

SCHEMES OF HIGH-VOLTAGE PULSE SHAPERS ON THE BASIS OF STEPPED TRANSMISSION LINES FOR HIGH-CURRENT ACCELERATORS

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INTRODUCTION

The systems of high-voltage pulses formation in the majority of high-current accelerators with pulse duration from several to hundreds ns are designed on the basis of single or double pulse forming lines. The disadvantage of these systems consists for a number of applications in the relatively low output voltage equal in the matched mode for a double forming line to the charging voltage while for a single line – only to a half of this value.

In the course of creating high current linear induction accelerators (LIA) there was developed a new type of multi-cascade high-voltage pulse generators designed of homogeneous transmission lines of equal electric length. As in similar devices the impedance changes stepwise passing from one cascade to another, they are called step-line (SL) generators and several tens of schemes are available [1–3]. The energy accumulated in many lines (cascades) is concentrated as a result of wave processes at generator output after the switch is turned on. At specified impedance relation it is possible to transfer entirely the energy stored to the resistive load under rectangular pulse formation. Pulse duration does not depend on the generator full size and is characterized only by a double electric length of a separate cascade. A considerable – up to 5-10 fold - increase of voltage or current is realized depending on the generator scheme through wave processes. There are also proposed the schemes capable of providing electric power increase through the reduction of pulse duration [3, 4].

As well as all generators on transmission lines such devices can be subdivided into two types – generator of capacitive and inductive energy storage depending on the fact whether the energy is stored in the form of only electric or only magnetic field. As we know, recently proposed were, for the first time, the schemes of generators of a new type. In connection with the fact that energy is stored in them in the form of electric and magnetic field such generators are called inductive-capacitive generators [2]. Basing on capacitive schemes there are created electron accelerators: I-3000 (3.5 MeV, 20 kA, 16 ns), STRAUS (2,3 MeV, 20 kA, 40 ns), STRAUS – 2 (3.3 MeV, 50 kA, 40 ns), LIA-10M (≤ 25 MeV, ≤ 50 kA, 25 ns) [3,5-10]. Below the examples of different-type schemes are given. The investigations of SL are carried out in the USA as well [11–13].

CAPACITIVE GENERATOR

The scheme of the capacitive generator formed by $n \geq 5$ homogeneous transmission lines of similar electric length T_0 is presented in Fig. 1a [1, 3]. At $t = 0$ time moment, when maximum charging voltage V_0 of four cascades with Z , Z_{n-3} ÷ Z_n impedances is

achieved, S_1 is turned on. As a result, there appear electromagnetic waves. Let us consider any place of different-impedance cascades junction. Let the first wave comes to it at t_1 time moment. The generator scheme, impedances and time of load connection are selected in such a way that by $t_1 + 2T_0$ time moment the energy is entirely extracted from all cascades included between the considered cross-section and S_1 switch. The voltage wave coming at that moment from the S_1 switch and completing energy extraction is partially reflected from the place of cascades junction. However, at the same time from the opposite side to the cross-section in question another voltage wave comes with such amplitude and polarity that as result of superposition the amplitude of a wave reflected towards the switch becomes zero. As a result, the energy is entirely accumulated near the generator output. Other generators on SL operate similarly. At the output of the generator with Z_1 impedance and beginning from $t = (n - 3)T_0$ time moment there formed are the voltage pulses of alternating polarity, their duration being equal to $2T_0$. The second pulse is the operating one. The first pulse is cut off from the load by a pre-pulse switch S_2 , that is turned on with $2T_0$ delay as related to the moment of the first wave (from S_1 switch) coming. At the matched load a voltage pulse of rectangular shape is formed within which the energy is entirely delivered to the load.

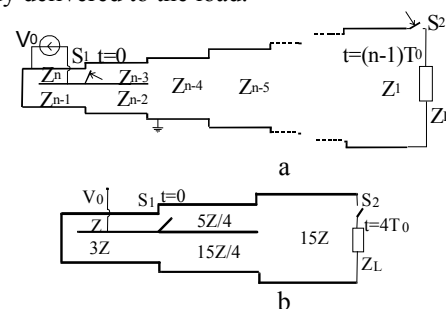


Fig. 1. Schemes of generators with capacitive method of energy storage for an arbitrary number of cascades (a) and the case of $n = 5$ (b).

To achieve in the ideal case a 100-% efficiency the impedances of the lines should be selected in accord with the following formulas: $Z_i = 2Z_1/[i(i + 1)]$ for $i = 1, 2, \dots, n - 4$, $Z_{n-3} = Z_1/[2(n - 3)(n - 2)]$, $Z_{n-2} = 3Z_{n-3}$, $Z_{n-1} = 3Z_n$, $Z_n = Z_1/[n(n - 2)]$, where Z_1 is the output generator impedance. The voltage on the matched load constitutes the value of

$(n - 2)V_0$. The appending of any additional cascade with the corresponding choice of impedances makes it possible to increase voltage on the matched load by V_0 , while in the idle mode – by $2V_0$. However, the growth of the number of cascades is accompanied by the increase of relation between maximum and minimum impedances of SL which does not exceed (as a rule) 20 for coaxial lines at using in the whole generator of one and the same type of dielectric.

In Fig. 1b specified is the ratio of impedances for a five-cascade generator when the output voltage in the idle mode is $6V_0$, while in the matched mode it is $3V_0$. On the basis of the scheme under consideration with $n = 5$, the first accelerator on SL called STRAUS (stepped transforming accelerator) and a more powerful accelerator STRAUS-2 are created. Its modification with $n = 4$ is used as a basis for LIA-10M inductor.

INDUCTIVE GENERATOR

Fig. 2 represents the example of a scheme with the inductive method of energy storage [2] for an arbitrary number of cascades (a) and for a case of $n = 3$ (b). In a closed contour formed by the SL electrodes and opening switch (OS) the I_0 current is generated and the energy is stored in the magnetic field. At $t = 0$ the time moment OS is turned on and under the effect of wave processes the energy is concentrated at the generator output. Under the matched load $Z_L = Z_n Z_0 / (Z_n + Z_0)$ which is turned on by the S switch at the moment of the first electromagnetic wave ($t = nT_0$) coming to it, a rectangular pulse of $2T_0$ duration is formed.

To achieve ideally 100-% efficiency the impedances should be selected according to the following formulas: $Z_i = 2Z_1 / [i(i + 1)]$ for $i = 1, 2, \dots, n - 4$, $Z_0 = 2Z_1 / (n + 1)$. The current in the matched load is as high as $(n + 1)I_0 / 2$. The inclusion of each additional cascade to the generator as a component makes it possible to increase current in the matched load by $0.5I_0$. In Fig. 2b it is demonstrated that an optimum ratio of impedances for the case of $n = 3$ will be with the current equal to $2I_0$.

INDUCTIVE-CAPACITATIVE GENERATOR

In Fig. 3 an example of an inductive-capacitive generator is shown. In a closed contour formed by a SL case and OS the I_0 current is generated under the effect of an external source, and the energy is stored in the magnetic field in the whole SL volume. At the same time, the high voltage-electrode is charged from another source up to V_0 voltage and the energy is stored in the cascades with $Z_{n-3} \div Z_n$ impedances in the electric field. At the moment of energy storage termination the S switch is turned on and in SL there appear electromagnetic waves. The generator scheme, the ratio of impedances as well as of I_0 and V_0 values are selected so that all the energy stored is concentrated at

the generator output. At the moment of the first wave arriving to it the OS interruption takes place and the energy is transferred to the load on which a $2T_0$ duration pulse of rectangular form is formed.

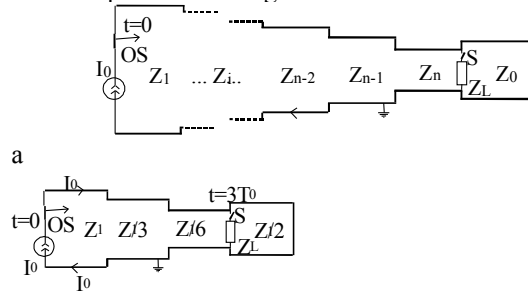


Fig. 2. Schemes of generators with inductive method of energy storage for an arbitrary number of cascades (a) and for a case of $n = 3$ (b).

To achieve a 100-% efficiency the impedances, I_0 and V_0 should be selected according to the formulas: $Z_i = Z_1[\alpha(\alpha + 1)] / [(\alpha + i - 1)(\alpha + i)]$ for $i = 1, 2, \dots, n - 4$, $Z_{n-3} = Z_1[\alpha(\alpha + 1)] / [2(\alpha + n - 3)(\alpha + n - 4)]$, $Z_{n-2} = Z_{n-3}$, $Z_{n-1} = Z_1[\alpha(\alpha + 1)] / [2(\alpha + n - 3)]$, $Z_n = Z_{n-1} \cdot I_0 = (V_0 / Z_1) \cdot [2(\alpha + n - 3)] / [\alpha(\alpha + 1)]$. The voltage on a matched load is found of the formula $V_L / V_0 = (\alpha + n - 3) / \alpha$. Here, we introduced the α

coefficient equal to the relation between electric and magnetic energy stored in the generator. The α ratio of charging voltage should be such that after the S switch turn-on the current in the line with Z_n impedance be decreased. The supplement of any additional cascade increases the voltage on a matched load by $V_0 / 2\alpha$. The optimum ratio of impedances for a special case ($n = 5$, $\alpha = 1$) when $V_L / V_0 = 3$ is presented in

Fig. 3b. To open OS one can take advantage of the fact that as a result of the first wave coming to it the current increases by a factor of $(\alpha + 1)$. It is the particular value for practical realization of synchronous operation of several generators.

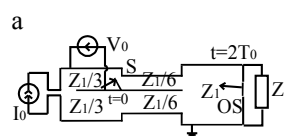


Fig. 3. Schemes of generators with inductive-capacitive method of energy storage for an arbitrary number of cascades (a) and for the case of $n = 5$ and $\alpha = 1$ (b)

Let us mention that there exists a considerable difference in the process of energy extraction in inductive-capacitive generators. After the completion of the energy storage the strength of electric (E) or magnetic (H) field in capacitive and inductive generators are correspondingly equal to zero. Thus, the

Pounting's vector is also equal to zero and the energy is at rest as related to electrodes. In the capacitive generator a spread takes place at high voltage gap closure by a switch along the lines of electromagnetic waves equating the voltage to zero. The electric energy transforms entirely to the magnetic energy, i.e. after the first wave passage from the switch the energy stays put, only its form changes. Thus, for entire extraction of energy the wave should be returned to the closed switch and reflected from it with the voltage polarity changed. The similar process takes place in the inductive generator on SL (Fig. 2). In this case after the first wave passage from OS the energy also stays put, while the magnetic energy transforms entirely to the electric energy.

For inductive – capacitive generators both E (near the high-voltage electrode) and H after the completion of the process of energy storage differ from zero, as well as, the Pounting's vector. As a result, the energy circulates around the high-voltage electrode. This effect should be necessarily taken into account in a set of cases to explain the satisfaction of the law of pulse moment conservation (see, for example, [14]). In the version of (Fig. 3) being considered the current direction as well as the polarity of charging voltage should be chosen in such a way that to realize the mode of entire energy extraction, the energy must circulate around a high-voltage electrode anti-clockwise. At high-voltage gap closure by S switch the way for the energy flow is cut off at this place. As a result of the ongoing circulation in a line with Z_n impedance, the quantity of energy will reduce, while in the line with Z_{n-3} impedance it will increase. Of most practical interest is the version of $I_0 = V_0 / Z_n$, where - after the first wave passage from the switch - the energy is entirely extracted from the line with Z_n impedance. At the high-voltage gap closure the voltage in the lines is zero-filled. At the same time, in the line with Z_n impedance there arises the current equal by value but opposite by direction to the initial current I_0 . As a result of superposition the current and the magnetic field in this line turn to zero, what – along with voltage zero-filling – provides entire extraction of energy from the line. One can easily check whether the law of energy conservation is satisfied or not.

PULSE DURATION CONVERTER

In Fig. 3 there is shown an example of a pulse duration converter. The transmission line with Z impedance is connected in series with step (Z_1, Z_2, \dots, Z_m) and single (Z_0) lines. The SL output is closed while the load is connected by S switch to the output of a single line with $2mT_0$ time delay as related to the first wave coming to it. The converter possesses a 100-% efficiency at selecting impedances according to the following formulas: $Z_0 = Z/(m+1)$, $Z_i = Z(m+1-i) \cdot (m+2-i)/(m+1)^2$ for $i = 1, 2, \dots, m$. The energy coming from the external generator in the form of rectangular pulse of $2(m+1)T_0$ duration is accumulated in the line with Z_0 impedance and then –

at S switch turn-on – is entirely transmitted to the matched load, the rectangular pulse (but of $2T_0$ duration) being formed in it. The output voltage pulse amplitude is equal to the voltage amplitude of external generator V_G while the current and power increase by a factor of $(m+1)$ through the corresponding reduction of pulse duration. In fig. 4b there is demonstrated the optimum relation of impedances for the case of $m = 3$ when the current on the matched load and power increase by a factor of 4.

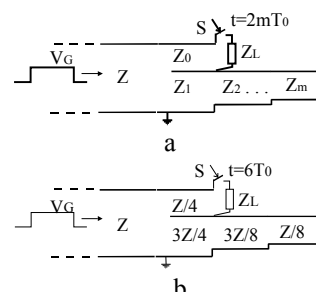


Fig. 4. Scheme of pulse duration converter for an arbitrary number of cascades (a) and a case of $m = 3$ (b).

There are also found the schemes of converters where before the achievement of the external generator pulse additional energy is accumulated in the form of electric or magnetic field [4]. Depending on the scheme there can be insured the increase of voltage and current.

It should be mentioned that by now there have been determined general regularities and developed calculation methods that simplify the search of optimum relations between impedances for SL-based devices.

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