Modeling and Study of Broadband Transmission Line Transformers

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***Abstract* – This report presents modelling and study of broadband transmission line transformers in frequency response 0,5÷30 [MHz] with coefficient of resistant ratio 1:1, 4:1 and 1:4. Two models are shown as a lumped equivalent circuit of the broadband transmission line transformer and their model parameters have been calculated. Some transformers with 3 twists of copper enamelled wires have been made in practice and studied. Their simulation and experimental qualitative parameters are given which allows model parameter values to be optimized.**

***Keywords* – Transmission Line Transformers, Ferrite Toroidal Cores of Amidon, Modeling, Model Parameters, Study.**

I. INTRODUCTION

Broadband co-ordination of input and output resistance of a high-frequency amplifier and between two adjacent amplifier stages can be carried out by transmission line transformers employing an electromagnetic connection between the primary and secondary windings. They ensure the required resistance transformation ratio and minimum deco-ordination in a broad frequency band though they have small sizes. They have high efficiency and reliability and through them can be made: galvanic dissociation between nodes and units of the equipment, transition from asymmetric to symmetric I/O and vice versa, broadband power aggregation and division, etc.

II. MODELING AND STUDY OF TRANSMISSION LINE TRANSFORMERS

Broadband Transmission Line Transformers (BTLT) are constructed employing appropriately interconnected transmission lines, positioned on a ferromagnetic core which is mostly of toroidal shape [3]. The input signal excites electromagnetic waves whose linear combinations depending on the type of line connection, determine the output signal voltage. The operating principle of this type of transformer is illustrated in Fig. 1.

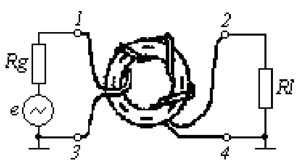

Fig. 1. Transmission Line Transformer

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The main component in transmission line transformers is the ferrite toroidal core used. The most important ferrite core parameters are:

- geometric dimensions: outside diameter $D_{\dim}$, inside diameter $d_{\dim}$ and height $h_{\dim}$ in [mm];
- average length of magnetic line of force l_e, [cm];
- cross-section area A_e, [cm^2];
- volume of ferrite V_e, [cm^3];
- frequency response Δf, [MHz];
- permeability of material μ_r;
- specific volume resistance ρ, [Ω.cm];
- induction factor A_l, which is given by the expression [6]

$$A_L = \frac{L}{\omega^2} = \frac{\mu.\mu_r}{C}, \text{[mH/1000winding]} \qquad (1)$$

Table 1 gives the main catalogue parameters of ferrite toroidal cores manufactured by the firm Amidon [1].

TABLE I
CATALOG PARAMETERS OF AMIDON FERRITE TOROIDAL CORES

Parameter	Ferrite core grade, Amidon			
	FT82-43	FT82-61	FT82-77	FT114-77
$D_{\dim}$, [mm]	21,000	21,000	21,000	29,000
$d_{\dim}$, [mm]	13,100	13,100	13,100	19,000
$h_{\dim}$, [mm]	6,350	6,350	6,350	7,000
l_e, [cm]	5,260	5,260	5,260	7,420
A_e, [cm^2]	0,246	0,246	0,246	0,375
V_e, [cm^3]	1,290	1,290	1,290	2,790
Δf, [MHz]	1÷50	10÷200	0,5÷30	0,5÷30
A_l,[mH/1000w]	557	73,3	1170	1270
μ_r	850	125	2000	2000
ρ, [Ω.cm]	1.10^5	1.10^8	1.10^2	1.10^2

A. Model Parameter Calculation of Ferrite Toroidal Cores

The equivalent diagram (model) of a ferrite toroidal core is presented in Fig. 2. The model parameter values *R*, *L* and *C* can be determined by the following dependencies:

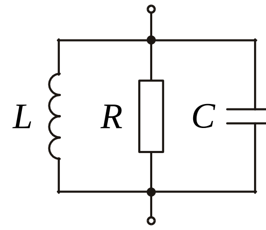

Fig. 2. Model Parameters of Ferrite Toroidal Core

- ***inductivity L*** is derived from the condition $B = \frac{\mu_r N.I}{2\pi r}$, hence

$$L_1 \approx \frac{\mu_r N^2 A_e[cm^2]}{2\pi r_{av}[cm]}.10^{-2} = \frac{\mu_r N^2 A_e[cm^2]}{l_e[cm]}.10^{-2}, [\mu H] \quad (2)$$

where B [Tesla] or [Gauss] is the magnetic field produced, A_e,[cm^2]=$(r_2-r_1).h_{\dim}$, r_{av},[cm] is the average radius of the ferrite toroidal core as r_{av}= [$(r_2-r_1)/2$]+r_1.

To determine inductivity L of a ferrite toroidal core, it is assumed that the number of windings N is equal to 1.

If the catalogue parameter l_e, [cm] is given, L can be determined by [6]

$$L_2 = 0{,}4\pi N^2 \mu_r \frac{A_e[cm^2]}{l_e[cm]}.10^{-8}\, [H]. \quad (3)$$

Owing to the existing roundness in the geometric shape of the ferrite toroidal cores, when calculating the average diameter r_{av} (through r_2 and r_1), an error appears and for $FT82_{AMIDON}$ it is +1,78 %, and for $FT114_{AMIDON}$ +1,56 %. To avoid this error r_{cp} should be determined as $r_{av}=l_e/(2\pi)$;

- ***capacitance C*** is determined by the geometric dimensions of the ferrite following:

$$C = 2{,}8\left(1{,}2781 - \frac{h_{\dim}}{D_{\dim}}\right).\sqrt{\frac{2\pi^2 (D_{\dim} - h_{\dim})\frac{h_{\dim}}{2}}{4\pi}}, \text{[pF]} \quad (4)$$

where $D_{\dim}$ and $h_{\dim}$ are in inches (1 [inch] = 25,4 [mm]). To calculate C in geometric dimensions in millimeters [mm], use (4) divided by 25,4;

- ***ohmic resistance R*** is determined from the catalogue parameter ρ by:

$$R = \frac{\rho.l_e}{S} = \frac{\rho.(2\pi r_{av})}{\pi.(r_2 - r_1)^2}, [\Omega] \quad (5)$$

for dimensions of r_2, r_1 and r_{av} (l_e) in [m].

On the basis of (2)÷(5) and catalogue parameters of ferrite toroidal cores of the firm AMIDON given in Table 1, their model parameters have been calculated and presented in Table 2.

TABLE 2
MODEL PARAMETERS OF AMIDON FERRITE TOROIDAL CORES

Trade Ferrite	L_1 [μH]	L_2 [μH]	C [pF]	R [kΩ]
FT82-43	0,398	0,499	0,919	$1{,}074.10^3$
FT82-61	0,058	0,073	0,919	$1{,}074.10^6$
FT82-77	0,935	1,175	0,919	1,074
FT114-77	1,011	1,270	1,256	0,945

Deductions: From the calculated model parameters of AMIDON ferrite toroidal cores presented in Table 2 it has been found that:

- for each overall dimension the ferrite inductivity value L varies within relatively close limits from a few tenths of μH to 1,3 μH, and it is directly proportional both to its dimensions and to its permeability value μ_r;

- since $tg\delta$ has very small values with ferrites, the capacitance C of the ferrite toroidal core depends only on its geometric dimensions - (4). From the obtained values of the model parameter C of the ferrite toroidal core it has been found that its values vary within (0,9÷1,3) pF, which allows in the general case its averaged value 1 [pF] to be adopted;

- due to great differences in the value of catalogue parameter "specific volume resistance" ρ of various grades of ferrite toroidal cores of the order of 10^6, its ohmic resistance value varies from several kΩ to several hundreds of MΩ and it is strictly individual.

B. Model Parameters Calculating of Broadband Transmission Line Transformer

The complete model of broadband transmission line transformer, with secondary side parameters reduced to the primary side is shown in Fig. 3. Resistors R_1 and R_2 connected in series, present the existing losses, respectively in the conductors of the primary and secondary windings. When transmission lines are used – small-length conductors in broadband transformers with ferromagnetic cores, the active loss share in the total losses is negligibly small.

C_{11} and C_{22} are the distributed shunt capacitances of the primary and secondary windings respectively, and C_{12} is the distributed capacitance between transmission lines which provides the electromagnetic connection at high frequencies. Capacitance C_{12} can form a transmission line together with distributed inductances L_{S1} and L_{S2}. The characteristic impedance of the transmission line can be regulated by changing the conductor length, number of windings, angle and pitch of twist, location of windings on ferrite core, etc.

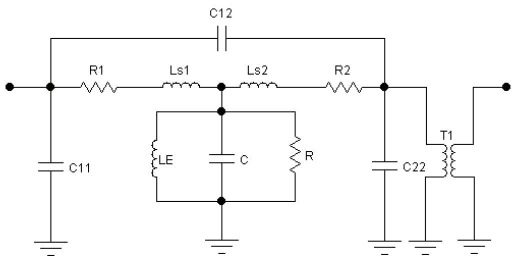

Fig. 3. Full Model of Broadband Transmission Line Transformer with Ideal Transformer

Model parameters of BTLT are determined as follows:

- ohmic resistance values R_1 and R_2 of the primary and secondary windings according to (5) are

$$R_1 = R_2 = N.\frac{\rho_{Cu}(2\pi r_{av})}{\pi(r_2 - r_1)^2}, [\Omega] \quad (6)$$

when ρ_{Cu}=1,66 [μΩ/cm];

- dissipation inductances (leakage) L_{S1} and L_{S2}, whose typical value is 1÷2 %, is assumed to be 1,3 % of the ferrite core inductance value L when N windings of the primary (L_{11}) and secondary (L_{22}) sides are available, calculated by (2) – $L_{S1}=L_{S2}=1{,}3\%.L$. Model parameter $LE=L_{11}+L_{22}+L_1$ ($L_{11}=L_{22}=L$);

- intrinsic capacitances C_{11} and C_{22} have been measured in practice using a passive bridge of BTLT constructed with the preset output data and $C_{11}=C_{22}=5$ [pF], and depending on the twist pitch of the transmission lines used (enamelled copper conductors) the inter-winding capacitance value C_{12} is adopted within (0,1÷10) pF.

Model parameters for the presented complete model of BTLT in Fig. 3 have been calculated using the following output data: ferrite core grades AMIDON FT82-77 and FT114-77, *nz*=1:1, number of windings *N*=7, diameter of the copper enamelled conductor used d_{Cu}=0,62 [mm], given in Table 3.

TABLE 3
MODEL PARAMETERS OF BROADBAND TRANSMISSION LINE TRANSFORMERS

BTLT	Model parameter values		
	R, [Ω]	*L*, [μH]	*C*, [pF]
Ferrite FT82-77	*R*=1074	*L*=0,935	*C*=0,919
Primary side	R_1=1,25	L_{11}=45,82 L_{S1}=0,6	C_{11}=5
Secondary side	R_2=1,25	L_{22}=45,82 L_{S2}=0,6	C_{22}=5
Model parameter LE	-	*LE*=92,58	-
Inter-winding capacitance C_{12}=2 [pF]			

BTLT	Model parameter values		
	R, [Ω]	*L*, [μH]	*C*, [pF]
Ferrite FT114-77	*R*=945	*L*=1,011	*C*=1,256
Primary side	R_1=1,1	L_{11}=49,54 L_{S1}=0,64	C_{11}=5
Secondary side	R_2=1,1	L_{22}=49,54 L_{S2}=0,64	C_{22}=5
Model parameter LE	-	*LE*=100,1	-
Inter-winding capacitance C_{12}=2 [pF]			

Fig. 4 presents a complete model of BTLT with Amidon FT82-77 ferrite core, containing a dependent voltage-controlled voltage source, in relation to which the calculated model parameters are symmetrical. The dependent voltage source V with transmission coefficient 1 when *nz*=1:1 is connected between the model parameter values R_1, L_{S1} and R_2, L_{S2} divided by two. Similar modeling of BTLT is closer to its real construction.

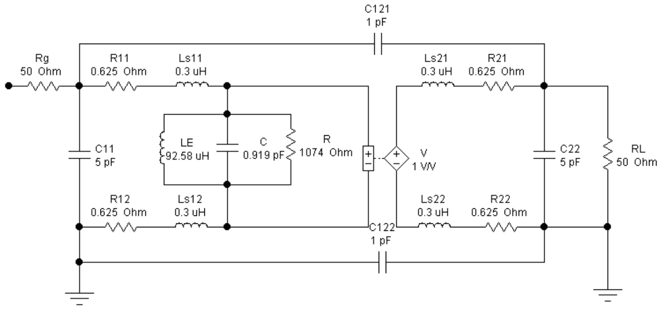

Fig. 4. Full Model of Broadband Transmission Line Transformer with Voltage-Controlled Voltage Source

The advantage of the proposed BTLT model with dependent voltage-controlled voltage source is that signal attenuation at its output can be compensated and thus to be able to specify and provide its high performance and efficiency.

When modeling BTLT with resistance transformation ratios *nz*≠1:1, it is necessary to preset the respective voltage transformation ratio. When *nz*=1:4 $U_2=2.U_1$ or n_U=1:2, and therefore the model of BTLT with a dependent voltage-controlled voltage source should be used. It is presented in Fig. 4 with voltage transmission coefficient, in this case V=2 (1V/2V). For BTLT with *nz*=4:1 n_U=2:1 and V=0,5.

C. Simulation Results of BTLT with nz=1:1, nz=4:1 and nz=1:4 for the model in Fig. 4

Using Multisim software, simulation study of amplitude-frequency responses of BTLT model with ferrite cores FT82-77 and FT114-77 with resistance transformation ratios *nz*=1:1, *nz*=4:1 and *nz*=1:4 (Fig. 4), presented in Fig. 5, has been conducted.

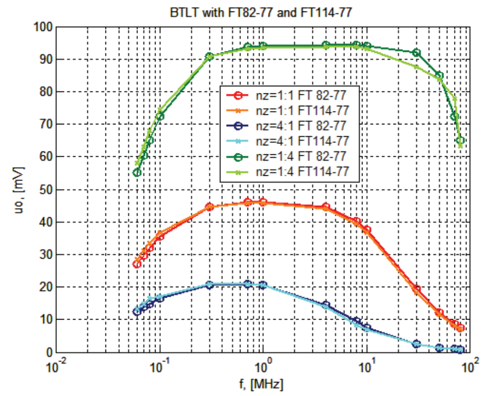

Fig. 5. Amplitude-frequency Responses of Broadband Transmission Line Transformer with Voltage-Controlled Voltage Source

Table 4 presents BTLT performance characteristics obtained: lower fb and upper fh cut-off frequency and bandwidth Δf.

TABLE 4
QUALITATIVE PARAMETERS OF BROADBAND TRANSMISSION LINE TRANSFORMERS

nz	BTLT with Amidon FT82-77		
	fb, [kHz]	fh, [MHz]	Δf, [MHz]
1:1	82,60	14,07	13,99
4:1	81,40	3,72	3,64
1:4	83,85	77,85	77,77
nz	BTLT with Amidon FT114-77		
	fb, [kHz]	fh, [MHz]	Δf, [MHz]
1:1	76,00	13,18	13,10
4:1	73,96	3,51	3,44
1:4	76,88	75,62	75,54

After a comparative evaluation of the obtained bandwidth Δf for various values of *nz* it has been found that it has the largest width when *nz*=1:4 (n_U=1:2), which exceeds the preset operating frequency range of the employed ferrite toroidal core more than twice.

Amplitude-frequency responses of BTLT with ferrite cores FT82-77 and FT114-77 with identical *nz* match. The greatest difference is in the values of fh and Δf when *nz*=1:4, which decrease with the larger ferrite core compared to the smaller one by about 3 %.

D. Experimental Results of BTLT with nz=1:1, nz=4:1 and nz=1:4

Experimental studies have been carried out to find the performance characteristics fb, fh and Δf of BTLT with ferrite toroidal cores manufactured by Amidon: FT82-77 and FT114-77 for *nz*=1:1, *nz*=4:1 and *nz*=1:4. BTLT were made in practice with 7 windings from a twisted couple of copper enameled conductors with diameter d=0,62 [mm] and 3 twists per 1 [cm].

Fig. 6 shows the amplitude-frequency responses obtained experimentally at input voltage Ui=48,76 [mV], and Table 5 lists the achieved performance characteristics.

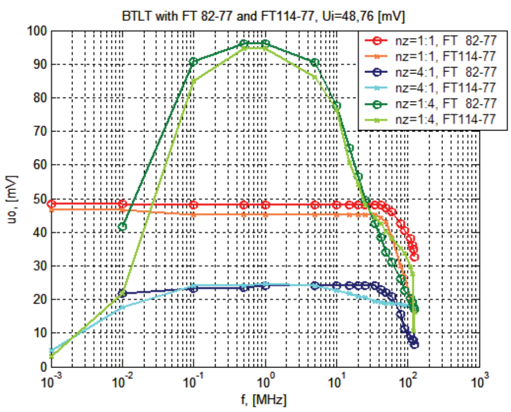

Fig. 6. Amplitude-frequency Responses of Broadband Transmission Line Transformer – Experimental Results

TABLE 5
QUALITATIVE PARAMETERS OF BROADBAND TRANSMISSION LINE TRANSFORMERS

nz	BTLT with Amidon FT82-77		
	fb, [kHz]	fh, [MHz]	Δf, [MHz]
1:1	1	120	119,99
4:1	1	78	77,99
1:4	50	14	13,95
nz	BTLT with Amidon FT114-77		
	fb, [kHz]	fh, [MHz]	Δf, [MHz]
1:1	1	73	72,99
4:1	10	125	124,99
1:4	80	13	12,92

On the basis of the experimentally obtained results, it has been found that:

- the transmission coefficients in the bandwidth for various resistance transformation ratios *nz* are different and they almost reach their respective theoretical values;
- for *nz*=1:1 the area with an even voltage transmission coefficient in the bandwidth is the largest and in this case no drop can be reported in the low frequency range;
- when *nz*=1:4 a drop in amplitude-frequency responses has been observed both at low and high frequencies, hence a clearly formed bandwidth exists.

III. CONCLUSION

This paper presents two models of BTLT with ferrite toroidal cores made by Amidon and a technique for calculating their model parameter values. Changes in their values could enable us to optimize performance characteristics: *f*b, *f*h and Δ*f*. This allows the proposed models to be used in modeling BTLT, in conducting simulation studies of broadband amplifier modules containing BTLT, powerful broadband amplifiers, bridge circuits for summing and division of signals, and other devices used in radio-transmission engineering.

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