EXCITING HIGH FREQUENCY OSCILLATIONS IN A COAXIAL TRANSMISSION LINE WITH A MAGNETIZED FERRITE: 2D APPROACH

J.W. Ahn[1], S.Yu Karelin[2], V.B. Krasovitsky[2], H.O. Kwon[1], I.I. Magda[2], V.S. Mukhin[2], V.G. Sinitsin[2]
[1]Hanwha Corporation, Gumi, Kyungbuk, Korea;
[2]National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: magda@kipt.kharkov.ua

1D and 2D simulation methods and research into the formation of high frequency oscillations in a coaxial nonlinear transmission line (NLTL) partially filled with a longitudinally magnetized ferrite are presented. Dynamics and structure of the electromagnetic wave fields produced in the NLTL with a transverse inhomogeneity are studied for the first time within a 2D model. Means for optimizing the electromagnetic system parameters, NLTL dimensions, and degree of the line filling, needed to increase the electric strength and maximize oscillation intensity are discussed.

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INTRODUCTION

Since 1960s, nonlinear phenomena arising when an electrical current impulse travels through the transmission line partially filled with ferromagnetic media, have been studied intensely - initially as a way to sharpen the pulse rise-time and create electromagnetic shock waves [1, 2]. Today, the attention of researchers is mostly focused to direct energy conversion from a short video-pulse to high-frequency oscillations, which can be extracted from the structure in the form of intense HF radiation [3 - 6]. This work is devoted to numerical study of the process of formation HF oscillations in the NLTL with a ferrite based on 1D and 2D theoretical models describing the phenomenon.

1. EXPERIMENT

The theoretical investigation was preceded by the experiments on inducing the HF oscillations in a NLTL partially filled with ferrite, which is in a state close to full magnetization [6].

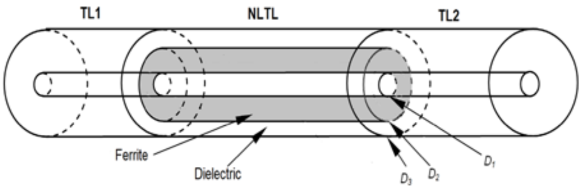

Fig. 1. Schematics of the analyzed system

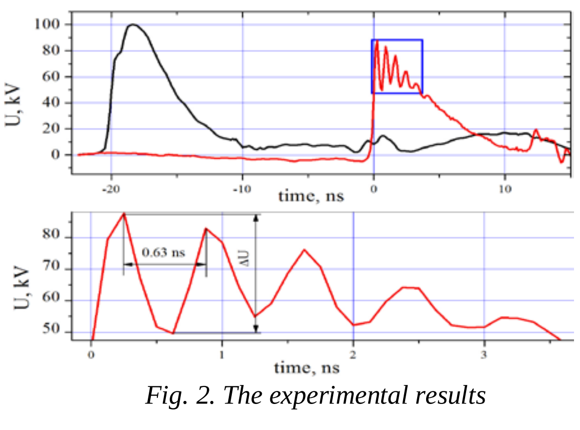

Fig. 2. The experimental results

The 200VNP-type NiZn ferrite was selected as the nonlinear material, which according to [2], provided the best results on formation the HF oscillations. The analyzed system (Fig. 1) consisted of the following elements: (i) two matching coaxial lines, TL1 and TL2, filled with a liquid dielectric (ε=2.25, *D3/D1*=26 mm/12 mm), and (ii) coaxial NLTL (*D3/D1* = 26 mm/12mm, length l = 850 mm), including the coaxial layers of ferrite (ε= 10, *D2/D1* = 20 mm/12 mm), and liquid dielectric (ε= 2.25, *D3/D2* = 26 mm/20 mm).

At H_0=110 kA/m and U_0=100 kV the HF oscillations with the frequency of 1.58 GHz and amplitude efficiency up to 27% were obtained (Fig. 2).

2. 1D MODEL

The analyzed system (Fig. 1) can be represented most simply in the form of a 1D model described elsewhere earlier [2, 3]. In this case, the propagation of the current impulse and related electromagnetic wave along the transmission line with a magnetic nonlinearity is described by telegraph equations [1, 2], which can be reduced to a second order equation for the current I:

$$\frac{\partial^2 I}{\partial z^2} = LC\frac{\partial^2\left(I + K\cdot M_\varphi\right)}{\partial t^2} + \frac{1}{C}\frac{\partial C}{\partial z}\frac{\partial I}{\partial z} - RC\frac{\partial I}{\partial t}, \quad (1)$$

where C and R are the specific capacitance and resistance of the line, L is the specific inductance of the line without regard to magnetic properties, $K = \mu_0(D2-D1)/2l$, μ_0 is the magnetic permeability of the vacuum, M_φ is the azimuthal component of the magnetization, *D2*, *D1* and l are the external and internal diameters and length of the ferrite.

The external longitudinal magnetic field H_0 turns the ferrite in a saturated state with the magnetization M_s. In these circumstances, the individual electron spins behave as single units, participating in creation of a common axial magnetic flux. The state of the ferrite dynamics can be described by one variable – the magnetic moment vector $\boldsymbol{M}$, while the azimuthal magnetic field of the high voltage impulse does not change its amplitude, but the direction only, $|\boldsymbol{M}|=Ms$=const. The vector $\boldsymbol{M}$ dynamics dependent on the magnetic field $\boldsymbol{H}$ is described by Landau-Lifshitz equation

$$\frac{d\boldsymbol{M}}{dt} = \gamma\mu_0\left[\boldsymbol{M}\times\boldsymbol{H}\right] - \alpha\frac{\gamma\mu_0}{M_s}\left[\boldsymbol{M}\times\left[\boldsymbol{M}\times\boldsymbol{H}\right]\right], \quad (2)$$

where γ is the electron gyromagnetic ratio, and α is the phenomenological relaxation factor.

The vector of the magnetization has the form

$$\boldsymbol{M}=\begin{bmatrix} M_\rho \\ M_\varphi \\ M_z \end{bmatrix},$$

and the initial states of its components are: $M_\rho=M_\varphi=0$, $M_z=M_s$. The magnetization moment at saturation Ms depends on properties of used ferrite.

The magnetic field vector $\boldsymbol{H}$ has the components: $H_\rho=(H_{dm})_\rho$, $H_\phi=qI$, $H_z=H_0+(H_{dm})_z$. Here qI is the azimuthal magnetic field of the high voltage pulse, where the form-factor q, according to [3] and assuming the absence of layered structure of the NLTL is defined as follows

$q=1/\pi d_{eff}$, where $d_{eff}=(D_2-D_1)/\ln\frac{D_2}{D_1}$. In this case, the radial effective magnetic field

$$(H_{dm})_\rho=-M_\rho, \tag{3}$$

depends on the ferrite shape, while the axial magnetic field with the magnetizing factor

$$(H_{dm})_z=-k(M_z-M_s), \tag{4}$$

takes into account the magnetic field of the solenoidal currents induced in the walls of the waveguide [1, 3] by means of the coupling coefficient $0<k<1$.

A method of numerical calculation of the presented model is proposed in [2], which is based on splitting the transmission line into a number of sections, with inserted voltage sources which correspond to the contribution of the magnetic subsystem (2). Unlike [2], this study presents a direct integration of the telegraph equation (1) together with equation (2) by the Runge-Kutta method. In addition, the present case takes into account not only the line with ferrite, but the matching lines TL1 and TL2 also. This allows to estimating the matching effects between the lines.

Thus, for combined solution of the equations (1) and (2) a grid is formed with the dimensions $n\times N$, where $n=l/\Delta z$, $N=T/\Delta t$, N is the calculation time, Δz and Δt are the lengths of discretization steps in space and time, respectively. Each cell of the grid is associated with a current of value Ii,j and magnetic moment $\boldsymbol{M}$i,j with three components, $(M_\rho)_{i,j}$, $(M_{\varphi i,j}$ and $(M_z)_{i,j}$, i=1,2,...n, j=1,2...N.

At each solution step the computation is performed in three stages:

(i) determining the net value of $I_S=I_{i+1,j}+K\cdot(M_\varphi)_{i+1,j}$ (whose individual components are not known yet) for the next step, through numerical solution of the telegraph equation (1) by the finite difference method;

(ii) determining the magnetic moment for the next time-step by means of numerical solution of the Landau-Lifshitz equation (2) by the Runge-Kutta method;

(iii) determining the current for the next time-step $I_{i+1,j}=I_S-K\cdot(M_\phi)_{i+1,j}$.

The results of numerical simulation are shown in Figs. 3 and 4. Fig. 3 demonstrates an increase of the oscillation frequency with the input voltage, and decrease with the longitudinal magnetizing field. This is in agreement with the experimental data [2], suggesting a qualitative correctness of the 1D model in describing the phenomenon under investigation. At the same time, the oscillation frequency obtained in the numerical experiment, which ignores the layered structure of the system, is substantially higher than in [2] and in our experiments [6] (see Fig. 4).

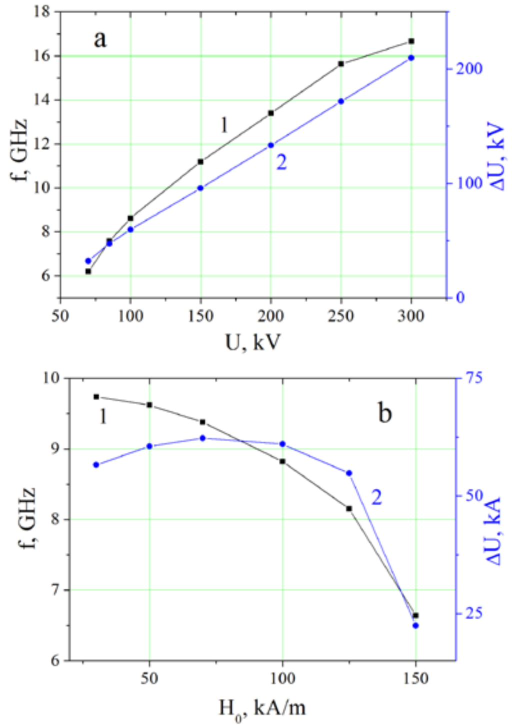

Fig. 3. 1D model: dependence of the oscillation frequency (1), and amplitude (2) on the input voltage for H_0=100 kA/m (a), and on the longitudinal magnetizing field for H_φ=110 kA/m (b)

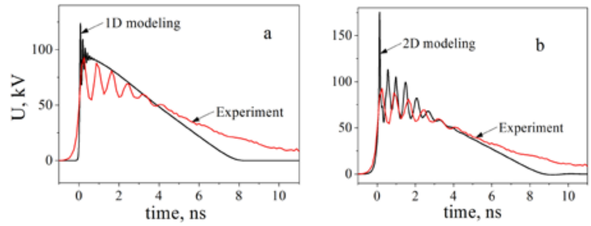

Fig. 4. Comparison of the output signals obtained in the experiment, and in 1D (a) and 2D (b) simulations

3. 2D MODEL

To create a 2D model of the system, the full set of Maxwell's equations for a cylindrical coordinate system (z,ρ,φ) is used: z is the distance along the coaxial structure, ρ is the distance from the axis of symmetry of the system, φ is the azimuthal angle with respect to the axis of symmetry. Due to homogeneity of the system and homogeneity of the initial and boundary conditions on angle φ) (the system is excited by a TEM wave), it can be accepted $d/d\varphi)\equiv 0$, thus going over to a two-dimensional model. Then the set of Maxwell equations splits into two independent sets,

$$\begin{cases} \frac{1}{\eta_0}\cdot\frac{\partial(\varepsilon E_\rho)}{\partial t}=-\frac{\partial H_\phi}{\partial z}; \\ \frac{1}{\eta_0}\cdot\frac{\partial(\varepsilon E_z)}{\partial t}=\frac{1}{\rho}\left[\frac{\partial(\rho H_\phi)}{\partial \rho}\right]; \\ \eta_0\frac{\partial(H_\phi+M_\phi)}{\partial t}=\frac{\partial E_z}{\partial \rho}-\frac{\partial E_\rho}{\partial z}. \end{cases} \tag{5}$$

$$
\begin{cases}
\eta_0 \dfrac{\partial\left(H_\rho + M_\rho\right)}{\partial t} = \dfrac{\partial E_\phi}{\partial z}; \\
\eta_0 \dfrac{\partial\left(H_z + M_z\right)}{\partial t} = -\dfrac{1}{\rho}\left[\dfrac{\partial\left(\rho E_\phi\right)}{\partial \rho}\right]; \\
\dfrac{1}{\eta_0}\cdot\dfrac{\partial\left(\varepsilon E_\phi\right)}{\partial t} = \dfrac{\partial H_\rho}{\partial z} - \dfrac{\partial H_z}{\partial \rho},
\end{cases} \tag{6}
$$

where η_0 is the free space impedance.

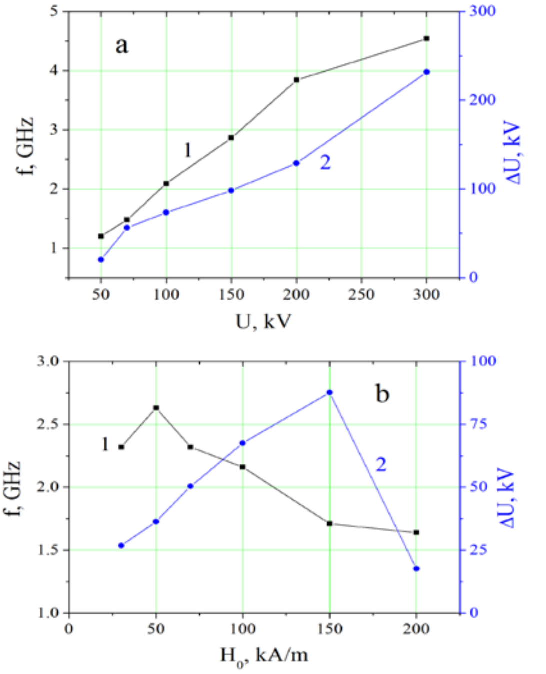

Fig. 5. 2D model: dependence of the oscillation frequency (1) and amplitude span (2) on the input voltage, for H_0=100 kA/m (a), and the longitudinal bias magnetic field for H_ϕ=110 kA/m (b)

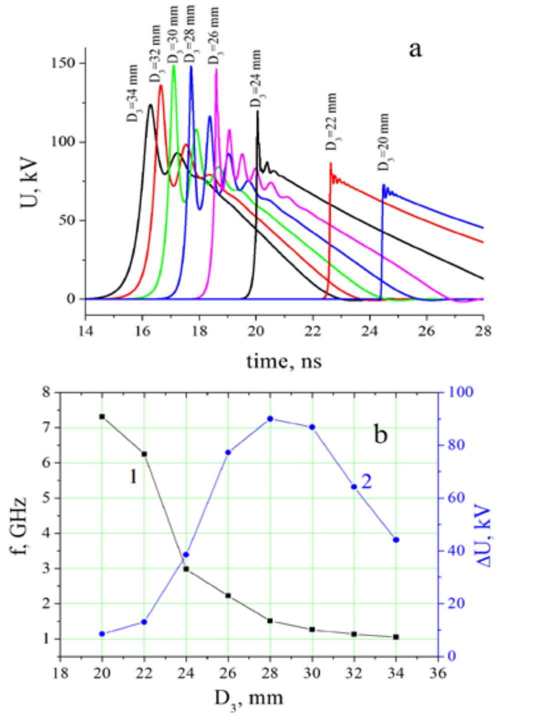

Fig. 6. Dependences of (a) the output waveform, and (b) of the oscillation frequency (1) and amplitude (2) on the outer diameter of the NLTL

The system of equations (5) describes a TE wave that is more general case of a TEM wave propagating in the coaxial structure. The equation set (6) describes a TM wave, which is not formed in the coaxial structure when it is excited by a TEM wave. But in the investigated system the TM wave can be formed as a result of interaction with the magnetic sub-system governed by equation (2). The numerical calculation of equations (5) and (6) is carried out in accordance with the methods established in [7], while with regard to the interaction between the electromagnetic fields and magnetic subsystem (2) we use the method described in the previous section. The results of numerical simulation are shown in Figs. 5 and 6. As can be seen, when 2D modeling is used the shape of the output impulse corresponds better to the experimental waveform than in the case of 1D modeling. In particular, the oscillation frequency obtained in the 2D model (2.05 GHz) is much closer to the experimental result (1.6 GHz) than to the 1D one (8.5 GHz).

4. DISCUSSION OF THE RESULTS

Based on the described 2D numerical study, several issues of practical interest can be considered.

(i) *Optimizing the filling factor of a coaxial NLTL with ferrite.* To study this effect, a series of numerical experiments with various outer diameters *D3* of the system (see Fig. 1) were produced. Fig. 6 indicates the existence of a maximum oscillation amplitude for a certain *D3*. In our case, it is observed for *D3*=28 mm, corresponding to the filling factor of the ferrite in the waveguide cross-section equal to 0.4. It is significant that when the filling factor is close to unity the oscillation frequency goes high and corresponds roughly to the results of the 1D model. However when the filling factor decreases the oscillation frequency also rapidly decreases. This suggests that the frequency of HF oscillations in a multilayered structure of the NLTL depends on the transverse distribution of the electromagnetic field that cannot be considered in a 1D model.

(ii) *The NLTL transverse dimensions.* To increase the power of HF oscillations the input voltage U_0 should be increased. Respectively, to provide a higher electrical strength it is necessary to increase the cross-section of the coaxial system. However, increasing the transverse dimensions necessarily leads to dominance of the effects specific for the layered waveguide structure, associated with the transformation of TEM wave, and, as the result, distortion of the output pulse. To explore this issue, a series of numerical experiments with a proportional variation of the input voltage $U=sU^0$ and transverse dimensions of the system $D_i=sD_i^0$, where s is a variable scale factor. Fig. 7,a presents a series of the output waveforms, obtained for the excitation signal of the amplitude U^0 = 100 kV and pulse width at half maximum $t_{p0.5}$ = 6 ns. It can be seen, the reduced span $\Delta U/s$ of the oscillation amplitude increases when s goes up to the value 3, i.e. the oscillation excitation efficiency arises.

It should be noted that the growth of s reduces the oscillation frequency (an effect that is absent in the 1D model) as well as the number of the observed oscillation periods since the current pulse width is limited. In fact, since s=3 (for $t_{p\,0.5}$ = 6 ns) the oscillations practically cease, such that no more than 1or 2 periods can be observed (see Fig. 7). With greater widths of the current impulse the oscillations are observed at lower frequencies.

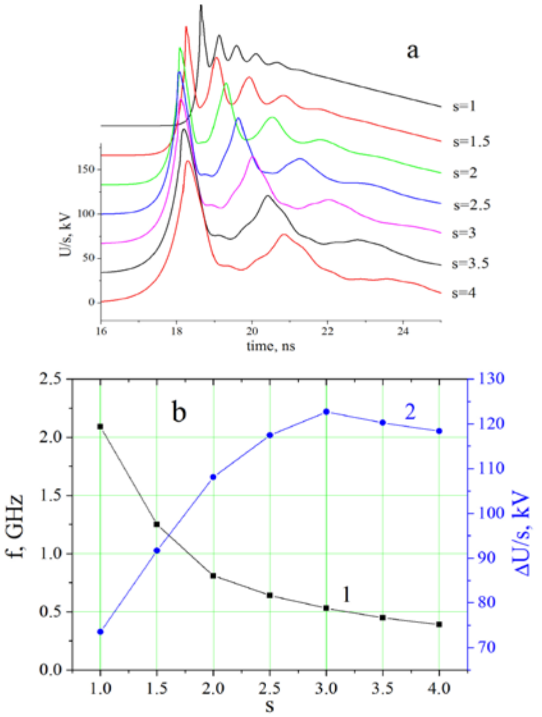

Fig. 7. The output impulse envelope vs s (a). Dependence of the oscillation frequency (1) and reduced amplitude span (2) on the scale factor s (b)

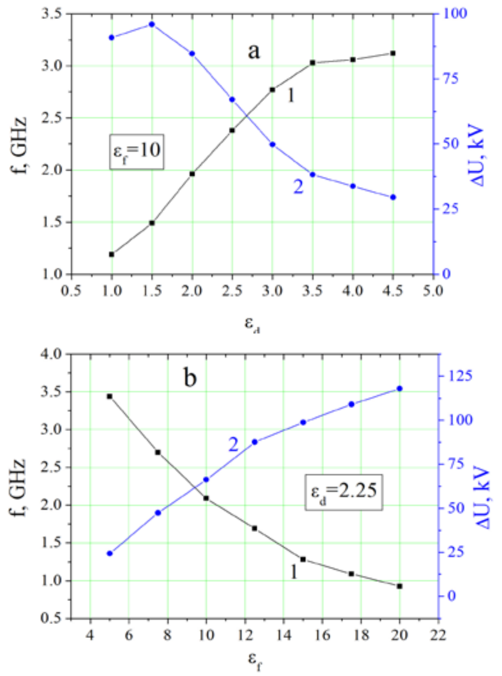

Fig. 8. Dependence of the oscillation frequency (1), and amplitude span (2) on the insulation (a) and ferrite (b) permittivity

(iii) *The effect of dielectric characteristics of the NLTL media on the excitation efficiency of oscillations.* A series of numerical experiments with variation of the permittivity of the liquid dielectric ε_d and ferrite material ε_f were performed. These results are shown in Fig. 8.

As can be seen, when ε_f decreases and ε_d increases, the oscillation frequency goes up, while the oscillation amplitude decreases. Thus, to provide for an efficient formation of HF oscillations the permittivity of the ferrite should significantly exceed the value of the permittivity of the insulating dielectric.

By way of example, for a coaxial NLTL with dimensions *D3/D1* = 2.2, excited by an input pulse of amplitude 100 kV and a 6 ns width the following conditions for effective excitation of oscillations can be obtained:

- the factor of filling the line's cross-section with the ferrite material should be about 0.4;

- the permittivity of an insulating dielectric should be at least three times lower than the permittivity of the ferrite, $\varepsilon_f > 3\varepsilon_d$.

CONCLUSIONS

A 2D simulation model has been used for the first time to describe the dynamics of the shock wave and the HF oscillations excited by a current impulse traveling along the nonlinear coaxial line partially filled with a longitudinally magnetized ferrite. The 2D model has major advantages over the 1D model and agrees much better with experimental results. The computations based on the 2D model allow formulating conditions for an effective formation of HF oscillations in the NLTL.

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ВОЗБУЖДЕНИЕ ВЫСОКОЧАСТОТНЫХ ОСЦИЛЛЯЦИЙ В КОАКСИАЛЬНОЙ ЛИНИИ С НАМАГНИЧЕННЫМ ФЕРРИТОМ. 2D-МОДЕЛЬ

Ч.В. Ан, С.Ю. Карелин, В.Б. Красовицкий, Х.О. Куон, И.И. Магда, В.С. Мухин, В.Г. Синицын

Представлена методика и результаты 1D- и 2D-численного моделирования процесса формирования высокочастотных колебаний в коаксиальной нелинейной линии, частично заполненной ферритом, который намагничен продольным магнитным полем. С помощью 2D-модели впервые исследованы динамика и структура волнового поля нелинейной линии с поперечной неоднородностью. Обсуждается оптимизация диэлектрических параметров системы, размеров линии и степени ее заполнения ферримагнитным материалом, необходимых для повышения электрической прочности и получения максимальной интенсивности колебаний.

ЗБУДЖЕННЯ ВИСОКОЧАСТОТНИХ ОСЦИЛЯЦІЙ В КОАКСІАЛЬНІЙ ЛІНІЇ З НАМАГНІЧЕНИМ ФЕРИТОМ. 2D-МОДЕЛЬ

Ч.В. Ан, С.Ю. Карелін, В.Б. Красовицький, Х.О. Куон, І.І. Магда, В.С. Мухін, В.Г. Сініцин

Представлено методику та результати 1D- і 2D-чисельного моделювання процесу формування високочастотних коливань у коаксіальній нелінійній лінії, що частково заповнена феритом, який намагнічено повздовжнім магнітним полем. За допомогою 2D-моделі вперше досліджено динаміку та структуру хвильового поля нелінійної лінії з поперечною неоднорідністю. Обговорюється оптимізація діелектричних параметрів системи, розмірів лінії та ступеня її заповнення феромагнітним матеріалом, які необхідні для підвищення електричної стійкості та отримання максимальної інтенсивності коливань.