High Voltage Pulser Based on a Tesla Transformer with a Pulse-Forming Line Using an Open Ferrite Magnetic Core

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Abstract – The design and the operation of a high voltage pulser based on a coaxial pulse-forming line with an incorporated Tesla transformer using an open ferrite magnetic core are described. The characteristics of the generated pulses whose peak voltage reached values from tens to hundreds of kilovolts have been measured and analyzed. It has been shown that the ferrite magnetic core substantially affected the pulse shape and length. Partial screening of the internal part of the magnetic core allows one to substantially stabilize the output pulses and estimate the dynamic characteristics of the pulse-forming line. The energy efficiency of the pulser has also been estimated. It has been shown that the machine is capable of transferring up to 80% of the energy stored in a 100-Ohm pulse-forming line to a 40.4-Ohm transmission line carrying a matched load.

1. Introduction

The main objective of the work was to develop and investigate the performance of a high voltage pulser based on a coaxial pulse-forming line which incorporated a Tesla transformer with an open ferrite core. The use of an open ferrite core instead of a steel ferromagnetic core [1] allows one to charge a pulse-forming line by means of a fast-acting circuit, thereby increasing the charge voltage not changing the machine dimensions [2]. The setup under investigation was designed as a nanosecond high voltage generator for biophysical X-ray sources.

2. Electric circuit and design

The electric circuit of the pulser (Fig. 1) contains the following main units:

– a primary energy store including a rectifier, a set of capacitors \(C_1, C_2\), and a thyristor switch \(VS_1, VS_2\);
– a low-inductance intermediate storage modulator consisting of a high-voltage pulse transformer \(TV_1\), a set of capacitors \(C_{m1}, C_{m2}\), and a pseudospark switch (cold-cathode thyatron) \(HL\), and
– a pulse-forming line, which incorporates an open ferrite magnetic core combined with a Tesla transformer \(TV_2\) and a high-voltage gas-filled spark gap \(GS\), as a main store.

The pulse-forming line and the modulator are shown schematically in Fig. 2. The design has the advantage of a reduced inductance of the pulse-forming line charging circuit because the modulator is placed immediately over the pulse-forming line. The significantly shorter charging time of the pulse-forming line compared to that peculiar to analogous SINUS systems [1] made it possible to use a Tesla transformer with a smaller number of coil turns.

3. Operation

The setup starts operating when the power supply is switched on to apply voltage to the rectifier, to the control circuits \(A_1, A_2\), and to the heating circuit of the thyatron hydrogen generator \(A_3\).

Control circuit \(A_1\) produces a triggering pulse to open thyristors \(VS_1\) and \(VS_2\). Thereafter, capacitors \(C_1\) and \(C_2\) are discharged via inductance coils \(L_1\) and \(L_2\), transformer \(TV_1\), and the primary coil of Tesla transformer \(TV_2\) to charge capacitors \(C_{m1}, C_{m2}\) of total capacitance 15.04 nF to \(U_{mod} = 10–25\) kV within 15–40 \(\mu\)s. The charging time and the charge voltage amplitude depend on the time delay of the thyatron triggering pulse produced by control circuit \(A_3\). As the thyatron is open, the modulator capacitors are connected to the coaxial pulse-forming line via the Tesla transformer. The charging time of the line is not over 100–150 ns, and it is determined, as well as the charge voltage \(U_f\) and the energy \(W_f\) stored in the line, by the...
threshold voltage of gas gap switch $GS$ that is controlled by varying the gas pressure in the switch. After switching, the pulse-forming line is connected to the coaxial transmission line of characteristic impedance $\rho_{fl} = 40.4$ Ohm. The transmission line is terminated with a 46.4-Ohm load. The output voltage of the pulse-forming line (input voltage of the transmission line) was measured with capacitive voltage divider $D_2$ (Fig. 1).

4. Dielectric permittivity of the core ferrite

The core incorporated in the coaxial pulse-forming line is made of type 200VNP3 ferrite. The mentioned pulse-forming line charging time (~ 100 ns) corresponds to a characteristic frequency of 5 MHz. The permittivity $\varepsilon$ of the ferrite corresponding to this frequency is not known. Therefore, this ferrite characteristic was measured as a function of frequency $f$. To do this, the capacitance of the capacitor formed by two identical copper plates and a plane ferrite sample placed between them was measured. The measurement data are presented in Fig. 3.

![Fig. 3. Ferrite permittivity versus frequency](image)

The permittivity corresponding to 5 MHz is 13.5.

5. Results

The tentative experiment has shown that that the system operated, on the whole, in compliance with the design. However, the pulse-forming line charge voltage amplitude was noticeably lower than its designed value because of the too low number of turns in the Tesla transformer coils, so that the ferrite core was saturated. The actual dimensions of the machine gave no way of increasing the core cross-section. Therefore, the coils turn number was doubled. Typical electric pulse waveforms recorded after modification are shown in Fig. 4.

![Fig. 4. Waveforms of the modulator charge voltage (a), of the pulse-forming line charge voltage (b), and of the voltage at the transmission line input (c, d)](image)

The waveforms of the pulse-forming line output voltage presented in Figs. 4, c and d show significant pulse-to-pulse instability. At the same time, the waveforms of the modulator and pulse-forming line charge voltages were much more stable. The instable shape of the high voltage pulse gave no way of estimating the dynamic characteristics of the pulse-forming line, such as inductance $L_{fl}$, capacitance $C_{fl}$, and characteristic impedance $\rho_{fl}$. The length of the recorded unstable pulses was of ~ 10 ns, and the estimated time of the voltage pulse doubled travel along the pulse-forming line without ferrite was ~ 4.2 ns. This indicates that the ferrite core strongly affects the shape and width of the electric pulse. To moderate the pulse instability, the internal ferrite core was partly screened with copper foil strips, as shown in Fig. 5.
The shape of the pulses recorded in this case (Fig. 6) was much more stable. This allowed us to estimate the dynamic characteristics of the pulse-forming line. The estimation was based on the supposition that the properties of the core ferrite are the same for the first (negative) and second (positive) half-waves, and the following system of equations was solved:

\[
\begin{align*}
U_{ir}^{(1)} &= K_{ir} U_{in}^{(1)}, \\
U_{ir}^{(2)} &= K_{ir} U_{in}^{(2)}, \\
U_{tr}^{(1)} &= K_{tr} U_{in}^{(1)}, \\
U_{tr}^{(2)} &= K_{tr} U_{in}^{(2)},
\end{align*}
\]

where \(U_{in}^{(1)}\) and \(U_{in}^{(2)}\) are the voltage amplitudes of the half-waves incident on the transmission line input, \(U_{ir}^{(1)}\) and \(U_{ir}^{(2)}\) are the voltage amplitudes of the reflected half-waves, \(U_{tr}^{(1)}\) and \(U_{tr}^{(2)}\) are the voltage amplitudes of the half-waves passed to the transmission line,

\[K_{ir} = \frac{2\rho_{ir}}{\rho_{ir} + \rho_{tr}} \]

is the transmission coefficient,

\[
\rho_{tr} = \rho_{ir} \frac{1 - \Gamma}{1 + \Gamma}, \\
\Gamma = \frac{U_{tr}^{(2)}}{U_{tr}^{(1)}}, \\
L_{tr} = \rho_{tr} \tau, \\
C_{tr} = \frac{\tau}{\rho_{tr}}
\]

and \(\tau\) is the pulse length.

The energy of the pulse in the transmission line was determined from the relation

\[
W_{tr} = \int_{t_1}^{t_2} \frac{1}{\rho_{tr}} U^2(t) dt,
\]

where \(U(t)\) is the running value of the voltage at the transmission line input. The limits of integration \(t_1\) and \(t_2\) are determined based on the needed accuracy of measurement of the energy \(W_{tr}\). The results of processing of the recorded pulses are presented in the Table.

### 7. Conclusion

The results of the investigations performed suggest that the properties of the pulse-forming line incorporated in the Tesla transformer with the 200VNP3 ferrite magnetic core without screening of the latter are determined by the temporal behavior of the ferrite. The shape and amplitude of the produced nanosecond high voltage pulses can significantly vary from pulse to pulse, whereas the pulsed charge voltage of the pulse-forming line remains rather stable. Partial screening of the internal part of the ferrite magnetic core substantially stabilizes the pulse shape. In this case, the doubled amplitude of the first half-wave voltage measured at the transmission line input \(U_{in}^{(1)}\), can be greater than that of the pulse-forming line charge voltage. This may be related either to measur-
ments errors or to some difference in ferrite properties during the first and the second half-wave, which may affect the solution of equations (1). The length of the first half-wave is twice that estimated for the case of no ferrite. This suggests that there is some residual effect of the ferrite on the process of electric pulse formation. The system is capable of transferring, about 80% of the energy stored in the coaxial pulse-forming line with an estimated dynamic characteristic impedance of ~ 100 Ohm to the transmission line with a characteristic impedance of 40.4 Ohm.

References