where the T is the transit time for the coil-mode signal to make a round trip on the coil-mode line. Here α stands for the ratio of the coil-mode line impedance to the output (or input) impedance. The frequency response function $A(\omega)$ of the TLBT can be obtained by the Fourier transform of Eq. (2) as follows

$$\left|A(\omega)\right|=\frac{1}{\sqrt{1+\frac{1}{4\alpha^2}\left(\frac{1+\cos\omega T}{1-\cos\omega T}\right)}} \qquad \left(\frac{2\alpha-1}{1+2\alpha}\right)<1 \quad . \quad (2)$$

The gain given by Eq. (2) has a maximum at the frequency f_c ($\omega T=\pi$) where the coil-mode line length is a quarter wavelength long. The f_c is designated as the fundamental coil-mode frequency of the TLBT since the frequency is determined by the time that is necessary for the coil-mode signal to traverse the coil-mode line. The gain is the minimum at even integer multiples of f_c. Eq. (2) exhibits repeated symmetric band pass characteristics centered at odd integer multiples of f_c.

To emphasize the properties of the gain characteristics, the TLBT with the coil-mode line length of 150 mm (T =1 ns, f_c =0.5 GHz) was calculated and is shown in Fig. 2.

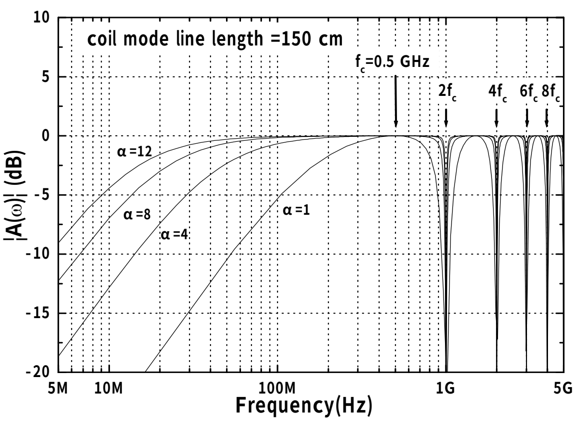

Fig. 2. Calculated response functions.

The 3 dB bandwidth of the band pass region for the TLBT is determined by the fundamental coil-mode frequency f_c. As the ratio α increases from unity to infinity, the bandwidth of the TLBT increases from zero to $2f_c$. Although theoretically these pass bands repeat indefinitely with increasing frequency, several effects not taken into account in the theory presented here limits the high frequency response of the TLBT.

4 RESULTS

To confirm the theory, the TLBT shown in Fig. 1 was constructed and tested. Semi-rigid co-axial cables (Miyazaki Densen Kogyo 219TB-25) with impedance 25 Ω (Z/2) and outer diameter d=2.1 mm were used as the co-axial lines for the prototype TLBT. The TLBT had a wire spacing D =30 mm and the line length L=120 mm. Input and output of the TLBT maintain an impedance Z= 50 Ω.

The gain was measured in the frequency range from 5 MHz to 5 GHz by a Network Analyzer. The result was presented in Fig. 3.

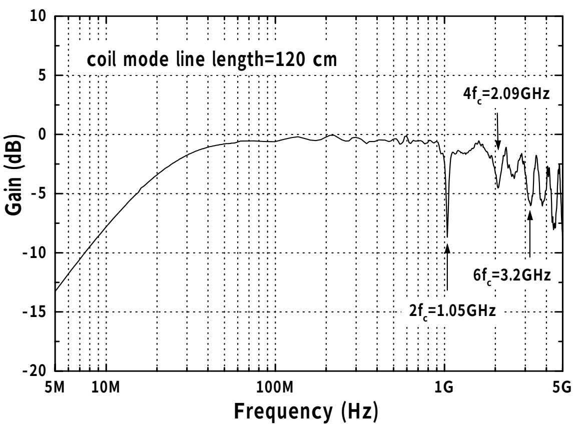

Fig. 3. Response of the prototype TLBT.

The minimum gain at even integer multiples of f_c were observed at frequencies of $2f_c$ =1.05 GHz, $4f_c$ =2.09 GHz, and $6f_c$ =3.2 GHz. With averaged values of these frequencies, the coil-mode frequency was determined as f_c =0.52 GHz (T = 0.96 nsec). At frequencies above $6f_c$, it was difficult to identify the frequency of even integer multiples of f_c because of a large increase in the attenuation at high frequencies that may be caused by electromagnetic field leakage at the junctions of the co-axial lines or the coil-mode line.

At very low frequencies where the wavelength of the input signal λ is much longer than the coil-mode line length, the low cutoff frequency $f_{Low\text{-}3dB}$ can be written as

$$f_{Low-3dB} = \frac{1}{2\pi\alpha T} \qquad \frac{l}{\lambda} \ll 1 \quad . \tag{3}$$

From the wire spacing and outer diameter of the cables, the coil-mode line impedance can be estimated as ≅ 400 Ω (α= 8) and then $f_{Low-3dB}$ ≅21 MHz was obtained by Eq. (3). With the result of the experiments shown in Fig. 3, $f_{Low-3dB}$ can be estimated to be about ≅21 MHz which agrees with the value estimated by the theory. If good low frequency characteristics are required, an increase in α with an increase in the distance between the co-axial lines or an increase in T lengthening the coil-mode line will be effective. Another way to increase α is to place magnetic material around the space of the coil-mode line. Then the transit time T will also increase because of the decrease in propagation velocity of the coil-mode signals.

The results also exhibit the 3 dB bandwidth of the TLBT as the practical operating range can be evaluated from about 20 MHz to 1 GHz.

The measured fundamental coil-mode frequency f_c =0.52 GHz was lower than the value of f_c =0.625 GHz expected as the coil-mode signal propagates with light velocity in the 120 mm long coil-mode line. This implies that the coil-mode signals may not propagate with the fundamental electromagnetic mode in the coil-mode line. Therefore, an estimate of the transit time T would be necessary in the design of an actual TLBT when a precise determination of the bandwidth is required.

The theory described here would be useful in the design of actual high frequency transformers and details of this will be reported elsewhere. [5]

REFERENCES

[1] J. O. Rossi and P. W. Smith, IEE Colloquium on Pulsed Power ’96 (Ref. No. 1996 / 059), 19 / 1-3, 140 (1996).

[2] A.N. Other, “A Very Interesting Paper”, EPAC’96, Sitges, June 1996.

[3] A. Homma and H.Yamazaki, Bulletin of the Faculty of Engineering, Hokkaido University, No. 131, 1986, p. 37.

[4] A.Homma, Rev. Sci. Instrum. 70, 232 (1999).

[5] A.Homma, Rev. Sci. Instrum. to be published.