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COMMUNICATIONS

PARAMETERIZED CALCULATION AND GAINFUL DESIGN OF HOMOGENEOUS COAXIAL LINES WITH NiZn FERRITE CORE

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This paper presents an original method for calculation and a gainful design of a non-linear homogeneous coaxial line with cylindrical ferrite cores. Parametrization of non-linear line equations, by elements of an equivalent linear line, and more accurate expression for magnetic flux of quickly re-magnetized non-rectangular ferrite, by means of functions known in mathematical statistics, allowed the effective calculation of a coaxial line with homogeneous ferrite filler. In this paper, the analysis of effects is related to shaping and transmission of the power shock wave pulses with field steepness $\mathrm{d}H/\mathrm{d}t \leq 10^{11}$ A/m/s. Predicted, and experimental results are compared on a line using NiZn ferrite cores.

K e y w o r d s: non-linear coaxial line, power shock wave pulses, NiZn ferrite, ferrite cores

1 INTRODUCTION

Homogeneous ferrite coaxial line is basic network for shaping the high-power shock waves (instantaneous power of 10^3 to 10^6 W) in very short domain (subμs, ns, subns). Design methods of non-linear wave-guides are very complicated [1] - [4]. Although they are based on equations with discontinuity zones of the shock waves; their parametrization by the elements of a geometrically identical linear coaxial waveguide and more accurate expression of the magnetic flux at fast re-magnetization lead to an effective calculation of the ferrite lines. At the same time, simple technique for the fabrication of non-linear waveguide is guaranteed. The dynamics of the fast re-magnetization of ferrite elements is to be taken into account if the magnetic field, higher than the coercive field, occurs within a time period shorter than is the period of free oscillations of spin regions. The majority of ferrite materials have the oscillation period of about 10^{-9} s, while the coercive field is about 100 A/m. It implies, that the effects of dynamic re-magnetization play a significant role in time changes of the magnetic field $\mathrm{d}H/\mathrm{d}t \leq 10^{11}$ A/m/s.

2 BRIEF DESCRIPTION OF DISCONTINUITY ZONE AT THE SHOCK WAVE FRONT IN HOMOGENEOUS FERRITE COAXIAL LINE

Important information about the properties of the stationary shock waves can be obtained by means of discontinuity zone equations [2]

$$\begin{aligned} I_2 - I_1 &= v_\mathrm{f} C_\mathrm{0f}(V_2 - V_1) \\ V_2 - V_1 &= v_\mathrm{f}\left[\phi(I_2) - \phi(I_1)\right] \end{aligned} \tag{1}$$

where subscripts $_{1,2}$ indicate the voltage, current and magnetic flux (the latter per unit length) in the front or behind the discontinuity of zone; V_1, I_1 =const, are the bias DC parameters of non-linear line, C_0f is the linear capacitance parameter (capacity per unit length, F/m) of the ferrite-loaded coaxial line. The whole discontinuity zone of a stationary shock wave propagates by the only velocity

$$v_\mathrm{f} = \frac{1}{\sqrt{C_\mathrm{0f}}}\sqrt{\frac{I_2 - I_1}{\phi(I_2) - \phi(I_1)}} \tag{1a}$$

For the transient time of the stationary shock wave it holds

$$\Delta t(I) = \frac{\ell}{v_\mathrm{f}} = \ell\sqrt{C_\mathrm{0f}\frac{\phi(I_2) - \phi(I_1)}{I_2 - I_1}} = \ell\sqrt{C_\mathrm{0f}\frac{\Delta\phi}{\Delta I}} \tag{2}$$

The relation

$$L_\mathrm{f}(I) = \frac{\phi(I_2) - \phi(I_1)}{I_2 - I_1} = \frac{\Delta\phi}{\Delta I} \tag{3}$$

is the difference inductance parameter (inductance per unit length, H/m) of the ferrite-loaded coaxial line. The non-linear resistance of the line opposite to the shock wave discontinuity can be expressed as follows

$$Z_\mathrm{f}(I) = \frac{1}{\sqrt{C_\mathrm{0f}}}\sqrt{\frac{\phi(I_2) - \phi(I_1)}{I_2 - I_1}} = \sqrt{\frac{L_f(I)}{C_{0f}}}. \tag{4}$$

3 NEW EXPRESSION FOR THE MAGNETIC FLUX AT FAST RE–MAGNETIZATION ON A LINE CONTAINING NiZn CYLINDRICAL FERRITE CORES

Using a special measurement technique we obtained dependence of the dynamic inductance of one line element (cylindrical ferrite core NiZn 50/6/1.5 mm). The

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experimentally obtained function for a non-rectangular ferrite element NiZn can be generally expressed in the form

$$L_{\mathrm{f}} = L_{\mathrm{f}}(0)\,\exp\left[-(qI)^2\right] = \frac{\mathrm{d}\phi(I)}{\mathrm{d}I} \tag{5}$$

where $L_{\mathrm{f}}(0)$ is the inductance parameter of passive line element (measured at a current close to zero); $q = \mathrm{const}, (\mathrm{A}^{-1})$. From(5) by integration of L_{f} will be

$$\phi(I) = L_{\mathrm{f}}(0) \int_{I_1}^{I} \exp\left[-(q\xi)^2\right] \mathrm{d}\xi \tag{6}$$

where $I_1 = \mathrm{const}$, is the DC bias parameter. The substitution $q\xi = \frac{t}{\sqrt{2}}$ yields

$$\int_{I_1}^{I} \exp\left[-(q\xi)^2\right] \mathrm{d}\xi = \frac{1}{2q\sqrt{\pi}} \int_{\sqrt{2}qI_1}^{\sqrt{2}qI} \exp\left[-\frac{t^2}{2}\right] \mathrm{d}t \tag{7}$$

and the solution of (6) can been expressed by the tabulated statistical distribution, which simplifies the calculation of dynamical characteristic $\phi(I)$. The final form (6), (7) is then

$$\phi(I) \;=\; L_{\mathrm{f}}(0)\,\frac{\sqrt{\pi}}{q}\left[P\,(\sqrt{2}\,q\,I) - P(\sqrt{2}\,q\,I_1)\right] \tag{8}$$

In the non-biased environment (*ie* $I_1 = 0$, $P(0) = 0.5$) equation (8) can be written in the form

$$\phi(I) \;=\; L_{\mathrm{f}}(0)\frac{\sqrt{\pi}}{q}\,R\,(\sqrt{2}\,q\,I) \tag{9}$$

where P, R are symbols denote the Gaussian distribution function contained in (7), or their difference according to (8).

4 PARAMETERIZED EQUATIONS OF A FERRITE–LOADED HOMOGENEOUS COAXIAL LINE WITH SHOCK WAVE PULSES

This part presents the experience gained while designing and constructing the coaxial lines with cylindrical NiZn ferrite cores; as are used for the shaping and transmission of extremely short power shock wave pulses. The essential feature of the new modified non-linear coaxial line is the replacement of filler of a commercially available coaxial cable by a geometrically identical ferrite cores.

4.1 Non-linear factor $\psi_s(I)$ for parametrization of the shock waves discontinuity equations

For inductances of an original and modified coaxial lines it holds: $L_0 = \phi_0/I_0 = \mathrm{const}$, in a linear coax; $L_{\mathrm{f}}(I) = \Delta\phi/\Delta I$, in a biased non-linear line; and $L_{\mathrm{f}} = \phi/I$ in a non-biased line.

The dominant effect in a shock wave circuit is the shaping of the unipolar pulses in non-biased lines, *ie*in equations (1)-(4) will be $V_1, I_1 = 0$.

For equal currents of the both systems ($I_0 = I$), we define the non-linear parametrization factor as

$$\psi(I) = \frac{\phi(I)}{\phi_0(I)} \tag{10}$$

In equation (10) the function of fast re-magnetization (9) is included.

Modifying equation (1a), with respect to (10), will give

$$\begin{aligned} v_{\mathrm{f}}^2 &= \frac{1}{C_{0\mathrm{f}}}\frac{1}{L_{\mathrm{f}}} = \frac{1}{C_{0\mathrm{f}}}\frac{1}{\psi(I)\,L_0} \\ &= \frac{1}{\varepsilon^*\psi(I)C_0L_0} = \frac{v_0^2}{\varepsilon^*\psi(I)} \end{aligned} \tag{11}$$

where v_{f} is the velocity of the shock front in the ferrite coaxial line, v_0 is the velocity of the wave in the geometrically identical linear line.

Experimentally obtained relation $C_{\mathrm{of}}/C_0 = \varepsilon^*$ for equal line elements is ≈ 9 (verified by measurement in frequency range 100 MHz to 1 GHz).

4.2 Parameterized equations of a discontinuity zone of the shock wave pulse

By application of (11) we obtain parameterized equations (1)-(4) of a non-biased homogeneous line with non-linear ferrites

$$\begin{aligned} I &= \frac{v_0}{\sqrt{\psi(I)}\sqrt{\varepsilon^*}}C_0V, & V &= \frac{v_0}{\sqrt{\psi(I)}\sqrt{\varepsilon^*}}\,\phi_f(I) \\ v_{\mathrm{f}} &= \frac{v_0}{\sqrt{\psi(I)}\sqrt{\varepsilon^*}}, & L_f &= \psi(I)L_0 \\ \Delta t &= \ell\sqrt{\varepsilon^*\psi(I)}\,\sqrt{C_0L_0}, & Z_{\mathrm{f}} &= Z_0\sqrt{\frac{\psi(I)}{\varepsilon^*}} \end{aligned} \tag{12}$$

4.3 Calculation results for three different working regimes of a line containing NiZn ferrites

Equations (11) and (12) can be used to calculate basic parameters of the coaxial ferrite line. A possibility to use available NiZn ferrite types is an advantage. The geometry of the non-linear line to be calculated is identical with that of commercial linear cable. The wave resistance of linear cable $Z_0 = 75\,\Omega$. Radii of the line with standard permittivity are $r_1 \cong 0.75$ mm, $r_2 \cong 3$ mm.

The NiZn filler of the calculated line consists of cylindrical cores: 50, 6, 1.5 mm, $H_c = 30$ A/m, $B_m(3\mathrm{kA/m}) \cong 0.4$ T. The calculation is conducted for equal currents in both systems with regard to three regimes: $I = 30$ (slightly over-saturated cores), $I = 150$ A (moderate over-saturation), and $I = 300$ A (highly over-saturated cores). The total length of constructed line $\ell = 130$ cm.

Magnetic fluxes in a single core ($\ell' = 50 \times 10^{-3}$ m, $L_f(0) = 4.8\mu\ \ H/\ell'$, $q = 0.12\,\mathrm{A}^{-1}$) per unit length will be according to (9)

$$\phi(I) = L_f(0)(\pi/q)R(\sqrt{2}qI)$$

$$\phi_f(30\,\mathrm{A}) = \underline{709.2\,\mu\mathrm{Wb/m}}$$
$$\phi_f(150\,\mathrm{A}) = \underline{742.4\,\mu\mathrm{Wb/m}}$$
$$\phi_f(300\,\mathrm{A}) = \underline{783.2\,\mu\mathrm{Wb/m}}$$

The flux of a linear line per unit length is

$$\phi_0(I) = \frac{I\mu}{2\pi}\ln\frac{r_2}{r_1}$$

$$\phi_0(30\,\mathrm{A}) = \underline{8.40\,\mu\mathrm{Wb/m}}$$
$$\phi_0(150\,\mathrm{A}) = \underline{41.6\,\mu\mathrm{Wb/m}}$$
$$\phi_0(300\,\mathrm{A}) = \underline{83.2\,\mu\mathrm{Wb/m}}$$

and thus we obtain the inductance parameters

$$L_f(I) = \frac{\phi_f}{I}$$

$$L_f(30\,\mathrm{A}) = \underline{23.64\,\mu\mathrm{H/m}}$$
$$L_f(150\,\mathrm{A}) = \underline{4.95\,\mu\mathrm{H/m}}$$
$$L_f(300\,\mathrm{A}) = \underline{2.61\,\mu\mathrm{H/m}}$$

and a constant value $L_0 = \underline{0.28\,\mu\mathrm{H/m.}}$

The capacitance of the linear coaxial line is

$$C_0 = \frac{L_0}{Z_0^2} = \underline{49,24\,\mathrm{pF/m}}$$

For the velocity of the propagation of linear wave then holds

$$v_0 = \frac{1}{\sqrt{(L_0C_0)}} = \underline{2.7 \times 10^8\,\mathrm{m/s}} = 27\,\mathrm{cm/ns}$$

The non-linear parameterized factor (10) will be

$$\psi(I) = \frac{L_f(I)}{L_0} = \frac{\phi_f(I)}{\phi_0}$$

$$\psi(30\,\mathrm{A}) = \underline{85.34;} \quad \sqrt{\psi} = 9.24$$
$$\psi(150\,\mathrm{A}) = \underline{17.87;} \quad \sqrt{\psi} = 4.23$$
$$\psi(300\,\mathrm{A}) = \underline{9.42;} \quad \sqrt{\psi} = 3.07$$

The velocity of the shock wave pulse for working regime

$$v_f(I) = \frac{v_0}{\sqrt{\varepsilon^*\psi(I)}}$$

$$v_f(30\,\mathrm{A}) = \underline{0.97\,\mathrm{cm/ns}}$$
$$v_f(150\,\mathrm{A}) = \underline{2.12\,\mathrm{cm/ns}}$$
$$v_f(300\,\mathrm{A}) = \underline{2.93\,\mathrm{cm/ns}}$$

For the transient time of the stationary shock wave, per unit length, it holds

$$\Delta t(I) = \sqrt{\varepsilon^*\psi(I)}\sqrt{L_0C_0}$$

$$\Delta t(30\,\mathrm{A}) = \underline{102.7\,\mathrm{ns}}$$
$$\Delta t(150\,\mathrm{A}) = \underline{47.2\,\mathrm{ns}}$$
$$\Delta t(300\,\mathrm{A}) = \underline{34.1\,\mathrm{ns}}$$

The wave resistances of the ferrite coaxial line opposite to shock wave discontinuity:

$$Z_f(I) = Z_0\sqrt{\frac{\psi(I)}{\varepsilon^*}}$$
$$Z_0 = 75\,\Omega$$

$$Z_f(30\,\mathrm{A}) = \underline{230.8\,\Omega}$$
$$Z_f(150\,\mathrm{A}) = \underline{105.7\,\Omega}$$
$$Z_f(300\,\mathrm{A}) = \underline{76.5\,\Omega}$$

Predicted and measured wave resistance $Z_f(75;50)\Omega$ as a function of current amplitude is shown in Figure 1. Measured output rise-times at 300 A were 170-180 ps.

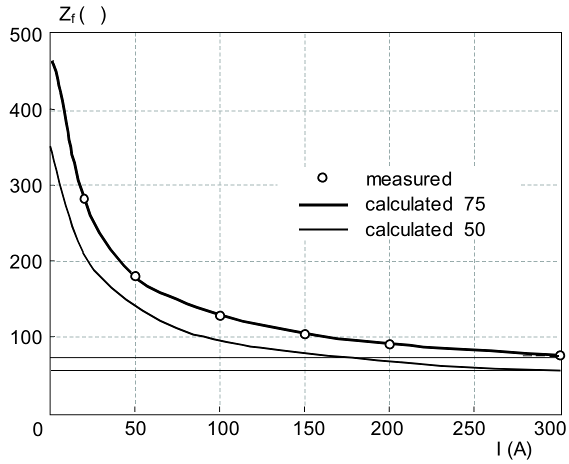

Fig. 1. Calculated (− − −) and measured (◯) wave resistance of the coaxial line with NiZn ferrite cylindrical cores

4.4 DESCRIPTION OF A EXPERIMENTAL EQUIPMENT FOR EXPLOITATION OF A LINE INCORPORATING NiZn CYLINDRICAL CORES

The ferrite line used in the experiments consisted of two identical sections and had overall length of 130 cm. The load comprised a series of 15 GHz bandwidth, high voltage attenuators, enabling the shock pulse waveform measurements on a sampling oscilloscope. The experimental equipment incorporated a special switched-pulse generator which produced pulses of both polarities with current amplitude over the 300 A (the load was in range 50-75 Ω), *ie* the peak value of the pulse field was ≈ 50 kA/m. The form of the pulses was usually trapezoidal with an adequate duration. The front of pulses $\langle 5; 10\rangle$ ns. The modes, realized in such a way, together with limit matching on the junctions (generator – coaxial cable – ferrite line – further coaxial cable – load), ensured the maximal readability of the processes in ns/subns and high-power domains.

5 CONCLUSIONS

This paper is based on the experience obtained at the design and construction of ferrite loaded coaxial lines. The aim was to obtain simple and highly precise method for the parameterized computation of considered nonlinear circuits. The construction essential feature is replacement of the dielectric in an commercial linear coaxial by geometrically identical coaxial ferrite cores. Parameters of the linear coaxial cable are transformed by means of parametrization factor $\psi(I)$, eqations (10), (13). It is necessary to obey a strong condition - this assumes a sufficiently exact expression of the magnetic flux at very fast re-magnetization of the ferrite coaxial cores. Our practice showed that for NiZn cores the approximation function (8), (9) generally holds. The deviation of the calculated and measured values of the considered ferrite line are $\leq$ 3%. Measured output rise–time at 300 A were 170–220 ps.

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