NEW CIRCUITS OF HIGH-VOLTAGE PULSE GENERATORS WITH INDUCTIVE-CAPACITIVE ENERGY STORAGE

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The paper describes new electric circuits of multi-cascade generators based on stepped lines. The distinction of the presented circuits consists in initial storage of energy in electric and magnetic fields simultaneously. The circuit of each generator, relations of impedances, values of initial current and charge voltages are selected in such a manner that the whole of initially stored energy is concentrated at the generator output as a result of transient wave processes. In ideal case the energy is transferred with 100% efficiency to the resistive load where a rectangular voltage pulse is formed, whose duration is equals to the double electrical length of the individual cascade. At the same time there is realized a several time increase of output voltage as compared to the charge voltage of the generator. The use of the circuits proposed makes it possible to ensure a several time increase (as compared to the selection of the number of cascades) of the generator energy storage, pulse current and output electric power.

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1 INTRODUCTION

Development of high-current linear induction accelerators at VNIIEF promotes a search for new circuits for systems of high-voltage pulse formation. As a result there were developed multi-cascade generators on stepped lines possessing 100% efficiency in ideal case [1, 2]. As well as all generators based on transmission lines they can be subdivided in two types - generators with capacitive and inductive energy storage depending on the fact whether an initial electromagnet energy is stored only in the electric field or the magnetic one. Below presented are circuits of new type [2-9]. Due to the fact that the energy in them is stored simultaneously in both the electric and magnetic fields, such devices are called generators with inductive-capacitive energy storage or inductive-capacitive generators. They are made of homogeneous line sections (cascades) of the same electrical length T_0 as a stepped line. A stepped line cased with a current interrupter placed at the output form an inductive storage. A matched load is connected to generator output in parallel with the current interrupter. In the internal space of stepped line there is placed a high-voltage electrode forming together with stepped line case a capacitive storage in the form of homogeneous line sections ($n \geq 2$) of the same electrical length T_0.

Generators operate in the following way. In the closed circuit formed by the stepped line case and current interrupter under the action of the external source there appears the current I_0 and the magnetic energy is stored in the whole volume of stepped lines. Simultaneously a high-voltage electrode is charged up to U_0 voltage from another external source, and the electric energy is stored in several cascades. At the moment when the energy storage process is finished a switch S_1 is turned on closing a gap between a high-voltage electrode and the stepped line case. As a result, electromagnet waves appear in the stepped line. A generator circuit, relations of cascade impedances as well as I_0 and U_0 values are selected in such a way that as a result of transient wave processes the whole energy is concentrated at the generator output. At the moment when the first wave arrives to it there occurs current interrupter S_2 disconnection, and energy is supplied to the load where a squared pulse is formed with $2T_0$ duration.

2 ELECTRIC CIRCUITS OF GENERATORS

Fig. 1 shows three circuits of generators with inductive-capacitive energy storage [2-6] that differ in configuration of capacitive storage. Capacitive storages in the first and second circuits consist of two cascades, and in the third circuit the number of charged cascades grows up to 4. Note that only those circuits have been found that raise the voltage.

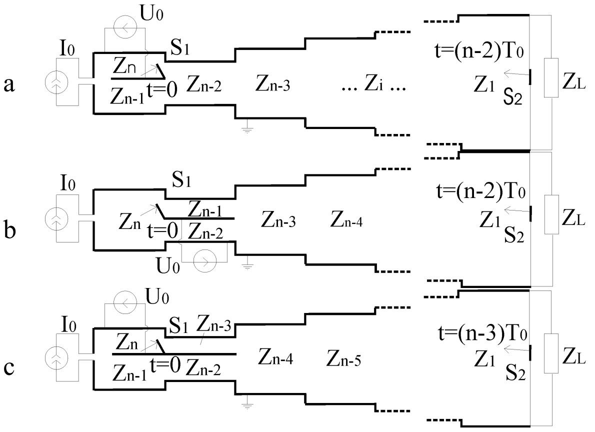

Fig. 1. Circuits of generators with inductive-capacitive energy storage.

In order to get 100% efficiency in ideal case, impedances as well as U_0 and I_0 should be selected according to the formulas given below.

For the first variant (Fig. 1a):

$Z_i = Z_1 \lambda (\lambda + 1)/[(\lambda + i - 1)(\lambda + i)],\ i = 1, 2, \ldots, (n - 2),$

$Z_{n-1} = Z_1\lambda\,(\lambda + 1)/[(\lambda + n - 2)(\lambda + n - 1)]$, $Z_n = Z_1\lambda \cdot (\lambda + 1)/(\lambda + n - 1)$, $I_0 = (U_0/Z_1)(\lambda + n - 1)/[\lambda\,(\lambda + 1)]$.

For the second variant (Fig. 1b):

$Z_i = Z_1\lambda\,(\lambda + 1)/[(\lambda + i - 1)(\lambda + i)], i = 1,2,...,n - 3$,

$Z_{n-2} = Z_{n-2} = Z_1\lambda\,(\lambda + 1)/[(\lambda + n - 3)(2\lambda + 2n - 5)]$,

$Z_{n-1} = Z_1\lambda\,(\lambda + 1)/[(\lambda + n - 2)(2\lambda + 2n - 5)]$, $Z_n = Z_1\lambda\,(\lambda + 1)/(\lambda + n - 2)$, $I_0 = (U_0/Z_1)(2\lambda + 2n - 5)/[\lambda\,(\lambda + 1)]$.

For the third variant (Fig. 1c):

$Z_i = Z_1\lambda\,(\lambda + 1)/[(\lambda + i - 1)(\lambda + i)], i = 1,2,...,n - 4$,

$Z_{n-3} = Z_1\lambda\,(\lambda + 1)/[2(\lambda + n - 3)\cdot(\lambda + n - 4)]$, $Z_{n-2} = Z_{n-3}$, $Z_{n-1} = Z_1\lambda\,(\lambda + 1)/[2(\lambda + n - 3)]$, $Z_n = Z_{n-1}$, $I_0 = (U_0/Z_1)2(\lambda + n - 3)/[\lambda\,(\lambda + 1)]$

Factor λ equals to the relation between electric and magnetic energies stored in the generator. The voltage on the matched load for the first, second and third variants exceeds U_0 by $(\lambda+n-1)/2\lambda$, $(2\lambda+2n-5)/2\lambda$ and $(\lambda+n-3)/\lambda$ times, respectively. Addition of every supplementary cascade to the generator raises the voltage on the load by for the first variant and by U_0/λ for the second and third variants.

As an example, Fig. 2 presents relations between impedances for generators with total electrical length of stepped lines equaling $3T_0$ for the case when in the electric and magnetic fields the equal energy is stored (λ=1). In the first and second variants the generator consists of four cascades, and in the fourth variant – of five cascades. The voltage on the matched load exceeds U_0 by 2, 2.5 and 3 times, respectively. Connection of each supplementary cascade raises the voltage for the first circuit by $0.5U_0$ and for the second and third one - by U_0.

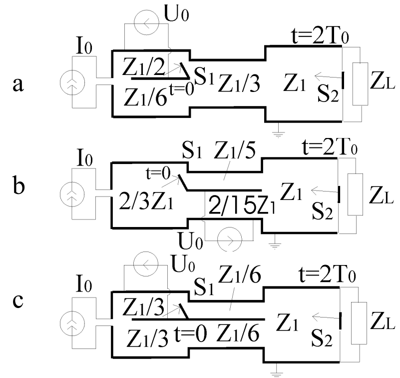

Fig. 2. Circuits of generators (see Fig.1) for the case when the total electrical length of stepped lines is $3T_0$ and λ=1.

In Fig. 3 presented are circuits similar to those shown in Fig. 1 but with connection of switch S_1 to the high-voltage electrode of capacitive storage through additionally charged (up to the voltage U_0) transmission line with impedance Z_0 [7-9]. In such devices, for example, those with a supplementary line in the form of high-voltage cable lines connected in parallel, switches of multi-channel commutator S_1 will be removed from the stepped line volume that will facilitate their maintenance and substitution.

For the circuits presented in Fig. 3 the relations of parameters have been obtained, provided they are adhered to, they possess 100% efficiency in the ideal case.

For the first variant (Fig. 3a):

$Z_i = Z_1\lambda\,(\lambda + 1)/[(\lambda + i)(\lambda - 1 + i)], i = 1,2,..., n - 1$,

$Z_n = Z_1 2\lambda\,(\lambda + 1)/(2\lambda + 2n - 3)$, $Z_0 = Z_1 2\lambda\,(\lambda + 1)/(2\lambda + 2n - 3)^2$, $I_0 = (U_0/Z_1)(2n + 2\lambda - 3)/[\lambda\,(\lambda + 1)]$.

For the second variant (Fig. 3b):

$Z_i = Z_1\lambda\,(\lambda + 1)/[(\lambda + i)\cdot(\lambda - 1 + i)], i = 1,2,...,n - 3$,

$Z_{n-2} = Z_1 2\lambda\,(\lambda + 1)/[(3n + 3\lambda - 7)(n + \lambda - 3)]$, $Z_{n-1} = Z_1\lambda\,(\lambda + 1)/[(3n + 3\lambda - 7)(n + \lambda - 2)]$, $Z_n = Z_1\lambda\,(\lambda + 1)/(n + \lambda - 2)$, $Z_0 = Z_1 2\lambda\,(\lambda + 1)/(3n + 3\lambda - 7)^2$, $I_0 = (U_0/Z_1)(3n + 3\lambda - 7)/[\lambda\,(\lambda + 1)]$.

For the third variant (Fig. 3c):

$Z_i = Z_1\lambda\,(\lambda + 1)/[(\lambda + i)(\lambda + i - 1)], i = 1,2,...,n - 4$,

$Z_{n-2} = Z_1\lambda\,(\lambda + 1)/[3(n + \lambda - 3)(n + \lambda - 4)]$, $Z_{n-3} = 2Z_{n-2}$, $Z_{n-1} = Z_1\lambda\,(\lambda + 1)/[3\,(n + \lambda - 3)]$, $Z_n = 2Z_{n-1}$, $Z_0 = Z_1 2\lambda\,(\lambda + 1)/[9\,(n + \lambda - 3)^2]$, $I_0 = (U_0/Z_1)\cdot 3(n + \lambda - 3)/[\lambda\,(\lambda + 1)]$.

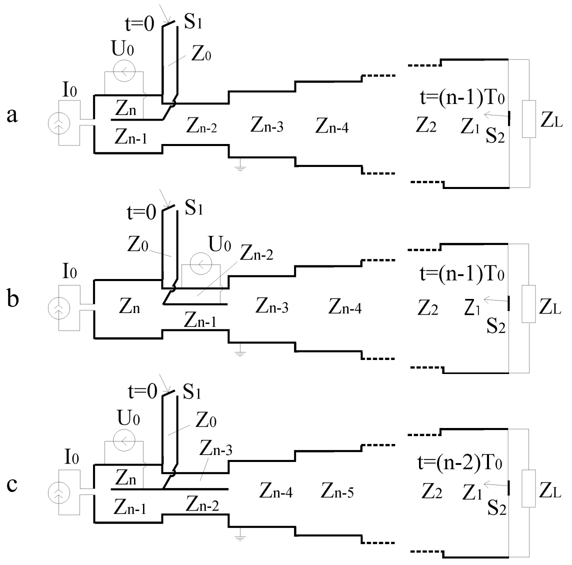

Fig. 3. Circuits similar to those presented in Fig. 1 but with connection of switch S_1 to a high-voltage electrode of the capacitive storage through a supplement transmission line.

The output voltage for the first, second and third variants exceeds U_0 by $(2n+2\lambda-3)/2\lambda$, $(3\lambda + 3n - 7)/2\lambda$ and $3(n+\lambda-3)/2\lambda$ times, respectively. Addition of every supplementary cascade to the generator raises the voltage by U_0/λ for the first variant and by $3U_0/2\lambda$ for the second and third variants.

As an example, Fig. 4 shows optimal relations of impedances for generators with a total electrical length of stepped lines of $3T_0$, for the case λ=1. The voltage on the matched load exceeds U_0 by 3.5, and 4.5 times, respectively. Connection of each supplementary cascade raises the voltage for the first circuit by U_0 and for the second and third circuits - by $1.5U_0$.

In order to raise the voltage on the load, in all circuits under consideration it is necessary to increase the number of cascades and/or diminish the parameter λ. Addition of supplementary cascades is accompanied by the growth of relation between maximal and minimal impedances of stepped line that for coaxial lines does not exceed 20, as a rule, provided one type dielectric is used in the whole generator.

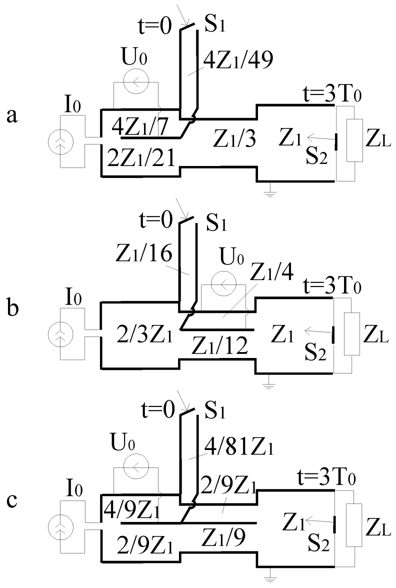

Fig. 4. Circuits of generators (see Fig. 3) for a particular case that the total electrical length of stepped lines is $3T_0$ and $\lambda=1$.

In order to disconnect the current interrupter, one can use the circumstance that at the moment when the first wave arrives to the current interrupter the current grows for all circuits discussed by (λ+1) times. This can simplify realization of synchronous operation of several generators as a part of the multi-module facility. To reliably disconnect the current interrupter, it is expedient to increase the parameter λ, i.e., to grow the electric energy fraction in the total energy storage. The analysis shows that the circuits proposed should possess a high efficiency at varying both cascade impedances and the parameter λ in rather a wide range.

3 COMPARISON OF CIRCUITS WITH INDUCTIVE-CAPACITIVE AND CAPACITIVE ENERGY STORAGE

To determine the field of possible application of the circuits proposed, let us compare characteristics of circuits with inductive-capacitive energy storage and those with capacitive energy storage. As the first one let us select a circuit of five-cascade inductive-capacitive generator (Fig. 5a) presented in Fig. 2c, and as the second one - a circuit of a similar five-cascade capacitive generator (Fig. 5b) [2]. The last circuit was used when developing accelerators STRAUS and STRAUS-2 [10].

In the ideal case both circuits possess 100% efficiency and form a squared pulse of voltage of $2T_0$ duration. To perform comparison, let us commit the values U_0, Z, T_0. In the first circuit the electric energy is stored $3U_0^2T_0/2Z$ as well as magnetic energy that is equal to it. That is, the total energy storage is $3U_0^2T_0/Z$. The output voltage, current and electrical power in the matched mode are $U=3U_0$, $I=U_0/2Z$, $P=3U_0^2/2Z$. In the second circuit, in the course of charging the forming line, the electric energy $6U_0^2T_0/5Z$ is stored. The output voltage, current and electrical power are $U=3U_0$, $I=U_0/5Z$, $P=3U_0^2/5Z$ in the matched mode.

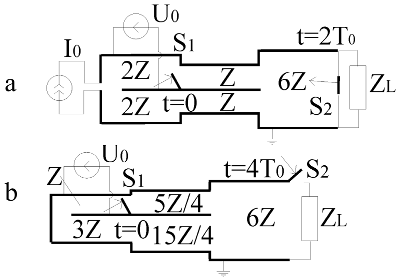

Fig. 5. Circuits of generators with inductive-capacitive (a) and capacitive (b) energy storage.

Thus, the inductive-capacitive generator provides the same voltage rise in the maximal efficiency mode as the capacitive generator. However, in the first case the energy storage, current and output power increase by 2.5 times.

From the comparison performed one can make a conclusion that generators with inductive-capacitive energy storage possess significant advantages. Along with a rather high factor of voltage increase they provide increase of energy storage, current and power by several times. An additional advantage of such devices (as compared to the capacitive generator discussed above (Fig. 5b) whose operating pulse is a second voltage one), is the absence of the pre-pulse voltage on the load. The last circumstance can be determinative for powerful generators with low-impedance loads.

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