PULSED POWER

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Preface

This monograph is devoted to pulsed power technology and high-power electronics – a new rapidly evolving field of research and development. Here, we deal with pulse power systems with tremendous parameters: powers up to 10^{14} W, voltages up to 10^6-10^7 V, and currents as high as 10^6 A and even higher. Recall that all world's power plants together produce a power of the order of 10^{12} W, i.e., one terawatt. The duration of pulses generated by pulse power systems is generally no more than 10^{-8} s. Thus, this is nanosecond high-power pulse technology. Depending on the purposes, pulse power devices may operate either in the single-pulse or in repetitively pulsed mode. It is clear that the highest parameters of pulses are achieved in the single-pulse mode. Pulse repetition rates of up to 10^4 are currently attainable at pulse parameters considerably lower than those mentioned above.

Pulsed power is not an alternative to traditional ac or dc power engineering. It is intended to solve other problems and deals with essentially different loads. Evolution of this "exotic" power engineering called for the creation of analogs to all devices used in conventional power engineering, such as pulse generators, switches, transformers, power transmission lines, systems for changing pulse waveforms, etc. The main peculiarity of pulsed power technology is that all system components must operate on the nanosecond time scale. The frequency spectrum of nanosecond pulses extends up to superhigh frequencies; therefore, the equipment designed to produce and transfer such pulses should have a wide bandwidth and, at the same time, be capable to hold off high voltages. The short times inherent in the operation of active components of pulsed power systems are attained by taking advantage of a variety of physical phenomena such as electrical discharges in gases, vacuum, and liquid and solid dielectrics; rapid remagnetization of ferromagnetics; fast processes in semiconductors; plasma instabilities; transient processes in nonlinear lines, etc.

It should be noted that the mechanisms of the processes occurring in the mentioned active components are identical over wide ranges of pulse parameters, and therefore the author of this book has been able to construct a rather consistent ideology of pulsed power for the range 10^6-10^{14} W.

Which are loads in pulsed power technology, viz., its applications? Chronologically, a first application was the study of the development of discharges in solid, liquid, and gaseous dielectrics exposed to strong electric fields. Another field of use to be mentioned is high-speed photography where high-voltage pulses of nanosecond duration have been used, initially with optical gates and then with electron-optical image converters, in studying fast processes in plasmas of exploded conductors, various types of electrical discharge, etc. In radiolocation, short pulses have long been employed for high-precision ranging. Production of short x-ray flashes has made it possible to obtain a series of fundamental results in ballistics and explosion physics. Nanosecond high-voltage pulse technology has played a key role in developing spark and streamer chambers, which are now the most-used instruments in nuclear physics. There are many other fields of application of pulsed power technology among which quantum electronics deserves mention. The progress in nanosecond pulsed power in the 1960s-1970s gave rise to a breakthrough in laser physics and engineering: first high-power pulse solid-state lasers were developed along with a variety of high-power gas lasers which cover the wave spectrum from ultraviolet to infrared.

However, a full-scale revolution in pulsed power technology occurred in the mid 1960s once nanosecond high-power pulse accelerators had been created independently in the United States and in the Soviet Union. Of crucial importance was the discovery made by the author of this monograph and his co-workers who revealed that the electron emission taking place in the diodes of accelerators of this type is an essentially new phenomenon unknown to physicists until that time (it was believed to be field emission). This phenomenon was given the name explosive electron emission. The creation of accelerators of this type and the use of high-power electron beams for various purposes permitted speaking of high-power pulse electronics. As demonstrated below, pulsed power technology and highpower electronics are intimately related; this is why the author has decided to combine them in one monograph.

High-power pulse electronics involves, first, the studies of explosive electron emission and electron beams at currents of up to 10^6 A; second, the studies of high-power ion beams which are produced from the plasma

generated due to the interaction of a high-power electron beam with an anode; third, production of various types of high-power pulsed electromagnetic radiation such as x rays, laser beams, and microwaves, and, finally, the creation of nanosecond pulsed electron accelerators capable of producing pulse powers of up to 10^9 W and electron energies of 10^5-10^6 eV and operating repetitively at pulse repetition rates of 10^2-10^3 Hz. They serve the same functions as conventional stationary accelerators, being used in medicine and food production, for sterilization and purification of air and water of harmful impurities, as units of medical x-ray apparatus, for modification of properties of various materials, etc. At the same time, they are smaller than conventional accelerators, compare with them in lifetime, and are not too expensive.

The monograph consists of 28 chapters subdivided into 9 parts. The first part describes the simplest schemes of pulse generation using lumped- and distributed-constant circuits. The consideration of these circuits implies that they operate with perfect switches.

The second part is devoted to the physics of pulsed electrical discharges in vacuum, gases, and liquid dielectrics. A knowledge of the properties of electrical discharges in vacuum helps the designer, on the one hand, to understand how to design the insulation in diodes of pulsed electron accelerators and, on the other hand, to choose a proper design for vacuum switches and understand the mechanism of their operation. Moreover, since the initial phase of a vacuum discharge is explosive electron emission, to gain a more penetrating insight into this phenomenon is to better understand the phenomenon of vacuum discharge. The study of pulsed discharges in gases provides data necessary to design gas-discharge switches and gas lasers, while information on the properties of electrical discharges in liquid dielectrics is helpful to the designers of liquid-insulated switches and coaxial lines.

The properties of coaxial lines with solid, liquid, and vacuum insulation are discussed in Part III. Coaxial lines are generally used for energy storage in high-power pulse generators and for transmission of pulsed energy. For vacuum lines, the mode of their operation under the conditions of magnetic self-insulation is considered, such that the self magnetic field of the current carried by the line is strong enough to return explosive emission electrons back to the cathode thereby impeding the development of a vacuum discharge in the line.

Part IV covers various types of spark gap switch, such as high-pressure and low-pressure spark gaps and switches with discharges in solid and liquid dielectrics. High-pressure spark gaps are in most common use; therefore, they are described in great detail. In particular, much attention is given to sequence multielectrode spark gaps which are candidates for switching very high pulsed powers.

All high-power pulse generators considered in this monograph depend for their operation on two principles. The first principle implies accumulation of energy in a capacitive energy store (capacitor or pulseforming line) which operates through a switch into a load. The relevant devices are referred to as generators with closing switches. The second principle consists in storing energy in an inductor, and an electric pulse is generated as the current flowing in the circuit containing the storage inductor is interrupted with the help of an opening switch. Therefore, Part V concentrates on the principles of operation and design of high-power pulse generators with plasma closing switches, viz., the spark gaps considered in Part IV. These are generators with discharging capacitors and energy storage lines, Marx generators, and generators with capacitive stores charged from various transformers and pulsed voltage multiplication devices.

The six part deals with high-power pulse generators with plasma current interrupters, such as generators with electrically exploded conductors, plasma opening switches, and gas-discharge switches triggered with the help of injection thyratrons.

Part VII describes semiconductor and magnetic switches and the nanosecond high-power pulse generators using these switches. The operation of semiconductor closing switches – microsecond, nanosecond, and picosecond thyristors – is discussed in detail. Of particular interest are semiconductor opening switches, so-called SOS diodes, which operate at voltages of up to 1 MV, diode current densities of up to 10^4 A/cm^2 , and pulse repetition rates over 10^3 Hz. Magnetic switches make it possible to compress energy in a pulse, i.e., to considerably increase the pulse power and decrease the pulse duration. Hybridization of SOS diodes and magnetic compressors gave rise in fact to a new field in pulsed power technology. This part terminates with a description of long lines with nonlinear line parameters in which, under certain conditions associated with the occurrence of electromagnetic shock waves, pulse rise times shorter than 1 ns can be attained.

In Part VIII, diodes are considered that produce high-power electron beams of various types, such as large-cross-section, annular, and dense and focused beams. The first-type beams are used for pumping das lasers and in technologies, beams of the second type for the production of microwaves, and the third-type beams for heating plasmas and investigating their properties.

The final, ninth part of the monograph is the largest one and contains four chapters. It is devoted to high-power pulsed electromagnetic radiation sources such as x-ray generators, gas lasers, microwave oscillators, and sources of ultrawideband radiation. It should be stressed that all these unique systems became feasible only due to the advances in pulsed power technology and high-power electronics. They are capable of producing pulse powers which are many orders of magnitude greater that those attainable with earlier devices.

A considerable body of the results presented in this monograph were obtained by the author and his co-workers at Tomsk Polytechnic University and at two institutes of the Russian Academy of Sciences that were established and long headed by the author: the Institute of High Current Electronics (Tomsk) and Institute of Electrophysics (Ekaterinburg). These results were published in author's numerous articles, theses, and patents and reviewed in a number of monographs the first of which goes back to 1963. Also used are the most important results obtained at other laboratories of the United States, Russia, Great Britain, and Germany. It should be noted that the most powerful pulse generators have been developed and built in the United States. The monograph has the feature that special attention is paid to the pioneering works that were responsible for the development of new fields in pulsed power technology and high-power electronics. However, the author is not sure that his choice was correct in all cases because a great deal of work in this field was security-guarded for years both in Russia and abroad. Therefore, he presents his apologies to the reader for possible incorrect citing of priority publications.

In conclusion, I would like to thank my colleagues who helped me in writing this book, in particular, V. D. Korolev and V. I. Koshelev who in fact co-authored Chapters 8 and 28, respectively. Helpful suggestions made by E. N. Abdullin, S. A. Barengolts, S. A. Darznek, Yu. D. Korolev, S. D. Korovin, B. M. Koval'chuk, D. I. Proskurovsky, N. A. Ratakhin, S. N. Rukin, V. G. Shpak, V. F. Tarasenko, and M. I. Yalandin in discussing particular topics of this work are also acknowledged. Thanks also go to V. D. Novikov for his advice in the course of preparation of the manuscript. Much work on typing the manuscript and preparing its camera-ready version was done by my assistants of many years Irina Kaminetskaya, Lena Uimanova, and Larisa Fridman, and it is a pleasure to gratefully acknowledge their contribution.

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G. A. Mesyats

PULSED POWER

PART 1. PULSED SYSTEMS: DESIGN PRINCIPLES

Chapter 1

LUMPED PARAMETER PULSE SYSTEMS

1. PRINCIPAL SCHEMES FOR PULSE GENERATION

There are two essentially different schemes for pulse generation (Fig. 1.1) with the storage of electrical energy either in a capacitor or in an inductor. In the first case (see Fig. 1.1, a), a pulse is produced when a capacitor C, previously charged to a voltage V_0 , discharges into a load of resistance R_{load} . The energy stored in the capacitor is $CV_0^2/2$.

In this case, the circuit carries a displacement current

$$I = C \frac{dV}{dt}, \tag{1.1}$$

where V(t) is the voltage across the capacitor during its discharge.

In the second case (see Fig. 1.1, b), a pulse is generated upon breakage of a circuit in which an inductor L carries an initial current I_0 . The inductor stores an energy $LI_0^2/2$, and a self-inductance emf, which is given by

$$\varepsilon = -L\frac{dI}{dt},\tag{1.2}$$

where I(t) is the current during the pulse formation, appears across the inductor.

Let us consider these schemes in more detail.



Figure 1.1. Capacitive (a) and inductive (b) schemes for pulse generation

Figure 1.1, *a* presents the simplest circuit of a generator with capacitive energy storage. Assume that the switch *S* is perfect, such that its resistance may change instantaneously from infinity to zero. If the load impedance R_{load} is purely active, an exponential pulse of rise time zero appears across the load:

$$V = V_0 e^{-\frac{l}{R_{\text{load}}C}}.$$
(1.3)

From (1.3) we have the pulse amplitude $V_a = V_0$ and FWHM $t_p = 0.7R_{load}C$.

In fact, the pulse rise time is other than zero. It is determined by the selfinductance of the circuit and by the resistance of the switch, $R_s(t)$, which depends on time. The time it takes a switch to go from the nonconductive to the completely conductive state is called the switching time, t_s . Since it is generally desirable to have $t_r \ll t_p$, where t_r is the pulse rise time and t_p is the pulse duration, for a circuit containing an inductor of inductance L, the 10%-90% rise time is determined as $t_r = 2.2L/R_{load}$. The switching time t_s is generally measured from the switching characteristic of the switch – the time dependence of the voltage between the switch terminals. This voltage is measured, as a rule, between 10% and 90% of the initial voltage across the switch. It is generally approximated by an exponential function:

$$V_{\rm s} = V_0 \mathrm{e}^{-at} \,, \tag{1.4}$$

where a is a quantity determined by the physical processes occurring in the switch. If we neglect the self-inductance of the circuit, the pulse rise time is given by

$$t_{\rm r} \approx t_{\rm s} = \frac{2.2}{a} \tag{1.5}$$

for $t_{\rm r} \ll t_{\rm p}$.

To calculate the transient process in a discharge circuit (see Fig. 1.1, a), we can formally use the Tevenin theorem and replace the voltage across the switch by the emf $V_s(t)$. (This approach is often used to calculate a pulse waveform).

LUMPED PARAMETER PULSE SYSTEMS

Let us now consider the scheme with inductive energy storage (see Fig. 1.1, b). The circuit involves a generator of current I_0 with zero internal resistance. Let the switch S_1 be perfect. As it opens, the voltage between its terminals becomes instantaneously infinitely high. This theoretical case is, of course, not realizable since, first, a capacitor C charged to a voltage V_0 is connected in the circuit instead of a current generator, and the switch S_1 opens as the current peaks. The switch S_2 connects the load R_{load} to the inductor L. Second, an opening switch is never perfect; it always has a time-increasing resistance $R_s(t)$.

Assume that this resistance increases linearly with time:

$$R_{\rm s} = bt, \tag{1.6}$$

where b is the resistance rise rate. In this case, a voltage pulse will appear across the load of resistance $R_{\text{load}} \gg R_s$. The time it takes the current to peak, t_{max} , and the peak voltage V_a are given by

$$t_{\max} = \sqrt{\frac{L}{b}} \text{ and } V_{a} = I_{0}\sqrt{\frac{bL}{e}},$$
 (1.7)

where *e* is the natural logarithm base.

For a more general evaluation of the operating parameters of a generator with inductive energy storage, we assume that the switch S_1 interrupts the current in a time t_{open} . The switch average resistance is then approximated as $R_{open} \approx L/t_{open}$. For this case, the voltage across the load is given by

$$V \approx \frac{LI_0}{t_{\text{open}}} \frac{x}{(1+x)^2},$$
 (1.8)

where $x = R_{\text{load}}/R_{\text{open}}$, and the power is given by

$$P \approx \frac{LI_0^2}{t_{\text{open}}} \frac{x}{(x+1)^2} \,. \tag{1.9}$$

Note that the quantity I_0/t_{open} characterizes the rate of current interruption.

The pulse power peaks as x = 1, i.e., as $R_{\text{load}} = R_{\text{open}} = L/t_{\text{open}}$, and it is given by $LI_0^2/4t_{\text{open}}$.

Proceeding from relations (1.6)-(1.9), we can state that to attain a short pulse rise time, a high peak voltage, and a high power at the load, it is necessary to have a high rise rate of the resistance of the switch S_1 , a short opening time, and a high rate of current interruption.

2. VOLTAGE MULTIPLICATION AND TRANSFORMATION

The simplest schemes considered above become ineffective if one needs to produce voltage pulses of amplitude 10^5-10^7 V for the lack of capacitors designed for such high voltages. In this case, schemes of voltage multiplication are applicable. The most commonly used is the Marx circuit (Fig. 1.2). This circuit operates in the following way: Several (*N*) capacitors of capacitance *C* each are connected in parallel and charged through resistors R_1 and *R* to a voltage V_0 . If all switches *S* close simultaneously, capacitors *C* become connected in series and a voltage pulse with amplitude close to NV_0 is generated across the load R_{load} . The total discharge capacitance will be C/N, and hence the pulse FWHM will be $t_p = 0.7R_{load}C/N$. The capacitance C/N is connected to the load through the switch S_1 .



Figure 1.2. The Marx circuit for voltage multiplication

An important condition for normal operation of a Marx generator (MG) is that the current that flows in the circuit as the capacitor C discharges through the resistor R should be low. Obviously, this takes place if $R \gg R_{\text{load}}/N$, i.e.,

$$\frac{R_{\text{load}}}{R_N} \ll 1. \tag{1.10}$$

A common choice for the switches S is spark gaps and, sometimes, thyratrons or thyristors. Various circuit designs of MG's and the features of their operation are considered in Chapter 13.

In the above scheme, the voltage is multiplied by the number of generator stages. A more efficient method of voltage multiplication was proposed by Mesyats (1963). The circuit consists of N stages, each containing an oscillatory LC circuit (Fig. 1.3), for which the following conditions are satisfied:

$$C_0 \gg C_1 \gg C_2 \dots \gg C_N,$$

$$L_0 \gg L_1 \gg L_2 \dots \gg L_N.$$
(1.11)

Here, C_0 is the capacitance of the smoothing filter of the rectifier. To ensure complete discharging of all *LC*-circuit capacitors, resistors R_1 , ..., R_N are connected in the circuit. Their resistances are generally two or three orders of magnitude greater than the wave resistances of the corresponding *LC* circuits, $R_i \ge (10^2 - 10^3) \sqrt{L_i/C_i}$, where *i* is the *LC*-circuit number.



Figure 1.3. Voltage multiplication circuit with 2^N efficiency

As the switch S_1 operates, the capacitor C_0 , charged to a voltage V_0 , discharges into the capacitor C_1 . Neglecting the resistive losses in this *LC* circuit, in view of condition (1.11), we obtain the time-varying voltage across the capacitor C_1 :

$$V_1 \approx V_0 \left[1 - \cos\left(\frac{t}{\sqrt{L_1 C_1}}\right) \right]. \tag{1.12}$$

From (1.12) we have that at $t = t_1 = \pi \sqrt{L_1 C_1}$ the maximum voltage $V_{1\text{max}}$ is equal to $2V_0$. If the switch S_2 closes at the time t_1 , then, in virtue of condition (1.11), C_1 discharges into C_2 much faster than into C_0 . In $t = t_2 = \pi \sqrt{L_2 C_2}$, the voltage across C_2 becomes $V_{2\text{max}} \approx 4V_0$. Thus, as each next-in-turn switch S_i closes, the maximum voltage across C_i becomes almost twice that across C_{i-1} . Eventually, the maximum voltage across C_N will be

$$V_N \approx 2^N V_0. \tag{1.13}$$

The actual voltage V_N will be lower than that given by formula (1.13) because of certain (not infinitely large) capacitance ratios C_0/C_1 , C_1/C_2 , ..., C_{N-1}/C_N , resistive losses in the *LC* circuits, and partial recharging of the capacitors.

Fitch and Howell (1964) described an *LC* generator in which the capacitors are switched in series upon reversal of polarity of the voltage across the even stages in oscillatory *LC* circuits. The circuit diagram of this generator is given in Fig. 1.4. Initially, the capacitors are charged from a dc voltage source, as in an MG circuit. At t = 0, as the switches close, the even capacitors start discharging through the inductors *L*. In a time $\tau = \pi \sqrt{LC}$, the voltage across the capacitors reverses sign, and the output voltage of the

generator becomes $V_{out} = NV_0$, where N is the number of stages. In no-load operation, the output voltage varies by the law

$$V_{\rm out}(t) = NV_0(1 - e^{\alpha t} \cos \omega t),$$
 (1.14)

where $\omega^2 = 1/LC$, $\alpha = R/2L$, and R is the resistance (in ohms) of the LC circuit. From (1.14) it can be seen that here, in contrast to an MG, the voltage rise time is determined by the inductance of an inductor specially connected in the circuit, and decreasing L may decrease the voltage multiplication factor because of the increase in parameter α .



Figure 1.4. An LC generator with reversal of voltage polarity

This scheme has the advantage over the Marx one that the number of switches is halved. However, the switches must be operated as simultaneously as possible by using special trigger circuits. Another advantage is that the resistances and inductances of the switches have no effect on the circuit output impedance if the LC generator picks up the load through an additional fast switch.

Pulse transformers with lumped parameters, because of their poor frequency characteristics, cannot be employed directly in nanosecond pulse power technology. However, as well as MG's, they are widely used as charging devices for pulse-forming lines. They generally operate on the microsecond time scale. The choice of this time scale is dictated by two factors. On the one hand, in order that the insulation of the components of pulse generators be reliable, it is necessary that the charging pulses be as short as possible. On the other hand, the charging pulse should be long enough so that all transient processes in the pulse-forming line have time to be completed and the switch connecting the line to the load operate reliably

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at a desired time. In this respect, the microsecond time scale is optimal. For this purpose, Tesla transformers, line transformers, conventional pulse transformers, and autotransformers are used. Transformers are more compact and reliable than MG's and they can be repetitively operated. A Tesla transformer contains two inductively coupled oscillatory *LC* circuits (Fig. 1.5). As the switch *S* closes, free oscillations appear in the L_1C_1 circuit and are transferred to the L_2C_2 circuit. For the capacitance C_2 , the capacitance of the pulse-forming line of the accelerator is generally used. In order that the energy transfer from the first to the second *LC* circuit be as complete as possible, it is necessary that the oscillation frequencies in these circuits be equal:

$$f_1 = \frac{1}{2\pi\sqrt{L_1C_1}} = f_2 = \frac{1}{2\pi\sqrt{L_2C_2}} \,. \tag{1.15}$$

Analyzing the transient processes in these circuits with no account of losses, we get for the voltage across the capacitor C_2

$$V_2 = -\frac{V_1}{2} \sqrt{\frac{C_1}{C_2}} \left(\cos \overline{\omega}_1 \tau - \cos \overline{\omega}_2 \tau \right), \qquad (1.16)$$

where $\tau = t/\sqrt{L_1C_1}$ is the dimensionless time; $\overline{\omega}_1 = 1/\sqrt{1+k}$ and $\overline{\omega}_2 = 1/\sqrt{1-k}$ are the dimensionless cyclic frequencies; $k = M/\sqrt{L_1L_2}$; *M* is the coefficient of mutual inductance between the circuits, and *t* is the time. From (1.16) it follows that the voltage V_2 is beating.



Figure 1.5. The original (a) and equivalent (b) circuits of a Tesla transformer

The highest possible value of the voltage V_2 across the capacitor C_2 is given by

$$V_{2\max} = V_1 \sqrt{\frac{C_1}{C_2}}.$$
 (1.17)

If we choose $C_1 = n^2 C_2$, then the voltage will be multiplied by a factor of *n*. For a pulse system to operate efficiently, it is important that V_2 reach a maximum during the first half-period of beats. In this case, the electric strength of the insulation will be higher. From (1.16) it follows that $V_2(t)$ reaches a maximum during the first half-period at some fixed k determined from the condition

$$\frac{\overline{\omega}_2 + \overline{\omega}_1}{\overline{\omega}_2 - \overline{\omega}_1} = \frac{\sqrt{1+k} + \sqrt{1-k}}{\sqrt{1+k} - \sqrt{1-k}} = n , \qquad (1.18)$$

where *n* is an odd integer. From (1.18) we obtain that the optimal *k* values are given by $k_0 = 2n(n^2 + 1)^{-1}$. For instance, for n = 1, 3, and 5 we have $k_0 = 1, 0.6$, and 0.385, respectively.

Figure 1.5, b presents the equivalent circuit of a Tesla transformer. Here, L_{s_1} and L_{s_2} are the effective stray inductances of the first and the second LC circuit, respectively, and L_{μ} is the magnetizing inductance.

Widely used in pulsed power technology are line pulse transformers (LPT's) (Mesyats, 1979). An LPT consists of N single-turn transformers with a common secondary winding. The secondary winding is a metal rod on which toroidal inductors carrying primary windings are put. Figure 1.6, a gives the equivalent circuit of an LPT. The circuit transformation is performed by reducing the primary winding to the secondary one. The primary windings of the inductors are connected in series. This is true since the current in each circuit element and the voltage across the element are invariable in amplitude, waveform, and duration. The inductance L_1 includes the capacitor, spark gap, and lead inductances and the stray inductance of the primary winding of the inductor; L_{s_2} is the stray inductance of the rod, and L_{load} is the inductance of the load. Experience of operating systems of this type shows that generally we have for the secondary winding capacitance $C_{s_2} \ll C_2$ and for the magnetizing inductance $L_{\mu} \gg L_{LPT} = NL_1 + L_{s_2} + L_{load}$; therefore, the influence of these quantities can be neglected. We also neglect the losses in the circuit elements.



Figure 1.6. The equivalent (a), reduced (b), and simplified circuit (c) of a line transformer

In this case, the voltage across the capacitive load (energy storage line) is written as

$$V_{\text{load}} = \left[\frac{NV_1\lambda}{1+\lambda}\right] (1 - \cos\omega t), \qquad (1.19)$$

where V_1 is the charge voltage across the capacitor C_1 ; $\lambda = C'_1/C_2$, where $C'_1 = C_1/n$ (in what follows we assume $\lambda = 1$), and the cyclic frequency $\omega = \sqrt{2/L_{\rm LPT}C_2}$.

For a given charging time τ , the inductance of an LPT is determined from the formula

$$L_{\rm LPT} \le \frac{2\tau^2}{\pi^2 C_2}$$
 (1.20)

If we know the operating voltage of an LPT, the capacitance C_2 , the inductance L_{LPT} , the induction in the magnetic core, and the admissible electric field strength in the insulation around the secondary winding (rod), we can determine the geometric dimensions and mass of the transformer.

J. C. Martin (Martin *et al.*,1996) used a pulse autotransformer to produce megavolt pulses. Figure 1.7 shows the circuit diagram of an autotransformer and its equivalent circuit. The primary voltage can be applied not only to the lower turns of the autotransformer, but also to its middle turns. In Fig. 1.7, C_i denotes the capacitance of the energy store, C_2N^2 is the reduced capacitance of the load, L_s is the stray inductance, L_1 and L_2 are the respective inductances of the primary and the secondary winding, L_0 is the net inductance of the capacitor, switch, and leads, and N is the transformation coefficient.



Figure 1.7. Circuit diagram of a pulse autotransformer (a) and its equivalent circuit reduced to the primary circuit with switch S_2 open (b)

We shall return to voltage multiplication and transformation circuits when describing the operation of pulse generators and accelerators, in particular, in Chapter 16.

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Chapter 2

PULSE GENERATION USING LONG LINES

1. GENERATION OF NANOSECOND PULSES

Transmission lines are widely used in the production and transformation of voltage and current pulses. For this purposes, three principal properties of the lines are exploited: the existence of a time delay, the purely active wave impedance, and the reflection of pulses. To simplify the description of the operation of generators and transformers, we do not use mathematical calculations (Lewis and Wells, 1954), but only outline the qualitative pattern of the processes involved.

A simple generator with an open energy storage line is shown in Fig. 2.1. If a line with a wave impedance Z_0 is charged to a voltage V_0 through a resistor of resistance $R \gg Z_0$ and then it is connected with a switch to a load of resistance $R_{\text{load}} = Z_0$, a rectangular pulse appears across the load. For charging the line, a source of dc voltage V_0 is used. The amplitudes of the current and voltage pulses that are generated as such a line discharges into a load of resistance $R_{\text{load}} = Z_0$ are given by

$$I_{a} = \frac{V_{0}}{2Z_{0}}, \quad V_{a} = \frac{V_{0}}{2}.$$
 (2.1)

Let us find out whence come these I_a and V_a . Once the switch S has closed, the line, charged to V_0 , cannot stay in equilibrium since the line elementary capacitors adjacent to the resistor R_{load} start discharging. This process develops gradually from the load end of the line to its charging end. Therefore, a backward wave of current \tilde{I} and the related wave of voltage $\tilde{V} = -\tilde{I}Z_0$ start propagating from the load end of the line. Thus, the voltage and current at the load end of the line (x = I) are expressed by the equations

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$$V = V_0 + \bar{V}, \quad I = \bar{I} = -\frac{\bar{V}}{Z_0},$$
 (2.2)

obtained in view of the initial conditions $V(x, 0) = V_0$ and I(x, 0) = 0.



Figure 2.1. Circuit diagram of a pulse generator with an open energy storage line

The value of \bar{V} is found from the boundary condition at the load end of the line (x = l), which is given by Ohm's law. As at x = l the voltage across the line and the current in the line coincide with the voltage across the load, V_{load} , and the current in the load, I_{load} , then $V_{\text{load}} = R_{\text{load}}I_{\text{load}}$. Substituting expressions (2.2) into this expression, we obtain

$$V_0 + \bar{V} = -R_{\text{load}}\left(\frac{\bar{V}}{Z_0}\right),$$

whence, putting $R_{\text{load}} = Z_0$, we find

$$\bar{V} = V_0 \frac{Z_0}{R_{\text{load}} + Z_0} = -\frac{V_0}{2}.$$
(2.3)

In view of relation (2.3), we have

$$V_{\text{load}} = V_0 + \bar{V} = \frac{V_0}{2}.$$
 (2.4)

The voltage and current that are expressed by relations (2.2) will also appear with time in other cross sections of the line as the first backward voltage wave and the related current wave will propagate along the line. At a time t = l/v = Tl, where v is the wave propagation velocity and T is the time per unit length for which the wave is delayed in the line, the \bar{V} and \bar{I} waves arrive at the open end of the line and then are reflected from this end. As a result, the \vec{V} and \vec{I} waves start propagating from the open end of the line toward the load. If we assume for the charging resistance $R \gg Z_0$, then the coefficient of reflection of the voltage wave will be equal to unity, and, therefore, $\vec{V} = -V_0/2$ and $\vec{I} = -V_0/2Z_0$. At the instant the \vec{I} and \vec{V} waves

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reach the load end, the voltage and current will be zero in all cross sections of the line, and the discharging process in the line will be completed. It should be borne in mind that as the forward waves arrive at the load end, reflected waves do not appear since $R_{load} = Z_0$ and so the coefficient of reflection is zero. Therefore, the amplitudes of the current and voltage pulses will be determined by formulas (2.1). In operator form, the input resistance of such a line is given by (Lewis and Wells, 1954)

$$Z_{\rm input} = Z_0 \operatorname{cth} pTl \,, \tag{2.5}$$

where *p* is the parameter in the Laplace transform.

The pulse duration t_p is twice the time it takes a wave to travel through the line:

$$t_{\rm p} = 2lT = \frac{2l}{v} = \frac{2\sqrt{\varepsilon\mu}}{c},\tag{2.6}$$

where ε and μ are the relative permittivity and permeability, respectively, and *c* is the velocity of light.

An open line segment (with a charging resistance $R \gg Z_0$) can be considered as a capacitive energy store with a total capacitance $C = lC_0$, where C_0 is the line capacitance per unit length. When the line is charged from a source of voltage V_0 through a resistor R, it stores an electric field energy $lC_0V_0^2/2$. As the switch (Fig. 2.1) operates to connect the line to a load of resistance $R_{\text{load}} = Z_0$, the energy stored in the capacitor is completely released in the load in time t_p , and thus we have

$$\frac{V_a^2 t_p}{Z_0} = \frac{V_0^2}{4} \sqrt{\frac{C_0}{L_0}} lT = \frac{V_0^2}{2} \sqrt{\frac{C_0}{L_0}} \sqrt{L_0 C_0} = \frac{V_0^2 l C_0}{2}.$$
(2.7)

If the load resistance is not matched to the wave impedance of the line $(R_{\text{load}} \neq Z_0)$, a stepped pulse with a step length t_p rather than a single pulse will appear across the load (Fig. 2.2). The waveform of the pulse across the load will vary depending on whether R_{load} is greater or lower than the wave impedance. For $R_{\text{load}} < Z_0$ the pulse steps periodically change sign (Fig. 2.2, *a*), while for $R_{\text{load}} > Z_0$ they are of the same sign. In the general case, the voltage of the *k*th step is given by

$$V_{k} = V_{0} \frac{R_{\text{load}}}{R_{\text{load}} + Z_{0}} \left(\frac{R_{\text{load}} - Z_{0}}{R_{\text{load}} + Z_{0}}\right)^{k-1}, \quad k = 1, 2, 3, \dots$$
(2.8)