Nonlinear Reactive Circuits Driven by Magnetic Flux Compression Generators

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Abstract

Presently, generators of broadband microwave radiation, using spiral magnetocumulative generator (MCG) as the energy source, are under intensive investigation [1,2]. In the majority of the existing designs, researchers are attempting to generate high-power radiation over a the broad spectral range by directly connecting the MCG to an antenna or by using the helical coil of the MCG as the radiating element [2,3]. These are called *direct drive* devices. It is understood that the efficiency of these devices is very low, which is attributed to the impossibility of matching the energy source, with output characteristics that change in time, with antenna sizes no greater than tens of centimeters and to the fact that the characteristic length of the MCG current pulse, driving the antenna, ranges from 10^{-7} to 10^{-6} s. In addition, the maximum amount of energy lies within the spectral range $10^6 - 10^7$ Hz, which corresponds to wavelengths of $300 - 30$ m. Since the effective length of the antenna for these devices comprises only a fraction of the wavelength of the driving oscillations, the radiation efficiency is very small. As a result, direct drive devices radiate relatively low powers and have virtually isotropic radiation patterns, which is unacceptable for a number of applications. These problems can be solved by several different methods. One of them is to design a modulator, operating over a broad frequency range, corresponding to a wavelength less than or close to the size of the transmitting antenna, for coupling energy from the MCG into the antenna. This kind of modulator would not only provide effective modulation of strong currents, generated by MCG, but also enrich the spectrum of the current fluctuations, by shifting the spectrum to higher frequencies [1]. This paper considers one possible type of modulator and presents the results of computer simulations.

I. EQUIVALENT CIRCUIT AND MATHEMATICAL MODEL OF MODULATOR

A simplified equivalent circuit diagram of the MCG and its modulator circuit is shown in the Fig. 1.
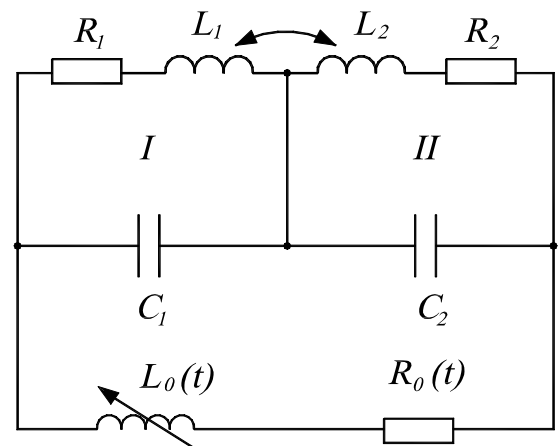

Fig. 1. Simplified equivalent circuit diagram of the MCG output current modulator, based on the two circuits with nonlinear coupling: $L_0(t)$ is the MCG inductance, changing with time; $R_0(t)$ is MCG resistance changing with time; L_1, C_1, R_1 are the inductance, capacitance, and, resistance of the 1st modulator circuit, respectively; and L_2, C_2, R_2 are the inductance, capacitance, and resistance of the second modulator circuit, respectively.

The modulator consists of two tank circuits having different resonant frequencies, with their inductances L_1 and L_2 coupled by a ferrite core. When the MCG is detonated, oscillating currents are excited in circuits I and II, whose frequencies are determined not only by the characteristics of the elements of each circuit, but also the MCG parameters, which vary during its operation. This results in multiple sharp changes in the ferrite magnetic permeability and, consequently, changes in the coupling factor between the circuit inductors. As a result, the load characteristics of the MCG change, which leads to modulation and the system switching to a nonlinear regime. This leads to an enrichment of the spectrum of the current oscillations flowing through the circuit.

Kirchhoff's equations, describing the equivalent circuit shown in the Fig. 1, have the form:

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14. ABSTRACT

Presently, generators of broadband micro-wave radiation, using spiral magnetocumulative gen-erator (MCG) as the energy source, are under inten-sive investigation [1,2]. In the majority of the exist-ing designs, researchers are attempting to generate high-power radiation over a the broad spectral range by directly connecting the MCG to an antenna or by using the helical coil of the MCG as the radiating element [2,3]. These are called direct drive devices. It is understood that the efficiency of these devices is very low, which is attributed to the impossibility of matching the energy source, with output characteris-tics that change in time, with antenna sizes no greater than tens of centimeters and to the fact that the char-acteristic length of the MCG current pulse, driving the antenna, ranges from 10-7 to 10-6 s. In addition, the maximum amount of energy lies within the spec-tral range 106 107 Hz, which corresponds to wave-lengths of 300 30 m. Since the effective length of the antenna for these devices comprises only a frac-tion of the wavelength of the driving oscillations, the radiation efficiency is very small. As a result, direct drive devices radiate relatively low powers and have virtually isotropic radiation patterns, which is unac-ceptable for a number of applications. These prob-lems can be solved by several different methods. One of them is to design a modulator, operating over a broad frequency range, corresponding to a wave-length less than or close to the size of the transmitting antenna, for coupling energy from the MCG into the antenna.

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$$R(t)I + Q_1C_1^{-1} + Q_2C_2^{-1} = -\frac{d(L(t)I)}{dt},$$

$$\dot{Q}_1 + I_1 = \dot{Q}_2 + I_2 = I, \qquad (1)$$

$$Q_1C_1^{-1} - I_1R_1 = \dot{\Phi}_1(I_1, I_2),$$

$$Q_2C_2^{-1} - I_2R_2 = \dot{\Phi}_2(I_1, I_2),$$

where I_1, I_2 are currents in the circuit, Q_1, Q_2 are the electric charges on the two capacitors C_1, C_2, I is the MCG output current, and Φ_1, Φ_2 are the flux linkages in the circuit inductors. The expressions describing the change in the inductance and active resistance, L, R, for the spiral MCG [4] are assumed to be

$$L(t) = L_0 \exp\left(-t\tau_L^{-1}\right) + l_0,$$

$$R(t) = R_0 \exp\left(-t\tau_L^{-1}\right) + r_0, \qquad (2)$$

where L_0, l_0 and R_0, r_0 designate the initial and final inductance and resistance of the MCG coil and τ_L is a characteristic time of associated with the MCG.

In order to produce high-frequency current fluctuations in the two tank circuit system with nonlinear coupling, it is required that the ferrites used undergo rapid changes in magnetization, that is, no worse than 1-10 ns. However, in order to do the simulation, it was necessary to take the magnetic viscosity into account, which lowers the speed at which the ferrite magnetization changes in circuits 1 and 2 [5].

The process of ferrite magnetization in alternating magnetic fields is described either by the Bloch-Blumbergen equation or the Landau equation [6]. In the simulation used for this analysis, the Landau equation, which, although phenomenological, allows one to utilize certain constants, which can be measured experimentally, was used. For the simulations, a ferrite with the greatest amount of experimentally available data [7,8] was used. However, it has to be noted that the most complete sets of measured constants are only known for the ferrites with low speed changes in magnetization.

However, since the goal of this project is the design of specialized software and computer experiments to show the feasibility of expanding the spectrum of the oscillations and up-shifting it to the high-frequency spectral domain, a low-frequency ferrites with a maximum number of known parameters was used.

In the simulation, it was assumed that the nonlinear coupling between the circuits is accomplished by using a long cylindrical ferrite rod in an alternating magnetic field $H_z(t)$ created by the circuit inductors and directed along the axis of the ferrite rod. Using the projection of the magnetization vector $J_z(t)$, directed opposite to the re-magnetizing field, on to a line parallel to the ferrite axis, the Landau equation [6] becomes:

$$\frac{dJ_z}{dt} = \gamma J_s \frac{\beta}{1+\beta^2}\left(1 - \frac{J_z^2}{J_s^2}\right)H_z(t), \qquad (3)$$

where $\gamma = 2.2 \cdot 10^5$ m/As is the gyromagnetic relationship for the electron, β is the magnetic viscosity factor, measured experimentally for the specific ferrite, and $J_s \cong B_s\mu_0^{-1}$ is the saturation magnetization.

The magnetic field strengths, H_1, H_2, created by the inductors, L_1 and L_2, of the 1st and 2nd circuits, together with the ferrite core placed inside them are described by the equations:

$$H_1 = \beta_1 \frac{N_1 I_1}{l_1} - k\beta_2 \frac{N_2 I_2}{l_2},$$

$$\qquad (4)$$

$$H_2 = \beta_2 \frac{N_2 I_2}{l_2} - k\beta_1 \frac{N_1 I_1}{l_1},$$

where N_1, N_2 are number of turns in the inductor coils, I_1 and I_2 are the currents flowing through the inductors of the 1st and 2nd circuits, respectively, and l_1, l_2 are the length of the inductor coil and part of the ferrite. It has to be noted that for the simulation, the inductors and capacitors in the circuits were selected so that their eigenfrequencies are essentially different.

II. RESULTS OF COMPUTER SIMULATIONS

Substituting the expressions for the flux linkages in the circuits and core magnetization (3) into the system of Kirchhoff equations for the modulator (1), a closed set of 7 equations is obtained, with the variables $I, Q_1, Q_2, I_1, I_2, J_1, J_2$, which describe the current fluctuations in the two tank circuit. The solution of this set of equations can only be found numerically. Since this set of equations is extremely stiff, the Gear method is used to solve it.

The computer simulation software package was designed to study system operation for different current pulse amplitudes from the MCG, as well as for different values of L_1, L_2, C_1, C_2, and R_1, R_2 by determining the frequencies of the tank circuits I and II. The software allows one to also calculate the influence of ferrite elements with different shapes and the broad spectrum characteristics on the circuit. However, since the goal of this effort was to demonstrate the feasibility of broadband spectrum generation and its shift to the high frequency region of the spectrum, circuits I and II were chosen to have different lower frequencies. A low frequency ferrite BT was also used as a coupling element.

The frequency of the first circuit was chosen to be equal to 5 MHz and the frequency of the second circuit was chosen to be 125 MHz. The ferrite, used to implement the nonlinear coupling, has the following parameters: length 10 cm, diameter 1 cm, magnetic viscosity $\mu = 0.5$ [5], and magnetization at saturation B_s=0.3 T [9].

Waveforms and spectra of the current fluctuations in the second (high-frequency) tank circuit for the specified parameters are shown in Fig. 2.
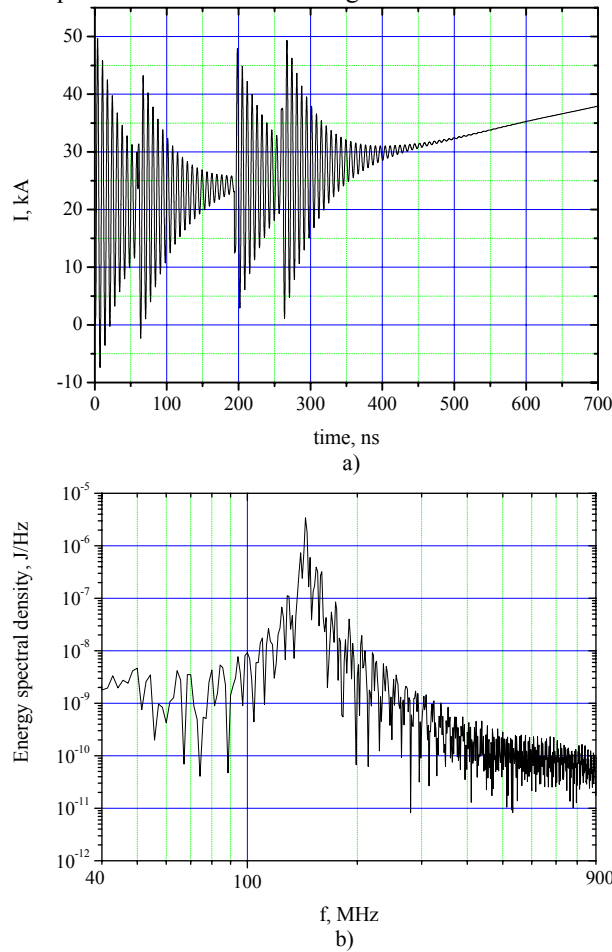

a)

f, MHz

b)

Fig. 2. Time history and spectrum of the current fluctuations in the high-frequency tank circuit and in the coupled circuits through the BT ferrite core. The amplitude of the current pulse generated by the MCG is 20 kA. MCG parameters: initial inductance $L_0 = 10$ μH, final inductance $l_0 = 2$ μH, characteristic time for inductance variation $\tau = 1$ μs, initial resistance $R_0 = 0.1$ Ohm, and final resistance $r_0 = 0.001$ Ohm. Ferrite 0.16BT parameters: 0.1 m length, 0.01 m radius, saturation magnetization is $B_s = 0.3$ T.

Magnetization of the ferrite rod in the first and second (high-frequency) tank circuits are shown in Fig. 3.
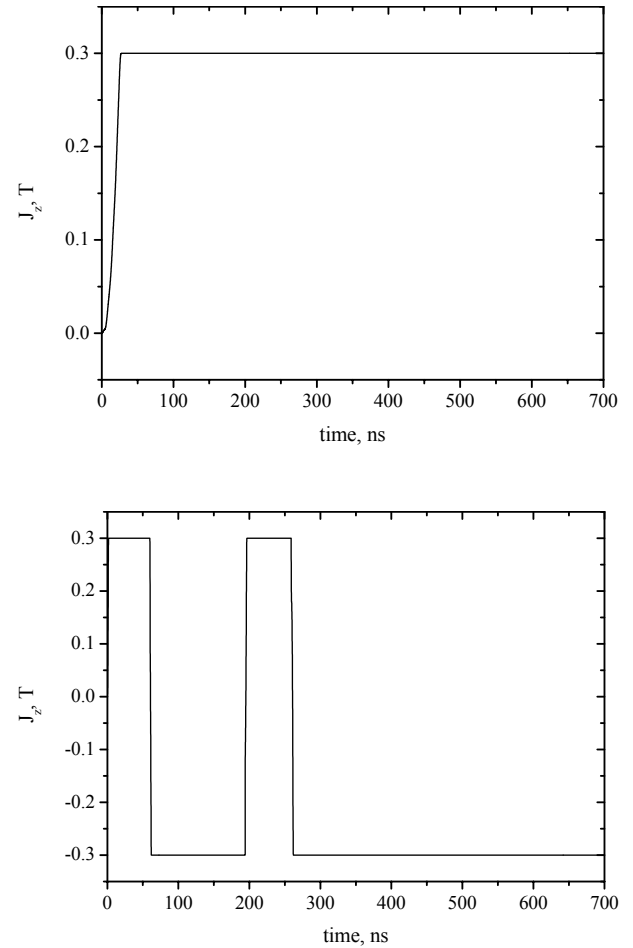

Fig. 3. Magnetization of the BT ferrite core as a function of time in the first and second resonant circuits.

It can be seen from Fig. 3 that the magnetization of the ferrite core in the second circuit (similar to the first one) changes in a step like manner. As a result, a substantially large share of the current fluctuation energy turns out to be concentrated in the high-frequency domain.

Fig. 4 shows the current waveform and spectrum of the current fluctuations in the first and second (high-frequency) tank circuits for other tank circuit frequencies. In this case, the frequency of the first circuit was chosen to be 7 MHz, while the frequency of the second was chosen to be 400 MHz.
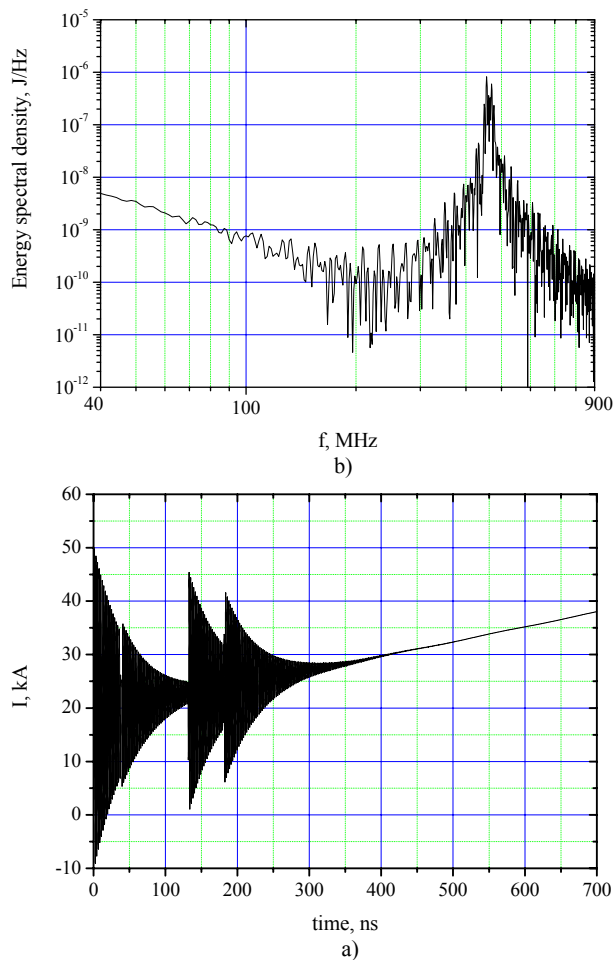
Fig.4. Waveform and spectrum of current fluctuations in the high-frequency tank circuit when a BT core is used. The amplitude of the MCG current is ~20 kA. MCG parameters: initial inductance L_0 = 10 µH, final inductance l_0=2 µH, characteristic time of inductance decrease τ=1 µs, initial resistance R_0=0.1 Ohm, and final resistance r_0=0.001 Ohm. Ferrite 0.16BT parameters: 0.1 length and 0.01 m radius, B_s = 0.3 T, µ = 0.5.

Computer simulations of the circuit in Fig. 1 proved that even in the case when low-frequency ferrites are used as the coupling elements, it is possible to generate current fluctuations in the second (high-frequency) circuit with a spectral content of 40-900MHz and with total powers of 24 MW in a pulse having a pulse length of 700 ns. For equivalent circuit parameters but at higher frequencies, the total power in the spectral band 40-900 MHz was 15 MW for the same pulse length of 700 ns.

Results of the computer simulation have been experimentally verified by using the test stand shown in Fig. 5. A comparison of the computer simulation results with initial experimental results confirmed the correctness of the computer model and

the feasibility of expanding the spectrum of the current fluctuations and of shifting it to a higher frequency regime of the spectrum, even for substantially long MCG pulses.

III. CONCLUSION

A specialized software package has been developed. Computer simulations of the high-current modulator have been performed for a system of circuits with nonlinear coupling, using ferrites with high speed changes in magnetization. These circuits have been shown to be able to effectively modulate high pulsed currents and to enrich the spectrum of these current fluctuations and at the same time to up shift the frequency of the oscillations.

Comparison of the computer simulation results with the experimental results has established the validity of the simulation and of the modulation concept.

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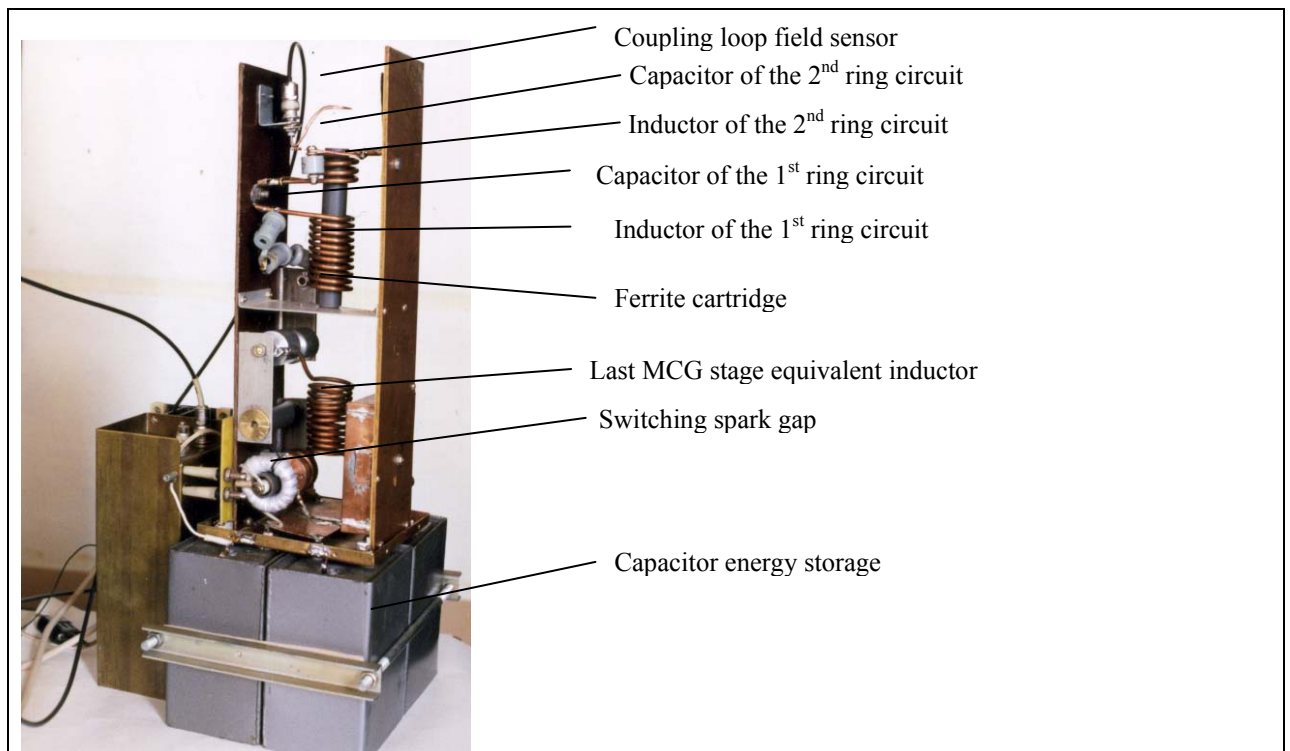9. Mesyats G.A., *Generation of High-Power Nanosecond Pulses*, Sovetskoe Radio, Moscow, p. 256 (1974).

Fig. 5 Photograph of the experimental stand used to study the two-tank circuit shown in Fig. 1