The charged particle accelerators subsystems modeling

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Abstract. Presented web-based resource for information support the engineering, science and education in Electrophysics, containing web-based tools for simulation subsystems charged particle accelerators. Formulated the development motivation of Web-Environment for Virtual Electrophysical Laboratories. Analyzes the trends of designs the dynamic web-environments for supporting of scientific research and E-learning, within the framework of Open Education concept.

1. Introduction

The modern charged particle accelerators regardless of their size and application are characterized by the common part of their technical subsystems. The functioning of these components and subsystems is based on the different physical principles. For their calculation and simulation we use the disciplines such as the theory of electrical circuits, radio and microwave facilities, vacuum facilities, physical electronics, and physics of discharges in a vacuum. Among the top-level this subsystems can be specified such as:

- Vacuum technique and physical electronics subsystems;
- Devices based on powerful pulse technology (PPT);
- Accelerators electronic subsystems;
- Channels transporting high-energy particles.

Each of these subsystems of accelerators can be structured with different granularity, depending on the solved task. The structuring algorithm requires caution because if each successive level comprises some subsystems, the total number of simulated devices is growing exponentially. This is easily illustrated by the example of structuring PPT-devices:

1. Transmission line with distributed parameters (Long lines);
2. Powerful pulse generators;
3. Powerful pulse transformers:

- *The pulse transformers with lump parameters:*
  - Transformers with a soft switch;
  - Transformers with a hard switch;
- *The pulse transformers with distributed parameters:*
  - The inverting transformer;
  - The non-inverting transformer.

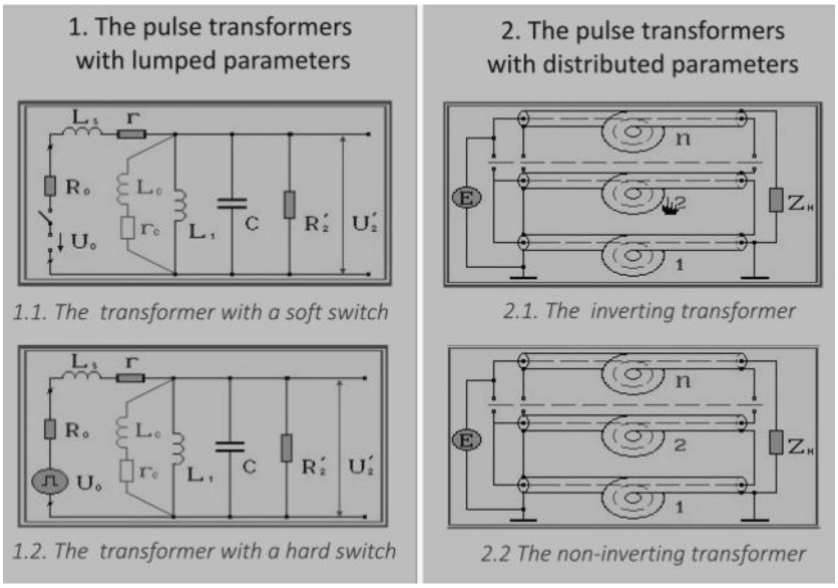

Figure 1. Pulse transformers classification.

A variety of powerful pulse transformers (figure 1) shows exponential growth in the total number of sub-systems in their structuring on several levels. To build complex models of systems of such complexity requires a systems approach. In particular, such the systematic approach may be the use of graph theory for the coupling of the devices mathematical models of high-power pulsed technology with lumped and distributed parameters in the design of high current accelerators (electronic beams currents up to 10^6 A).

2. The models of particle accelerator subsystems

The design of accelerator complex subsystems is associated with the choice of a large number of parameters for a large number of components and devices interconnected in sequence. The structure of such electrophysical installation may be represented in the form of an electrical circuit. However, despite the external similarity with the conventional electrical circuits, applied and designed in radio electronics, low-power pulsed facilities and computing hardware, it has a number of features, because it contains devices forming powerful electromagnetic pulses.

The modeling of these elements related to the solution of the complicated mathematical problems (nonstationary tasks, three-dimensional elements with the distributed parameters, nonlinear elements). The problems can be solved by a variety of numerical methods of modern electrophysics. The efficiency of the algorithms used in the simulation of high-power pulsed devices is evaluated by the accuracy and precision of the results and the time of their receiving. In this case the methods of forming the systems of equations for different topologies of electrical circuits and methods of the implementing distributed nonstationary tasks to specific component equations are equally relevant.

The complication of the mathematical models of accelerator complexes subsystems depends on the modeling purposes. For simulation PPT-subsystems and high current accelerators in science and industry used specialized CAD, based on a combination of graph theory for electrical circuits with lumped parameters as well as methods of solution for nonstationary problems for transmission lines with distributed non-linear electrical parameters. The methods based on graph theory, allow to separately consider the circuit topology and equations for constituent elements, for this are used topological and components matrices, respectively. Selection of the tree of connected graph for most convenient analysis is the main problem for the circuits with a sufficiently large number of branches. After selecting the optimal tree in terms of computing automation, two methods are used: Node-voltage analysis and Branch current method.

1. The node-voltage analysis – allows to calculate the voltage in all the branches of the circuit through the nodal currents.

$$Y_{ij}u_{i0} = j_{i0} \tag{1}$$

where Y_{ij} – matrix of nodal conductivities, u_{i0} – voltage of the i-th node relative to 0-th node, j_{i0} – column matrix of nodal currents.

2. Loop currents method – allows to compose the system equations for a loops current in the matrix form.

$$Z_{ij}j_{ii} = e_{ii} \tag{2}$$

here Z_{ij} – loop impedance matrix, j_{ii} – matrix column loop currents, e_{ii} – column matrix of contour emf.

Application different variants of the characteristics method for solve telegraph equations makes it possible to consider transmission line with wave resistance, which arbitrarily changing along its length, as an element the electrical circuit with lumped parameters. The method of characteristics involves consideration the long line like a series of sections with slightly varying characteristic impedance and the same electrical length. In particular, on the base of the method developed the library specialized programs for CAD «Atlas».

Passage of the pulse in the segment of long line with the losses can be described by a system of telegraph equations:

$$\begin{cases} -\dfrac{\partial}{\partial x}u = \left(R + \rho\tau\dfrac{\partial}{\partial x}\right)i \\ -\rho\dfrac{\partial}{\partial x}i = \left(\rho R + \tau\dfrac{\partial}{\partial x}\right)u \end{cases} \tag{3}$$

with next distributed electrical parameters: L – inductance, C – capacitance, R – resistance, G – conductivity, τ – delay (or electrical length), ρ – wave resistance, where $u = u(x,t)$ – function voltage and $i = i(x,t)$ function current.

Solution of system (3) can be obtained by characteristics method as a recurrent finite-difference scheme for function of current and voltage, dependent of time – t:

$$\begin{cases} u_{k+1}(t+T_k) + \rho_k i_{k+1}(t+T_k) = (1-\rho_k g_k)u_k(t) + (\rho_k - r_k)i_k(t) \\ u_k(t+T_k) - \rho_k i_k(t+T_k) = (1-\rho_k g_k)u_{k+1}(t) + (\rho_k - r_k)i_{k+1}(t) \end{cases} \tag{4}$$

Where the values of current – i_{k+1} and voltage – u_{k+1} in the line section with number $(k+1)$ determined from the values current – i_k and voltage – u_k as well as from electrical length – T_k, resistance – r_k and conductivity – g_k, calculated for previous lines segment (with number k).

During the various types of educational process it is expedient to use the most simple and fast mathematical models. The characteristics method, possessing a high degree of accuracy, is resource-intensive and is redundant for basic educational purposes for which is sufficient to consider the long lines without losses and work out mathematical model based on the Laplace transform, Expressions for the voltage-function $\vec{V}_x(p)$ and $\overleftarrow{V}_x(p)$ is the standard solution of one-dimensional systems of telegraph equations for finite-length lines and presented in the operator form (upper arrows indicate the direction of wave propagation – forward wave and backward wave).

$$\begin{cases} \vec{V}_x(p) = \dfrac{Z_0}{Z_0 + Z_s} + V_s(p)\Gamma_0 \sum_{k=0}^{\infty} \Gamma_l^k \, e^{-\gamma(2kl+x)} \\ \overleftarrow{V}_x(p) = \dfrac{Z_0}{Z_0 + Z_s} + V_s(p)\Gamma_0 \sum_{k=0}^{\infty} \Gamma_l^{k+1} \, e^{-\gamma(2(k+1)l-x)} \end{cases} \quad (5)$$

here p – Laplace operator, $Z_0 = const$ – the characteristic impedance of line, V_s – a function of the voltage source, V_s – the internal resistance of the source Γ_0 = const – the reflection coefficient at the line input, k – number of the reflected wave, $\Gamma_l = \Gamma_l(p)$ – the waves reflection coefficients on the load.

Get a universal formula of inverse Laplas transform for reflection waves is allow the coefficient of reflection from load, if represented it in the next form:

$$\Gamma_l(p) = \frac{\lambda}{p+\beta} + \delta \quad (6)$$

where p – Laplace operator, and constants λ, β and δ depend on the load parameters and type of the compound (sequential or parallel). For this expression the inverse Laplace transform is performed quite easily.

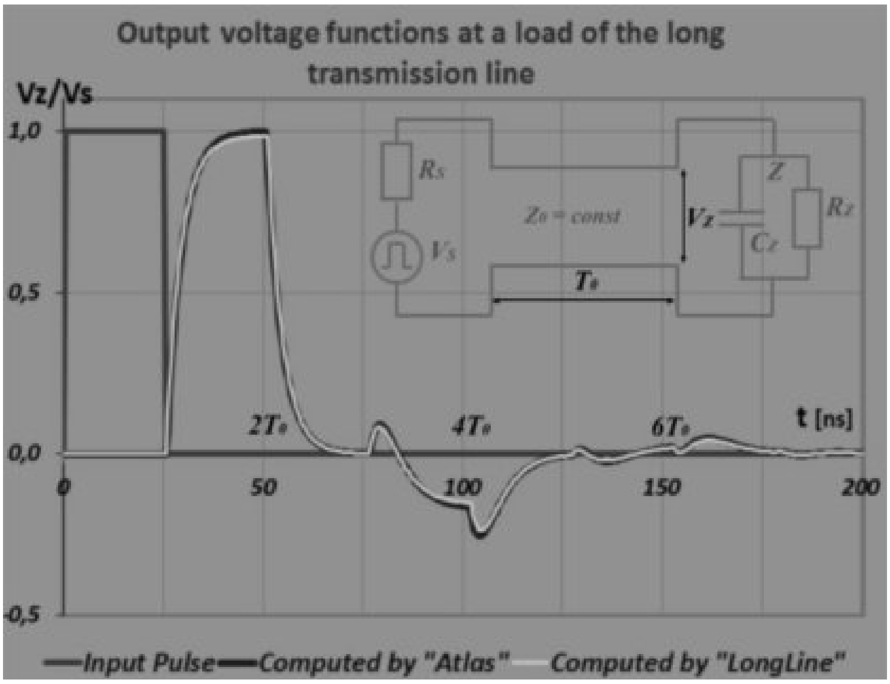

Figure 2. The comparison of the transient process calculation results in the line obtained from CAD “Atlas” and the educational software “LongLine”

Such models contain simplifications associated with the formulation of educational tasks, as well as, allow to obtain accurate results which can be compared with the ones obtained by using specialized CAD software with the error not exceeding 5% (figure 2).

3. The interfaces for working with models

The graphic design of any RFP simulates the electrical installations of the individual subsystems can distinguish five basic elements:

- Item data entry. Used to specify. Specific numerical values of physical quantities. It has properties limits the range and accuracy of input values;
- Display element schedules. The main functions - it is static or dynamic display pictures of the physical process. As well as the ability to scale plots and measured values. Ability to add the simplest elements of mathematical analysis of dependencies like finding the maximum or minimum of the function;
- Reflective element diagram. The main condition is that the address line contains enough data for a complete description of the circuit configuration. When the sample scheme, the address bar can be rewritten as the application status bar, every object has a list of states in which it exists;
- Aid element of reflection, descriptions of laboratory work, also based on loading web pages of relevant content;

When modeling the charged particle accelerator subsystems the most important questions are connected with the structure of the software interfaces. As in the case of the mathematical models, the software interfaces designed for the purpose of initial education should be much simpler. Elements of the group include a set of input data for the delineation of blocks, respectively tool for creating pop-up windows, tabs, or simply dividing lines.

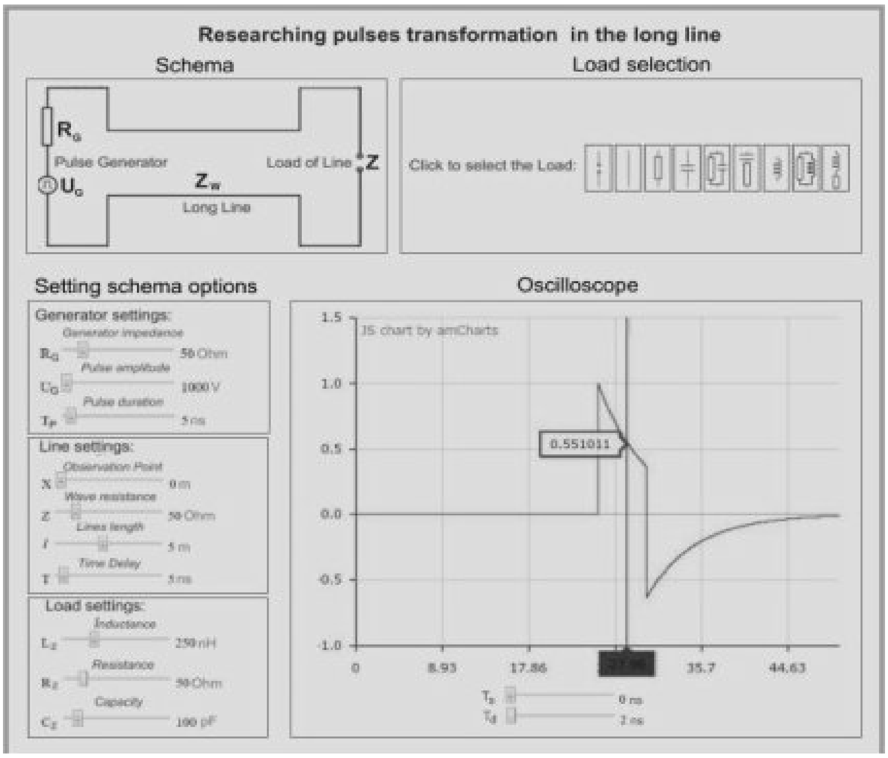

Figure 3. The interface of educational software "LongLine" to study the transient processes in the transmission lines of high-power pulsed facilities.

This is especially in the concept of open-education, taking into account the probability of large loads on both computing resources and teachers (tutors). In this case it is expedient to deal with the fixed electrical circuits of the studied devices (figure 3), allowing the change of discrete elements of the circuit, but excluding the device assembly. So that the task is to understand the working principles and the influence of the elements of the device on its work, but not to learn how to build circuits. The assembly of the accelerators subsystems circuitry in specialized editor software and the use of complicated mathematical models in the study of their functioning are appropriate at the next stage, during the education on the specialized CAD software, when the main principles of basic components operation are already known. The separation of the operation principles study and getting skills of circuit assembly in CAD software makes the learning curve less sloping and increases the efficiency of the educational process. This is especially in the concept of open-education, taking into account the probability of large loads on both computing resources and teachers (tutors). In this case it is expedient to deal with the fixed electrical circuits of the studied devices (figure 3), allowing the change of discrete elements of the circuit, but excluding the device assembly.

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4. Conclusion

The systematic approach, which provides the functional coupling of the mathematical models that are limited by the requirements of discrete technical disciplines and physics, is required for the simulation of the whole accelerator complex. PPT-subsystems of accelerators can be represented as a circuits containing conventional elements with lumped parameters and elements with distributed parameters, such as transmission line with variable distributed electrical parameters.

The result of the analysis of transient processes in long line of recurrent expressions and direct calculations shows the priority of using simulator based on direct calculations for training and demonstration objectives, including the development of Web-based applications for educational virtual laboratories of powerful pulse technology.

The software interfaces designed for the purpose of initial education should be much simpler compared to professional CAD interfaces. Task is to understand the working principles and the influence of the elements of the device on its work, but not to learn how to build circuits. The training on assembly of the accelerators subsystems circuitry is necessary to during operating with specialized software and the use of complicated mathematical models. The separation of the operation principles study and getting skills of circuit assembly in CAD software makes the learning curve less sloping and increases the efficiency of the educational process.

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