Identifying of the Special Purpose Generator Pulses

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Abstract — There are some suitable methods for the measurement of ultra-short solitary electromagnetic pulses (EMP) that are generated by high power microwave generators. The characteristics of EMPs are high power level ($P_{\text{max}} = 250 \text{ MW}$) and very short time duration ($t_p \in (< 1, 60 > \text{ ns})$). Special requirements for measurement methods have to be considered because of the specific EMPs properties. In the paper, two suitable methods for this application are presented. The first one, the calorimetric method, utilizes the thermal impacts of microwave absorption. The second method presented — the magneto-optic method — uses the Faraday’s magneto-optic effect as a sensor principle. A combined calorimetric sensor was realized and there were made some experimental EMP measurements with good results. The sensor utilizing the magneto-optic method is still in development.

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1. INTRODUCTION

In connection with the events of the last few years and with the increased number of terrorist activities, the problem of identifying and measuring the impact of electromagnetic weapons or other systems occurred. Among these weapons or systems there are also microwave sources which can reach extensive peak power of up to $P_{\text{max}} = 250 \text{ MW}$. Solitary, in some cases several times repeated, pulses lasting from $t_p \in (< 1, 60 > \text{ ns})$ cause the destruction of semiconductor junctions.

The analysis of possible measuring methods convenient for the identification and measurement of the ultra-short solitary electromagnetic (EM) pulses is presented in this paper; some of the methods were selected and used for practical measurement.

2. METHODS

2.1. Method Based on Faraday’s Induction Law

One group of methods is based on the application of Faraday’s induction law where the pulse is located by sensor (coil with $N_s = 1 \div 50$ turns). The signal induced in the coil is led to the recording device, generally an oscilloscope. Due to safety requirements, the distance between the sensor and the oscilloscope is $l = 50 \text{ m}$. This parameter introduces quality decrease of the recorded information in the way of the signal amplitude reduction, change of the signal phase and the pulse prolongation.

The elimination of this limitation is in Version I, depicted in Figure 1, made by backward correction exploiting the Laplace transform. Pulses up to limit pulse length $T_{\text{max}} = 1 \text{ ns}$ were measured by this method and magnetic flux $\phi$ was evaluated [4]. Version II exploits the possibility of principal elimination of influence of the transmitting line between the sensor and the measuring device by an analogue U/f. converter. Available measuring devices can achieve measured pulses with the limit length $T_{\text{max}} = 5 \text{ ns}$.

The solution in Version III is similar to Version II; the difference is in the digital converter applied. By an available measuring devices application and fulfilled sampling theorem we can measure pulses with the limit length $T_{\text{max}} = 20 \text{ ns}$.

2.2. Method Based on Faraday’s Magneto-optic Effect

Version IV in Figure 1 is based on Faraday’s magneto-optic effect [4]. The connection between the sensor and the measuring device is implemented in the optical wavelength.

There are three basic types of the possible active sensors. The first type is a garnet with high Verdet constant, the second one is an optic fiber and the third one is based on magneto-optic properties of ferromagnetic mono/multi thin film. Other types of Version IV sensors are based on the magneto-optic Kerr’s effects (MOKE), or surface MOKE (SMOKE) effect. By an available measuring devices application we can measure pulses with the limit length $T_{\text{max}} = 0.1 \text{ ns}$.

The named methods indicate the electromagnetic parts of the wave — electric or magnetic. They don’t express the power conditions of the electromagnetic wave. For some of the measurement it is essential to evaluate power flow through the defined area.
2.3. Calorimetric Methods

The group of calorimetric methods represents another type of converter to be introduced. We can measure power supplied by pulse (Poynting’s vector when we use the calorimetric converter. The sensor is connected to the measuring device (oscilloscope) by an optic fiber of \( l = 50 \text{ m} \) length. Figure 2 depicts four versions of the method utilizing calorimetric measurement.

Version I discussed in [5, 6] has a sensor in the form of an ideal resistor and enables measurement of the maximum value of microwave power \( P_{\text{max}} \). The analyzed peak voltage corresponds to peak value of power \( P_{\text{max}} \). For available measuring devices we can measure pulses with the limit length \( T_{\text{max}} = 50 \text{ ps} \).

Version II scans the change of resistance of the sensor, created by an evaporated thin layer, in dependence on the pulse energy. For available measuring devices we can reach the accuracy of 30% up to impulse limit length \( T_{\text{max}} = 0.1 \text{ ns} \).

Version III is based on the measurement of the temperature change of the thermistor placed in contact with the layer. Under the same conditions as for the previous version we can reach the accuracy improvement of an order of magnitude.

Version IV is the bridge connection of version III. Several thermistors are attached in series to the evaporated layer; then, three resistors create a DC bridge of Weston type with the thermistors. The change of resistance in the thermistor arm is evaluated. The voltage in measuring the bridge diagonal is consequently integrated. Thus, the value of the pulse energy is obtained (and recorded by the measuring device). For available measuring devices we can measure pulses with the limit length \( T_{\text{max}} = 0.03 \text{ ns} \) with accuracy to 10%.

3. USED CALORIMETRIC METHOD

The advantage of the calorimetric method is the capability of physically correct high power measurement. However, it doesn’t provide the information about pulse waveform.

The calorimetric sensor was of the disc design. The carbon with changed crystal lattice was designed for use as one of the thin layer types.

3.1. Mathematical Model

It is possible to carry out an analysis of an MG model as a numerical solution by means of the Finite element method (FEM). The electromagnetic part of the model is based on the solution of full Maxwell’s equations

\[
\nabla \times E = \frac{\partial B}{\partial t}, \ \nabla \times H = \sigma E + \frac{\partial D}{\partial t} + J, \ \nabla \cdot D = \rho, \ \nabla \cdot B = 0 \text{ in } \Omega, \quad (1)
\]
where $\mathbf{E}$ and $\mathbf{H}$ are the electrical field intensity vector and the magnetic field intensity vector, $\mathbf{D}$ and $\mathbf{B}$ are the electrical field density vector and the magnetic flux density vector, $\mathbf{J}_s$ is the current density vector of the sources, $\rho$ is the density of free electrical charge, $\gamma$ is the conductivity of the material and $\Omega$ is the definition area of the model. The relationships between electrical and magnetic field intensities and densities are given by material relationships

$$ \mathbf{D} = \varepsilon \mathbf{E}, \quad \mathbf{B} = \mu \mathbf{H}. $$

The permittivity $\varepsilon$, the permeability $\mu$ and the conductivity $\gamma$ in HFM are generally tensors with main axes in the direction of the Cartesian coordinates $x$, $y$, $z$. When all the field vectors perform rotation with the same angular frequency $\omega$, it is possible to rewrite the first Maxwell equations

$$ \nabla \times \mathbf{E} = -j\omega \mu \mathbf{H}, \quad \nabla \times \mathbf{H} = (\sigma + j\omega \varepsilon)\mathbf{E} + \mathbf{J}_s \text{ in } \Omega. $$

where $\mathbf{E}$, $\mathbf{H}$, $\mathbf{J}_s$ are field complex vectors. Taking into account boundary conditions given in (1) and after rearranging (3) we get

$$ (j\omega)^2 \varepsilon \mathbf{E} + \sigma \mathbf{E} + \nabla \times \mu^{-1} \nabla \times \mathbf{E} = -j\omega \mathbf{J}_s. $$

We apply Galerkin’s method with vector approximation functions $\mathbf{W}_i$ and use vector form of the Green theorem on the double rotation element [3]. After discretisation we get the expression

$$ -k_0[M]\{\mathbf{E}\} + jk_0[C]\{\mathbf{E}\} + [K]\{\mathbf{E}\} = \{\mathbf{F}\}, $$

where $\{\mathbf{E}\}$ is column matrix of electrical intensity complex vectors. The matrixes $[K]$, $[C]$ and $[M]$ are in the form that is given in manual [4] and vector $\{\mathbf{F}\}$ is evaluated from the expression

$$ \{\mathbf{F}\} = -jk_0 Z_0 \int_{\Omega} [\mathbf{W}_i]\{\mathbf{J}_s\} d\Omega + jk_0 Z_0 \int_{\Gamma_{\Omega} + \Gamma_1} [\mathbf{W}_i]\{n \times \mathbf{H}\} d\Gamma. $$

Vector approximation functions $\mathbf{W}$ are given in manual [4]; $k_0$ is the wave number for vacuum, $Z_0$ is the impedance of free space. The set of equations (5) is independent of time and gives $\mathbf{E}$. For transient vector $\mathbf{E}$ we can write

$$ \mathbf{E} = \text{Re}\{\mathbf{E}e^{j\omega t}\}. $$

3.2. Model in FEM

The geometrical model was created with standard tools in ANSYS program using the automated generator of mesh and nodes; then the mathematical model is formed. The applied element is HF120.

![Figure 3: Experimental construction of vircator, $P_{max} = 250$ MW.](image1)

![Figure 4: Waveform of vircator’s anode current.](image2)
4. REALIZATION OF THE CALORIMETRIC SENSOR

Pursuant to the results obtained by numerical analysis, the calorimetric sensor was built. The prototype of the sensor was designed for the measurement of vircator with output power of $P_{\text{max}} = 250 \text{ MW}$, length of pulse $t_p \in <10, 60> \text{ ns}$. Vircator is a pulse high-energy source of microwave energy based on the virtual cathode effect; its experimental construction is shown in Figure 3. Figure 4 shows the waveform of vircator’s anode current by initiation. The concept was designed after consultation [7] for the supposed power and pulse length with room for absorption and damping of the possible back EMG wave.

4.1. Waveguide-fitted Calorimetric Sensor

The first prototype of the calorimetric sensor was intended for waveguide connection with a microwave vircator. Figure 5 shows the outer shell. The purpose of the calorimetric sensor was to measure the energy (power) of the emitted EMP. It was not possible to use the probe because the mode of the field, waveform and spectrum were not known.

4.2. Free-space Combined Calorimetric Sensor

For the measurement of free-space vircator EMP, the new combined calorimetric sensor was built. The sensor operation is based on version I and version IV of the calorimetric method in Figure 2. The first part (version I) serves as the sensor of instantaneous power and the second part (version IV) serves as the sensor of pulse energy. The realization of the combined sensor is shown in Figure 6. Both parts are equipped with Horn antennas to ensure the matching of the free-space EMG wave to the sensor input.

The sensor was calibrated with an RF generator in an absorption room. The calibration was performed for microwave pulses with defined duration and power level.

Due to safety requirements, the connection between the sensor and the measuring device was ensured by means of coaxial cable of the minimum length $l_{\text{min}} = 10 \text{ m}$.

The combined calorimetric sensor was used for the measurement of vircator-emitted EMP. The supply of the vircator was provided by pulse high-voltage source powered by Marx bank. When the vircator is in the operational mode, hard RTG emission is generated in addition to the microwave emission. The energy of the electron beam is $W_b = 1 \text{ MeV}$. Therefore, safety requirements equal to those mentioned above have to be considered.

The waveform of the measured small microwave power is in Figure 7. The peak value of the vircator-emitted EMP reached $P_{\text{max}} = 50 \text{ kW}$ in this experiment.

However, vircator is able to emit EMP with peak value of hundreds of MW when supplied with pulsed power generators.

5. DESIGN OF THE MAGNETO-OPTIC METHOD

The magneto-optic (MO) method is proposed for further experiments. The magnetooptic method allows ultra-short pulses waveform measurement because of its high bandwidth. The polarization rotation of light passing the MO sensor is affected by the magnetic part of EM pulse. The rotation is due to the magnetic field and properties of the sensor material (Verdet constant). For free space measurement the MO garnet, glass or thin film may be used.
Figure 7: Measured waveform of small microwave power, $P_{\text{max}} = 50\,\text{kW}$.

The absolute measurement method utilizing the MO glass element was experimentally realized with low frequency magnetic field. Laser beam with linear polarization passes the MO glass placed in Helmholtz coil. The laser beam is subsequently fed through an analyzer and the polarization rotation is converted to intensity modulation. The intensity of light is sensed by a photodiode. The magneto-optic glass FR-5 by Hoyoa Optics was used in this experiment.

6. CONCLUSION

The overview of several methods suitable for the measurement of short solitary pulses with high power level was given. The characteristics of the designed method were discussed. Some methods were experimentally tested and evaluated. A combined calorimetric sensor for free-space measurement was built and the functionality of the calorimetric sensor was proved by real measurement of vircator-emitted EMP.

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REFERENCES