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SWITCHNG TRANSIENTS IN ELECTRICAL AND ELECTRONIC APPARATUS

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Basic practical situations and processes in electrical contact-based and electronic switching devices followed by switching transients are represented in the textbook. The textbook includes also physical representation and main methods for analysis and calculations of the switching transients.

The textbook is intended for higher educational students, as well as may be useful for electrical and electromechanical engineers.

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INTRODUCTION

Switching processes (switching transients) play a significant role in the operation of electrical equipment. The parameters of the switching transients in full degree define ability of electrical and electronic apparatuses to functioning in normal and extreme (faulty) circumstances. In this situation, the analysis and determination of the switching transient parameters is a very important task. Their findings are applied in the development process of new equipment, its research and testing.

Switching transient takes place whenever a certain parameters of an electrical circuit change in stepwise manner. In real electrical networks, switching transients occur with stepwise changing operating duty of electrical equipment. They are, first, associated with its individual operational specifications resulting in necessity of periodical scheduled switching operations in electrical systems, as well as in the events of faults and their clearing. Among them, in the first place, it should be noted such processes as:

- coming into operation of powerful generating units or load equipment and outgoing from operation for the purpose of maintenance;
- starting and stopping electric motors in normal and abnormal circumstances;
- short-circuits in power systems, as well as reclosing operations at faulty subsystems;
- voltage regulation in electrical systems made by power transformer tap changing;
- forced excitation of powerful synchronous machines, as well as killing their magnetic field;
- occurrence of local three phase unbalance in electrical system (line breaking);
- non-synchronous paralleling of synchronous machines and others.

Thus, the processes denoted above that happen in electrical systems are frequently associated with switching (make-break) operations in electrical circuits in various duties with the help of switching apparatus. Vital importance in the operation process of electrical equipment is switching transients occurred with faults in power systems, since initiation and clearing fault occurred with appearance of new or cessation of existing current path, i.e. switching electrical circuits.

1. GENERAL REGULARITIES OF THE SWITCHING TRANSIENTS

1.1 The Concept, Varieties and Basic Investigational Methods of Switching Transients

It is well known that the switching process is intimately associated with an *electrical transient.* This process occupies a certain time span, involved with changing the energetic state of the electrical circuit. Certain store of electrical and/or magnetic field energy corresponds to every steady state of this circuit:

$$W_{\text{магн}} = \frac{Li^2}{2}; W_{\text{эл}} = \frac{Cu^2}{2}. \tag{1.1}$$

The transition to a new steady state of an electrical circuit is occurred with the generation or absorption of electrical and/or magnetic field energy. It complies with the well-known transient switching laws defining the starting conditions to analyze the switching transient that can be formally written as follows:

$$L^- i^- = L^+ i^+; \quad C^- u^- = C^+ u^+, \tag{1.2}$$

where L^- and i^- refer to the inductance and current prior to switching, and the plus signs denote current and inductance just after switching has occurred but before any time has elapsed.

Although there may be situations where the inductance or capacitance changes during the switching operation, most applications will be based on the assumption that L^- is identical to L^+ and C^- is identical to C^+. The net result is that in almost all cases, the current through an inductance and the voltage across a capacitor cannot instantaneously change at the instant of switching.

The analysis of the switching transient (and in particular the process of interrupting the electric circuit) is usually performed by integrating the system of integrodifferential equations setup in compliance with Ohm`s law, as well as current and voltage Kirchhoff's laws. Such a system is usually reduced to an *n*-th order differential equation, which has the following form:

$$a_{\text{n}} \frac{d^{\text{n}} y}{dt^{\text{n}}} + a_{\text{n}-1} \frac{d^{\text{n}-1} y}{dt^{\text{n}-1}} + \ldots + a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 = B(t), \tag{1.3}$$

where *y* is the function explored (voltage across particular components of the electric circuit, voltage across switching element, load current etc.);

t is the time;

B(*t*) is the disturbing function (for example, time-changing power voltage);

$a_0 \ldots a_n$ are the equation coefficients that may be constant (then the equation is linear) or time-variable (then the equation is non-linear).

To solve differential equations governing switching transients in electrical circuits, *operational Laplace method* is frequently applied. It implies that the solution is transferred from the real variable to the complex one. The transformed equation is solved algebraically. The resulting solution is inversely transferred to the real variable using special tables, thereby dependence of the function investigated is found from the determining parameters. The operational Laplace transformation makes solving the linear differential equations available and relatively simple. It can be also applied to solve equations with variable coefficients.

When the circuit investigated has constant parameters and switching transient is governed by a set of linear equations, the superposition principle is also applied that implies in the following. The resultant switched factor is determined as the sum of the steady state factor and equalizing transient factor. The equalizing transient factor (current, voltage) damps so that it could be act alone with no action of an externally applied voltage.

Integration of nonlinear differential equations is frequently performed by *successive approximations*, when the solution is started, the nonlinear characteristic of the element, included to the circuit, is substituted by a linear one and hence the problem is reduced to solving a linear differential equation. Then, the found solution (first approximation) is made more precise according to a predetermined non-linear characteristic and a more precise solution (second approximation) is found so forth.

The methods of *integrated non-linear* and *piecewise-linear approximation* are extensively used to integrate non-linear differential equations. The first is based on substitution (approximation) of non-linear element characteristic by another non-linear characteristic that enables to integrate initial equations with known functions that exactly enough represent characteristic of the real element. The second is based on substitution of actual non-linear element characteristic by polygonal curve that consists of rectilinear sections. This enables in some instances to go from non-linear equation to some linear equations distinguished only values of the coefficients and are valid for corresponding time interval (approximation section).

Now *numerical methods* or *methods of sequential intervals* are extensively used to integrate nonlinear differential equations. This is primarily due to the recent development of appropriate software for PCs

(MathCad, MatLab, etc.). The essence of these methods is the original differential equation is substituted by an algebraic equation for the increment of functions at certain time intervals. The solution is made by "step by step" from one interval to another.

Analysis of transients in nonlinear electric circuits is also carried out with the methods of *stability theory* (disturbances and perturbations). However, it should be noted that the stability theory is extensively applied to analyze automatic control systems (electrical regulators) and practically not applied to analyze switching transients.

1.2 Simplest Cases of Switching Electric Circuits

Let us consider the simplest, but very important cases for practice, when electrical circuits with lumped parameters are energized by DC voltage or AC sine voltage using the so-called *ideal switch*. The ideal switch in the closed position is an ideal conductor, having zero resistance, and in the open position is an ideal isolator, having infinite resistance. An ideal switch changes from closed to open position instantly, and the sinusoidal current is always interrupted in zero of the current.

Switching on dc circuits. Let us consider at first a typical case of energizing a resistive-inductive circuit by dc voltage. Such case is of practically vital importance. Firstly, it occurs when dc electromagnet, used, for example, as an actuator for switching or other device, is energized. The transient parameters of the electromagnet to be energized define one of most important its performance that is speed response during actuation. Secondly, given case takes place when switching tests of electrical apparatus are performed. In particular, the transient parameters of the testing circuit are used for its adjustment. Another practical example is the charging by current the coil of the inductive energy storage. Such devices in some cases are used to perform synthetic testing high-voltage circuit breakers [17, 22, 23, 26 30].

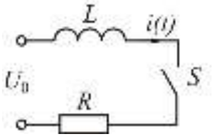

Figure 1.1 – Active-inductive circuit energized by dc voltage

The circuit contains series connected and constant in value active resistance R and inductance L connected to a dc source with driving voltage U_0 with the help of an ideal switch S, as shown in Figure 1.1. The transient process of energizing the circuit is governed by the following equation:

$$U_0 = iR + L\frac{di}{dt} \tag{1.4}$$

General solution of given equation will be

$$i = \frac{U_0}{R} + C_1 e^{-\frac{R}{L}t} \tag{1.5}$$

At zero initial conditions: $i(0) = 0$ integration constant will be $C_1 = -U_0/R$, then solution of equation (1.4) will be as follows:

$$i = \frac{U_0}{R}\left(1 - e^{-\frac{R}{L}t}\right) \tag{1.6}$$

Curve of time-changing current is shown in Figure 1.2.

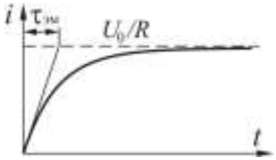

Figure 1.2 – Changing the current in active-inductive circuit energized by direct voltage

The inherent parameter for discussed process is electromagnetic time constant:

$$\tau_{\text{em}} = \frac{L}{R}. \tag{1.7}$$

The tangent line drawn to the current curve at initial section of its change cuts off on the steady state current line I_0 the time span, which is identical to τ_{em}. The time constant defines the rate of rise of the current at switching on the circuit. For low-voltage networks, it is usually in the range of 1 to 10 milliseconds [22].

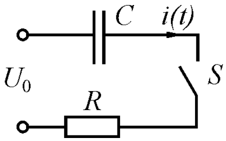

Figure 1.3 – Active-capacitive circuit energized by dc voltage

Let us consider also the case of the active-capacitive circuit energization that shown in Figure 1.3. This case is also of practical importance. A case in point is a capacitor bank charged from dc power source via resistor. It should be noted that powerful capacitor banks are important elements of testing equipment, such as, *short-circuit generators* for short-circuit testing applications, *high-voltage impulse generators* for dielectric testing applications, and others.

When the ideal switching element S closes, a switching transient occurs defined by the following equation:

$$U_0 = iR + \frac{1}{C}\int i\,dt \tag{1.8}$$

The corresponding Laplace transform equation is then:

$$\frac{U_0}{p} = i(p)R + \frac{1}{pC} i(p) + \frac{U_{\text{in}}}{p} \tag{1.9}$$

where U_{in} is the initial value of capacitor voltage at the instant the switching element is closed. Assuming that U_{in} is zero, the current as function of time is obtained by rearranging equation (1.9), and the inverse is:

$$i(t) = \frac{U_0}{R} e^{-t/(RC)}. \tag{1.10}$$

The transform of the voltage across the capacitor is

$$u_C(p) = \frac{1}{pC} i(p) \tag{1.11}$$

or

$$u_C(t) = U_0 \left(1 - e^{-t/(RC)}\right) \tag{1.12}$$

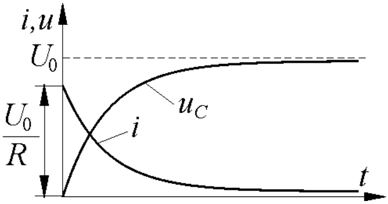

Figure 1.4 – Changing the current and voltage on the capacitor in active-capacitive circuit

The time diagrams of the current and voltage on the capacitor at zero initial conditions are shown in Figure 1.4. Just after switching the voltage on the capacitor begins to build from zero up to U_0, but the current through the capacitor decays from initial value, defined by driving voltage U_0 divided by the circuit resistance R, down to zero. A characteristic parameter of this process is the time constant defining the rate of charge of the capacitor.

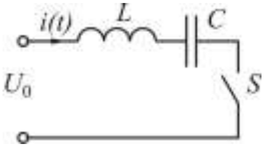

Figure 1.5 – Inductive-capacitive circuit energized by dc voltage

Let us consider another basic case the series connection of an inductance L and a capacitance C energized by dc power source. In fact, the simplest representation of such process is a high-voltage circuit breaker switching a capacitor bank or a cable network. At the instant $t = 0$ a dc power source energizes the circuit by closing the ideal switch S, as shown in Figure 1.5.

As can be seen from Figure 1.5, there are two energy-storage components – the inductance storing the magnetic energy and the capacitance storing the electric energy. After closing the switch, an oscillation can occur in the network.

This is because an exchange of energy takes place between the two energy-storage devices with a certain frequency.

The applying of Kirchhoff's voltage law results in the equation governing the switching transient:

$$U_0 = L\frac{di}{dt} + \frac{1}{C}\int i dt \tag{1.13}$$

When we look for the initial conditions, it is clear that $i(0) = 0$, as the current in the network is zero before the switch closes. This is the case immediately after closing of the switch too. In the case of the capacitor, the situation is not so easy because the capacitor can have an initial voltage, for instance, because of a trapped charge on a capacitor bank.

Let us assume that there is no charge on the capacitor and therefore $U_C(0) = 0$, then the solution of equation (1.13) will be as follows:

$$i(t) = U_0\sqrt{\frac{C}{L}}\sin\omega_0 t, \tag{1.14}$$

In equation (1.14), we can recognize two important properties of the *LC* series network:

- after closing the switch at time $t = 0$, an oscillating current starts to flow with a natural frequency

$$\omega_0 = \sqrt{LC}, \tag{1.15}$$

- the *characteristic* or *surge impedance*, $Z_0 = (L/C)^{1/2}$, together with the value of the source voltage U_0, determines the peak value of the oscillating current.

When there is a charge present on the capacitor, solution of equation (1.13) becomes:

$$i(t) = [U_0 - U_C(0)]\sqrt{\frac{C}{L}}\sin\omega_0 t, \tag{1.16}$$

In the process, the voltage across the capacitance will change according to the following expression

$$U_C(t) = U_0 - [U_0 - U_C(0)]\cos\omega_0 t, \tag{1.17}$$

Figure 1.6 shows the voltage waveforms for three initial values of the capacitor voltage. From these voltage waveforms, it can be seen that for $U_C(0) = 0$ the voltage waveform has what is called a $(1 - \text{cosine})$ shape and that it can reach twice the value of the peak of the source voltage. For a negative charge, the peak voltage exceeds this value, since the electric charge cannot change instantly after the switch closes. In addition, when the characteristic impedance of the circuit has a low value, for example, in the case of switching a capacitor bank (a large *C*) and a strong supply (a small *L*), the peak of the inrush current after the switch closes can reach a high value.

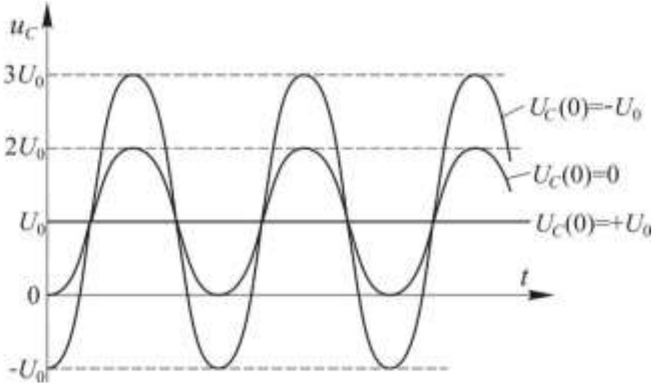

Figure 1.6 – Voltage across the capacitor for three different initial values of the capacitor voltage

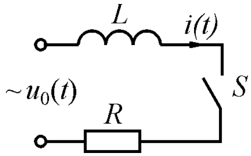

Figure 1.7 – Active-inductive circuit energized by ac voltage

Switching on ac circuits. Important practical application for electric equipment is energization of active-inductive circuit from sine voltage source, as shown in Figure 1.7. The closure of an ideal switching element *S*, in certain degree, simulates the initiation of a fault in an actual network (this process will be in more detail discussed in section 4). Inductance *L* comprises the synchronous inductance of feeding generators, the leakage inductance of the power transformers, and the inductance of the bus bars, cables, and power transmission lines. Resistive losses of the supply circuit are represented by the resistance R. The voltage of the network is represented by the following function:

$$u = U_{\text{m}} \sin(\omega t + \Psi) = \sqrt{2} U_{\text{ном}} \sin(\omega t + \Psi), \tag{1.18}$$

where U_0 is rms voltage supply;

Ψ is switching phase defining instantaneous value of voltage supply at the instant of switching the circuit ($u(0)=\sqrt{2}U_0\sin\Psi$).

Applying the Kirchhoff's voltage law gives us the nonhomogeneous differential equation:

$$\sqrt{2}U_0\sin(\omega t+\Psi)=iR+L\frac{di}{dt} \qquad (1.19)$$

For the purpose to simplify the task, the initial current through the inductance prior to switching is assumed to be zero, i.e. $i(0)=0$. The solution of given equation for the current under this condition will be as follows:

$$i=\frac{\sqrt{2}U_0}{\sqrt{R^2+(\omega L)^2}}\left[\sin(\omega t+\Psi-\varphi)-e^{-\frac{R}{L}t}\sin(\Psi-\varphi)\right], \qquad (1.20)$$

The solution includes *periodical* or *steady state component* and *transient* or *aperiodic component*, which is required to satisfy the conservation of flux linkage and results, as shown in Figure 1.8, in an offset (dc) term, which initially displaces the sinusoidal current. Since this type of transient occurs during fault initiation, breaker designs must account for the additional mechanical stresses imposed by the peak of the offset current and the interrupting function must consider requirements imposed by the unequal spacing of current zeros and the changes in current slope. At this diagram, the curves of the voltage supply u_0 and the total current *i* are also shown (see Figure 1.8).

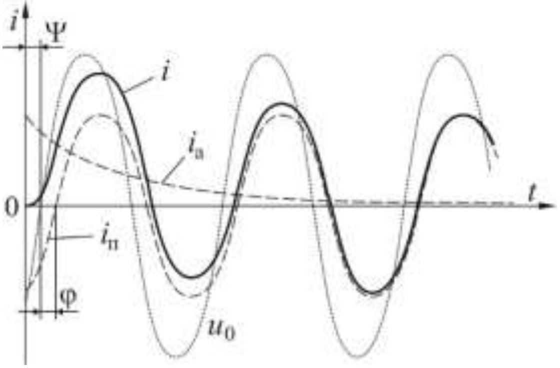

Figure 1.8 – Time diagrams of the current and voltage supply in active-inductive circuit energized by alternating voltage

An analysis of expression (1.20) shows the significance of the *electromagnetic time constant* $\tau_{эм}$ that define the rate of damping the aperiodic component and, hence, the duration of the transient process.

As already noted, the energization of ac circuit can occur with the initiation of a so-called *peak current of switching on* that can exceed amplitude of the steady state current: $I_m = \sqrt{2}U_0 / Z$.The value of the peak current and the time required to attain it can be determined from the condition $di/dt = 0$ according to (1.20):

$$i = \frac{\sqrt{2}U_{\text{ном}}}{Z}\left[\sin(\pi + \Psi - \varphi) - e^{-\frac{R\pi}{\omega L}}\sin(\Psi - \varphi)\right];\ t_{\text{н}} \approx \frac{\pi}{\omega} = \frac{1}{2f}, \tag{1.21}$$

From expression (1.20) it follows that in pure active circuit, when $\omega L << R$, $\varphi \approx 0$ and $\tau_{\text{эм}} = 0$, the peak current value practically does not exceed amplitude value of steady state current (at $\Psi = \pi/2$).

The most severe conditions of the switching on will take place in the inductive circuit, when we have $\omega L >> R$ and $\varphi \approx \pi/2$. The peak current achieves its maximal value in the case when switching on instant corresponds to zero moment of the voltage curve ($\Psi = 0$). In this case, the peak current value will be determined by the following expression:

$$i = \frac{\sqrt{2}U_0}{Z}\left(1 + e^{-\frac{R\pi}{\omega L}}\right), \tag{1.22}$$

The expression in brackets is usually named the *peak factor for current of switching on*. It is the ratio of the peak current to the amplitude value of the steady state current

$$\kappa_{\text{уд}} = \frac{i_{\text{уд}}}{I_{\text{m}}} = 1 + e^{-\frac{\pi R}{\omega L}}, \tag{1.23}$$

The peak factor depends upon the degree of damping the aperiodic component of the current that is defined by the value of the circuit electromagnetic time constant. For low voltage networks (below 1000 V), its value is of the order of 1,3; for the networks of high and medium voltages it is 1,8 [1, 2, 6, 10].

Switching on a power transformer. Let us discuss the switching on of a single-phase power transformer with an open secondary winding to a sinusoidal voltage. Basing upon Kirchhoff voltage law for the primary winding, the following equation can be written:

$$\sqrt{2}U_0\sin(\omega t + \Psi) = iR + w\frac{d\Phi}{dt}, \tag{1.24}$$

where *R*, *w* are active resistance and the number of turns of the primary winding, respectively;

i is the current in the winding;

Φ is the magnetic flux in the transformer magnetic circuit;

Ψ is the phase angle defining the instantaneous value of the voltage supply at the switching on instant (at $t = 0$).

The second term of the equation right-hand part defines counter-EMF induced in the primary winding caused by its changing flux linkage. It is presumed in the case that all primary winding turns linkage with common magnetic flux Φ. Therefore the winding inductance is $L = w\Phi / i$, that gives $i = w\Phi / L$. Substitution of this expression into equation (1.24) leads to the following equation:

$$\frac{\sqrt{2}U_{\text{ном}}}{w}\sin(\omega t + \Psi) = \frac{d\Phi}{dt} + \frac{R}{L}\Phi, \tag{1.25}$$

The initial conditions for solving this equation will be as follows:

$$i(0) = 0; \quad \Phi(0) = \Phi_0,$$

where Φ_0 is the residual magnetic flux.

Thus, the solution of given equation will be as follows

$$\Phi = \Phi_m \left[e^{-\frac{R}{L}t}\cos\Psi - \cos(\omega t + \Psi) \right] \pm \Phi_0 e^{-\frac{R}{L}t}, \tag{1.26}$$

where Φ_0 is the amplitude value of the steady state flux; its magnitude without taking into account active losses will be determined by the following expression:

$$\Phi_m = \frac{\sqrt{2}U_{\text{ном}}}{\omega w}. \tag{1.27}$$

Thus, when the transformer is switched on, an aperiodic component of the magnetic flux will take place, causing the flux inrush that is significantly greater than the amplitude of the steady state value. The most its value will be at $\Psi = 0$, and also under condition that the residual flux has sign minus, that is, it is in opposite direction relatively to the instantaneous value of steady state flux at $t = 0$. The peak value of the inrush flux will take place at a time instant $t_{\text{н}} \approx \pi / \omega$:

$$\Phi_{\text{уд}} = \Phi_m + (\Phi_m + \Phi_0)e^{-\frac{\pi R}{\omega L}}. \tag{1.28}$$

Because the magnetization curve is non-linear, switching on a transformer will occur with saturation of its core; therefore, the magnetic flux actual values will be less than that calculated according to the expression

(1.28). The current through the transformer winding is related with magnetic flux by the following expression:

$$i = \frac{Hl}{w}, \qquad (1.29)$$

where H is the magnetic field intensity defined by the magnetization curve, that is, by the dependency $\Phi = f(H)$;

l is the average magnetic line length in the transformer magnetic circuit.

Thus, a more accurate solution of equation (1.19) can be found with considering expression (1.24) and magnetization curve $\Phi = f(H)$. However, more essential in this case is that the increase in magnetic flux, when switching on the transformer, is occurred with significant inrush of the magnetizing current. It is physically explained by the fact that high fluxes result in saturation of the transformer core and, accordingly, high magnetic field intensities that can be induced by the corresponding values of the magnetizing currents [22].

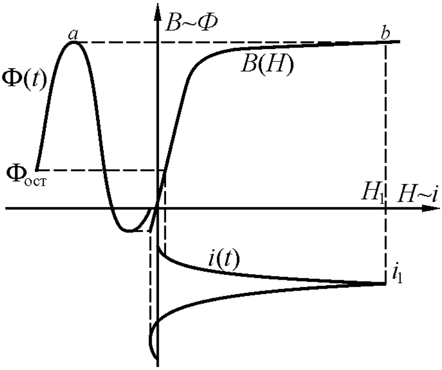

Figure 1.9 – Magnetic flux and magnetizing current as a transformer is energized

Figure 1.9 shows a graphical determining of the current of switching on the transformer with use of the magnetizing curve of the transformer core material $\Phi \sim B(H)$. Point *a* on a predetermined magnetic flux curve $\Phi(t)$ is corresponded to point *b* on the *B*-*H* curve that is corresponded to intensity H_1 of the magnetic field and, in turn, to the current i_1. Analogous constructions are performed for other points of the magnetic flux curve (see fig. 1.9). It results in the magnetizing current $i(t)$ with well-defined inrush i_1. Total duration of the power transformer switching transient is usually a few AC cycles.

1.3 Electrical Circuit Interruption

Interruption of an electric circuit, especially at faults in a power system, is very complex problem. It occurs with series of complex phenomena that are not completely understood even at the present time.

Interruption of an electrical circuit is a process of highly quick cessation of electrical current flowing through it, i.e. alteration of the electrical circuit from the on state, when $i(0) = I_o$, to the off state, when $i(t_{\text{int}}) = 0$. Circuit interruption (and switching in general) is carried out by changing the impedance of the switching element in a wide range. It is featured with so named *switching depth* expressed by the following ratio:

$$\eta = \frac{Z_{\text{off}}}{Z_{\text{on}}},$$

where Z_{off}, Z_{on} are the switching element impedance in the off and on position, respectively.

The ideal switch discussed above has infinitely high switching depth. In actual situation, the switching depth depends on the type of switching element being used. There are two basic variations of switching elements applied in real switching devices:

- *contact-based switching elements* carrying out physical (i.e. mechanical) breaking (rupture) of the electric circuit; they are characterized by a very high switching depth ($\eta = 10^{10} - 10^{14}$);
- *contactless switching elements*: among these, switch-operated semiconductor devices or magnetic amplifiers are used. They switch the electric circuit by changing its resistance or reactance in a wide range. The contactless switching elements offer vastly lower switching depth ($\eta = 10^{4} - 10^{7}$) [8, 14, 19–20].

Energy analysis of the circuit interruption process. As noted above, switching an electrical circuit is occurred with a transient process, which involved with change in its energy state. The process of interrupting a circuit is first involved with *dissipating the storage of electromagnetic energy accumulated by inductive elements* included by any real electric circuit. It should be noted that most elements of an actual circuit offer a capacitance (windings of electrical machines and power transformers, power transmission lines etc.) and respectively have a store of electrostatic energy that also play significant role in the interruption process. In the process, any actual electric circuit of any complexity may be simplified as shown in Figure 1.10.

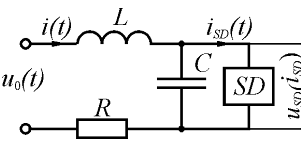

Figure 1.10 – Typical structure of interrupted active-inductive circuit

Such a circuit contains: power source $u_0(t)$ with generally time-varying voltage; R, L, C are total reduced parameters of the circuit being interrupted; a switching device SD carrying out interruption of the circuit; its properties are featured with a dynamic volt-ampere characteristic $u_{SD}(i_{SD})$.

When the switching device SD interrupts this circuit, the transient process occurs governed with the following set of differential equations:

$$\begin{cases} u_0(t) = iR + L\dfrac{di}{dt} + u_{SD} \\ i = C\dfrac{du_{SD}}{dt} + i_{SD} \end{cases}. \tag{1.30}$$

Multiplying both sides of the 1st equation by idt, we get:

$$u_0(t)idt = i^2Rdt + Lidi + u_{SD}dt\left(C\frac{du_{SD}}{dt} + i_{SD}\right).$$

Integration of both parts of the equation gives:

$$\int_0^{t_{inter}} u_0(t)idt = \int_0^{t_{inter}} i^2Rdt + \int_{I_0}^{0} Lidi + C\int_0^{u_0} u_{SD}du_{SD} + \int_0^{t_{inter}} u_{SD}i_{SD}dt$$

or $$W_0 + L\frac{i^2}{2} = W_R + C\frac{u_0^2}{2} + W_{SD}, \tag{1.31}$$

where W_0 is the energy coming from the power source for the time of the circuit interruption defined by the integral:

$$W_0 = \int_0^{t_{inter}} u_0(t)idt;$$

W_R is the Joule’s heat generated by the resistance for the time of the circuit interruption defined by the integral:

$$W_R = \int_0^{t_{inter}} i^2Rdt;$$

W_{SD} is the energy generated by the switching device for the time of the circuit interruption defined by the integral:

$$W_{SD} = \int_0^{t_{inter}} u_{SD}i_{SD}dt.$$

Consequently, when the electric circuit is interrupted, the electromagnetic energy accumulated in the inductance $Li^2/2$, as well as the energy coming from the power supply W_0 is dissipated in the resistance (as a thermal energy), in the circuit capacitive elements $Cu_0^2/2$ (as an electric field energy) and also in a switching device W_{SD}. It should be pointed out that when the circuit is interrupted with a contact-based switching device, the energy dissipates by means of the initiation of an *electric arc discharge* between the parting contacts. More detail study has shown that in this case, the main source of energy dissipated in interrupting electrical circuits is the electromagnetic energy stored by the inductive elements and its main absorbent is the electric arc discharge.

It is quite evident that the more energy is generated by the switching device (and, correspondingly, by the electric arc), the worse technical-and-economical performances of the switching device as a whole will be. Therefore, one of the challenges to engineers, creating switching devices, is to minimize the energy generated by the switching element. What are the ways to reduce the energy generated in contact switching elements by electric arc discharges?

One of such ways may be connection of additional capacitance. Its required value can be determined from the simplified energy balance equation:

$$L\frac{I_\text{o}^2}{2}=C\frac{U_\text{c}^2}{2}. \tag{1.32}$$

Assuming parameters of interrupted circuit that are typical for low voltage network: L = 10^{-3} Гн; U_c = 500 В; I_o = 1000 А, required capacitance is evaluated:

$$C=0{,}001\frac{\left(10^3\right)^2}{500^2}=0{,}004\,\Phi.$$

It is very large and therefore this way to reduce the energy generated by the switching elements is not real.

Another way to reduce the arcing energy can be to decrease the value of current being interrupted (cut off). This method can be used for interruption of ac circuits, in which the value of current twice for a cycle becomes zero. If the contacts of the switching device is started to separation precisely at this (or close to it) instant, then the energy generated by the switching element will be zero (or minimal value). Switching devices, in which this method is used are named *synchronous switches*. However, investigations have shown that the realization of the synchronous interruption of an electrical circuit is technically complex problem; therefore, at the present time synchronous switches are developed as prototypes and are not produced by the industry [14, 20, 21–23].

An electrical circuit can be also interrupted with no arcing by using power semiconductor devices. They possess the property to be cut off at the passage of the current through zero value and thereby to interrupt the circuit. Semiconductor-based switching devices are extensively used in low voltage networks for switching low currents and some application for switching high currents. Nevertheless, semiconductor-based switching devices have series of grave shortcomings that significantly limit its further acceptance [14, 22].

Thus, contact-based switching devices are extensively used now and yet relatively long time will be used for switching power electric circuits. Such switching devices usually have the contacts started to separation at an arbitrary time instant relative to a sine-varying current to be interrupted. Under such conditions, the behavior of the switching transient in interrupting the circuit will be defined also by the properties of the electric arc discharge – its volt-ampere characteristic that, in turn, is defined by the *physical processes in switching arc* (*arcing*). More exactly, it is defined by the cooling and deionizing effects of the surrounding medium (i.e., the arc-extinguishing technology being used and the specific design of the switching apparatus arcing device). The characteristics and arc-extinguishing methods are in more detail represented in section 2.

Interruption of dc circuit with arcing. A distinctive feature of dc circuit interruption process is that the circuit is interrupted by means of the time-rising resistance of the switching element (of the contact gap in this case). During the circuit interruption, its resistance varies from the resistance of the closed contacts to the resistance corresponding to its "cold" strength when the contacts have been opened. An intermediate element between these extreme positions is an electrical arc that is extinguished in the process of interrupting the circuit and behaves as its nonlinear element.

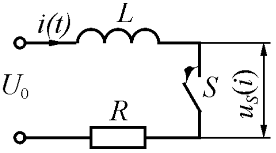

Figure 1.11 – Interruption of dc active-inductive circuit

Consider the most typical example, which is interrupting the active-inductive circuit shown in Figure 1.11. Opening the contacts *S* is occurred with a switching transient governed by the following differential equation:

$$U_0 = iR + L\frac{di}{dt} + u_S(i), \qquad (1.33)$$

where $u_S(i)$ is the expression of the arc dynamic volt-ampere characteristic written in general form; its specific analytical expression is defined by the way of mathematic modeling a dynamic arc (see section 2).

The solution of equation (1.33) in the presence of the dynamic arc model would enable us to determine the basic parameters of the circuit interruption process:

- the *duration of the interruption process*, defined mainly by the time of the arc existence across the contact gap or *arcing time*;
- *energy dissipated by the electric arc*;
- *overvoltage levels* etc.

These findings are required to analyze the engineering solutions for switch design, in particular to fulfill the requirements imposed upon the arc control system in respect to its normal operation. For example, the duration of the circuit interruption process (arcing time) must not exceed 0.1 s; the overvoltages must not exceed the specified values of test voltages etc. [14].

Let us first consider the general regularities of circuit interruption, in particular, determine the conditions of interruption of a circuit. Note that a *general condition of interruption of an electrical circuit is a stable decrease of the current* in the circuit from maximal value (i.e., prior to its interruption) down to zero. Let us present the equation (1.33) in the following form:

$$L\frac{di}{dt} = \left(U_0 - iR\right) - u_S(i)\,. \tag{1.34}$$

The expression (U_0–iR) in this equation is the so-called *external characteristic* or (U_0–iR)-*line* of the circuit to be interrupted. At the initial time instant, this expression corresponds to a zero value, therefore the value *di/dt* becomes a negative as soon as voltage u_S appears between the opening contacts. It leads to the current initially decreases, but thereafter this process will be defined by the relationship between (U_0–iR)-line of the circuit and the volt-ampere characteristic of the arc.

Figure 1.12 shows the external characteristic of the interrupted circuit and the current-voltage characteristic of the arc. However, in this case, these characteristics intersect, forming a point of stable arc burning (point B), therefore, a steady decrease in current is not provided, and accordingly, the circuit is not interrupted. It should be noted that in this case a section of the static current-voltage characteristic of the electric arc discharge of constant length is presented having a falling behavior, (see Section 2).

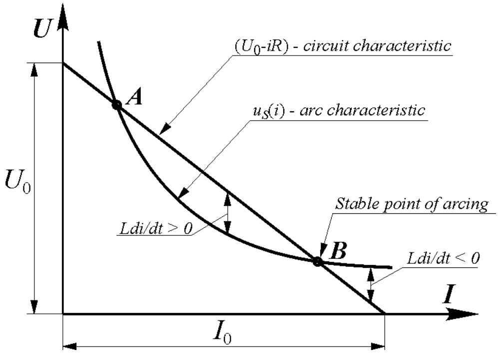

Figure 1.12 – Graphical representation of equation (1.34)

To ensure the circuit interruption, the stable arcing point must be eliminated. Arc current-voltage characteristic should be placed so that it does not intersect the external characteristic. This is possible only in the case, when the arc current-voltage characteristic lies above the external characteristic of the circuit to be interrupted. Hence, the condition of dc circuit interruption is stated as follows: *dc circuit interruption will be ensured only in the case if the current-voltage characteristic of the switching element (electrical arc) lies above the external characteristic of the circuit being interrupted.*

Consider the influence of various factors on the duration of a circuit interruption (arcing time). For this purpose, equation (1.34) is to be written as expression defining the rate of decrease of the current during the circuit interruption, and hence the time of its interruption:

$$\frac{di}{dt} = \frac{(U_0 - iR) - u_S(i)}{L} = \frac{\Delta U}{L}. \tag{1.35}$$

This expression shows that the current decrease rate and, accordingly, the circuit interruption time depends, first, on the inductance contained by the circuit, as well as the difference between the arc voltage and the external voltage ΔU. It means that:

- the high inductive circuits are more heavy to interrupt, since a greater accumulated electromagnetic energy must be dissipated during the circuit interruption;
- the higher the arc current-voltage characteristic with respect to the external characteristic is, the faster the circuit is interrupted.

The key point in this case is the question about specific methods or techniques to provide increase in voltage across the arc gap and, accordingly, fulfill the condition of the circuit interruption. As noted above, the arc discharge characteristic and hence the voltage drop across it, are defined by the arc-extinguishing method (see section 2). It should be pointed out that a significant increase in arc voltage is attained by a highly intensive deionizing effect on the arc column and, accordingly, by more complex and more expensive arcing devices. In other words, in order to provide a characteristic lying significantly above (U–iR)-line, the more complicated arcing device and the more expensive apparatus as whole are required.

This raises the question, is there a necessity for rapid arc quenching and, respectively, circuit interruption with high rate? On the one hand, such necessity exists, since reduction of arcing time provides lowering an electric erosion wear of the contacts and enhancement of the switching life of the device. However, on the other hand, circuit interruption with high rate leads to appearance of overvoltages, since voltage across the switching element essentially depends on the rate of decrease of current:

$$u_S(t) = \left(U_0 - iR\right) - L\frac{di}{dt} \tag{1.36}$$

Taking into account that in circuit interrupting process $\frac{di}{dt} < 0$, during all this time the arc voltage will build up. Its maximum value will occur at the arc extinction instant (at $i = 0$ or $t = t_{\text{д}}$). This value is usually named *extinction peak*:

$$u_{\max} = U_0 + L\left.\frac{di}{dt}\right|_{t=t_{\text{д}}} \tag{1.37}$$

Figure 1.13 shows a typical behavior of switching transient, at different arcing time and the same current being interrupted, when a DC circuit is interrupted. The time-changing current during a DC circuit interruption is frequently described by the following expression [14, 18]:

$$i = I_{\text{o}}\left[1-\left(\frac{t}{t_{\text{д}}}\right)^{\text{n}}\right]. \tag{1.38}$$

Hence: $\frac{di}{dt} = -\frac{nI_{\text{o}}}{t_{\text{д}}^{\text{n}}}\,t^{\text{n}-1}\Big|_{t=t_{\text{д}}} = -\frac{nI_o}{t_{\text{д}}}$;

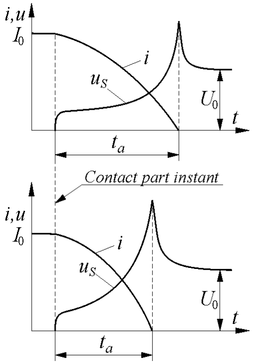

Figure 1.13 – Typical time diagrams of transient for dc circuit interruption

$$u_{\max} = U_0 + \frac{nLI_o}{t_д}.$$

It is seen that the overvoltage, in DC circuit interrupting, is defined by the relationship of the current to be interrupted and the arcing time, as well as the circuit inductance. That is, the more rapid the arc is quenched, the higher the overvoltage level will be, under all other factors being the same.

When designing arcing devices of switching apparatuses, there is need to seek to optimal values, that is, the arcing time should be as short as possible, but the overvoltages appearing across the switching elements of the apparatuses must not exceed the test voltage level.

Interruption of ac circuit. Sinusoidal time-varying alternating current has two natural zero values each cycle. When a current zero occurs, the magnetic energy in the circuit becomes zero, by that favorable conditions for interruption of the circuit are formed. Therefore, in this case it is not necessary to provide an increase in the resistance of the switching element. The task of interruption is to prevent a reignition (i.e., the initiation of an arc discharge after the current-zero moment). As an example, we shall consider the most frequent case, namely, the interruption of active-inductive circuit, which is shown in Figure 1.14.

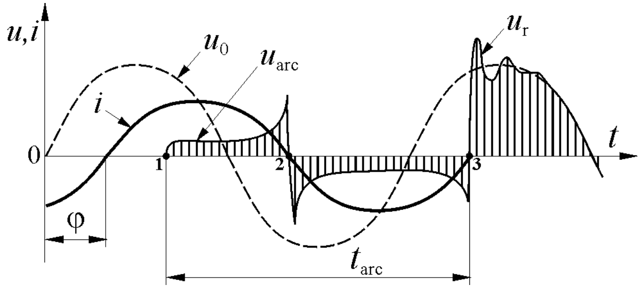

Figure 1.14 – Typical time diagrams of transient for ac circuit interruption

When the contacts are started to separate (instant 1), an electric arc is initiated between them and therefore the current continues to flow in the circuit saving own practically sine waveform. The waveform of the voltage across the contacts u_S, in the process, has a specific behavior defined by the arc dynamic volt-ampere characteristic and the electrode falls (see section 2).

As already denoted, an arc discharge is nonlinear element of an electric circuit. It should be clarified that in ac circuit the arc behaves like a nonlinear resistor, while the arc voltage in phase with the arc current. The most time of the half-cycle the voltage across arc gap practically does not change, but in the neighborhood of current-zeros it significantly higher and has peak values. At the beginning of the half-cycle, the so-called *arc reignition peak* takes place, at the end of half-cycle, when the current approaches zero value, (as noted above) the so-called *arc extinction peak* occurs.

Let us assume that at the first current-zero (instant 2) arc extinction is not ensured, so the circuit remains closed, a sine current continues to flow in opposite direction. Suppose that at the following current-zero (instant 3) the arc extinguishes and the arc voltage at this moment corresponds to extinction voltage. However, the circuit is interrupted completely only after the voltage across the contacts become equal to the supply voltage u_0. Such transition cannot occur instantaneously, since the actual circuit elements (windings of electrical machines, transformers and reactors, as well as power transmission lines) possess a capacitance. At this moment, another switching transient happens named the *transient recovery voltage process*. (see chapter 3).

Consequently, the time moments, when the current passes through zero value, have the key role and decisive importance at AC circuit interruption. More specifically, it is dealt with minor spans just after current-zero. Exactly within these minor spans (tens to hundreds of microseconds), the character of further progressing the circuit interruption process is defined.

Immediately after current-zero, within very short interval the contact gap resistance rises from essentially small values, corresponding to the arc resistance up to quite high values, corresponding to the electric strength of the completely deionized contact gap. The physical phenomena in the arc column and near-electrode zones will be consider in more detail below in chapter 2. It can be only pointed out that within this time interval, two parallel mutually influencing processes occur:

- *the transient recovery voltage process* that consists in steadying the power voltage across the switching element; this process characterizes mainly the properties of the interrupted circuit (electrical subsystem, wherein the device is installed);
- *the recovery of dielectric strength* that consists in establishing the so-called "cold" strength across the contact gap, that is, the electrical strength corresponding to completely deionized contact gap; the behavior of this process is defined by properties of the switching device (i.e., its arc-extinguishing system).

The relation of these processes plays a key role in interrupting the circuit. If in post current-zero period the dielectric strength in excess of the transient recovery voltage, favorable conditions for final decay of the residual space and the complete restoration of the medium dielectric properties are offered in the contact gap. That is, in this case, the arc is extinguished and the circuit is interrupted. If there is an inverse relationship between the transient recovery voltage and the dielectric strength, the intensive ionization process occurs in the residual space, leading to the *arc reignition*, that is, the formation of a self-maintained electric arc discharge. In this case, the arc is not extinguished and the circuit is not interrupted.

Thus, the condition of interruption of AC circuit states as follows: *the electrical arc will be extinguished and the circuit will be interrupted, when the dielectric strength after the current-zero instant exceeds the transient recovery voltage.*

1.4 Circuit Interruption with No and Limited Arcing

In this subsection, we will discuss the methods that enable us either fully to avoid the initiation of an arc discharge or to reduce significantly the time of its existence.

Synchronous circuit interruption. Synchronous switching is not a recent idea and for at least the last 50–60 years the feasibility of synchronized switching has been studied; many concepts have been investigated and even some commercial equipment has been built and utilized. Synchronous interrupting ac circuits is usually carried out by contact systems opening shortly before the current-zero instant, when the storage of electromagnetic energy in the electric circuit is very small. If by the current-zero instant the contacts will be apart such distance as recovery voltage will not be able to strike the contact gap, then an arc discharge will not be initiated in the following half-cycle in it. It is clearly that for this purpose a sufficiently high velocity of the contact separation must be provided. Under these conditions, an arc discharge exists a highly small time span across the contact gap. It enables to create switching devices offering by high breaking capability and switching wear-resistance [14, 18, 19, 22].

Since the time span between the moments the contacts are started to open and the current-zero is very small, even at high opening velocities, the contacts have no time to be apart a relatively long distance. This circumstance enables to construct synchronous contact systems with significantly lower contact gap in comparison with contact systems carrying out circuit interruption with arcing. This, in turn, allows significantly reduce the magnitude of the operating stroke and, hence, the power and overall dimensions of the actuator.

However, it should be also noted the main shortcoming of synchronous switching elements; it is complex construction realizing synchronous contact opening. Therefore, as denoted above, now synchronous switching devices are not extensively used and are not mass-produced.

Circuit interruption with combined contact systems. Contacts of switching devices must provide not only reliable switching (make-break operations) of the electric circuit, but also reliably operate in a closed state under continuous current load. This is very important in cases when the switching device continuously operates under load current, while does not execute switching operations. It is typical situation for devices such as high and low voltage circuit breakers. When the circuit is interrupted, the contact faces, due to arc erosion (thermal action of arc discharge), become worse and by that reduce the reliability of operation in the closed position. One of techniques to ensure reliable operation of the device, both in interrupting the circuit and the closed position, is to subdivide the functions of the contacts. This is realized by the so called *combined contact systems*. In the simplest case, it is a contact system including *main and arcing contacts*. The main contacts carry the load current, when the switching device is in the close position. The arcing contacts are used to interrupt the electric circuit and so they are fitted with an arcing device.

When the switching device is in the on state, the main and arcing contacts are closed. In interrupting the circuit, the combined contact system operates in the following order. At first, the main contacts open, a short-time arc discharge is initiated between them, since the current quickly transfers into the arcing contacts subcircuit. In the process, the arcing time across the arcing contacts must be limited as low as full absence of arcing. This is necessary for the purpose to limit arc erosion and thereby save the main contacts faces in a normal state. After that, the arcing contacts are opened, which execute the arc quenching and final interruption of the circuit. The main task in this case is to analyze the conditions of arcing across the main contacts. The full equivalent circuit for such an analysis is shown in Figure 1.15.

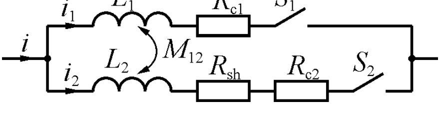

Figure 1.15 – Equivalent circuit for analysis of arc shunting

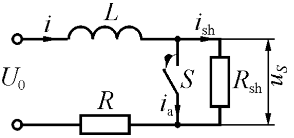

Figure 1.16 – Interruption of ac circuit with arc shunted by resistance

The circuit contains the main S_1 and arcing contacts S_2, as well as their contact resistances R_{c1} and R_{c2}. The arcing contacts subcircuit can also include shunting resistance of relatively great magnitude: $R_{\text{sh}} >> R_{c1}$; $R_{\text{sh}} >> R_{c2}$. The inductances of the main L_1 and arcing L_2 subcircuits, and, consequently their mutual inductance M_{12} in this case can be neglected. Such case corresponds to arc quenching by shunting by an active resistance. The scheme of arcing interruption of a dc circuit with a shunted arc is shown in Figure 1.16.

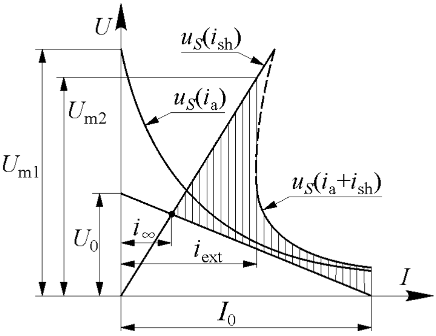

Figure 1.17 – Characteristics of interrupted circuit and the arc shunted by resistance

If shunt R_{sh} is absent (i.e., $R_{\text{sh}} = \infty$), the circuit interruption condition is fulfilled; however, it is close to the limiting case, as shown in Figure 1.17. In the process, the overvoltage at the arc extinction instant corresponds to value U_{m1}. In the presence of the shunt, the aggregate volt-ampere characteristic of the switching element $u_S = f(i_{\text{sh}} + i_{\text{a}})$ lies significantly higher than the external characteristic of the circuit, therefore the rate of decrease of the current will be higher, and subsequently arc extinguishing will happen more rapidly. At point $i = i_{\text{ext}}$ the arc decays, because for its further existence the current should increase, but this cannot happen, since:

$$\Delta U = L\frac{di}{dt} < 0 .$$

By this why, starting from point i_{ext} the current through the shunting resistor becomes equal to the current in the external circuit. In the process at first, the voltage across the shunting resistance increases to the value U_{m2}, and then decreases to the point of crossing with the external characteristic of the circuit to be interrupted. Correspondingly, the current in the circuit decreases to steady state value i_∞. This current remains in the circuit; to break the circuit finally, this current must be interrupted by arcing contacts.

Thus, the availability of shunting resistor leads to that the arc is extinguished more rapidly and the overvoltage across the switching element at the arc extinction instant is essentially lower. Under decreasing the shunting resistance, ΔU increases resulting in a growth of the rate of decrease of the arc current and reduction of the arcing time across the main contacts. However, in the process the current being interrupted by the arcing contacts i_∞ also increases. This cause the question. Is it possible fully to eliminate the arcing across the main contacts if the shunting resistance will be decreased down to zero?

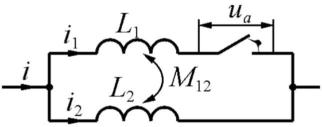

Figure 1.18 – Equivalent circuit for analysis of the current transferring from main to arcing contacts

In this case, the analysis of transition of the current from the main contacts subcircuit to the arcing one is executed with the help of the foregoing equivalent circuit. In the process, the values of contact resistances are neglected $\left(R_{c1}=R_{c2}=0\right)$ and the equivalent circuit takes the form shown in Figure 1.18.

The applying Kirchhoff's voltage law for given circuit results in the following equation:

$$L_1\frac{di_1}{dt}+u_{\text{д}}+M_{12}\frac{di_2}{dt}-L_2\frac{di_2}{dt}-M_{12}\frac{di_1}{dt}=0. \tag{1.40}$$

Suppose that transition of the current to the arcing contacts subcircuit happens sufficiently rapidly and the aggregate current has no time to change appreciably, then:

$$\frac{di_1}{dt}=-\frac{di_2}{dt}.$$

In the process, the voltage across the contact gap will be expressed as follows:

$$u_{\text{д}}=\left(L_1+L_2-2M_{12}\right)\frac{di_1}{dt}. \tag{1.41}$$

In order to preclude an arcing across the main contacts it is required that during the current transition the voltage across the switching element does not exceed the arc formation voltage. From the derived equation, it follows that the arcing across the main contacts can be precluded by two ways. The first is to decrease the rate of fall of the current; for example, because of slow reduction of the contact pressure in opening the main contacts. The second way is to decrease the total inductance of the circuit $L_1+L_2-2M_{12}$: to reduce self-inductances of subcircuits L_1 and L_2, or increase the mutual inductance of the subcircuits M_{12}, i.e. amplify their magnetic coupling. When magnetic coupling is absolute $M_{12} = \sqrt{L_1 L_2}$ and $L_1 = L_2$, the total inductance of the circuit becomes zero, and the main contacts open without arcing. One of technical solutions that enables in maximal degree to decrease the total inductance of the circuit is, for example, construction “pipe within pipe”.

Switching of circuits by semiconductor devices. One of important directions of the switching devices development is application of power semiconductor devices (PSCD) as switching elements. Now PSCD are extensively used in low voltage switching and protection devices. Due to the latest advances in power semiconductor engineering (PSCD with a repeating voltage of 5 kV and an average current of 2.5 kA have been created) real prerequisites for the effective application of PSCD in high voltage switching engineering are provided. As practice has shown, the application of PSCD in combination with traditional arc quenching technologies, that is, creating combined (contact-and-semiconductor-based) switching devices is highly effective. There are many various circuital solutions realizing the construction of PSCD-based switching elements and, accordingly, schemes of switching electrical circuits [14, 18, 20]. Let us consider the simplest ones.

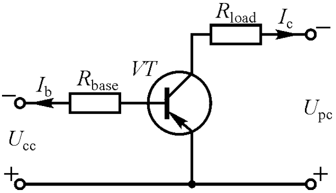

Figure 1.19 – Switching ac circuit with application of power BJT

At relatively small switched currents, wide application have power *bipolar transistors*. Consider the simplest variant of an electric circuit to be switched with use of *p-n-p* type transistor connected according to a common emitter circuit, shown in Figure 1.19. In this circuit, the transistor *VT* is in so-called *switching operation*. The base-emitter subcircuit is a *control circuit* energized by the driving voltage U_{cc} and includes the ballast resistor R_{base}. The subcircuit collector-emitter is a *power* (*controlled*) *circuit*, with load R_{load}, energized by the driving voltage U_{pc}. According to the voltage Kirchhoff’s law for the power circuit, the following equation can be written:

$$U_{\text{pc}} = I_c R_{\text{load}} + U_{\text{ce}}(I_c), \tag{1.42}$$

were I_c is the collector current;

$U_{\text{ce}}(I_c)$ is the so-called *output characteristic* of the transistor, expressed in a general form.

The operation of the simple bipolar switch is illustrated in Figure 1.20 that shows the *external characteristic* or *load-line* of the power circuit $\left(U_{\text{pc}} - I_{\text{c}} R_{\text{load}}\right)$ and a set the of the output characteristics of the transistor at different base currents.

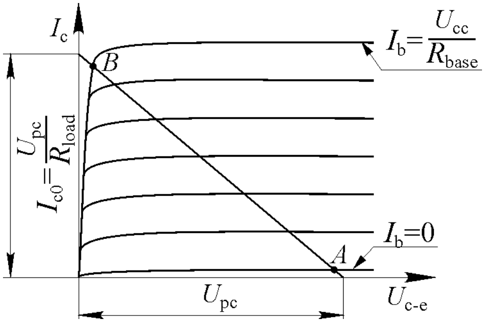

Figure 1.20 – Switching operation of power BJ

The operational point will be defined by the cross point of the power circuit external characteristic with the corresponding output characteristic of the transistor. The operational points of the transistor being in switching operation will correspond to two values of the base current. When the voltage U_{cc} is zero, then the base current of the transistor is zero as well and the collector current will correspond to the minimal value. In this case, the operational point is point *A* that corresponds to the cutoff region, that is, locked state of the transistor as leakage current flows through the controlled circuit. This is equivalent to the interrupted state of the power circuit, when the switching element is in the open state. As voltage is applied to the transistor base $\left(U_{\text{cc}} \neq 0\right)$, current starts to flow in it $\left(I_{\text{b}} \neq 0\right)$; if its value is such that point *B* is operational one, then the transistor will be in the saturation region and the current through the power circuit will be defined mainly by the load resistance R_{load}. Such state of the power circuit corresponds to its energized state and, accordingly, to the closed position of the switching element.

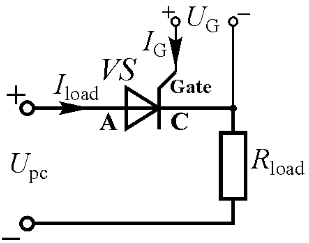

Figure 1.21 – Switching dc circuit with application of power thyristor

In devices that switch high currents, power thyristors (with four-layer structure) are extensively used. The simplest circuitry for switching dc circuit is shown in Figure 1.21. Thyristor *VS* has three electrodes: A is anode; C is cathode and gate. In this case, similar to the transistor-based circuitry variant, the operational points are defined by the intersection of the external characteristic of the circuit with the volt-ampere characteristic of the thyristor as shown in Figure 1.22. If the current through the thyristor gate IG is zero, the operational point corresponds to point A, then a small leakage current passes through the controlled (load) circuit. This situation corresponds to the off (i.e. non-conducting) state of the thyristor and the circuit is practically in dead state. If current flows through the thyristor gate, the operational point in this case corresponds to point B, then a current, defined practically only load resistance R_{load}, will flow through the load circuit. This situation corresponds to the on (i.e. conductive) state of the thyristor and the circuit in this case is energized.

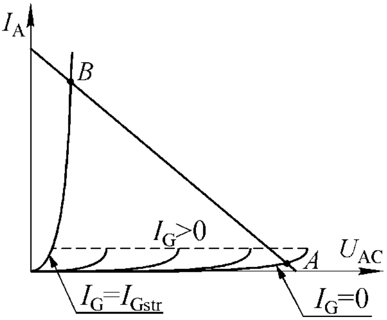

Figure 1.22 – Switching operation of a power thyristor

It should be noted that a thyristor is usually switched on (i.e., transfers from point *A* to point *B*) by applying a short-term current pulse to the gate. To switch off the thyristor, it is required to decrease the anode current down to the value lower than the so-called *holding current* i_{hold}. Since its value is usually very insignificant, to change the thyristor to the off state, the anode current should be decreased practically down to zero value. In the case of dc circuit interruption, *forced cutting off* the thyristor is used. It is realized, for the most part, by applying the anode current reverse pulse from a pre-charged capacitance [14, 18, 20].

Figure 1.23 shows an AC electric circuit being switched by the so-called *bi-rectifier* (two parallel-opposite-connected thyristors). The circuit is

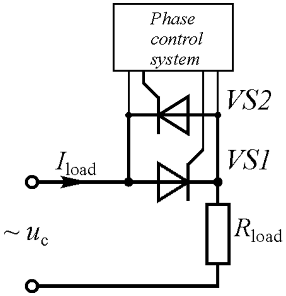

Figure 1.23 – Switching ac circuit with application of bi-rectifier

energized by applying a control signal (control pulses) to the thyristors *VS1* and *VS2* from control-phase system. In this case, the control-phase system must be designed so that to provide alternate applying the control impulses to both thyristors, depending on the polarity of the network voltage, each half-cycle, since the thyristors cut off at the current-zero moments.

The time diagram of the current in the working circuit at resistive load is shown in Figure 1.24.

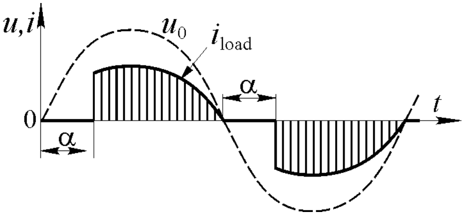

Figure 1.24 – Time diagrams of the driving voltage and load current

The rms value of the current through the load will be defined by the instant of applying the control pulses to the thyristors gates, that is, by control angle (see Figure 1.24). The control-phase system usually provides regulation of the control angle. In such a way, along with the function of switching an electric circuit, such element provides also the function of the load current regulation. Therein lays a very important advantage of semiconductor-based switching elements. The circuit is in this case interrupted by stopping the application of control pulses to the bi-rectifier; as current passes through zero value, the thyristor cuts off.

The most important advantages of semiconductor-based switching elements are as follows:

- *no movable parts*, therefore there is no mechanical wear and mechanical life is almost unlimited;
- *no arcing and electric erosion* at circuit interruption, therefore the switching life of the device is practically unlimited;
- very *low expense for maintenance* and a big life expectancy;
- *no sound and lighting effects*;

- they provide not only switching, but also *regulation of the load current.*

The disadvantages of semiconductor-based switching elements are as follows:

- *low switching depth and the absence of a visible rupture* in the electric circuit;
- *no galvanic decoupling* between the control and the controlled circuits; application of optoelectronic devices partially eliminates denoted shortcoming, but semiconductor-based switching elements in safety level are as whole essentially below than contact-based ones;
- *great thermal losses*: they are by two-three orders more than in contact systems, that’s why, powerful cooling systems (heat sinks etc.) are used to drive out generated heat; it leads to an increase in the mass and dimensions of the device and to complication of its construction;
- *low stability to overloads and overvoltages*, therefore, for semiconductor-based switching elements especial high-speed protection is necessary;
- *high cost.*

The switching properties (i.e., behavior in transition from the on to off state and vice versa) of semiconductor devices are defined by theirs dynamic characteristics. Time diagrams of the anode current and voltage in switching on the thyristor are shown in Figure 1.25. It includes three typical stages:

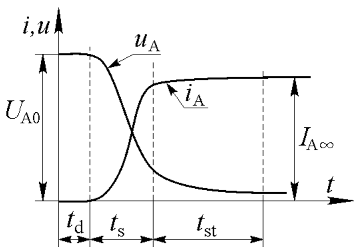

Figure 1.25 – Time diagrams of the anode current and voltage for thyristor in switching on

1. The *delay of switching on* is characterized by a slight changing the anode voltage; its duration t_d is defined by the parameters of the control signal, as well as the processes of diffusion and drift of carriers in the bases necessary to start the regenerative process in the *p-n* junction;

2. *Switching* is characterized by an avalanche-wise rising the anode current; its duration t_s is defined by the velocity of spreading the on-state over the area of the *p-n* junction;

3. *Establishment of the on-state* is characterized by a relatively slight rising the anode current and lowering the anode voltage; this process continues during the time t_{st} until these quantities will correspond to the static characteristic.

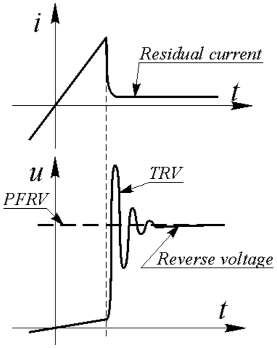

Figure 1.26 – Time diagrams of the anode current and voltage for thyristor in switching off

Thyristors are switched off as the current passes through its zero value, Figure 1.26. Just after current zero for some time (tens of microseconds), the current continues to flow through the thyristor in the reverse direction. This phenomenon is caused by the processes of cleaning-out the excessive carriers in the wide base region. After a lapse of this time, the reverse voltage and the central junction capacitance rapidly enough recovery and the current falls to a steady state leakage current. At this moment, the process of recovery reverse voltage begins. Its behavior is defined by the same regularities as in ac circuit interrupting occurred with arcing. It should be pointed out here that overvoltages taking place in the process might be hazard for the thyristors. In order to decrease overvoltages, thyristors are usually shunted by *R-C* circuits or varistors.

Switching circuits with contact-semiconductor-based elements. Efforts to integrate the positive qualities of contacts and semiconductor devices have led to the creation of so-called *combined* (*contact-semiconductor-based*) *switching elements* and switching devices based on them (hybrid switches). Now hybrid switches for low voltage applications (dc and ac contactors) have been developed and are successfully operated. At the last time, intensive investigations aimed to design contact-semiconductor-based switching devices for high voltage applications are made. In these switches the arc interrupting technologies commonly used in circuit breakers for high voltage applications are combined with semiconductor elements [10, 11].

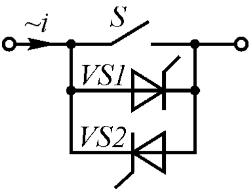

Figure 1.27 – Power circuit of combined switching element

Let us consider one of the simplest circuits of combined switching elements shown in Figure 1.27. It includes contacts *S* with parallel connected semiconductor devices *VS1* and *VS2*. The positive effect of combined switching elements is attained by the separation of functions performed by contacts and semiconductor devices. The contacts perform function of carrying the load current whenever the switching device is in closed position. The semiconductor component performs the function of switching an electric circuit.

The combined contact system carries out making a circuit in the following order. At first, the circuit is switched on with semiconductor component, and then the contacts are closed. It should be noted however, that the time span from the instant of the thyristors are switched on until the contacts touch is usually no more than 1–2 half-cycles. At the instant the contacts touch, the process of transition of the current from the semiconductor component into the contacts begins. It is known that the contacts closing is usually occurred with contact bounce and momentary arcing. The presence of the semiconductor component practically does not effect to the arcing time due to the delay of switching on semiconductor devices.

Interrupting a circuit involves two stages. The first stage is the contact opening occurred with momentary arcing. This stage continues until the current completely passes into the semiconductor component. The second stage is the operation of the semiconductor component under load. In the case of ac circuit interruption, this stage continues until the first current-zero occurs. At this moment, the thyristor switches off and, consequently, the process of the circuit interrupting process is terminated. It should be pointed out here that semiconductor devices in this case operate under load for a very short time and therefore do not require intensive cooling and are not fitted with heat sinks or other cooling systems.

The arcing time in this case essentially depends on many factors; primarily, it is defined by the characteristics the arc discharge and the semiconductor device. On this basis, the arcing time across the contacts of the contact-semiconductor-based switching element will be added of three components:

$$t_{д} = t_{н} + t_{з} + t_{п}, \qquad (1.43)$$

where $t_{н}$ – is the *rise time* of the voltage across the contacts up to threshold value U_0; this component is mainly dependent upon the electrode voltage drop, the contacts opening speed and the threshold voltage of the semiconductor device;

$t_{з}$ is the *delay time* for switching on the semiconductor device;

$t_{п}$ is the *transition time* of the current from the contacts to the semiconductor device; it is defined by the parameters of the components of the circuit being formed.

As an example, let us consider the process of interrupting a circuit by contact-semiconductor-based switching element, which is shown in Figure

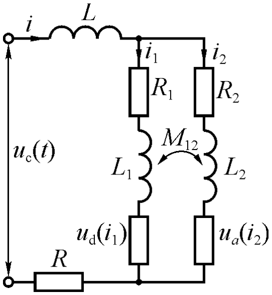

Figure 1.28 – The analysis of the circuit interruption by the combined switching element

1.28. The circuit includes the parameters of the circuit being interrupted *R*, *L*, as well as the switching element parameters, namely: active resistances R_1, R_2, inductances L_1, L_2, as well as mutual inductance M_{12} of the incoming buses, wires, cables of the semiconductor unit and the contact system; $u_{\text{п}}(i_1)$ is the dynamic characteristic of the semiconductor element; $u_{\text{д}}(i_2)$ is the dynamic characteristic of the arc appearing across the contacts.

Basing upon the equivalent circuit represented by Figure 1.28, the following set of differential equations, governing the transition process of the current from the contacts into the semiconductor component, can be written:

$$\begin{cases} u_{\text{c}}(t) = iR + L\dfrac{di}{dt} + i_1R_1 + L_1\dfrac{di_1}{dt} + u_{\text{d}}(i_1) + M_{12}\dfrac{di_2}{dt}; \\ u_{\text{c}}(t) = iR + L\dfrac{di}{dt} + i_2R_2 + L_2\dfrac{di_2}{dt} + u_a(i_2) + M_{12}\dfrac{di_1}{dt}; \\ i = i_1 + i_2 \end{cases} \qquad (1.44)$$

Taking into account that the current transition process occurs sufficiently rapidly (50–100 µs), the supplying voltage has no time to change essentially, so it can be accepted as invariable [10, 11].

Thus, whenever a circuit is interrupted by a contact-semiconductor-based switching element the arcing is not excluded. Nevertheless, it should be noted that its duration is in this case reduced down to 100–200 µs That is why contact-semiconductor-based switching devices have a significantly higher switching life in comparison with purely contact-based apparatus [10, 11].

2. PROPERTIES AND CHARACTERISTICS OF THE ARC DISCHARGE

As it was noted above, the interruption of the electric circuit (i.e. cessation of the current passing through it) by the contact-based switching element is occurred with a number of complex phenomena that have not studied in full degree until present time. One of such phenomenon is an electric arc discharge, which is an absorber of energy stored in inductive elements of an electric circuit. It should be noted that an arc discharge is initiated also due to the bounce of the contacts carrying out making the electric circuit.

It was also noted above that contact systems remain the dominant type of switching elements used at the present time for switching power electrical circuits and contact-based switching devices. At the same time, the behavior of the switching process will be also determined by the properties of the arc discharge – its volt-ampere characteristic, which, in turn, determined by the physical processes that occur in the switching arc (i.e., arcing).

2.1 General Description of Electric Arc Discharge

The phenomenon of *electric arc discharge* (*electric arc*) was discovered in 1802 by Russian scientist, professor of the St Petersburg Military Medical and Surgical Academy Vasilij Petrov. According to his suggestion, in April 1802, the most powerful at that time power source was constructed. It was “voltaic pile” packed of copper and zinc plates. In the same year, V.V Petrov performed researches, and in November 1803 the findings of these researches were published in his book “*Izvestie o galvani-voltovskikh opytakh*…” (“News of Galvanic-Voltaic Experiments…”. The electric arc in this book is characterized as “a light-carrying phenomena originating from the galvanic-voltaic liquid”. [4, 6–8, 14]

In a number of (mainly Western) publications the priority of electric arc discovery is attributed to the English chemist *Humphry Davy*. Nevertheless, an analysis of his scientific works has shown that his experiments only repeated the researches performed by V.V. Petrov ten years ago. Although it should be noted that H. Davy has performed more detailed researches and has introduced the term "electric arc".

At present time, electric arc discharge is extensively used in a variety of technical devices and, especially in industrial technological installations:

- *arc steel-melting furnaces*, in which an electric arc is used as a powerful thermal source for steel melting;

- *installations for arc welding,* in which an electric arc is used to produce non-releasable joints in metal constructions;
- *plasma generators,* where an electric arc is used for a variety of purposes: for example, jet spraying of materials on the solid surfaces;
- *powerful lighting devices* where an electric arc is used as a light source; a distinctive feature of arc lighting devices is high luminous efficiency and, accordingly, high capacity at small dimensions.

If in the cases considered above the electric arc plays a predominantly positive role, then in the switching devices it plays mainly negative role, but there is also a positive one. The positive role of the electric arc implies that it is an absorbent of energy generated during the circuit interruption and prevents the appearance of overvoltages. The negative role of the electric arc in switching devices is in the following. When the arc discharge is in contact with the electrode (contact) surface, electric erosion wear of the contact (i.e. loss of the contact mass,) occurs limiting the switching life of the device.

An electric arc discharge (electric arc) is a type of *gaseous discharge*, i.e. phenomenon of electric current passage through a gaseous medium. There are two main types of gaseous discharges: *self-sustained* (*self-maintained*) and *non-self-sustained* (*non-self-maintained*) ones. The last one includes discharge wherein electric current carriers are produced mainly by external ionizing agents (cosmic emission, X-rays etc.). As soon as the agents are removed, the existence of discharge becomes impossible.

A typical representation of non-self-sustained discharges is the so-called *dark discharge*. Its main distinctive feature is significantly small current values (10^{-11} and below). At relatively small values of the voltage applied across the electrodes, the magnitude of the discharge current is proportional to its magnitude. However, at a certain value of the applied voltage, saturation occurs, when its further growth does not lead to an increase in the discharge current. The minimal value of the voltage leading to saturation depends first upon the environmental conditions defining the ionization intensity, as well as on the volume of the gas filling the space between electrodes and its pressure.

The discharge referred to the self-sustained discharge is that where the current carriers are produced by means of processes occurring within the discharge itself. Typical, in qualitative respect, varieties of self-sustained discharges are Townsend's one (named after the scientist Townsend, which has developed theory for this type of discharge), glow and electric arc ones.

The *Townsend's discharge* is usually observed at a low capacity of the source, which, however, provides a high voltage and, accordingly, high electrical field intensity between the electrodes. In the process, the velocity and kinetic energy of the charged particles available in the space between the electrodes increases substantially that is sufficient to ionize neutral particles (i.e. so-called *field ionization* takes place in this case). Therefore, Townsend's discharge is a self-sustained one; however, it is mostly represented as a transitional form between dark and glow discharges, since it is not luminous but is dark discharge. The current magnitudes, typical for this discharge type, are of the order of 10^{-6}

The *glow discharge* is most frequently represented as a natural development of the Townsend's discharge. However, unlike the Townsend's discharge, a glow discharge is specifically luminous (i.e. is not dark discharge), as well as it has inhomogeneous structure along its length. The most part of the voltage applied across electrodes accounts for the cathode space with length in the range 0.1–0.2 mm, where an increased current density is observed. The cathode region of the glow discharge has a fall of potential in the range of 100 to 400 V. The current magnitudes, typical for this discharge, range up to 1 A.

An *electric arc discharge* (*electric arc*) takes place in the case when the voltage and current in excess of the corresponding critical values of the arcing. These values depend upon many factors and, at first, on the contacts (electrodes) material, as well as the gas composition and the pressure of its surroundings. From a qualitative standpoint, two main identifiable types of arc discharges are usually distinguished. The first type is identified as *high-pressure arcs* (i.e. arc discharges that exist at, and above atmospheric pressure) and the second type, which is low-pressure arcs (i.e. arc discharges that exist in vacuum environment or so-called *vacuum arcs*).

Let us consider, first, the properties of high-pressure arcs. Their basic distinctive feature is the presence of a brightly luminous column, which is a plasma channel including ionized gases, wherein the electric current flows from one electrode (contact) to another. An idealized view of a high-pressure electric arc discharge and a typical potential distribution along the arc channel between the cathode and anode are shown in Figure 2.1.

The plasma channel of the electric arc discharge has three characteristic and qualitatively distinctive regions: the cathode region 1, the column in the middle 2, and the anode region 3. It should be pointed out that the cathode and anode regions have highly small extents (10^{-4}–10^{-5} sm) and constricted cross-sections (at current densities as high as 10^{7} A/sm^{2}). However, essential voltage drops (10–30 V at the cathode and up to 10–12 V at the anode) and, subsequently, high energy densities are concentrated in these regions. The arc column has a high temperature, while the temperature on the electrode (contact) surfaces is limited by the boiling points of their materials.

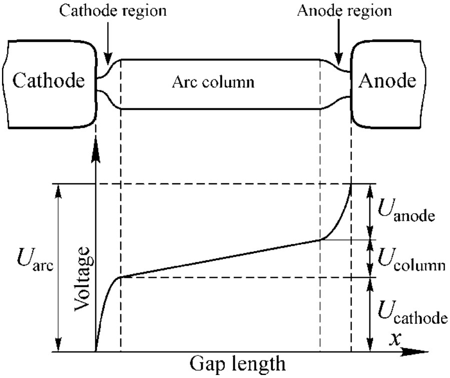

Figure 2.1 – Arc channel and its typical axial potential distribution

The potential gradient in the column is dependent on the arc current and heat exchange with the environment, including the gas type and pressure, flow velocity, and the presence of solid surfaces. The column cross-section tends to adjust itself automatically so that the potential gradient has the lowest possible value. This potential gradient can vary by more than two orders of magnitude according to the design of the arcing device. The mechanism itself, which provides the required charge carrier densities, depends strongly on the pressure in the arc column. For example, in vacuum arcs, current carriers are produced exclusively due to the ejection of electrons and ions from the cathode (see subsection), whereas in high-pressure arcs, current carriers are produced almost exclusively because of thermal ionization.

Electrode regions adjacent to the arcing contacts perform two functions for the arc column. They serve as a transition from a gaseous conductor with variable conductivity (an arc column) to a solid conductor with essentially constant conductivity.

The features noted show a qualitative distinction of the physical processes occurring in the arc column and near-electrode regions. Let us consider these processes in more detail.

2.2 The Processes in High-Pressure Arc Column

As already noted, the arc column is a channel containing *electric arc plasma* through which electric current flows. *Plasma* is generally a gas heated up to a high temperature, containing *ionized particles*: the positive ions and free electrons. It is distinguished *high-temperature plasma* with a temperature of more than 50,000 K and *low-temperature plasma* with a temperature less than 50,000 K. The electric arc plasma resulted from circuit interruption, named *switching arc*, and is the low-temperature plasma. The maximum temperature in the arc column can range from 7000 to 25000 K, according to on the arcing medium and configuration of the arcing device. The arc column has the properties of *quasi-neutrality* (i.e., the concentration of positive ions and negative electrons is identical) and *thermodynamic equilibrium*, when its physical properties are uniquely defined by the temperature.

One of the key parameters of electric arc plasma, defining the properties of the arc column as an electric circuit element, is its electric conductivity. It should be noted that its value is quite high and approaches the conductivity of metals. It is determined according to the following expression:

$$\eta = q \cdot n \cdot b , \tag{2.1}$$

where q, n, b are the charge, concentration and mobility of ionized particles, respectively.

It should keep in mind that practically only free electrons can be considered as the main current carriers because their mobility is several thousand times higher than the mobility of positive ions. Free electrons permanently come into existence in the arc column as a result of ionization of neutral particles available within the column, as well as *thermionic* and *field emission* (i.e., electrons leaving the contact body). Let us briefly consider the principle and main mechanisms of these phenomena.

Ionization is the process of ionized particles generation, carried out mainly by the disintegration of neutral atoms into a positive ions and free electrons resulted from their collision with a high-speed electron or other atom. For ionization, a certain energy, called *ionization energy*, is required, which depends mainly upon the gas composition in the arc column, as well as the presence of metal vapors in it. There are two variations of ionization – field and thermal ones.

Field ionization is caused by the collision of a free electron, accelerated by an electric field with a neutral atom. Under the action of an electric field, the speed of electron motion increases, its kinetic energy increases as well. Therefore, the probability of collision of an electron with atoms and the formation of ionized particles increases essentially. It should be pointed out that field ionization plays a key role in the formation of ionized particles in the Townsend's and glow discharges and is of low importance in the electric arc discharge, where ionized particles are almost fully generated by the way of thermal ionization.

Thermal ionization usually occurs through the collision of neutral particles resulted from their chaotic (thermal) motion. As the gas temperature increases, the rms velocity of particles increases, their kinetic energy and, correspondingly, the probability of collision between them with the formation of ionized particles increase as well. The process of thermal ionization is preceded by the *dissociation process*, that is, disintegration of molecules into single atoms resulted from collision during their thermal motion.

The concentration of ionized particles in the arc column is determined by the ionization degree, i.e. the ratio of the ionized particles concentration to the one of all particles. Thermal ionization degree x_{th} of plasma being in thermodynamic equilibrium state at relatively modest pressures is frequently determined by the Saha's equation:

$$\frac{x_{\mathrm{th}}^{2}p}{1-x_{\mathrm{th}}^{2}}=3{,}16\cdot10^{-7}T^{2{,}5}\mathrm{e}^{-\frac{e\varphi_{\mathrm{i}}}{kT}}, \qquad (2.2)$$

where p is the gas pressure;
T is the gas temperature;
φ_{i} is the ionization potential of the gaseous medium;
k is the Boltzmann’s constant equal $1{,}38\cdot10^{-23}$.
e is the charge of an electron equal $1{,}6\cdot10^{-19}$.

As can be seen from equation (2.2), the degree of thermal ionization is a complex function of temperature. In addition, it should be pointed out that degree of the thermal ionization depends significantly on the pressure, namely, it decreases under increasing pressure. The degree of thermal ionization is depends significantly also on the ionization potential defined by the gas composition of the arc plasma, especially the presence of metal vapor in the plasma. Even if little metal vapors is available in the arc plasma, the ionization potential essentially decreases and, hence, the degree of thermal ionization increases. The relationship defined by the Saha’s relation for normal atmospheric pressure is shown in graphical form for oxygen, hydrogen, and nitrogen and for the metal vapors of copper and mercury in Figure 2.2 [22, 26].

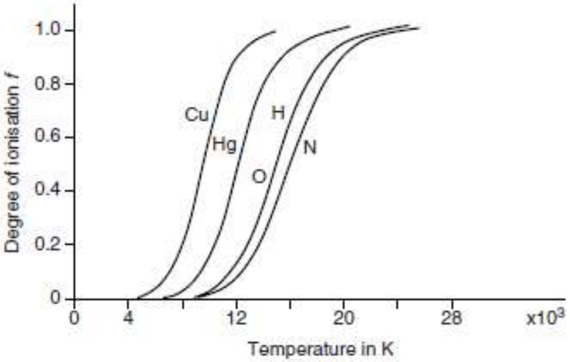

Figure 2.2 – The degree of thermal ionization for some metal vapors and atomic gases

From the graphical diagrams represented, it can be seen that in air at normal pressure, thermal ionization begins approximately at 8000 K and is completed around of 22000 K. It is also informatively represented that metal vapors at the same temperature have essentially higher degrees of thermal ionization. Considering the fact that the arc plasma existing during interrupting an electric circuit (switching arc) has a relatively low thermal ionization degree, all denoted parameters substantially affect it and largely determine the properties of the electric arc as the electric circuit component in general.

In parallel with ionization, the reverse process, called *de-ionization*, happens in arc plasma. It occurs through recombination and diffusion. *Recombination* implies that oppositely charged particles combine together, for example, two ions with opposite charges or a positive ion with free electron. Recombination process is considerably influenced by the density of the gas, its temperature, the velocity of the arc column motion, as well as presence of neutral solids (flats) in the arc plasma zone. *Diffusion* implies that ionized particles go out from the arc column to its surroundings. It is resulted from non-uniform distribution of the ionized particles density over the cross-sectional area of the arc column. It should keep in mind that the density at the outlying zone of the arc column is considerably lower than at its axis.

2.3 Energy Balance of an Arc Column

As discussed above, the process of electric circuit interruption is defined by the switching element properties defined in turn by the energetic state (energy balance) of the arc discharge at every instant. In its turn, the energetic state of the arc column, as any thermodynamic object, at every moment of time is determined by the ratio between the energy generated in it (input energy) and the energy dissipated (driven out from it).

As already noted the main parameter characterizing the state of the arc column is its electrical conductivity determined mainly by its temperature. Just these parameters, in much degree, define the characteristic of the arc column as a component of the electric circuit and the process of its interruption. It should keep in mind that the main condition of circuit interruption is a stable decrease in the electrical conductivity of the arc column plasma. For this purpose, it is necessary to provide a stable reduction of the degree of thermal ionization in the arc column, and, consequently, its temperature. In other words, in order to provide the circuit interruption, it is necessary to make *arc-extinguishing* or *to have quenched the arc*.

The energy balance equation for a volume unit of the arc column in general case has the following form:

$$c_{\mathrm{p}}\gamma\frac{dT}{dt}=jE-p_{\mathrm{o}}\,. \tag{2.3}$$

This equation includes the thermo-physical parameters of the arcing plasma: c_{p} is specific heat at constant pressure; T is the temperature; γ is the density. The equation also contains the parameters of the arc column: j is the current density; E is the voltage gradient; p_{o} is the specific power driven out from the arc column. Analytic solution of this equation is formidable task, since almost all quantities included by it depend in complex manner on the arcing plasma temperature and its distribution over the volume of the arc column. Therefore, let us consider this task from qualitative standpoint.

The left-hand side of the equation characterizes the change of the arc column internal energy; the right-hand side determines the relationship between the power generated by the arc column (input power) and the power dissipated (driven out from it. If the power generated by volume unit of the arc column in excess of the power driven out from it, then the internal energy will increase. Accordingly, the temperature, thermal ionization degree and specific conductivity of the arc plasma will increase as well. Under such conditions, the electric arc will not be quenched and, accordingly, the electric circuit will not be interrupted. Under a reversal relationship between the generated and driven out powers, the process will change in the reverse direction. Internal energy, the temperature, thermal ionization degree and specific conductivity of the arc plasma will decrease. In this case, the electric arc will be quenched and the electric circuit will be interrupted.

In such a way, the main technique of arc extinguishing and, accordingly, the circuit interruption is to increase the power driven out from the arc column, i.e. its cooling. Let us consider the features of heat exchange between an arc column and its surrounding medium. It should keep in mind that the heat exchange between arc column and environment occurs through all three ways, that is, radiation, conduction and convection.

Radiation. Due to the high temperature, electric arc plasma is a source of the radiant energy. It is distinguished:

- *deceleration radiation* or *bremsstrahlung* resulted from the collision of a free electron with an atom leading to the loss of the kinetic energy and the emission of a certain energy by the electron;

- *recombination emission* resulted from recombination (i.e., capture of a free electron by a positive ion); the energy emitted in this case corresponds to the sum of the kinetic energies of the particles;

- *excitation emission* resulted from the transfer of atoms or ions from an excited energy state to a normal one.

The emission of the arc plasma is substantially affected by the external pressure. At low pressures (of the order of free air or higher), the arc plasma is transparent, and the arc column is a *volumetric emitter*. At high pressures (tens, hundreds of atmospheres), the arc plasma is not transparent (opaque to radiation), and the arc column in this case is *superficial emitter*. The electrode (contact) material also significantly affects the emission process through the presence of metal vapors in the arc column. The fraction of emission energy in the total amount of energy driven out from an arc column varies in wide range from a few percent to 80-90% according to the temperature, pressure and composition of the arc plasma.

Conduction. The rate of heat loss by the arc column through conduction depends essentially upon temperature, pressure as well as the gaseous composition of the arc column and its surrounding medium. Highly significant example for this case is comparison of an arc in air with an arc burning in a hydrogenous medium. At the same temperature, the power dissipated in a hydrogenous medium is 8 times higher. Taking into account that the temperature of the hydrogenous arc is 1.5–2 times higher, the total power dissipated in hydrogen will be 20 times more than that in air. This situation enables to use substances generating hydrogen at elevated temperature for arc extinguishing. This is, first and foremost, transformer oil, as well as solid substances, such as, fiber, acrylic plastic, boric acid and others.

Convection. In this case, it implies in that particles of cold gas penetrate into the arc column or, in contact with its surface, acquire kinetic energy and go out beyond it. The fraction of energy driven out through convection is significant in those cases when the arc column experiences intensive axial or cross blowing. It can be pointed out that the hot gas column like a solid rod, therefore the most mass of the cold gas bypasses (i.e., flows around) the arc column.

2.4 Processes in the Electrode Regions

As already noted, the arc discharge has three characteristic regions: the arc column and near-electrode regions, namely, the anode region and the cathode region. Let us consider in more detail the processes that occur in the near-electrode regions.

The surfaces of the electrodes that are in direct contact with the arc column are named *root points* or *arc spots*. It is distinguished a *cathode spot* and an *anode spot*, that is, the surfaces of the anode and the cathode, respectively, which are in contact with an arc column. As noted above, a very small length and a significantly smaller cross-sectional area, compared with the arc column, is highly typical for near-electrode zones (i.e., the regions directly adjacent to the arc spots). Due to this, they are featured by a very high energy density and contain the gas in the state of strongly compressed plasma. Its properties are still not clearly understood at the present day.

The cathode region. According to the present day notions, because of highly different speeds of electrons and ions, the so-called *excessive space positive charge* is formed in the cathode region. This positive charge produces a potential barrier, which is the main cause of cathode voltage drop, and electrical field accelerating the electrons, released from the cathode. The cathode spot is bombarded with positive ions resulting in the generation of the energy providing the ejection of electrons from the cathode spot to the arc column called *emission of electrons*. In this complex combination of correlated processes the emission of electrons plays governing role that may behaves differently under various environmental conditions.

First and foremost, it should be noted that the mechanism by which the electrons leave the cathode (emission of electrons) depends on its material. Refractory materials with high boiling points, such as tungsten, carbon, molybdenum, or zirconium, emit electrons when they are heated to a temperature higher than their evaporation temperature, that is, in given case, the so-called *filament* or *thermionic emission* occurs. In the process, there is typically one stationary hot spot with a temperature over 3500 K, which is heated predominantly through the bombardment by ions accelerated in the cathode sheath. The current densities *j*, which can be resulted from the thermionic cathodes, is given by the Richardson-Dushman equation:

$$j = AT^2 \exp\left(-\frac{e\varphi}{kT}\right), \qquad (2.4)$$

where T is the cathode temperature;

φ is the work function of the cathode material, that is, the energy required to release one electron from a metal surface, typically from 4 to 5 V for electronegative metals and 1.5 to 4 V for electropositive metals, such as thorium;

e is the electronic charge;

k is the Boltzmann constant;

A is the materials constant with value ~60 A/(cm^2 K^2) for most metals.

A cathode made of a non-refractory material with a low boiling point, such as copper and mercury, undergoes significant evaporation of the material. These materials emit electrons at significantly lower temperatures. Calculations in accordance with equation (2.4) show that the current density of thermionic emission must be three orders less than that actually occurs during burning an arc. Higher current densities in the cathode region are evidence that in this case the mechanism of electron emission is more complex. Many investigators consider that cathode spot electron emission involves a combination of thermionic and *cold* or *field emission* (i.e. leaving electrons from a metal surface under the action of an electric field), called *TF emission*.

The anode region. The role of the anode spot in the process of arcing is mainly passive. It serves as a receiver of electrons carrying current from the arc column. Nevertheless, the anode spot plays an active role as well. The bombardment of the anode by the electrons current leads to its heating; thereby the mechanism of thermionic emission comes into act. However, electrons releasing from the anode spot return under the action of an electric field. Positive ions are not released from the anode, whereas positive ions produced in the vicinity of the anode spot come to the arc column. In such a way, an excess of electrons is produced at the anode region, i.e. a space negative charge, generating the anode fall, is formed in the anode region. The current density across the anode spot is a few times less than that across the cathode spot, and the anode region is significantly larger in length than the cathode one. Therefore, much lower energy densities take place in the anode region.

Plasma jets in the arc column. The availability of axial plasma jets in the arc column has been discovered relatively recently. However, this phenomenon quickly has called attention to researchers, since it exerts significant effect upon the features of the arcing and some other processes associated with the arc discharges [7, 24, 29]. Let us briefly consider the essence of the phenomenon and its influence on the behavior of the physical processes taking place in the arc column.

It was found long time ago that the arc column deflects from the shortest distance between the electrodes (contacts) and takes a highly whimsical shape, with no experience of visible external forces. In the process, fast-moving flame tails emanate from the arc roots. This phenomenon was explained by the presence of axial plasma jets caused by electromagnetic forces produced by the self-magnetic field of the arc column.

It is evident that any conductor with an electric current excites a magnetic field producing radial forces tending to compress the conductor and to reduce its cross-sectional area. In solid conductors, these forces do not lead to any changes, although at very high currents they can result in deformation or collapse of the tubular shaped conductors. In gaseous and plasma mediums, including in the arc column, these forces lead to uneven distribution of pressure over the cross-section. So, the maximal pressure will be observed at the arc column core. This phenomenon is named the *pinch-effect.*

Moreover, as it was noted above, the arc column cross-section is uneven along its length. In the vicinity of the electrodes (contacts), it drastically reduces that lead to uneven distribution of pressure along the arc column. In the neighborhood of the arc spots, a considerable difference of pressures is produced that is the cause of the axial plasma jets emanating out from the near-electrode regions. In the present day, it has been found that electrodynamic forces and the pinch-effect produced by it is an important, but not the only cause of axial plasma jets. Under certain conditions, thermal processes play an important role for coming of the plasma jets into existence.

Important factors of the availability of axial plasma jets and their intensity are the magnitude of the current, external pressure and the rate of heat driving out. Axial plasma jets occur only in the event, when the current value is higher than a certain level called the *boundary current.* Increase in external pressure and rate of driving out of heat contribute decrease of the plasma jets intensity and vice versa. An important feature of axial plasma jets is that they are always perpendicular to the electrodes (contacts) surface.

Axial plasma jets essentially influence on the processes occurring in the arc column. First and foremost, the *influence of plasma jets on the processes of its cooling* should be mentioned. The plasma jet, due to friction, captures a layer of cold gas, which exposes the arc column to intense axial blowing and, accordingly, cooling. The more intensive plasma jets are, the more intensively arc is cooled. However, the cooling process in this case essentially depends upon the direction of the plasma jets and, accordingly, the mutual arrangement of the electrodes (contacts) surfaces. When the electrodes are in align arranged and, accordingly, the surfaces are parallel, the plasma jets are oppositely directed: in this case, cooling process becomes significantly more difficult. However, when the electrodes are positioned at an angle (i.e., the surfaces are non-paralleled), the plasma jets are directed into the outer space, in this case the arc column is cooled considerably better.

The *effect of plasma jets upon electro-erosion phenomena* in electrodes (contacts) must be pointed out as well. In the present day, majority of researches are inclined to opinion that the carrying away the material from the electrodes (contacts) surface occur by means of the axial plasma jets. Hence, their intensity is directly associated with the intensity of the contacts wear due to electrical erosion.

2.5 Mathematical Modeling of Arc Discharges.

The electric arc discharge, initiated as the electric circuit is interrupted, becomes one of its components. Like other electric circuit components, an arc discharge is characterized by its *current-voltage* or *volt-ampere characteristic*. It represents the dependence of the voltage drop across the arc column (including near-electrode zones) from the value of the current passing through it $u_д = f(i_д)$.

Note that an arc, as an electric circuit component, is a non-linear element. Its V-A curve is generally determined by complex physicochemical phenomena taking place in the arc column and near-electrode regions that have not been studied in full degree until the present day. An essential influence of environmental factors on the behavior of the arc and, hence, its volt-ampere characteristic must be noted as well. Therefore, to set up equations governing the volt-ampere characteristic of an arc, or to construct the model of an arc is a very difficult task. At the same time, it should be noted that this task is extremely important as arc mathematical models are used not only in the development of new constructions, but also in practice of investigation and testing of switching devices.

Arc models can be classified into three categories: black box (also often called P-τ) models, physical and parameter models. The circuit breaker design engineers work mostly with physical arc models when designing a new prototype. They consist of a large number of differential equations. Physical arc models are based on the equations of fluid dynamics and obey the laws of thermodynamics in combination with the Maxwell’s equations. The arc-plasma is a chemical reaction and, in addition to the conservation of mass equation, describes the rate equations of the different chemical reactions. In the case of a local thermodynamic equilibrium, the rate equations become the equilibrium mass action laws and that, in the simplified case of the reaction of a monatomic gas, becomes the Saha equation, describing the degree of ionization in the gas. Because the arc-plasma is conducting electrically in the momentum equation, also terms describing the interaction with magnetic fields either coming from outside, or generated by the arc current, must be taken into account. Because of the resistive heat dissipation of electric energy calculated with the Ohm’s law, a volumetric heat generation term is part of the energy equation.

The arc-plasma is strongly radiating and this makes the radiation-transport term in the energy equation very important. A considerable portion of this radiated energy, however, is being reabsorbed in the plasma and this is described by the radiation-transfer equation or by the tabulated value for the net emission coefficient. For every component in the plasma, such as electrons, ions, atoms, and molecular species there is a thermodynamic equation of state present in the equations.

Thus, taking all these physical considerations into account, we arrive at the very comprehensive a set of equations [22]. It should be noted that solution of such set of general equations is a formidable task, but for most practical purposes, considerable simplifications can be made. In particular, some qualitative predictions of the arc behavior can be made by using the simplest form of the energy conservation equation [e.g. equation (2.3)].

In the Black box or the so-called *adaptive models*, the arc is described by a simple mathematical equation and gives the relation between the arc conductance and measurable parameters such as arc voltage and arc current. These black box models are not suited to design circuit breaker interrupters but are very useful to simulate arc-circuit interaction in the network studies.

Black box models are based on physical considerations but are, in fact, mathematical models; the behavior of the arc rather than the physical processes is of importance. Usually, black box models consist of one or two differential equations. Parameter models are a variation on black box models in the sense that more complex functions and tables are used for the essential parameters of the black box models [20, 22].

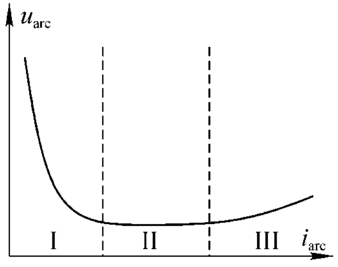

Figure 2.3 – Typical static arc volt-ampere characteristic in free air

Volt-ampere characteristics of the electric arc. There are two variations of characteristics of an electric arc: static and dynamic ones. *Static V-A curves* are characteristics gained at invariable (steady-state) current and voltage values. One of the well-known static V-A curves an arc is the characteristic of an arc burning in free air, shown in Figure 2.3, which has three specific zones. At relatively small currents (up to 10...20 A, zone I) V-A curve of the arc has a falling behavior, i.e. with growth of current the voltage drop decreases. Over a wide range of currents (up to 8...10 kA, zone II) the arc voltage drop is practically independent upon the current; this is explained by the fact that under increasing current, the cross-sectional area of the arc column increases almost proportionally. At very high currents (zone III) due to the pinch-effect, the cross-sectional area of the arc column is practically independent on the current; therefore, the arc V-A curve is similar to an active resistor characteristic, i.e. with growth of current, the voltage drop increases.

The mathematical description of the falling part of the arc characteristic is frequently carried out by applying the so-called Ayrton's formula expressed as follows:

$$E_{\text{arc}} = C_0 i_{\text{arc}}^{-\text{n}} p^{\text{m}}, \tag{2.5}$$

where E_{arc} is the arc column gradient;

p is the pressure;

C_0, n, m are constants depending on environmental factors.

Equation (2.5) is the simplest black box model of an electric arc.

The simplest physical model of an arc static characteristic (stationary arc) is so-called *channel model* based on the following assumptions. The arc column is cylindrically symmetric and wall-constricted with a predetermined radius. The axial pressure drop is negligible in the arc column and, hence, in this case the one-dimensional task is considered. The arc column cross-sectional area includes conductive and non-conductive parts with predetermined dimensions. The arc column is relatively long, by this why the processes in the column are dominant compared with the electrode processes. The arc column has local thermodynamic equilibrium. The thermal energy is driven out from the arc column to the wall mostly through conduction (convection and radiation are absent). Under these conditions, the energy balance equation, known as the Elenbaas-Heller equation, is written in the following form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right) = -\eta E^2, \qquad (2.6)$$

where η, λ are the electric and thermal conductivity, respectively, of the arc plasma;

r is the variable radius of the arc column.

This equation is derived in 1935.

It should be pointed out that circuit interruption processes, especially the clearing faults, are usually featured by high rate of change of current and their analysis applying static characteristics (i.e. stationary arc models) leads to significant errors caused by considerable thermal lag of the arc column. As it was noted above, the characteristic of the arc is determined by its thermal state at each time instant, which has no time to change according to the changing current. That is why the analysis of processes of interrupting circuits by the switching devices is performed by applying dynamic characteristics (i.e. dynamic arc models).

Dynamic V-A curves are characteristics gained in the process of changing current. It is highly evident that they will behave not only in accordance with the value of the current, but with its rate of change.

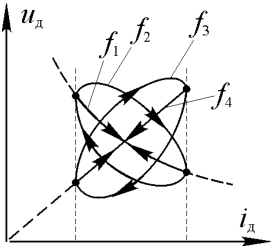

Figure 2.4 – Dynamic characteristics of an arc at different frequencies of pulsating current

Evident example of the dynamic characteristics is the set of V-A curves gained for the arc current containing two components: dc and sine-waved. In the process, the sine-waved component varies with different frequencies, as shown in Figure 2.4, where f_1 is very low frequency, at which dynamic V-A curve practically coincides with static curve; f_2 is low frequency; f_3 is high frequency, at which dynamic characteristic significantly differs from static curve; f_4 is very high frequency, at which dynamic V-A curve practically coincides with characteristic of the ohmic resistance [22].

Thus, to analyze the arcing system, it is necessary to have a mathematical model of the arc dynamic characteristic.

Mathematic models of the arc dynamic characteristics. There is a great variety of mathematic models of the dynamic characteristics for the switching arc. Majority of them is constructed with the help of the power balance equation (2.3), which in this case is written as follows:

$$\frac{dW}{dt} = Ei - P_{\text{out}}, \tag{2.7}$$

where expression $\frac{dW}{dt}$ features in this case the change in the arc column internal energy that determines the electrical conductivity of the arc plasma.

To construct an arc model, a specific dependence $g = f(W)$ should be available. Among the multitude of arc dynamic models the most extensive application has the Cassie and Mayr models developed for axially blown arcs (i.e., for high-voltage circuit breakers with air arc quenching). These models are classical representatives of black box models.

Cassie model: this model is constructed basing on the following assumptions:

- the temperature over the arc column cross-section is invariable (i.e., $T = const$);
- the cross-sectional area of the arc column is proportional to the magnitude of the current;
- thermal energy is driven out from the arc column through radiation and the arc column is considered as a volumetric emitter.

Taking these assumptions into account, the cross-sectional area of the arc column can be expressed in terms of its internal energy

$$S = \frac{W}{c_{\text{p}}}, \tag{2.8}$$

where c_{p} is the specific heat of the arc plasma at constant pressure.

Hence, the dependence of the arc plasma conductivity from the internal energy will be as follows:

$$g = \frac{W}{c_{\text{p}}\rho}, \tag{2.9}$$

where ρ is the electrical conductivity of the arc plasma.

Differentiation of expression (2.9) with respect to time gives:

$$\frac{dg}{dt}=\frac{1}{c_{\mathrm{p}}\rho}\cdot\frac{dW}{dt}. \tag{2.10}$$

Dividing both sides of equation (2.10) by g, and also taking into account the power balance equation (2.7), we obtain:

$$\frac{1}{g}\cdot\frac{dg}{dt}=\frac{1}{gc_{\mathrm{p}}\rho}\cdot\left(Ei-P_{\mathrm{out}}\right). \tag{2.11}$$

Thermal power driven out through emission per length unit will be proportional to the cross-sectional area of the arc column. Taking into account that the arc column cross-sectional area is expressed as $S=\rho g$, it will be as follows:

$$P_{\mathrm{out}}=g\rho p_0, \tag{2.12}$$

where p_0 is the specific (per arc column volume unit) power output.

Substitution of expression (2.12) into equation (2.11), with consideration $g=i/E$, gives the Cassie's equation:

$$\frac{1}{i}\cdot\frac{di}{dt}-\frac{1}{E}\cdot\frac{dE}{dt}=\frac{1}{c_{\mathrm{p}}}\cdot\left(\frac{E^2}{\rho}-p_0\right). \tag{2.13}$$

In static state (i.e., at $di/dt=0$ and $dE/dt=0$), the Cassie's equation will look like:

$$E=\sqrt{\rho p_0}. \tag{2.14}$$

Hence, the arc static characteristic in accordance with the Cassie model will behave as a current-independent curve, which corresponds to the characteristics of an actual arc discharges in a wide range of currents (zone 2, Figure 2.3). Note, however, that the Cassie model does not correspond to the actual arc characteristics at low currents, i.e. in the region of the current-zero crossing.

The *Mayr model* is based on the following assumptions:

- the arc column cross-sectional area is independent upon the current (i.e., $S=const$);
- the temperature of the arc is proportional to the magnitude of the current.

Hence, the electrical conductivity of the arc column in compliance with the Saha equation exponentially depends upon the internal energy:

$$g=g_0e^{W/W_0}, \tag{2.15}$$

where W_0, g_0 are the internal energy and electrical conductivity, respectively, of the arc column under predetermined conditions.

Differentiation of equation (2.15) with respect to time with consideration $S = const$, and hence $P_{\text{out}} = P_0 = const$, gives:

$$\frac{dg}{dt} = \frac{g_0}{W_0} e^{W/W_0} \left(Ei - p_0 \right) \tag{2.16}$$

Dividing equation (2.16) by g, and also taking into account $g = i/E$, we get the Mayr equation:

$$\frac{1}{i} \cdot \frac{di}{dt} - \frac{1}{E} \cdot \frac{dE}{dt} = \frac{1}{\vartheta} \cdot \left(\frac{Ei}{P_0} - 1 \right), \tag{2.17}$$

where $\vartheta = \dfrac{W_0}{P_0}$ is the arc thermal time constant that features its thermal lag in the circuit interrupting process.

The magnitude the arc thermal constant is usually from 1 to 10 μs (for the high-voltage switching devices) and for the low-voltage devices, it is in the range from 50 to 200 μs [8, 14, 17–20].

The represented arc models deal with very rough assumptions and, therefore, are highly inaccurate. Attempts to construct unified model, based on these two models, involved considerable mathematic complications.

2.6 Dielectric Recovery during the Near-Current-Zero Period

Near-current-zero processes. As it was noted above (see section 1), when an electric circuit is interrupted, the processes occurring in the region where the alternating current reaches its normal zero value play the key role. Just here (i.e., in the neighborhood of current-zero) the behavior of further progressing of the circuit interruption process is determined. Either the electric arc will has been quenched and, accordingly, the circuit will has been interrupted, or in the next half-cycle of the current a self-sustained arc discharge will has been initiated and, accordingly, the circuit will has been not interrupted. It should be pointed out here that the arc existence after a current-zero value is an emergency condition for majority of switching devices. For example, for a high voltage circuit breaker that interrupt short-circuit current the appearance of an arc discharge after current-zero means a failure to operation.

When the arc current approaches to zero, a very intensive deionization process and a drastic reduction of the degree of thermal ionization occur.

Shortly before the nominal current zero crossing, the arc plasma very quickly decays and the contact gap resistance increases drastically. For a very short time span, it changes from very small values corresponding to the arc resistance to very large values corresponding to dielectric strength of the almost fully deionized contact gap. The arc current in the process is somewhat differentiated from the sine waveform and becomes practically equal to zero prior to its normal zero. In such a way, the arc column losses the properties of a self-sustained discharge and comes to take qualitatively new properties named *residual arc space.* From this moment, in essence, the recovery of dielectric strength in the contact gap begins to occur; nevertheless, there is still-hot gas between the contacts.

In parallel, the transient recovery voltage process begins to occur between the contacts of the switching device (see chapters 3 and 4). Under the recovery voltage stress, a very low *post-arc current* flows across the residual space. If the energy generated in the residual space is high enough, a process of active ionization occurs that can eventually lead to initiation of the self-sustained arc discharge. Note that from the moment the residual arc space forms until the moment when the arc discharge is again initiated, a certain time elapses, conventionally called the *current zero pause*.

Consequently, the recovery process plays an essential role in interrupting a circuit. As differentiated from the recovery voltage, the dielectric recovery represents the switching device properties. It characterizes appearing and rising in time the dielectric properties of the contact gap in the vicinity of the current-zero value, namely, a highly rapid transition of the contact gap from a state of high conductivity to dielectric state.

The notion of dielectric recovery. The notion itself of dielectric recovery evidently derives from the general notion of *dielectric strength*, which is the minimal voltage, which is able to produce a strike of the electrode (contact) gap. That is, the minimal voltage which is able to initiate an electric discharge in it, and thereby to transfer it from the dielectric state to the state of high conductivity.

The *dielectric recovery* is the instantaneous value of the dielectric strength of the switching device contact gap rising during the interruption process. The recovery of dielectric strength of the arc residual space during tens-and-hundreds microseconds after the current-zero instant is of the greatest importance for contact-based switching devices. For semiconductor-based switching devices, dielectric recovery implies in establishing the off-state of a semiconductor device (see chapter 1).

The recovery of dielectric strength during the interruption process is determined by the maximal voltage, which the switching device contact gap is able to withstand with no strike. From other hand, the dielectric recovery can be determined as the minimal voltage causing the residual arc space to transfer in the state of a self-sustained arc discharge. In the contact-based switching devices, strike of the contact gap after the current-zero results in the appearance of an arc discharge (electric arc). In this case, an unsuccessful interruption of the electric circuit happens that means in some cases a failure to operation of the switching device. In semiconductor-based switching devices usually breakdown of the p-n junction of the semiconductor device occurs. In this case, switching device fully losses its operability. Let us consider the recovery processes in the contact-based switching devices.

Recovery of dielectric strength, i.e. the $u_{\mathrm{rd}}(t)$ curve is usually determined for the most critical stage of the interruption process, namely, time span from 10 to 100 μs after the current-zero crossing. For most switching devices for high and low voltage applications, the dielectric recovery curve behaves as shown in Figure 2.5, where $U_{\mathrm{c.str}}$ is the so-called "cold" strength that establishes across the contact gap after the circuit interruption completion.

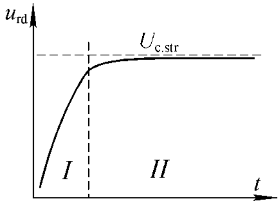

Figure 2.5 – Typical dielectric recovery curve

The recovery of dielectric strength across the contact gap usually consists of two typical stages. The first is the so-called "transition" stage or *thermal breakdown* or *reignition zone* when relatively rapid rise of the dielectric recovery happens (zone I, see Figure 2.5). At this stage, an arc discharge rapidly transforms to other types of gaseous discharges. The residual arc space is still significantly ionized and relatively modest voltage can lead to strike of the contact gap. The second stage is the establishment of "cold" strength, or *electric breakdown* or *restrike zone* when relatively slow growth of the dielectric recovery occurs (zone II, see Figure 2.5). The existence of other types of gaseous discharges (glow, Townsend) is typical for this stage. The residual arc space is just practically almost deionized and to strike the contact gap, a sufficiently high voltage is required.

It should be noted that the mechanism of the arc discharge restoration after current-zero moment is not completely understood at present time. Nevertheless, the available findings suggest that there are two ways to restore the arcing after the current passes through zero value:

- *thermal breakdown,* also known as *reignition*, exhibited in those cases when $u_r(t)$ curve crosses $u_{rd}(t)$ at the moment when the residual arc space has been still ionized in significant degree; i.e., mostly at the instant corresponding the first stage of dielectric recovery ;
- *electric breakdown,* also known as *restrike,* exhibited in the cases when $u_r(t)$ curve crosses $u_{rd}(t)$ at the moment when the residual arc space has been almost fully deionized and practically has been restored its dielectric properties, i.e. mostly at the instant corresponding to the second stage of dielectric recovery.

Operational experience of switching devices for high and low voltage applications has shown that electrical breakdown (restrike) is extremely seldom the case. These are mainly cases when a low rate of rise of recovery voltage at its high amplitude (i.e. interruption of low inductive and capacitive currents) occurs. The regularities of restoring the arc discharge in this case are the same as the breakdown of "cold" inter-electrode gaps. In the great majority of events of circuits interruption (load, overload and short-circuit currents) at high and low voltage, the arc restoration is exceptionally resulted from thermal breakdown (reignition).

Dielectric recovery in switching devices. In spite of the qualitative apparent similarity, the recovery processes in interrupting the electrical circuits of high (medium) and low voltage are significantly different both in respect to parameters and to qualitative respect. First and foremost, it should be noted that as low voltage circuit is interrupted the contact gap strength recovers up to several thousand volts while interrupting a high (medium) voltage circuit the recovery voltage reaches as high as hundreds of thousands and even several million volts.

When the high (medium) voltage electric circuit is interrupted, the values of the power frequency recovery voltage and, correspondingly, the recovery strength are several orders of magnitude higher than the values of electrode fall (usually 20–50 V, depending on the contact material, see above). That is why, in the high voltage switching devices, exclusively processes that occur in the residual arc space determine the process of recovery voltage. To analyze the process of raising the recovery strength, the Mayr equation in this case can be applied:

$$\frac{1}{g}\cdot\frac{dg}{dt}=\frac{1}{\vartheta}\cdot\left(\frac{E^2 g}{p_0}-1\right), \tag{2.18}$$

where g is the residual arc space conductivity;

E is the voltage gradient;

p_0 is the specific power output.

At invariable conductance of the residual arc space (i.e., at $dg/dt=0$), the value of the dielectric recovery will be determined by the following expression:

$$E_{\text{rd}}=\sqrt{\frac{p_0}{g}}\,. \tag{2.19}$$

Consequently, in order to ensure normal operability in respect to electric circuit interruption and, respectively, interrupting ability, switching devices for high voltage applications must have powerful arcing devices providing large values of the output power and high rate of rise of the recovery strength across the contact gap. Taking into account the fact that relatively low rate of rise of recovery voltage takes place in high voltage power systems, the circuit interruption process will be determined mainly by the relation between rates of rise of recovery voltage and dielectric recovery.

As differentiated from high voltage apparatus, switching devices for low voltage applications usually have low-power arcing devices in terms of the power output. Therefore, they provide a significantly lower rate of rise of dielectric recovery that is usually governed by an equation like as follows [14, 18, 19]:

$$u_{\text{rd}}=U_{\text{rd0}}+K_{\Sigma}t\,, \tag{2.20}$$

where U_{rd0} is the initial dielectric recovery;

K_{Σ} is the rate of rise of the dielectric recovery.

It should be noted that low voltage power systems are characterized by significantly higher rates of rise of recovery voltage. Therefore, in this case, the value of initial dielectric recovery U_{rd0} plays an essential role in the circuit interruption process. The initial dielectric recovery is a conditional value found by the way of extrapolation of the experimentally gained $u_{\text{rd}}(t)$ curve. In actual situation, the value of dielectric strength immediately at the current-zero instant can substantially differ from U_{rd0}. However, this is insignificant, since in real situation thermal breakdown happens after laps of sometime the current-zero, depending on the rate of rise of recovery voltage.

The value of the initial dielectric recovery is defined by the processes occurring in the near-electrode regions. Just in their immediately after current-zero instant generated heat is intensively driven out to the contact body. Thus, the value $U_{\text{rd}0}$ is significantly dependent on the contact material properties: heat conductivity; boiling point; work on escaping; ionization potential etc. It should be noted the influence of other factors on the value $U_{\text{вп}0}$: current interrupted; type of the switched load; velocity of the arc movement; the instant of the contact parting relative to sine wave-form of the current; the environmental gaseous mix; external pressure and others.

3. CONTACTS AND ARCING DEVICES OF SWITCHING APPARATUS

3.1 General Insight into Electric Contacts

As it was noted in the foregoing sections, at present time the *contact-based switching elements* are mainly used in switching apparatus as the elements providing switching of the electric circuits. It is usually a pair of solid conductors having *electric contact*. It should be noted that electrical contact is an integral part of not only switching apparatus. Almost any electrical equipment and all electrical installations include electrical contacts, because their current-carrying systems are not all-metal constructions, but usually consist of several separate conductors. Electrical contact is also an integral part of relay protections and automatics, microelectronic and microprocessor-based devices, computers and computer systems, all of which include at least contact joints for connection to an external circuit.

The operating experience of electrical installations shows that electrical contact is the weakest (in terms of reliability) elements of the electric circuit. A sufficiently high percentage of damages in electrical installations is the result of failures in the contact functioning. Therefore, the questions related to the reliable operation of contacts are of vital importance. It can be pointed out that the operation of electrical contacts is occurred with very complex and diverse thermo-physical and gaseous-dynamic phenomena that still to date have not been adequately studied. Nowadays electrical contact is the object of wide scientific researches. The study of phenomena in electrical contacts is large enough scientific segment including a few separate scientific directions.

An *electrical contact* is a place of touch of two conductors, which serves for transition of current in an electric circuit from one conductor to another. In some cases, an electrical contact is defined as the interface between the current-carrying members of electrical/electronic devices that assure the continuity of electric circuit. In general case, an electrical contact can be formed by conductors being in various aggregative states. From this standpoint, the following types of electrical contacts are distinguished:

- *metal–metal* (i.e., the contact formed with solid conductors);
- *metal–liquid metal* (i.e., the contact formed with solid and liquid conductors);
- *liquid metal–liquid metal* (i.e., the contact formed with liquid conductors);
- *metal–arc discharge* (i.e., the contact formed with solid conductor

and plasma);

- *liquid metal–arc discharge* (i.e., the contact formed with liquid conductor and plasma).

In this section, first and foremost, electrical contacts formed by solid metal conductors are considered. The classification of contacts considered below refers to this type of contacts. Another contact types take place usually in the cases, when solid contacts fulfill switching operations in an electric circuit (i.e., in closing and opening state) under current load, as well as in the event of an emergency situation (short circuit). The exception is the so-called *liquid-metal contacts*, in which an electrical contact in normal static state is provided with liquid metals [14, 20].

The main constructive elements and concepts that characterize the contacts in electric equipment are as follows:

- *contact face* is the surface of solid conductors contacting directly to the surface of another conductor and producing an electrical contact;
- *contact piece* or *contact member* is a conductor directly forming an electrical contact in electrical apparatuses;
- *contact pressure* or *contact load* is the force acting between the closed contact-pieces, normal to the contact face; to ensure operability of the electrical contact, the contact faces must be pressed to one another with predetermined force;
- *contact unit* is an assemblage of contact-pieces with the elements providing contact pressure.

Contact units perform different functions in electrical installations and individual electrical apparatuses and, correspondingly, are variously designed. Depending on the functions performed, they may be shared into two fundamental groups: non-arcing contacts (connectors) and arcing (switching) contacts.

Connectors are electric circuit contacts intended for conduction of electrical current only and not intended for switching an electric current. Connectors perform the function of electrical connection of conductors and do not rupture the electric circuit in the functioning process. The main constructive and functional varieties of connectors are as follows.

Bolted connectors. In this case, contact-pieces are connected and pressed by means of fasteners (bolts, screws etc.). The connectors of such type are extensively used in electricity distribution centers, electrical apparatuses for the electrical connections of buses, cables and other current-carrying parts, as well as electrical machines and apparatuses with other equipment of the electrical power system. According to the material of the conductors being connected and other factors, there are connectors that do not require the use of means for electrical resistance stabilization and ones that require the use of such means. In the first case, connectors are provided with steel fasteners protected from corrosion. The stabilization of the electrical resistance is usually ensured by the application of color metal fasteners, disc springs, protective metallic coats, transition plates, transition and pin points, electrically conductive lubrications etc.

Plug-and-socket connectors. This type of connector is intended for quick electrical engagement and disengagement of electrical or electronic units. Distinctive feature of this type of connectors is they provide make-break operations in dead electric circuits without the use of a tool.

Current-collecting connectors. This type of connector is intended for current collection by movable contact from fixed one. In such connectors, the movable contact-piece moves relatively to the fixed one without disturbance of the electrical contact between them. They are permanently in closed position with the corresponding contact pressure. A sliding or a rolling contact is usually used in this type of connectors: in the first case, the contact exists when movable contact-piece slides over fixed one, in the second case the rolling occurs, correspondingly.

Permanent connectors. In this case, the electrical connections are performed by means of welding, soldering, rivet and finally cemented connectors have been used recently.

Switching contacts. Switching contacts are the contacts of an electric circuit, intended not only for conducting electric current, but also for switching (make-break, changeover) operations in alive electrical circuits. In the switching process, they carry out the physical (mechanical) rupture (break) of the electric circuit under current flowing or without one and its restoration. The switching contacts usually have a moving contact-piece termed as *movable contact* and stationary contact-piece termed as *fixed contact*.

While the device is operated, the switching contacts can be in two static positions: open (off) and closed (on). In the stationary open position, the switching contacts are featured by the so-called *contact gap*. It is the shortest distance between contact faces of the movable and fixed contacts. In a stationary closed position, as it was noted, the switching contacts are featured by the magnitude of the *contact pressure* or *contact load*.

Contact pressure of the switching contacts is mainly carried out with springs of various types. In order to ensure a predetermined contact pressure, it is necessary, by construction way, to provide a predetermined deformation (stroke) of the spring. The travel of the switching apparatus movable parts required to press the contact force spring and to provide predetermined contact pressure is usually called *contact follow-through*. In other words, contact follow-through is the distance that one (movable) contact-piece moves from a closed position as another (fixed) contact-piece is withdrawn.

Switching contacts usually perform different functions. For example, in switching apparatus for high current switching applications, combined contact systems are used (see section 1). In such apparatus, the *main contacts* carry the current load, and the *arcing contacts* perform make-break operations in the electric circuit. A great variety of switching devices contain the *main circuit contacts* (power or main contacts) and *auxiliary* (*secondary*) *circuit contacts* (auxiliary contacts). Depending on the contact position in dead and alive state of the apparatus, *normally open* (NO), *normally closed* (NC) and *changeover contacts* are distinguished. NO contacts are in the open position as the apparatus is in dead state, and transfers to the closed position as the apparatus is energized. NC contacts are, in contrast, in the closed position as the apparatus is in dead state, and transfer to open position as the apparatus is energized. The changeover contact opens one circuit and closes another one when the apparatus is energized (de-energized).

Depending on the character of the contact interface, the *point*, *linear* and *surface contacts* are distinguished. In the first case, contact occurs at least at one point. For example, when a contact is formed by two spherical surfaces or a spherical surface with a plane one. Such contacts are mostly used at low currents. In the second case, contact occurs by the line, when it is produced, for example, by a cylindrical surface with a plane one. Finally, in the third case, two plane surfaces form the contact. Linear and surface contacts are used at high currents.

There are a number of other indications by which electric contacts can be classified, but they have a secondary importance and are in detail described by textbooks [13, 14, 18–20, 29].

3.2 Transition Contact Resistance

Contact resistance is the resistance of a current-carrying subsystem resulted from the availability of electrical contact, that is, this is the electric resistance of the contact zone, defined by the effective (real) contact area and equal to the relation of the contact voltage drop to the current through this contact.

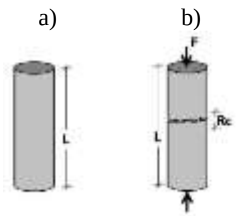

Figure 3.1 – Conductors:
a) without contact;
b) with available contact

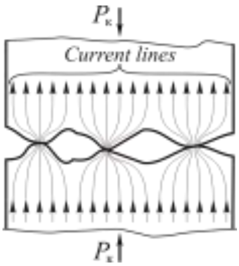

Figure 3.2 – Distribution of current lines in the vicinity of contact interface

Let there be a conductor section of length l and resistance R, as shown in Figure 3.1a. If to cut the conductor across and then to press the two gained sections face-to-face with a certain force $P_{\text{к}}$, as shown in Figure 3.1b, then the total resistance of the conductor will be somewhat higher:

$$R' = R + R_{\text{c}}, \tag{3.1}$$

where R_{c} is the contact resistance.

The availability of contact resistance is, first and foremost, resulted from the fact that the contact interface is only an apparent (nominal) contact area. In actual situation, direct contact is discrete and occurs just over separate sections with area that is many times smaller than the nominal contact area. This interface is usually named the *effective* or *real contact area*. If even the contact surface has been finish-machined, it will have asperities (microroughnesses, macroroughnesses, waviness), which lead to formation of zones of the actual contact called *contact spots* (α-*spots*), as shown in Figure 3.2.

Because of this, in the neighborhood of the contact interface, the current lines bend and pull into converge at the contact spots. Thus, the lines path of the current significantly increases. Additionally, the dimensions of the contact spots will be defined by the presence of various films caused by the interaction of the contact material with its surroundings.

Accordingly, the contact resistance in general case has two components:

$$R_{\text{c}} = R_{\text{constr}} + R_{\text{f}} \tag{3.2}$$

where R_{constr} is the constriction resistance caused by curvature of the current lines in the neighborhood of the contact interface;

R_{f} is the resistance caused by pollutions and various films available on the contact faces.

Let us consider every of these components in more detail.

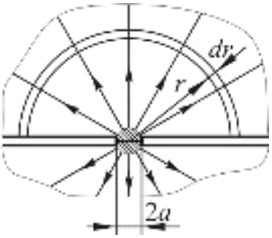

Figure 3.3 – Spherical model of contact

Contact constriction resistance is formed in the region, where bending (constriction) of current lines occurs. This region is named the *constriction region*. To determine the constriction resistance, let us consider an idealized contact formed by two isotropic conductors of infinite dimensions. The contact has one circular-shaped contact spot of radius *a*. In the process, the current lines equally radiate outward from the contact spot center, and the equipotential surfaces are half-spheres as shown in section in Figure 3.3. Such a representation of the constriction region is named a *spherical model of contact*.

The electrical resistance of the elemental layer of the constriction region of thickness *dr* located at a distance *r* from the center of the contact spot will be expressed as follows:

$$dR_c = \rho \frac{dr}{2\pi r^2} \tag{3.3}$$

Integration of this expression in the limits from a to ∞ gives the expression for constriction resistance of either of the contacts:

$$R_{c1/2} = \frac{\rho}{2\pi}\int_a^\infty \frac{dr}{r^2} = \frac{\rho}{2\pi}\left(-\frac{1}{r}\right)\Bigg|_a^\infty = \frac{\rho}{2\pi}\left(-\frac{1}{\infty}+\frac{1}{a}\right) = \frac{\rho}{2\pi a} \tag{3.4}$$

The total constriction resistance of contacts of the same materials will be twice as large:

$$R_c = \frac{\rho}{\pi a} \tag{3.5}$$

It should be noted that in practical engineering the spherical model is used seldom, because it operates with very rough assumptions. In the theory of electrical contacts, there exists a more accurate *elliptical model*, which has gained extensive application. The main assumption of this model is that the equipotential surfaces in the constriction region are the rotational half-ellipsoid shaped (for a circular contact spot) with focuses located on the boundary of the contact spot. In this case, to find the constriction resistance, an analogy between the pattern of the current lines outgoing from the contact spot of radius *a* and the pattern of the electrical field of an infinitely thin charged disc of radius a is used. For such analogy, there is well-known ratio between capacitance of the disc C and electrical resistance of the medium R:

$$RC = \rho\varepsilon\varepsilon_0\,, \tag{3.6}$$

where $\rho, \varepsilon, \varepsilon_0$ are the parameters of the medium; in this case it is the contact material.

The disc capacitance relative to the half-space being considered is determined in accordance with the well-known expression:

$$C = 4\varepsilon\varepsilon_0 a\,. \tag{3.7}$$

Substitution of this expression into the previous one gives the formula for determining the constriction resistance:

$$R_{\text{c}1/2} = \frac{\rho}{4a}\,. \tag{3.8}$$

The total constriction resistance of contacts of the same materials will be twice as large:

$$R_{\text{c}} = \frac{\rho}{2a}\,. \tag{3.9}$$

The expression derived is named the *Holm's formula*. If the actual contact occurs by a few spots located far enough from each other, (mutual effect on the pattern of the current lines radiation will be absent), then the constriction resistance will be proportional to the number of contact spots n:

$$R_{\text{c}} = \frac{\rho}{2an}\,. \tag{3.10}$$

The area and, accordingly, the radius of the contact spot a depends on the contact pressure. Its value defines the behavior of the contact face deformation. At relatively small values of the contact pressure (a few Newtons) elastic deformation usually takes place.

In the case, when the contact faces (plane and spherical of radius r) are pressed, then the radius of the contact spot can be evaluated by the Hertz' formula [13, 18–20, 29]:

$$a = 1{,}11\sqrt[3]{\frac{r \cdot P_{\text{c}}}{E}}\,, \tag{3.11}$$

where $P_{\text{к}}$ is the value of the contact pressure;
r is the radius of the contact face sphere;
E is the modulus of elasticity.

As two spherical surfaces with the same radiuses are pressed, the radius of the contact spot will be determined by the following expression [13, 18–20, 29]:

$$a = 0{,}86\sqrt[3]{\frac{r \cdot P_{\text{с}}}{E}}\,, \tag{3.12}$$

It should be noted that elastic deformation occurs in contacts designed for small currents (relay contacts etc.), when contact pressure values are of order of few Newtons. Under high contact loads, the contact pressure per unit of the contact spot area usually in excess of the ultimate bearing strength of the contact material. In this case, the so-called *plastic deformation* will take place in the contacts and the contact material bearing strength $[\sigma_{\text{см}}]$ will determine the radius of the contact spot:

$$a = \sqrt{\frac{P_{\text{к}}}{\pi[\sigma_{\text{см}}]}}\,. \tag{3.13}$$

Substituting this expression into the Holm's formula, we will derive an expression for evaluation of the constriction resistance for the case of plastic deformation:

$$R_{\text{с}} = \frac{\rho}{2}\sqrt{\frac{\pi[\sigma_{\text{см}}]}{nP_{\text{к}}}}\,. \tag{3.14}$$

It should be pointed out that multiple close operations of switching contacts lead to certain changes on the contact face and to determine the contact spot radius, the following dependence is used [13, 18–20, 29]:

$$a = \sqrt{\frac{P_{\text{к}}}{\pi\xi_{\text{м}}H_{\text{Б}}}}\,, \tag{3.15}$$

where $H_{\text{Б}}$ is the Brinell hardness number (BHN) of the contact material;

$\xi_{\text{м}}$ is a coefficient characterizing the contact surface finish machining; its magnitude usually ranges from 0,02 to 1.

Correspondingly, the constriction resistance will be:

$$R_{\text{с}} = \frac{\rho}{2}\sqrt{\frac{\pi\xi_{\text{м}}H_{\text{Б}}}{nP_{\text{к}}}}\,. \tag{3.16}$$

It should be noted that the expressions represented above are appropriate only for a qualitative estimation of the contact resistance magnitude. Nevertheless, they good represent the factors affecting the constriction resistance, which depends, first and foremost, on the properties of the contact material, such as, resistivity, ductility (hardness), as well as on the contact load and the contact spots number.

Theoretical and experimental findings show that the number of contact spots is a random quantity, defined by the probability to come the microroughnesses into contact under the contact pressure action. By this why, it is naturally that the constriction resistance will take on different values after each close operation at the same magnitude of the contact pressure. The spread in these values is characterized by a quantity called *static instability* of the constriction resistance. It is defined as *mean square* or *standard deviation* of the constriction resistance. At sufficiently large contact pressures, the distribution of the constriction resistance values for the same contact pair complies with *normal law*. Under decreasing contact pressures, an asymmetry of distribution comes into appearance, approaching to a *logarithmically normal law* or *lognormal law*.

Along with the notion of static instability, there exists also the notion of *dynamic instability* of contact resistance (constriction resistance). Dynamic instability takes place at the presence of mechanical (shock and vibration) loads action upon the switching apparatus, and accordingly, to the contacts. In the process, the contact resistance can both increase and decrease. The range of this change will be defined by the load action intensity (frequency, acceleration etc.) that determines the dynamic instability value.

In practical engineering calculations of the magnitude (mathematical expectation) of the transition contact resistance, empirical formulas (i.e., formulas based on experimental findings) are usually used. The most extensively used expression is as follows [13, 14, 18–20]:

$$R_c = R_0 + \frac{\kappa}{\left(0{,}102 P_c\right)^m}\,, \tag{3.17}$$

where R_0, κ and m are the contacts depending on the materials, shape and condition of the contact interface;

P_c is the contact pressure value.

Thus, the contact resistance for a given contact pair is mainly dependent on contact pressure. A typical experimental dependence between the contact resistance and contact pressure is shown in Figure 3.4. In the region of small contact pressures, the contact resistance is highly dependent on contact pressure. It is explained by the fact that the conditions of bearing here are more favorable and a small increase in contact pressure leads to a substantial increase in the total actual contact area. At high contact loads, the larger real contact area undergoes the pressure and the contact resistance increases insignificantly according to curve 1 (see Figure 3.4). Under decreasing contact pressure, the contact resistance increases by curve 2 (see Figure 3.4), because the micro-ridges are partially broken under plastic deformation.

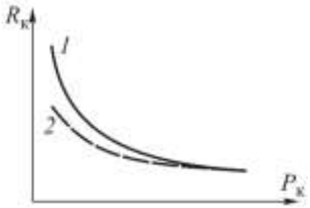

Figure 3.4 – Typical experimental dependence of contact resistance from the contact load

The factors considered above, defining the contact resistance, are valid only for case the contact faces are brightly scraped, when the constriction of the current is practically the only cause of the availability of contact resistance. However, in real conditions of production, transportation, storage and operation the contact faces interact with its surroundings. This results in the formation of the surface layer (superficial film) on the contact face. Its properties may be drastically distinct on the properties of the metals producing the contact interface. It concerns, first and foremost, such a property as electrical conductivity. The formation of films is highly probable on the faces of the contacts operating in aggressive environments, in conditions of elevated temperatures, humidity, dust, etc. In this case, the constriction of current lines is important, but not only it, is the cause of the availability of contact resistance. The presence of surface films on contact face in some cases increases the contact resistance by tens of thousands of times. It in turn results in additional heat generation in the contacts, a reduction of their reliability and service life, and in some cases to a complete failure of the contacts.

Physicochemical phenomena occurring during the formation of superficial films are highly diverse. There are several variations of superficial films on the metal surface. It is, first and foremost, so-called *tarnish films* that are usually referred to dielectric films. Tarnish films encountered on a metal surface are essentially of two types, *oxide films*, formed as result of compounding a metal with air oxygen, and *sulfide films* (compound of metal with sulfur). Tarnish films have usually an uneven thickness (of the order of 10^{-6} sm); their resistivity ranges usually from 10^4 to 10^9 Ohm·sm [19, 29].

Oxide film is formed in the following manner. At first, oxygen deposits on the metal surface, forming an oxide film. Metal atoms penetrate (by the way of diffusion) into this film resulting, due to a chemical reaction, in the formation of the metal oxide molecules. This process is usually called *metal corrosion* in free air. The corrosion is generally the process of chemical changing and destruction of the metal surface layers resulted from the chemical and electro-chemical exposure of its surroundings. The intensity of corrosive processes significantly depends on the temperature on the contact surface.

Elevated temperature contributes to higher rate of the diffusion process and the oxide formation. Therefore, this process is activated when the contact face is in contact with an arc discharge, when the current continuously flows through the contacts, as well as when the contact face is surrounded by the medium with high oxygen content. Humidity of the atmosphere, its pollution by dust and gases increase the intensity of corrosive processes. The contacts operating in the conditions of tropical and marine climate are exposed by intensive corrosion. A number of metals are coated with an oxide film, which inhibits further disintegration of the metal. Noble metals are little or absolutely unexposed by corrosion and, therefore, are frequently used as contact material.

When H_2S (hydrogen sulfide) or SO_2 (sulfur dioxide) is available in the atmosphere, sulfide films offering high enough resistivity (up to 10^8 Ohm·sm) are produced on the metal surface [29].

In parallel with tarnish films, there exists another variation of superficial films. This is so-called *adhesion films* formed because of *absorption* and *adhesive effect*, that is, taking up and deposition of substances on contact surfaces. Such films have frequently a sufficiently high resistivity. For example, the deposition of evaporation solid insulation products (coil wire, coil forms, etc.); deposition of arc thermal action products (contact erosion, soot, thermal black, etc.); pollution by products of mechanical wear (friction of the apparatus pieces), industrial dust and so forth.

Films of this type frequently have a relatively small thickness (in the range of 2.5 to 3 nm), nevertheless, they withstand significant mechanical loads and do not destruct in closing the contacts. Due to the tunnel effect, they are not isolators of the electric current circuit. However, whenever the film thickness increases, the tunnel effect ceases and it becomes a dielectric.

Passivating films as for conductivity take intermediate state between tarnish films and adhesion ones. They are frequently made right on the metal surface to preclude corrosion. They are often artificially made on a metal surface to prevent corrosion. The thickness of passivating films is usually from 1 to 1.5 nm, so they, like adhesive films, are not insulators due to the tunnel effect.

When a relative humidity of the atmosphere is 70–80% and above, the metal surface adsorbs water and forms a water film with a thickness of up to 10 nm. It contains metal ions incoming to it under action of the electric field produced by water dipole molecules. It should be noted that the water film is easily destructed under the contact load action.

Thus, a contact spot or a real (effective) contact area generally contains three types of areas:

1) ones including *organic* and *tarnish films* (*oxide* and *sulfide*) that refer to isolating (practically non-conductive) films;

2) ones including *thin* (*adhesion* and *passivating*) *films* with thickness of up to 3 nm having tunnel conduction; they are usually named *quasi-metallic contact areas*;

3) ones where *pure metallic contact* takes place; they are formed due to great forces disrupting the superficial film.

It should be pointed out that at zones of purely metallic contacting large forces of intermolecular and interatomic bonds are produced, therefore it occurs only at very small areas; otherwise, such a contact could not be broken by the forces taking place in real devices. Hence, films available on the metal surface play positive role, precluding the development of large forces of intermolecular couplings. In addition, the films play the role of specific type lubricant, reducing the friction force during the mutual sliding of the contacts.

A wide variety of processes leading to the formation of superficial films, as well as a rather complicated structure of the contact area, do not allow us to analytically evaluate the contact resistance taking into consideration the resistance of superficial films. That is why, in engineering practice, the contact resistance due to the presence of superficial films is taken into account on the base of experimental researches, mathematical statistic methods, etc.

In the contacts designed for operation under high currents, tarnish (non-conductive) film is mechanically destroyed under the action of large contact loads. If contact pressure is sufficiently small, it may be destroyed under action of a voltage drop because of electrical puncture with the formation of a thin metal bridge. This phenomenon derived name *film fritting*. Thus, for switching devices designed for operation under high currents the formation of non-conductive films does not substantially effect on the contact operation and is not a problem of great concern.

For the contacts designed for operation under small currents and correspondingly having small contact loads the superficial films is a great problem because they do not destroy when the contacts are closed. In this case, the engineering solutions of the contact systems are usually aimed to restrict the production of non-conductive films, first and foremost, by the use of noble metals, such as silver, gold, platinum and others. Another method to reduce the formation of superficial films is encapsulation of contacts. An example of such technical solutions is the use of hermetically sealed and magnetically operated contacts of reed switches. The contact elements of the reed switches are made of ferromagnetic material and at the contact place are coated with a thin layer noble metal (gold, palladium etc.). Such technology enables to stabilize the contact resistance since the exposure of environment (including the active medium) is precluded. There are also other constructive techniques to reduce the influence of superficial films on the contacts operation. It is, first and foremost, application of so-called *self-scraped bright* (*wiping*) *contacts*.

3.3 Arc Extinguishing in Switching Devices

As it was already mentioned, interrupting the electrical circuit by contact-based switching devices is impossible without arc quenching, i.e. a certain action on the arc column for the purpose its deionization and increase its electric resistance.

Arc extinguishing (quenching) in contact-based switching devices is carried out by the so-called *arc control systems* or *arcing devices*. Since arcing devices operate in combination and strong interaction with parting contacts of the switching device, this component is frequently named a contact-arcing system.

The arc column touching with contact faces and arcing device components causes their heating and wear. Therefore, the main requirement imposed upon arcing device is to limit the arc column thermal action on the switching device components. In most cases, the arcing time is confined by a few hundredths of a second (maximal time is 0.1 s). At the present time, there is a wide variety of technologies to extinguish an arc. Let us consider the most extensively used ones in switching devices for high and low voltage applications.

Arc extinguishing in free-air (unclosed rupture). This technology consists in mechanically stretching of the arc column by opening contacts. It should be pointed out here that to stretch the arc column, the magnetic field, produced by the current-carrying parts or magnetic systems designed for this purpose, plays an essential role. The use of such a simplest arc extinguishing technology is possible in the case of low voltage circuit interruption at relatively modest currents (lower than 50 A).

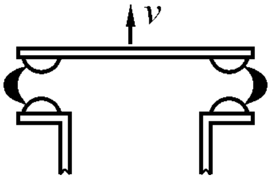

Figure 3.5 – Bridge contact system

In order to increase the interrupting ability, when this arc extinguishing technology is applied, the so-called *multiple rupture* is frequently used (i.e., the circuit is interrupted by simultaneous formation of a few series contact gaps). The performance of such a method is caused by the fact that increase in the number of series contact gaps results in proportional increasing in the value of initial recovery strength. The most extensive application has devices with a double rupture, realized by the so-called *bridge contacts* represented in Figure 3.5.

An essential advantage of the systems with unclosed arc extinguishing is simplicity of the construction. Disadvantage is the relatively small currents to be interrupted.

Arc extinguishing with deion grid. This technology of arc extinguishing was offered by the Russian scientist Dolivo-Dobrowolsky in 1912. It is extensively used in switching devices for high and low voltage applications. The arc chute with deion grid is a stack of copper-covered 2-3 mm thin steel plates placed on some distance one from another as shown in Figure 3.6.

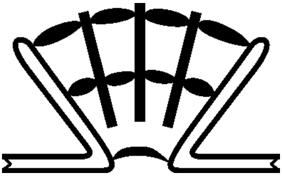

Figure 3.6 – Arc chute with deion grid

In the circuit interrupting process, the arc column is drawn into the chute where it is split into ~~a~~ series of short arcs. The grid plates serve in this case as heat sinks intensively cooling the arc column. In the near-electrode regions, that is, at each plate, the initial recovery strength is initiated. Its total value determines arc extinguishing performance and, respectively, the interrupting capability of the switching device. It should be noted that experimental findings do not confirm the direct proportionality between the number of plates in the grid and the total value of the initial recovery strength. Nevertheless, this technique is very effective. Its basic advantages are as follows:

- high interrupted currents: switching devices with application of deion plates offer high interrupting capability;

- comparative simplicity of construction; the arc column is drawn into a grid and held within it by means of self-magnetic field, therefore additional elements for this purpose are not required;

- deion grid possess the property to limit overvoltages, their values are determined by the number of plates.

- The main disadvantages of this arc extinguishing technology are as follows:

- the arc chute withstands a small number of switching operations, since the plates are quickly destructed under the thermal action of the arc column;

- in the grid made of simple plane plates, the reverse movement of individual arcs is possible caused by the action of electrodynamic forces.

Gapped arc chute with magnetic blowout. This arc extinguishing technique has found extensive application in low voltage switching devices, carrying out frequent switching (make-break) operations. The simplest contact-extinguishing system with application of gapped arc chute combined with magnetic blowout system is represented in Figure 3.7.

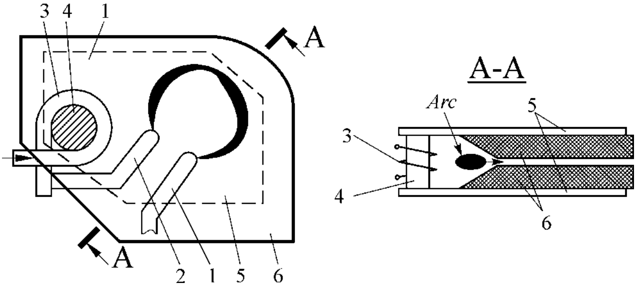

Figure 3.7 – Gapped arc chute with magnetic blowout system

It consists of a movable 1 and fixed 2 contacts, magnetic blowout coil 3 with a core 4, magnetic blowout system poles 5 and gapped chute 6. If the blowout coil are in series with the contacts, so the system is a *series magnetic blowout system*. When they are parallel connected, then it is a *parallel magnetic blowout system*. One of the key elements of the arcing device is a *gapped chute* made of an arc-resistant material, such as asbestos cement, arc-resistant ceramic etc. The chute has a narrow clearance (slot) into which the arc column is drawn, where it is deformed and, being in touch with the chute walls, is deionized and quenched. Driving the arc column towards the chute is carried out by the action of a magnetic field produced by a magnetic blowout coil. Magnetic flux, providing magnetic blowing out, is conducted to the arc column zone with the help of poles made of ferromagnetic material.

The main advantage of such an arc extinguishing system implies in that it provides a great number and a high frequency of switching operations. The shortcoming is the limited interrupting capability.

Arc extinguishing by an airflow. This technique has found extensive application in high voltage circuit breakers since make possible to construct arcing devices for the ultimate parameters of the circuit to be interrupted (current 80 kA at voltage 1150 kV). The arc extinguishing in this case occurs within enclosed chambers, where the arc column is cooled and deionized under the action of a powerful high-speed airflow. There are arcing chambers, in which the airflow is axially directed in relation to the arc column (*axial-blast type* chambers) and directed across to the arc column (*cross-blast type* chambers).

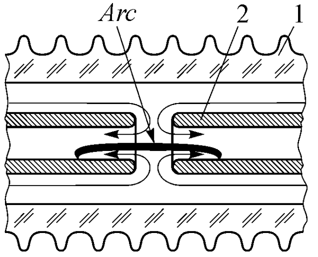

Figure 3.8 – Arc extinguishing within air axial-blast chamber

As an example, let us consider an arcing device of axial-blast type represented in Figure 3.8. Such devices are most extensively used at present time. It consists of a porcelain shell 1, in which tubular contacts 2 are placed. The internal space of the tubular contacts is communicated with free air. Compressed blast air is conducted to the arcing chamber from a special-purpose tank. As the contacts open, the appearing arc column is stretched and cooled by the intensive airflow, which rushes into the internal space of the contacts.

The main advantage of this arc extinguishing technique is a very high breaking capacity. Until the recent time, just this arc technique had the most extensive application in the circuit breakers rated by the voltage 110 kV a higher. Correspondingly, air-blast circuit breakers (i.e., switching devices, wherein this technique is used) occupied a dominant position; however, at present time the situation changes significantly, since the so-called SF_6 circuit breakers have become available. Disadvantages: sufficiently complex construction of switching devices where this principle is realized; the need to have a compressed air source and, as a result, great energy expense is required.

Arc quenching in SF_6 gas medium. SF_6 gas (sulfur hexafluoride) was first prepared as long ago as 1890 by Henri Moissan and Paul Lebeau. At this time, it was revealed that it possess enhanced (compared with air) electrical strength had been. In the 30s of the last century, in the context of wide researches performed in the field of nuclear physics, the Soviet scientist B. Gokhberg and his research workers complexly investigated the electrical strength and other properties of various vapors and gases. Among all investigated substances, only sulfur hexafluoride most fully meets all the requirements with respect to application in switching devices and other electrical equipment. This gas possess good combination of electrical, physical and chemical properties; that is why it is frequently named *electrotechnical gas* (*elegas*).

Pure gaseous sulfur hexafluoride offers the following properties:

- *enhanced electrical strength*: it is 2,5 times higher than that of free air; besides growth of pressure leads to increase in this difference;
- *excellent ability to quench an arc*: interrupting capability of the contacts that open in SF_6 gas medium is 4–5 times higher than in free air;
- *enhanced cooling ability*: it enables to increase the load of current-carrying parts and, accordingly, reduce their mass and cost;
- *absolute harmless* (no toxicity);
- *no chemical activity*: in normal conditions it does not react with materials applied in electric equipment;
- the one *has a low liquefaction point*: i.e., electrical equipment can be operated with no additional heating in normal conditions;
- it does not burn and does not maintain burning (i.e. equipment is explosion-proof and is no fire hazardous;
- *almost no ageing*: therefore the electrical equipment does not require specific maintenance and has low exploitation expenses;
- solid products of SF_6 gas thermal destruction under the action of an arc practically do not affect the electric insulation strength.

The positive electrical qualities of SF_6 gas result from its the so-called *electronegative properties*. At a relatively low temperature (of the order of 3000...4000 K) SF_6 gas almost fully dissociates with the formation of a sulfur atom and six atoms of fluorine. Fluorine atoms offer the feature to capture free electrons, forming massive negatively charged ions with very low mobility. These ions are slightly involved in the current carrying. However, the number of the electrons (involved dominantly in the current carrying) reduces significantly, what leads to a drastic decrease in the arc plasma electric conductivity. This is especially important when the current reaches a zero value and due to electrons capture the dielectric strength sharply increases that results in the contact gap becomes little sensitive to the rate of rise of recovery voltage

A number of investigators, however, consider that the electronegative properties of SF_6 gas play an auxiliary role, whereas the thermo-chemical processes that occur under the action of high temperature are of main importance. In particular, the main meaning have the property of SF_6 gas, that makes possible to decrease rapidly the temperature of the residual arc space at current-zero moment [17, 20].

In 1956, the first switching device with employment of SF_6 gas was patented. By now, high-voltage circuit breakers with arc quenching in SF_6 gas medium have been designed and successfully operated. In SF_6 gas circuit breakers the arc is quenched, at the same manner as in the air-blast ones, by means of intensive cooling of the arc column by SF_6 gas current. SF_6 gas circuit breakers have an extremely high switching capability per one contact pair at present time. 245 kV contact gap is standard today. For voltage of 420 kV two contact pairs in series per one pole are used. The application of four contact pairs per one pole is known (US, 800-kV substation). At present time, SF_6 gas circuit breakers intensively supersede air-blast ones and, as estimated by leading experts, in the near future they will take dominant positions at voltage ratings 220 kV and above.

Arc extinguishing in a vacuum medium. First and foremost, it should be pointed out that an electrical arc discharge in a vacuum medium differs significantly from high pressure arc discharge, in which current carriers (free electrons and positive ions) are mainly produced from neutral atoms of the medium (air, SF6 or oil) that surrounds the opening contacts. In a vacuum medium, where ionized gas particles are practically not available, an arc discharge is initiated due to the presence of ionized metal vapors produced by the explosion of metal bridge produced on the early stage of the contacts opening. Its further existence is maintained due to metal vapor coming from the cathode spots, while in the high-pressure arc the metal vapors coming from the cathode and anode spots play an insignificant role. That is the main distinctive feature of the vacuum arc.

Thus, because of the high electric conductivity of ionized metal vapors, a steady arc discharge is produced across the contact gap. As differentiated from high-pressure arcs, a multitude of fast-moving cathode spots is produced in vacuum arcs. The number of cathode spots is determined by the value of interrupted current. The magnitude of the current being carried by each of the cathode spots is a function of the contact material, and in most cases it is approximately 60–100 A. Considering that the sizes of cathode spots are very small (from units to several tens of microns), current densities as high as of 10^6 A/mm^2 that leads to intensive heating the metal in the cathode spots up to several thousand degrees, its boiling and evaporation. Furthermore, a very high pressure (tens of atmospheres) is produced in the cathode spot resulting in outflowing from the cathode spot supersonic jets of dense highly ionized plasma.

As the current passes through zero value, the metal vapors condense very rapidly (within about 10 μs). It results in disappearance of electric current carriers across the contact gap, which practically completely recovers its dielectric properties. The possibility of arc reignition resulted from the recovery voltage comes after 50 ... 60 μs. This phenomenon explains high interrupting capability of switching devices, in which an arc is quenched in a vacuum medium. It should be pointed out that attempts to employ vacuum as an arc-extinguishing medium for interruption of dc circuits did not yield positive outcomes because the current does not pass naturally through zero values.

Vacuum arc can be exist in two modes according to the value of the current being interrupted. At currents below 8–10 kA, the vacuum arc is usually in *diffuse mode*; when a certain part of the contact gap space is evenly filled with an arc plasma having a characteristic glow. Under increasing current, the arc volume increases and, at a certain its value, fills all space of the interrupting chamber. At currents above 8–10 kA, the behavior of the vacuum arc drastically changes taking *coalescent* or *constricted mode*. The arc column becomes like brightly glowing cord and a single anode spot appears thus creating a new source of metal vapors, which because of the thermal constant of the anode spot continues to produce vapors even after current zero that makes difficult the interruption. At a certain current value, reignition occurs, i.e. a current of reverse direction is started to flow across the contact gap. This phenomenon is considered a circuit breaker failure.

To interrupt the current successfully, it is necessary to preclude the appearance of anode spots because of constriction of the arc. The minimal current at which the vacuum arc takes the constriction mode, is the physical limit of the current to be interrupted. For butt type contacts, this value is 8...10 kA. Currently, more advanced constructions of contact systems with a significantly higher interrupting capability have been developed [13, 19, 20, 23]. Nevertheless, the condition stays invariant, that is, constriction of the arc discharge must be excluded.

The vacuum interrupter is structurally shown in Figure 3.9. It is an encapsulated vessel evacuated to that or other degree: low vacuum ($10^5…10^2$ Pa); medium vacuum ($10^2…0{,}1$ Pa); high vacuum ($0{,}1…10^{-5}$ Pa); deep vacuum (below 10^{-5} Pa). The interrupter consists of a case 1 with a ceramic insulator 2, a fixed 3 contact, movable contact 4 fastened to the case by means of bellows 5 (flexible corrugated tube of sheet steel) that enable its movement.

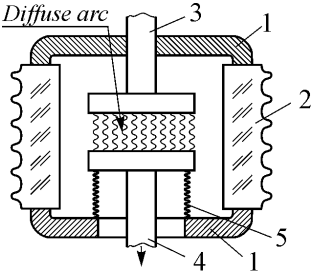

Figure 3.9 – Vacuum interrupter

The evident at first glance simplicity of the vacuum interrupter construction is highly deceptive. In actual situation, it includes many scientific and technological innovations (“know-how”). At present time, vacuum interrupters are extensively used in the switching devices for high and low voltage applications. Suffice it to note that vacuum circuit breakers are now the dominant switching devices in 6...35 kV electrical power systems. Vacuum switching devices have a number of important advantages:

- *high switching wear-resistance*: they ensure a great number of switching operations by the same contact pair; therefore, vacuum interrupters are used in apparatus for frequent switching operations (control apparatus);
- *minimal maintenance*: expenses for service significantly less than ones for service of apparatus with other types of arcing devices;
- *full safety against explosion and fire*;
- enhanced *stability against impact and vibration loads*;
- normal operation *under conditions of pollution and dust content*;
- *small dimensions and mass*.

It should be noted also the disadvantages of vacuum interrupters: difficulties in matching the contact materials as well as great capital outlays for setting mass production because vacuum industry is sufficiently complex.

Arc extinguishing in transformer oil medium. Transformer oil is a product of the petroleum refining, a hydrocarbon liquid with excellent dielectric properties. The use of transformer oil as an arc-quenching medium has long history. In first switching devices for high voltage applications, the only transformer oil was used. E. Thomson (USA) proposed this arc extinguishing technology in 1893; engineers D. Hyllardy and Ch. Parsons (USA) developed the first construction of an oil switching device. In 1907, J.N. Kelman (USA) patented the first oil circuit breaker.

Let us consider the properties of an electric arc burning in a medium of transformer oil. Burning of an arc in a liquid, and in particular in transformer oil, is occurred with the formation and expansion of a gas-vapor cavity (gas-vapor bubble) resulted from its thermal action. Thus, in the process of arc quenching the arc column is surrounded by inhomogeneous gas-and-vapor mix. It includes, first, *transformer oil vapors* located at the periphery of the cavity. The layers located closer to the arc column are heated more strongly and therefore the transformer oil vapors decompose into the *hydrocarbon gases* C_2H_4, C_2H_2 etc. At a temperature of 1500 K and above, in the layers that contact immediately with the arc column, hydrocarbon gases decompose into *hydrogen* and *carbon*.

The hydrogen, which forms in the process, possess high heat conductivity and carries out intensive driving of the heat out from the arc column, and thereby provides its quenching. Arcing within a closed space is occurred with drastic increase of pressure within the cavity that also contribute to the arc-extinguishing process. However, in real oil-based switching devices, arc quenching is mainly carried out by means of positive pressure produced by the arc (self-blast). Such principle is used in the so-called *minimum oil circuit breakers*. Operating cycle of such an arcing device is represented in Figure 3.10.

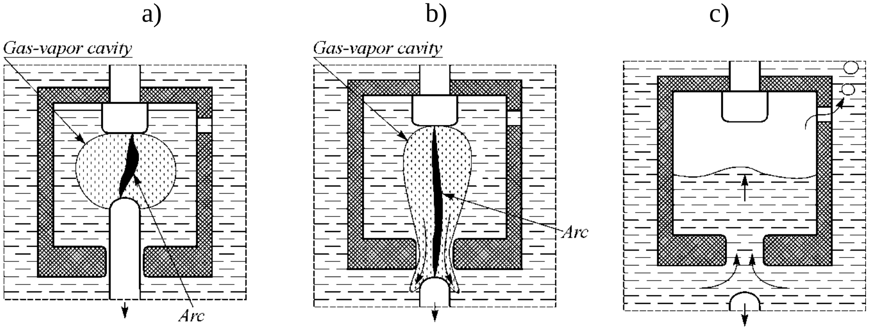

Figure 3.10 – Operating cycle of minimum oil circuit breaker

It includes three typical stages:

I. Just after the contacts are started to open, *the arcing occurs within a closed gas-vapor cavity*, as shown in Figure 3.10a; in the process, a rather high pressure (30...40 atm) is produced in the chamber;

II. As the movable contact is beyond the arcing chamber, under the action of positive pressure, the gas-vapor mix begins to flow outside the arcing chamber as shown in Figure 3.10b; in the process, *axial blowing the arc column happens*;

III. After the current-zero moment, the arc extinguishes and the hot gases start to outgo from the arcing chamber, which is filled with transformer oil as shown in Figure 3.10c.

Among the numerous existing methods to extinguish an arc, one more method, used extensively in switching devices for low and high voltage applications, is worth to consider. The case in point is the so-called *self-gas* arcing devices. In such systems, an arc is quenched with the flow of a gas produced because of the arc column thermal action on solid gas-generating material, such as red fiber, polymethacrylic acid (organic glass) and a number of other materials. Under the action of high temperature, these materials decompose to a number of components: CO_2, CO, H_2, vapors of H_2O. Such arcing devices are usually enclosed chambers that result in high pressure (2...5 amp) is produced during the arc-quenching. The combination of these factors exhibits a deionizing effect on the arc column. In a number of such types of the arcing devices, a pressure drop is produced resulting in *self-gas blast*.

3.4 Electric Erosion Phenomena in Switching Contacts

General notions and classification. Electric erosion phenomena are highly typical for switching devices, in particular for contacts that fulfill make-break operations in electric circuits (i.e., switching contacts). It is well known that opening the contacts under current load leads necessarily to the initiation of an arc discharge, which attacks the contact surface resulting in its erosion destruction. It should be pointed out that such phenomena are typical not only for switching devices. The phenomena occurring on electrode surfaces and across electrode gaps, selection of electrode materials and structural materials operating under conditions of contact with arc discharge plasma are investigated by a wide circle of scientists and investigators working in various scientific and engineering fields.

Among them, first and foremost, it should be noted such important industry as *electric technology*, which, in turn, has several large scientific directions. It is based on the employment of electric erosion phenomena in such technologies as arc and resistance welding, electric erosion (discharge) machining, electro-thermal, electro-physical methods of machining metals (electron-beam technology and others), technologies of plasma jet spraying of materials and number of some others.

Another important direction associated with the study of electric erosion phenomena is the development of *high intensive light sources*. At present time, it happens by the employment of arc and impulse-arc technologies. Besides, to ensure high technical-and-economical performances of arc light sources, it is necessary to choose rationally electrode material with predetermined emissive and thermophysical properties that is impossible with no consideration of electric erosion phenomena. This enumeration could be continued. In this case, we consider electric erosion processes at the contacts of switching devices taking place during the contacts close and open under current load.

Electric erosion is a combined notion including a complex of phenomena resulting in local destruction of the material in places, where heat is locally generated, under current flowing. Hence, electric erosion phenomena are not always associated with the action of an arc discharge on electrodes (contacts). They have wide variety and, depending on the feature of the local heat generation, these phenomena can be subdivided into two groups: contact erosion phenomena and contactless erosion phenomena.

Contact erosion phenomena take place, where metallic contact of electrodes or narrow bridges of monolithic conductors are located, under current load. First and foremost, the so-called *bridge erosion* refers to the contact erosion. It takes place when the contacts, designed for low current devices (such as relays), are opened, as well as at the initial stages of opening the contacts, designed for switching high currents. In this case, the contact surface zones being immediately at electric contact are exposed by local destruction. The cases when electric contact itself is absent, but a constriction of current lines takes place, are also referred to contact erosion phenomena. When let through current density becomes as high as a certain critical value, the so-called *electro-explosive erosion* takes place in narrow bridges of monolithic conductor. Such processes occur, for example, in the narrow necks of safety fuse links in interrupting of the fault current.

Contactless erosion phenomena are referred by forms of electric erosion involved in the availability of electric discharges and their exposure on electrodes (contacts) and other structural components of apparatus. It is, first and foremost, *gas discharge erosion,* when electrodes exposed by the discharge involved in its initiation. The contact surfaces of switching devices are most frequently subjected by the attack of an arc discharge. Respectively, in this case we deal with gas discharge erosion named *electric arc erosion*. Another variety of contactless erosion is the so-called *plasma erosion,* when an electric discharge attacks components that are not involved in its initiation. The types of electric erosion discussed above take place in switching devices when contacts close and open. As practical experience shows, electric erosion processes during contacts opening in most degree effect on the contacts operability. By this why, let us consider first electric erosion phenomena occurred with the process of contacts opening.

Electric erosion during opening contacts. When the contacts being under load current open, it is evident typical sequence of processes. At the initial state, when the contacts are in close position, the contact spots are available on the contact surfaces, produced by the action of the contact force through elastic or plastic deformation. When the contacts is started to open, at first, the contact pressure is decreased and relatively the contact spot area is gradually reduced. Its instantaneous disappearing is impossible, since the speed of contacts opening in real apparatus constructions is much lower than propagation speed of an elastic wave in metals. That is, on early stage of the contact opening the contact spot area will decrease proportionally to the contact pressure.

Accordingly, the contact resistance grows leading to heating of the metal near to contact spot, its melting and formation of the molten metal "bridge". After the contact load has decreased to zero, the contacts start going apart with certain speed and thereby draw formed metal "bridge". As the temperature in any point of the "bridge" as high as boiling point, explosion occurs resulting in break of the "bridge".

Thus, in the early stage of contact parting until the rupture of the "bridge", contact erosion takes place usually called *bridge erosion*. The main feature of this process is the outcome of bridge erosion is usually the transfer of the material piece from one contact to another known as *bridge transfer*. As practical experience shows, bridge transfer occurs even in the case when the anode and cathode are made of the same materials and the contact system is symmetrical.

There are a number attempts to explain the cause of the bridge transfer. However, the *thermal theory of bridge erosion* is the most recognized today. According to this theory, its main cause is the thermal asymmetry of the bridge, that is, asymmetric temperature distribution along the stretching bridge, which is explained by distinctive conditions of heat generation at the contacts. In some cases, the bridge thermal asymmetry can be resulted from the electro-thermal effects, such as Thomson effect, Peltier effect, Kohler effect. One way or another, the bridge thermal asymmetry leads to its break not at the middle point, but at the point shifted to one of the contacts (more often closer to anode). The outcome of these phenomena is usually the formation of incrustations and hollows on the contact surfaces that can cause disturbance of the contacts normal operation. It should be noted that the selection of the dissimilar materials and their thermal-and-physical parameters could compensate bridge erosion.

Bridge erosion and bridge transfer play a significant role in switching devices in which electric arc discharges do not form in the process of interrupting electrical circuits. First and foremost, it refers to switching contacts interrupting small currents at small circuit driving voltage (relay contacts). In this case the current being interrupted and (or) power frequency recovery voltage can be less than the corresponding values of arcing. Bridge erosion can play a significant role in the contacts shunted by semiconductor devices or arcing contacts (see chapter 1). In this case, the initial stage of contact parting proceeds in the same manner followed by the current being interrupted transits into a parallel circuit, thereby significantly reducing the arcing time.

The volume of bridge erosion (bridge transfer) per one interruption of the circuit can be evaluated by the following empirical formula [13, 18, 19]:

$$V_{\text{м}} = \kappa_{\text{м}} I_{\text{o}}^{3}, \tag{3.18}$$

where I_{o} is the current to be interrupted;

$\kappa_{\text{м}}$ is a constant, depending on the thermal-and-physical properties of the contact material.

If the interrupted current and voltage of the interrupted circuit exceed the corresponding arcing parameters, then the next stage of the contact opening, from qualitative standpoint, is the initiation of an electric arc discharge. This stage is occurred with the so-called *arc erosion*. Just this process plays a key role in contacts destruction due to electric erosion and determines their life span (switching life). In actual practical situation, the destruction (wear) of contacts because of arc erosion is 15-20 times more than due to bridge transfer.

First of all, it should be pointed out that the electric erosion exposure of an electric arc discharge to contact surfaces is occurred with interaction of complex thermophysical and gas-dynamic processes occurring in small spaces, namely, the places where the arc column in contact with the contact surfaces (i.e., in the anode and cathode spots). These spots are inhomogeneous in their structure and are multitude of elementary spots with a very high current density (10^7–10^8 A/sm^2). The concentrative generation of thermal energy in the near-electrode zones of the arc column (in the anode and cathode spots) results in local heating of the surface and near-surface layer of the contact faces that leads to melting, vaporization and partial ejection (carrying away) of the contact material from the regions of anode and cathode spots.

In spite of the apparent simplicity and evidence of the processes, the specific mechanism of arc erosion stays currently not clearly established. The complexity to study of these processes implies in in the fact that they occur within extremely short time spans (measured in the range from fractions to a few milliseconds) and depend on specific conditions of arc extinguishing (technique, medium, pressure, structure of the contact material, etc.).

At the same time, complex thermophysical and gas-dynamic processes, which occur across the contact gap, are governed by complex systems of differential equations that usually include heat conduction equation, Navier-Stokes equation, continuity equation and others. Moreover, these equations have indefinite boundary conditions in zones sharing the high-temperature arc roots and phase changes of the contact material in vaporous, molten and solid states. The analytic solution of such systems is a formidable task, but just they determine the processes of erosive destruction and, in particular, one of the most important among them is the mechanism of ejection of the contact material from the anode and cathode spots. In this regard, the calculations of the arc resistance of contacts (i.e. quantifiable determining arc erosion) are mostly performed by empirical formulas derived on the base of experimental investigations.

Thus, the so-called *thermal hypothesis of arc erosion* is the most recognized at present time. According to this theory, the destruction and ejection (carrying away) of the contact material occur in a few manners according to the type of the switching device operation. At relatively small interrupted currents and a short arcing time, arc erosion occurs in separate *micro-craters* and mainly because of the vaporization of the contact material due to the so-called *superficial thermal source* (i.e. thermal energy generated in near-electrode zones). Under increasing the interrupted current and the arcing time, a continuous pool of molten metal, called usually *macro-pool*, is formed. At this time, boiling and intensive vaporization occur with *spraying of molten fractions of metal*. In addition, the ejection of the molten metal drops can occur under the action of electrostatic and electrodynamic forces. Recently the prevailing standpoint that explains the mechanism of material ejection and erosive wear of contacts as a whole is the assumption that contact material is ejected by virtue of *axial plasma jets* (see subdivision 2.).

A quantitative performance for arc erosion is *wear of the contacts*, i.e. reduction of their mass (volume) under the exposure of arc discharges. For low-voltage apparatus, the most frequently used performance for contacts wear is a reduction the "follow-trough" of contacts. In some cases, the so-called *arc erosion rate* (dm/dt), i.e. loss of contact material per unit of arcing time for a given interrupted current is used as such performance. However, most extensively used performance is the *specific wear* $m_{\text{уд}}$ ($V_{\text{уд}}$) expressed as the ratio of the lost contact material mass (volume) to rms current and time (i.e. quantity of electricity) of the arc discharge. Numerous investigations dealing with arc erosion show that wear of contacts depends on many factors. Let us consider the most significant ones.

First and foremost, the rate of arc erosion of contacts is dependent upon the value of the current being interrupted. This dependence behaves usually in sophisticated manner and is determined by environmental conditions. For contacts, opening in a gaseous medium, typical experimental curve for the rate of contacts erosion as function of the interrupted current is shown in Figure 3.11a [8].

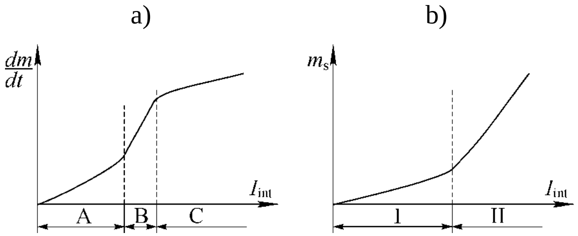

Figure 3.11 – Typical dependencies the contact wear vs the interrupted current.

As can be seen, the contacts wear has the tendency to grow under increasing the current being interrupted. The dependency represented has three characteristic regions. *A* is the region of light interrupted currents wherein the contacts wear is mainly determined by the vaporization of the material and its ejection by plasma jets. *B* is the transition region. *C* is the region of high interrupted currents, wherein enhanced wear is resulted not only by the contact material vaporization, but also spraying of molten metal. For contacts opening in a vacuum medium, such dependency behaves as shown in Figure 3.11b [20]. It has two regions with a practically linear increasing the contacts wear and dissimilar slopes. Region *I* accords to the diffuse vacuum arc; region *II* accords to the constricted vacuum arc.

The rate of electric arc erosion also substantially depends upon the contact material. In particular, the melting point of the metal plays a significant role; the more refractory metal is, the less the contacts wear rate, at other equal factors, will be. In this case, the transition region is right shifted, that is, the transition from region *A* to region *C* happens at higher currents. In addition, it should be pointed out the influence of the material heat conductivity on the erosion rate that consists in the following. Materials having high thermal conductivity cause more intensive plasma jets and, hence, undergo more intense wear.

The arc erosion rate of also depends on the design of the contact unit construction. In this case, the mutual arrangement of the contact faces has essential significance. The least wear takes place in the case when the plasma jets are directed to encounter and partially compensate each other. The intensity of plasma jets is also affected by the contact face area. The larger area is, the less the plasma jets intensity and, accordingly, wear of the contacts will be. The design of the contact unit defines the velocity of the arc roots movement over the contact surfaces. The higher the movement velocity is, the less the rate of wear will be.

Contact surface temperature cases can play a certain role in individual cases. It effects, first, on the plasma jets intensity: an elevation of temperature leads to a decrease in the intensity of plasma jets and, accordingly, the contacts wear. Contact heating by extraneous source can significantly weaken the plasma jets intensity.

It should be pointed out here practically no effect of arc-extinguishing medium on the rate of electric arc erosion. Experimental findings has ascertained that the rates of arc erosion are practically identical both in free air and in transformer oil at the same interrupted currents, arcing times and other equal factors.

As already noted, mathematical simulation of electric arc erosion is highly difficult because of the wide variety of metal ejection mechanisms. Therefore, at present time electro-erosive wear of contacts is evaluated mainly by use of experimental findings and empirical dependencies.

For example, in practical engineering calculations, the following formula is frequently used [13, 18, 19]:

$$\frac{dm}{dt} = \kappa I_{\mathrm{o}}^{1,6} \tag{3.19}$$

where I_{o} is the current being interrupted;

κ is a constant depending on the contact material properties.

The erosion rate both in region A and in region C (see Figure 3.11a) is determined from given formula, but the constant κ will be different in magnitude. It should be noted that there exists a number of other empirical dependences to evaluate the arc erosive wear for specific constructions of contact units and conditions for the existence of an electric arc discharge [16, 20, 24, 29].

Electric erosion of the contacts on closing. It should be keep in mind that in a number of electric apparatus, switching devices, in particular, for high voltage applications, the erosive processes on closing contacts may play a significant role in their wear. In the process, both contact-based forms of erosion and its contactless forms take place. Whenever contacts close, as well as during the opening, a certain attributive sequence of processes is evident. When the contact faces having different potentials approach to each other, in many cases, at a certain gap (that depends on many factors) an electric breakdown happens, and accordingly, an electric discharge initiates

There are various explanations for the mechanism of breakdown of contact gap during the closing contacts. The most well-known standpoint is pre-changes on the contacts faces under the action of an electric field occurring with drawing macro-particles out from the contact body, the formation of "bridges" and "nibs" that cause a reduction of the gap or its full overlap. The electric discharge, appearing in the process, causes electric erosion. Its intensity is determined by the form and duration of the discharge, generated power and properties the contact material.

By further rapprochement of contact faces, a metal contact forms with a changing resistance down to a certain minimal value determined by the contact load. At this stage under the action of the flowing current, thermal energy is generated that leads to the formation of molten zones and redistribution of material over the contact face. The intensity of contact-based erosion at this stage depends on the contact material properties, the conditions of its closing and the parameters of the circuit to be interrupted.

When the contacts, moving on closing with certain velocity, collide, the kinetic energy converses into potential one, which, in turn, is liberated resulting in the opening of the contacts. The next stage is the approach of the contacts under the action of external driving forces, and the process qualitatively occurs repeatedly until the system fully damps. This process is named *contact bounce* (*chatter*). As the contacts open in a bouncing process, the phenomena discussed above, such as bridge erosion and then arc erosion, take place. The operating practice of switching devices shows that just the contact bounce plays key role in erosive wear of the contacts on closing under current load.

It should be noted that, in general, electrical erosion of contacts on closing is usually not significant in the total volume of electric erosion processes in switching devices. Nevertheless, in certain cases it can play a quit appreciable role. For example, in contacts shunted by semiconductor devices or arcing contacts, wherein an electric arc is practically eliminated when the contacts open and electrical erosion is resulted only from the bounce when the contacts close, as well as in the early stages of the contacts opening.

4. TRANSIENT RECOVERY VOLTAGE PROCESSES AT INTERRUPTING ELECTRIC CIRCUITS

In parallel with the dielectric recovery, the transient recovery voltage is one of the most important quantity defining the interruption process of ac electric circuits. To the present day, it has been reliably established that the switching capability of the apparatuses is defined not only by the parameters of the circuit being interrupted (its value, cosφ), but also by the parameters of the transient recovery voltage.

4.1 The Definition and Specification of Transient Recovery Voltage

Transient recovery voltage (TRV) is the instantaneous voltage value across the contacts of the switching device during the transient process of the recovery voltage. As the transient recovery voltage process has completed, the power frequency voltage restores between the contacts of the switching device named *power frequency recovery voltage* (PFRV). Let us consider at first the recovery process in interrupting the simplest electric circuits.

In a pure resistive circuit, shown in Figure 4.1a, the current being interrupted *i* is in phase with the supply voltage u_0. As the current passes through zero value, its instantaneous value equals zero as well. If no arcing after current-zero, the voltage identical to supply voltage u_0 restores across the switching element *S* as shown in Figure 4.1b.

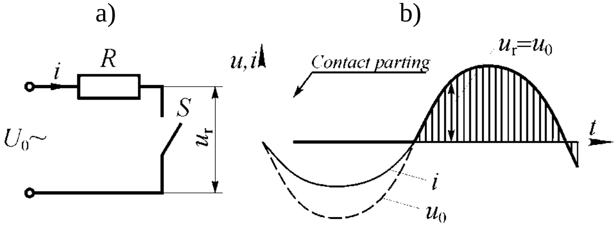

Figure 4.1 – The recovery process in a pure resistive circuit:
a) equivalent circuit; b) time diagrams

In a pure capacitive circuit, shown in Figure 4.2a, the current being interrupted *i* leads the supply voltage *u* by 90°. At the current-zero instant the supply voltage corresponds to its crest value. If after the current-zero no arcing, the voltage on the capacitance *C* is trapped at the crest value while the supply voltage continues to follow its sine waveform. In the process, a voltage equal to the sum of these voltages will restore across the switching element *S*, as shown in Figure 4.2b. In such a way, one-half cycle after the current-zero instant the voltage across the switching element S will become equal to the doubled supply voltage amplitude.

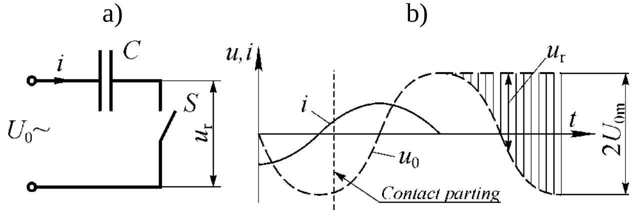

Figure 4.2: – The recovery process in a pure capacitive circuit:
a) equivalent circuit; b) time diagrams

In a pure inductive circuit, shown in Figure 4.3a, the current being interrupted *i* lags the supply voltage *u* by 90°. At the current-zero instant the supply voltage *u* equals to its crest value, therefore the voltage across the switching element *S* rapidly restores as high as this value, as shown in Figure 4.3b. In this case, the transient recovery voltage may have a high-frequency component and an overshoot. An inductive circuit is significantly more difficult to interrupt than resistive one.

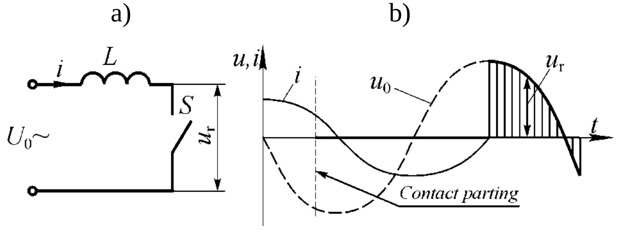

Figure 4.3 – The recovery process in a pure inductive circuit:
a) equivalent circuit; b) time diagrams

It should be noted that real electric circuits that usually contain supplying generators, power transformers, power transmission lines etc., include all these (resistive, capacitive and inductive) components. In such case, the transient recovery voltage behaves in a more complex manner, since all these components essentially affect its behavior and parameters. Let us consider the most typical practical case, that is, the transient recovery voltage across the contacts of the switching device SD when it interrupts the active-inductive circuit as shown in the equivalent circuit represented in Figure 4.4.

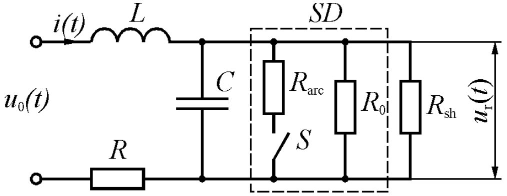

Figure 4.4 – Equivalent circuit for determining TRV

In the circuit represented, *L*, *R*, *C* are the parameters of the circuit being interrupted. Note that the capacitance *C* is in this case a significance in the recovery process, but does not affect the value of the current to be interrupted. R_{arc}, R_o are the parameters of the switching device *SD*, namely, resistance of the electric arc at the instant of its extinction and resistance of the residual arc space just after the arc extinction, respectively. *S* is an ideal switching element that opens at the current-zero instant with no arcing, having zero impedance in the closed position and infinite one in the open position (see Chapter 1). R_{sh} is shunting resistance, i.e. resistance connected across the switching device *SD*. $u_0(t)$ is time-varying PFRV. It should be noted that the duration the recovery process is very short; its instantaneous value has no time to change substantially. Therefore, in analyzing the recovery process it is assumed to be time-invariable and corresponding to its instantaneous value at the arc current-zero:

$$U_0 = \sqrt{2} U_{ph} K_{circuit} \sin\varphi, \qquad (4.1)$$

where U_{ph} is the phase supply voltage;

φ is the phase angle between current and voltage;

$K_{circuit}$ is the coefficient of circuit; for most typical cases, it equals to:

- 1.5 when 3-phase circuit is interrupted with a 3-pole switching device (for a first pole to clear);

- 0.865 when a single-phase circuit is interrupted with a 2-pole switching device;

- 1.73 when a single -phase circuit is interrupted with a one-pole switching device [3, 4, 13, 18, 19].

For the equivalent circuit represented in Figure 4.1, the following set of differential equations is valid:

$$\left\{\begin{aligned} & U_0 = iR + L\frac{di}{dt} + u_\mathrm{r} \\ & i = C\frac{du_\mathrm{r}}{\mathrm{dt}} + \frac{u_\mathrm{r}}{R_\mathrm{o}(t)} + \frac{u_\mathrm{r}}{R_\mathrm{sh}} \end{aligned}\right\}. \tag{4.2}$$

From this system of equations, it can be seen that the behavior of the recovery process is determined by the parameters of the circuit being interrupted (L, R, C, R_sh, U_o) as well as by the properties of the switching device: R_arc, R_o(t).

The transient recovery voltage, which is determined with taking into account the properties of the switching device, is named *actual TRV*. It should be noted that the actual TRV is of exceptionally scientific significance, but has no wide practical importance. Of vital significance is the so-called *system TRV*, which is determined without taking into account the properties of the switching device. This enables us objectively to evaluate the switching conditions generated by the power network.

Such approach makes it possible to estimate the operational conditions for switching devices, because the actual TRV (taking place when the circuit is interrupted with a real switching device) is dependent upon the properties of arc-quenching system. Thus, when the same circuit is interrupted with different switching devices, the behavior and parameters of TRV will be different, while the operational conditions will be identical. At the present day, it has been reliably established that interrupting capability of circuit breakers is in much degree defined by the parameters of the system TRV, which are specified by standards as for the corresponding types of switching devices.

The main parameters characterizing the TRV are the following:

- *fundamental frequency* (for oscillating behavior of the TRV);
- *maximal value* (*peak of TRV*);
- *rate of rise of recovery voltage* (*RRRV*); it is the most important parameter for medium and high voltage power systems.

Until recently, to specify the TRV, its average rate of rise and the peak value had been used. Currently, the TRV for medium voltage switching devices (with voltage ratings from 3 to 35 kV) is specified by *two-parameter reference line* 1, shown in Figure 4.5a.; for switching devices of high and ultrahigh voltages (with voltage ratings of 110 kV and above) one is specified by *four-parameter reference line* 1, shown in Figure 4.5b. In both cases, TRV is also specified by the so-called *delay line* 2 [17, 23, 24, 26, 27, 30].

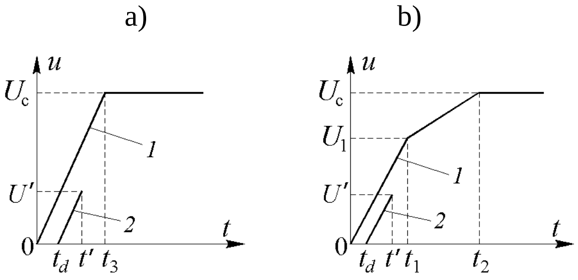

Figure 4.5 – Representation of a specified TRV by a two-parameter (a) and four-parameter (b) reference line and a delay line

The magnitudes of these parameters depend upon the rated voltage, as well as the relation between the short-circuit current to be cleared and rated short-circuit current of the breaker [17, 23]. The TRV curve complies with norm, if it lies below the reference line and only once crosses the delay line. It should be pointed out that during testing of medium, high and ultrahigh voltage circuit breakers in order to provide a margin, a TRV curve is generated so that it lay somewhat above the reference line.

For switching devices for low voltage applications, in compliance with ДСТУ 2993-95 (ГОСТ 2933-93) TRV parameters are specified by free frequency f_0 and peak factor k_a, and determined from the following empirical formulas:

$$f_0 = A I_0^{0,2} U_0^{-0,8} \pm 10\%, \text{ кГц} ; \tag{4.3}$$

$$k_a = B + C \cdot exp\left(-0{,}016 A I_0^{0,2} U_0^{-0,8}\right) \pm 0{,}05, \tag{4.4}$$

where I_0 is the value of the current interrupted;

U_0 is the power frequency recovery voltage;

A, B, C are constants depending on service conditions of the apparatus.

The parameters of TRV can be calculated, however, if the electric system has a complex configuration, includes components with distributed parameters, the computational determining the TRV parameters is highly difficult problem. The TRV parameters frequently enough are found from experiment [3, 18, 19]. Let us consider at first the most frequent practical cases of the computational determining the TRV parameters.

4.2 Simplest Cases of Transient Recovery Voltage

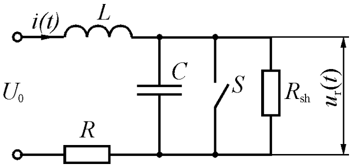

Figure 4.6 – Single-frequency circuit for determining the system TRV

Single-frequency circuit. The discussed above electric circuit (see Figure 4.4) is the simplest single-frequency circuit. The system TRV is determined under assumption that the circuit is interrupted with the ideal switching element *S* and, hence, the equivalent circuit becomes simpler as shown in Figure 4.6.

The system of differential equations describing the transient recovery voltage process, in this case, will have the following form:

$$\left\{\begin{aligned} U_0 &= iR + L\frac{di}{dt} + u_\mathrm{r} \\ i &= C\frac{du_\mathrm{r}}{dt} + \frac{u_\mathrm{r}}{R_\mathrm{sh}} \end{aligned}\right\}. \tag{4.5}$$

Differentiation of the 2-nd equation gives:

$$\frac{di}{dt} = C\frac{d^2u_\mathrm{r}}{dt^2} + \frac{1}{R_\mathrm{sh}}\frac{du_\mathrm{r}}{dt}. \tag{4.6}$$

Substitution of this expression into the first equation of system (4.5) gives a differential equation of the second order:

$$\frac{d^2u_\mathrm{r}}{dt^2} + \left(\frac{R}{L} + \frac{1}{R_\mathrm{sh}C}\right)\frac{du_\mathrm{r}}{dt} + \frac{1}{LC}\left(1 + \frac{R}{R_\mathrm{sh}}\right)u_\mathrm{r} = \frac{U_o}{LC}. \tag{4.7}$$

Solution of this equation with the initial conditions:

$u_\mathrm{r}(0) = 0;\ \left.\frac{du_\mathrm{r}}{dt}\right|_{t=0} = 0$, will be as follows:

$$u_\mathrm{r} = U_\mathrm{o}\left[1 - \left(\frac{a}{\omega_0}sh\omega_0 t + ch\omega_0 t\right)e^{-at}\right], \tag{4.8}$$

where $a = \frac{1}{2}\left(\frac{R}{L} + \frac{1}{R_\mathrm{sh}C}\right)$ is the damping factor of the TRV;

$\omega_0 = \sqrt{\frac{1}{4}\left(\frac{R}{L} + \frac{1}{R_{sh}C}\right) - \frac{1}{LC}}$ is the fundamental angular frequency of the transient recovery voltage.

If $\frac{1}{LC} > \frac{1}{4}\left(\frac{R}{L} + \frac{1}{R_{sh}C}\right)$, then the hyperbolic functions become harmonic ones and hence the recovery process will have an *oscillatory* behavior.

If $\frac{1}{LC} < \frac{1}{4}\left(\frac{R}{L} + \frac{1}{R_{sh}C}\right)$, then the hyperbolic functions become exponential ones and the recovery process in this case will have an *aperiodic* behavior.

It should be noted that parameters of the circuit to be interrupted *R, L, C* can always be consider as predetermined for a given electric subsystem. The value of shunting resistance $R_{\text{ш}}$ depends on its operating conditions: first and foremost, on the location of the switching device in the system. Let us consider the effect of shunting resistance value on the recovery process behavior.

When shunting resistance is not available in the circuit, or its value high enough (100 kilo-ohms and above), the recovery process has usually clearly defined oscillatory behavior with a very slight damping as shown in Figure 4.7a. Power systems wherein the transient recovery voltage behaves in such manner are named "*rigid*" systems. If shunting resistance ranging from a few to several tens kilo-ohms is available, the recovery process is "damped". It means that oscillatory behavior of the process persists, but it decays considerably more rapidly than in the absence of R_{sh}. The lower its value is, the more rapidly transient recovery voltage process decays as shown Figures 4.7b and 4.7c. Under significant decreasing the value of shunting resistance (below 1 kilo-ohm) the recovery process becomes aperiodic one as shown in Figure 4.7d.

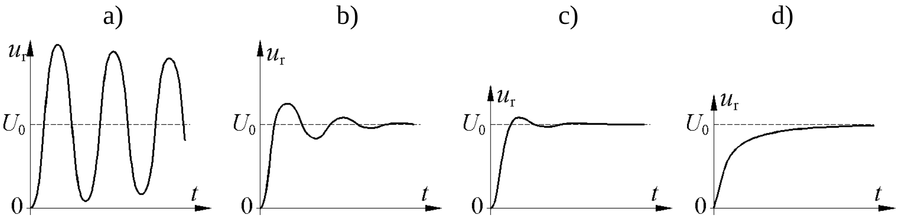

Figure 4.7 – Transient recovery voltage at different values of shunting resistance

The frequent enough practical case is interruption of a practically pure inductive circuit ($R \approx 0$) in the absence of shunting resistance ($R_{\mathrm{sh}} = \infty$). In this case, the following inequality will be almost always valid:

$$\frac{1}{LC} > \frac{1}{4}\frac{R}{L}, \tag{4.9}$$

and hence the transient recovery voltage will behave as oscillating practically non-damping process:

$$u_{\mathrm{r}} = U_{\mathrm{o}}\left(1 - \cos\omega_0 t \cdot e^{-at}\right), \tag{4.10}$$

where $\omega_0 = 2\pi f_0$;

$f_0 = \dfrac{1}{2\pi\sqrt{LC}}$ is the natural frequency of the TRV.

Double-frequency circuit. There are frequent cases, when the circuit being interrupted contains two inductances L_1 and L_2 with the corresponding capacitances C_1 and C_2 in the absence of shunting resistance and small values of active resistance, as shown in Figure 4.8. Such circuit is named a *double-frequency* one.

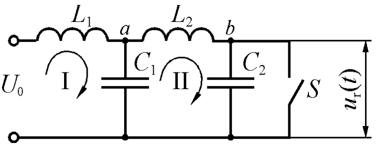

Figure 4.8 – Double-frequency circuit for determining the system TRV

In this case, the recovery process will be more complex in behavior. Typical for practice is the case when subcircuit L_1–C_1 is formed by power generator, and subcircuit L_2–C_2 is formed by power transformer. It is well known that the capacitance of the generator windings laid in stator slots considerably greater than the one of transformer windings (i.e., $C_1 >> C_2$). The subcircuits I and II form in this case practically autonomous (i.e. non-interacting) subcircuits. In the process, the natural frequency of the subcircuit II

$$f_{02} = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{4.11}$$

will be significantly higher than the one of the subcircuit I

$$f_{01} = \frac{1}{2\pi\sqrt{L_1 C_1}}. \tag{4.12}$$

The high-frequency oscillations of subcircuit II will practically freely close through a great capacitance C1 as through a jumper with an almost zero impedance, whereas the low-frequency oscillations of subcircuit I cannot close through subcircuit II, since a small capacitance C2 represents a very high impedance for them.

When current flows through the circuit, the PFRV U_0 will be distributed proportionally to the inductance values of:

$$U_{01} = U_0 \frac{L_1}{L_1 + L_2}; \; U_{02} = U_0 \frac{L_2}{L_1 + L_2}. \tag{4.13}$$

At the current-zero moment the voltage across the capacitance C_2 will be zero and the voltage across the capacitance C_1 will be equal to U_{02}. During the recovery process, the voltage u_{02} with the frequency f_{02} will restore across the capacitance C_2, and the voltage u_{01} from the value U_{02} up to U_0, with frequency f_{01}, will restore across the capacitance C_1. Since no current in the circuit, the potential at the point *a* will be identical to the potential at the point *b*. As a result, the total voltage of these oscillations will restore across the switching element *S*:

$$u_\mathrm{r} = U_{01}\left(1 - \cos\omega_{01}t \cdot e^{-a_1 t}\right) + U_{02}\left(1 - \cos\omega_{02}t \cdot e^{-a_2 t}\right). \tag{4.14}$$

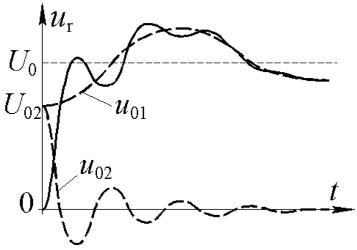

Figure 4.9 – Double-frequency transient recovery voltage process

Double-frequency recovery processes, shown in Figure 4.9, are typical for high voltage systems 110 kV and higher.

Circuit with a transmission line. In the operational practice of electric equipment, there is frequently a necessity to interrupt electric circuits containing sections of power transmission lines. These are, as a rule, events of clearing fault in transmission line at some distance from the circuit breaker. In this case, the behavior of the recovery process is affected not only by the power source side processes, but also by the transmission line side processes.

An equivalent circuit to determine the transient recovery voltage for this case is represented in Figure 4.10. In this circuit L_source and C_source are the parameters of the circuit being interrupted, from the power source side; L_line, and C_line are the parameters of the transmission line section. As the current passes through the circuit, the PFRV U_0 is distributed into two components: the supply side voltage U_source caused by the voltage drop across the inductance L_source and the line side voltage U_line resulted from the voltage drop across the line section L_line (see Figure 4.10).

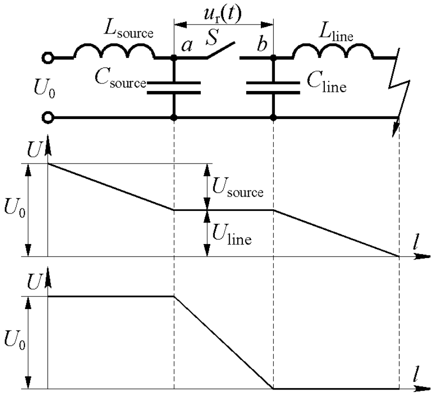

Figure 4.10 – Equivalent circuit to find TRV with power transmission line

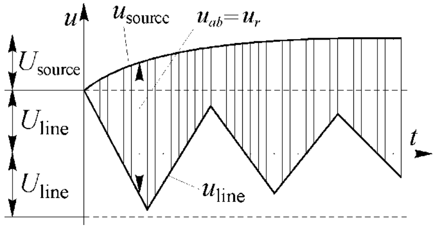

Figure 4.11 – Time diagrams of the supply and line side transient recovery voltages

Once the circuit is interrupted, the potential of point A increases by the value U_{source} (from U_{line} up to U_0), and the potential of point B decreases from U_{line} down to zero (see Figure 4.10). The TRV on source side behaves usually as an aperiodic process. The TRV on line side will be determined by wave processes in the transmission line, that is, by travelling and reflecting wave of the voltage with an amplitude U_{line}. The TRV on line side has usually saw-tooth oscillating waveform, as shown in Figure 4.11. In the process, the following cases are possible:

I. *The section of the line is long enough* (50…100 km); in this case, the reflected voltage wave comes already after the termination of the recovery process and practically does not affect its behavior;

II. *The line section has very small length* (less than 1 km): in this case the TRV on line side has very low amplitude and does not play a significant role in the recovery process, i.e. the TRV is defined by the only parameters of the supply subcircuit (as in the discussed above cases);

III. In the operating practice of switching devices, there is frequently need to interrupt the circuit containing the line section of relatively small length (2...5 km), the so-called *short line fault*. In this case, the TRV curve has sawtooth waveform, and the especially heavy-duty takes place for the circuit breaker that clears short-circuit. It is caused by a combination of sufficiently high current being interrupted with high rate of rise of the recovery voltage.

When the fault is located on a small distance from the circuit breaker, high-frequency TRV sawtooth oscillations at small its amplitude takes place. In this case, the dielectric recovery curve lies above the TRV curve, as shown in Figure 4.12a, because of that *successful clearing fault* occurs. Under some increasing the fault location distance, the frequency of sawtooth TRV, and hence its rate of rise, decreases. In this case as the dielectric strength yet has not sufficiently increased, as shown in Figure 4.12b, thermal breakdown and, accordingly, the arc reignition can take place. It disturbs design operation duty of the circuit breaker, i.e. in this case *unsuccessful fault clearing* happens. Further increasing the fault location distance leads to still further decrease in short-circuit current and, accordingly, to an increase in the dielectric strength of the contact gap. In the process, the frequency of sawtooth TRV and its rate of rise decrease, because of that the first peak of the TRV reaches its maximum when the dielectric strength has already increased sufficiently that is shown in Figure 4.12c.

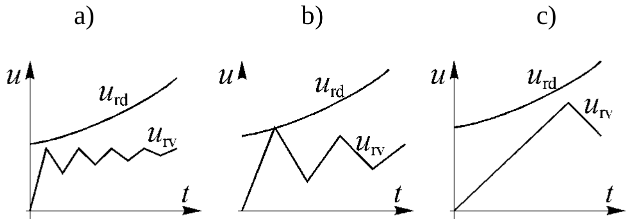

Figure 4.12 – The behavior of the TRV and the dielectric recovery at different distances from the fault location: a) small distance; b) moderate distance; c) great distance

4.3 Practical Methods for TRV Parameters Calculations

Above we have dealt with relatively simple cases, when finding the TRV parameters is not a difficult task. However, in a number of cases this problem is difficult due to the complex configuration of the electrical system, which cannot be reduced to the elementary schemes. In such cases, this problem is solved using specific calculation procedures, as well as the experimental measurements, as already noted [3, 18, 19, 30]. Let us consider the basic computational methods to find the TRV parameters.

Mesh-current (loop) method. This method is used for computational equivalent circuits, containing mainly elements with lumped parameters. It is based on direct employment of Kirchhoff's current and voltage laws to analyze transients in electrical circuits. Just this method was used above to determine the TRV parameters. It consists in the following. For the computational circuit resulted from opening the switching element, in compliance with Kirchhoff's current and voltage laws the required number of differential equations are compiled. From the resultant system of equations, all unknowns are eliminated, except for the desired value of the TRV u_B, that results in the following differential equation:

$$\frac{d^n u_r}{dt^n}+a_1\frac{d^{n-1}u_r}{dt^{n-1}}+\ldots+a_{n-1}\frac{du_r}{dt}+a_n u_r = f(t). \tag{4.15}$$

where *n* is the order of the equation defined by the number of energy storages.

The solution to this equation is the solution of the task. Methods for solving such equations are well known: classic, operational, numerical with application of software for PC.

Current opposition (countercurrent) method. This method is based on the Thévenin's theorem [28], which in this case states that the TRV across the breaker contacts coincides in value and waveform with the voltage that should be applied to the breaker contacts that results in the current equal but opposite to the interrupted current in this branch at zero driving voltage.

Thus, the fault clearing process by the circuit breaker Q, shown in Figure 4.13a, is substituted by the insertion of a conditional power source into the closed breaker branch so that it provides in this branch the current, equal in magnitude and opposite in direction, to the fault current. It results in the total current in this branch is zero that becomes identical to the interrupted circuit, as shown in Figure 4.13b.

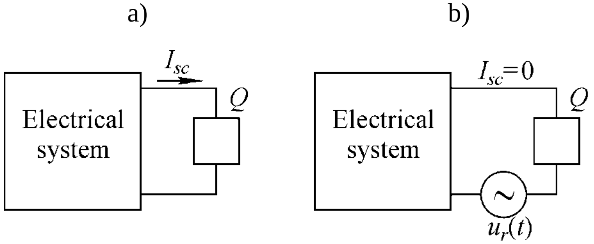

Figure 4.13

Countercurrent method is usually used in combination with the operational (symbolic) method. Applying the Laplace transformation, the TRV value being found is generally expressed as follows:

$$u_r(p)=I(p)\cdot Z(p), \tag{4.16}$$

where *Z*(*p*) is the Laplace transform of the input impedance seen from the breaker with shorted terminals of the generators;

I(*p*) is the Laplace transform of the fault current being interrupted whose time form is:

$$i(t) = \sqrt{2} I_{\text{p}0} \sin \omega t\,, \tag{4.17}$$

where $I_{\text{p}0}$ is rms symmetric component of the fault current.

Assuming that the time of the recovery process is very short and the process is considered in the neighborhood of the current-zero, this expression can be written as follows:

$$i(t) = \sqrt{2} I_{\text{p}0} \omega t\,. \tag{4.18}$$

Its Laplace transform is:

$$I(p) = \frac{\sqrt{2} I_{\text{p}0} \omega}{p}\,. \tag{4.19}$$

Hence, the Laplace transform of the unknown TRV will be as follows:

$$u_{\text{r}}(p) = \frac{\sqrt{2} I_{\text{p}0} \omega}{p} \cdot Z(p)\,. \tag{4.20}$$

The time form of this expression $u_{\text{в}}(t)$ can be found by the way of inverse Laplace transformation.

Thus, the task to determine the TRV in this case is reduced to finding the Laplace transform of the circuit impedance seen from the breaker contacts *Z*(*p*). Let us consider an example of using the countercurrent method for the elementary single-frequency circuit (see Figure 4.6).

The time form of the fault current is:

$$i(t) = \frac{U_0}{\omega L} \cdot \omega t = \frac{U_0}{L} \cdot t\,; \tag{4.21}$$

its Laplace transform is:

$$i(p) = \frac{U_0}{pL}\,. \tag{4.22}$$

Laplace transforms of impedances for the circuit components:

$$x_L(p) = pL;\; x_C(p) = \frac{1}{pC}\,. \tag{4.23}$$

The total operational impedance of the circuit seen from the breaker contacts:

$$Z(p) = \frac{pL}{1 + p^2 LC}\,. \tag{4.23}$$

The Laplace transform of the unknown TRV:

$$u_{\mathrm{r}}(p)=\frac{U_0}{1+p^2LC}. \tag{4.24}$$

Its time form is:

$$u_{\mathrm{r}}(t)=U_0\left(1-\cos\omega_0 t\right), \tag{4.25}$$

where $\omega_0=\frac{1}{\sqrt{LC}}$.

The expression derived is analog to the one derived above (4.10), except that it does not take into account the decaying of the process.

When the TRV process is analyzed in three-phase systems relative to the first pole to clear, it should be taken into account that at once the arc is extinguished after the current-zero, an asymmetrical mode is produced. Therefore, the countercurrent method is usually used in combination with method of symmetrical components.

Short circuit interruption is the heaviest mode of circuit interruption, especially clearing short line fault. In this case, interruption of a high current is combined with a high rate of rise of the TRV, which often leads to failure of the circuit breaker. However, the operational practice of circuit breakers shows that in some cases rather heavy duty in terms of TRV are produced when modest (small capacitive or inductive) currents are interrupted.

4.4 Recovery Process in Interrupting Small Capacitive Currents

Power systems contain lumped capacitors, such as capacitor banks for the voltage regulation or the power factor improvement and capacitors that are an integral part of filter banks to filter out higher harmonics. Practically net capacitive circuits are formed in distribution switchboards giving out power energy to outgoing overhead or cable transmission lines. In this case a pure capacitive current flows through open-ended or no-load line of relatively large length.

The capacitive current is small (from a few Amperes to several hundred Amperes) compared with the rated short-circuit current for which the circuit breaker is designed, and nevertheless capacitive switching requires special attention because, after current interruption, the capacitive circuit contains an electrical charge and can cause a dielectric re-ignition of the switching device. When this process repeats, interruption of the capacitive currents causes high overvoltages. Figure 4.14 shows a single-phase representation of a real capacitive circuit.

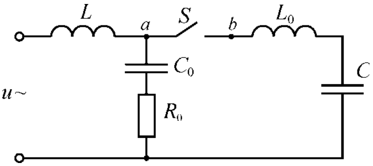

Figure 4.14 – Equivalent scheme to determine TRV in interrupting capacitive circuit

The inductance *L* is the inductance of the supply and represents the synchronous inductance of the supplying generators and the leakage inductance of the power transformers. R_0 and C_0 generate together the supply side TRV and represent respective parameters of the equipment connected to the switchboard bus bars (power and instrument transformers, reactors, and so forth). Capacitive load is represented by the lumped capacitor *C*, connected via a stray inductance L_0 with the load side of the circuit breaker.

When $L >> L_0$ and $\omega L << 1/\omega C$, then we have an almost purely capacitive circuit. When the circuit breaker *S* is in a closed position, the capacitive current *i*, leading the supply voltage *u* by 90°, flows through the circuit, as shown by the time diagram in Figure 4.15.

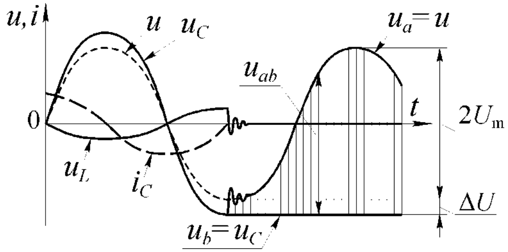

Figure 4.15 – Time diagrams of current and voltages during interrupting a small capacitive current.

The voltage across capacitive load U_C is higher than the supply voltage due to the so-called Ferranti rise. This voltage difference is

$$\Delta U = U_C - U \ . \tag{4.26}$$

At the instant the current *i* is interrupted (if the arc between the breaker contacts *S* extinguishes at its zero crossing), the capacitor *C* is fully charged and the voltage is approximately equal to the peak voltage of the supply. If the circuit remains to be interrupted (i.e., no re-ignition), the voltage across capacitor *C* will decay exponentially due to a leakage. At the same instant, the supply voltage rapidly restores at the supply side of the breaker. Because of the Ferranti rise, a voltage jump occurs in the voltage at the supply side of the breaker. The frequency of the transient oscillation because of this voltage jump is :

$$f = \frac{1}{2\pi\sqrt{LC_0}}\,. \tag{4.27}$$

Hence, the voltage, equal the sum of the charged capacitor voltage u_C and power voltage u, begins to recover between the breaker's contacts. If no taking the leakage in capacitor C into account, then after half a cycle, the supply voltage has reversed its polarity and the voltage across the breaker terminals is twice the peak value of the supply voltage, as can be seen in Figure 4.16.

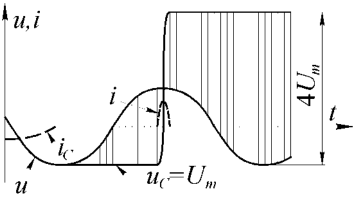

Figure 4.16 – Time diagrams of voltages under restrike of the contact gap

If at this moment the dielectric strength of the contact gap will be insufficient (this most frequently happens at still narrow contact gap, as the breaker arcing contacts by this moment have no time to travel far enough), a dielectric breakdown of extinguishing medium and re-ignition occur. The capacitance C recharges itself via the re-ignited arc channel and the inductances L and L_0. The result is an oscillating current with the following frequency and peak value:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}\,;\; I = \frac{2U}{\sqrt{L/C}} \text{ for } C_0 >> C\,. \tag{4.28}$$

The smaller the value L is, the higher the frequency and higher the amplitude of the transient current. When at the re-ignition instant the voltage across the capacitor C was $-U_m$, the voltage is then $+3U_m$ at the first zero crossing of the transient current. When the arc channel extinguishes, the circuit breaker interrupts the oscillating current and the voltage across the capacitor again remains to be constant. After half-cycle of power frequency, the voltage across the breaker contacts will be as high as $4U_m$. If at this moment another the re-ignition of the extinguishing medium occurs, the capacitance C will recharge via the same circuit. The result of this second re-ignition is an oscillating current with doubled amplitude compared with the first one. While recharging the voltage on capacitor C has increased to $5U_m$. When the breaker interrupts the transient current at its first zero crossing, then the voltage across the breaker contacts has reached $6U_m$ one-half cycle of power frequency later.

When couple of re-ignitions occurs in this way, very high voltages build up across the interrupting chamber. It should be noted that in real electrical systems they significantly less (up to 3...3,5U$_m$) [13, 17, 22–28], but are serious hazard for the insulation of electric equipment and devices. In particular, it is most likely that a flashover on the outside of the interrupter chamber takes place. The circuit breaker is short-circuited out of the system in this way and cannot function anymore; this is a very dangerous and an unwanted situation. High-voltage circuit breakers, which have to perform capacitive current switching, should be restrike-free to avoid overvoltages.

4.5 Recovery Process in Interrupting Small Inductive Currents

In operating practice of electrical equipment, small inductive currents take place in power transformers being in no-load operation. The values of no-load currents of powerful transformers in no excess of 50...100 A. However, interruption of this current by a circuit breaker, having a high interrupting capability, occurs usually prior to its natural zero. This phenomenon is known as *current chopping*. Note that current chopping may occur at any moment relative to the current sine waveform, including the current crest.

The current chopping mechanism has not been still adequately studied at the present time. Nevertheless, the available findings of experimental investigations suggest that they are resulted from the high frequency currents superimposed on the arc power frequency current. The amplitude of high frequency currents is frequently comparable with the amplitude of small inductive currents. When these currents are oppositely directed, zero values are produced and arc extinguishes prior to the natural current-zero. The high frequency component of the arc current is generated in a circuit formed by circuit capacitances located on both sides of the circuit breaker. The cause of the generating of the high frequency arc current component is assumed to be drastic change of the voltage of the arc column resulted from its intensive de-ionization [13, 14, 17, 22–28].

At the instant of current chopping, the electromagnetic energy stored in the inductance converses into electrostatic one. At this moment, the recovery voltage begin to occur that is accompanied with considerable overvoltage. Its magnitude can be determined from energy conservation equation that in this case will be as follows:

$$\eta^2 L_1 \frac{i_{\text{ch}}^2}{2} = C \frac{u_{\text{r max}}^2}{2}, \qquad (4.29)$$

where i_{ch} is the value of the current chopping;

L_1, C_1 is the parameters of the power transformer in no-load duty;

η is the usage coefficient of electromagnetic energy, taking into account copper and iron losses in the transformer; its magnitude is usually in the range of 0.3 to 0.45.

From equation (4.29) the maximal value of the recovery voltage will be as follows:

$$u_{\mathrm{r\,max}} = \eta i_{\mathrm{ch}} \sqrt{\frac{L_1}{C_1}} \,. \tag{4.30}$$

In the event when the current chopping occurs at the instant the arc current corresponds its crest value, the highest expected overvoltage will be:

$$u_{\mathrm{r\,max}}^{\mathrm{highest}} = \eta I_{\mathrm{no\,m}} \sqrt{\frac{L_1}{C_1}} \,, \tag{4.31}$$

where $I_{\mathrm{no\,m}}$ is the amplitude value of the transformer no-load current expressed as:

$$I_{\mathrm{no\,m}} = \frac{U_{\mathrm{m}}}{2\pi f L_1} \,. \tag{4.32}$$

Substitution of this expression into (4.31) gives us:

$$u_{\mathrm{r\,max}}^{\mathrm{highest}} = \eta \frac{U_{\mathrm{m}}}{2\pi f \sqrt{L_1 C_1}} \,, \tag{4.33}$$

where $\frac{1}{2\pi\sqrt{L_1 C_1}} = f_0$ is the natural frequency of the transformer in no-load operation.

Hence, the relation of the transformer natural frequency to the power frequency will define the most overvoltage multiplicity:

$$\kappa_{\mathrm{most}} = \frac{u_{\mathrm{r\,max}}^{\mathrm{highest}}}{U_{\mathrm{m}}} = \eta \frac{f_0}{f} \tag{4.34}$$

The overvoltage magnitude will be also defined by the relative magnitude of the copper and iron losses in the transformer. It should be noted that the losses in the transformer significantly reduce overvoltages generated by the interruption of no-load current. Nevertheless, they are great enough and constitute a serious hazard for the insulation of electrical equipment. The main techniques to limit overevoltages are the application of surge arresters, as well as shunting switching devices by active resistances.

5. ANALYSIS OF FAULT CONDITIONS IN ELECTRICAL SYSTEMS

As already noted, in the operation process of electrical equipment in electrical systems, different types of failures occur that are the causes of emergency situations or disturbance of the normal operation of electrical installations. The most frequent failures in electrical systems are the following: short-circuits, partial grounds, overloads, fall out of synchronism of power generators, local unbalance, overvoltages (lightning surges, switching surges, temporary overvoltages, etc.). Most of these failures is occurred with shortings.

5.1 Failures Occurred with Shortings

Shorting is any non-designed electrical connection of lines with the "ground" or among themselves. There are a number of variations of the short-ins that are schematically shown in Figure 5.1

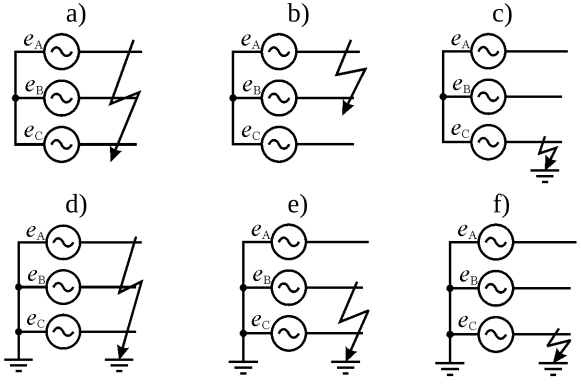

Figure 5.1 – The main types of shortings: *a*) three-phase fault; *b*) two-phase fault; *c*) partial ground; *d*) triple-ground fault; *e*) double-ground fault *f*) ground fault.

The following types of shortings are distinguished: *three-phase* (see Figure 5.1a) and *two-phase* (see Figure 5.1b) named also *line-to-line faults*; *partial ground* (see Figure 5.1c); in effectively grounded systems there exist also *triple-ground* (see Figure 5.1d), *double-ground* (see Figure 5.1e) and *ground* (see Figure 5.1f) *faults*.

The greatest hazard for electric installations is short-circuit fault, when currents at faulty subsystems drastically increase, exceeding tens of times the values permissible at a normal operation. Among the noted types of shortings, only 1-phase shorting in ungrounded systems named *partial ground* is not a short-circuit and is not accompanied with high currents. Nevertheless, this type of shorting is failure; however, it is not necessary in this case to de-energize immediately the faulty subsystem. In the event of partial ground, the operational personnel has to be informed about the behavior and location of the failure, and to make all measures to clear it. In response to the event of partial ground, protective facilities generate signal.

Let us consider short-circuits faults in more detail. First and foremost, it should be noted that there are *accidental faults* and *short-circuits produced artificially* with the help of short-circuiters. Accidental faults are mainly resulted from disturbance of electric insulation. Their causes may be the following: *overvoltages* resulted usually from partial ground, direct lightning stroke, switching operations in the system, etc.; *ageing* of solid insulation or its *mechanical injuries*; *falling foreign bodies on current-carrying parts:* passage of oversized mechanisms under transmission line, high lifted up crane boom, etc.

There are not infrequent events of short-circuits because of erroneous operations of personnel or mounters: operations to open disconnectors under current; operations to close disconnectors under short-circuit; erroneous switching operations in main and control circuits; incorrect connections when equipment is mounted.

There also distinguished *arcing faults,* as electric connections are produced by means of an electric arc and *metallic* or *solid faults,* when connections occur directly or via metallic parts. In the great majority of events, arcing faults take place. An electric arc can be initiated as result of breakdown or flash over of the insulating gap, as well as burning out or carrying away (under the action of electrodynamic forces) of the metal jumpers that have caused short-circuit. In the second case, metallic fault transfers to arcing fault. Hence, short-circuits in power systems are mostly momentary in behavior, since the causes leading to the fault are eliminated (e.g., the electric arc is extinguished). The exception is the so-called *dead metallic fault,* when the cause leading to the fault is not eliminated and the fault is permanent. This happens usually because of incorrect wiring of the current-carrying parts in given subsystem called also sometimes *bolted fault.*

Short-circuit faults cause severe consequences for electrical equipment: ignitions, mechanical and thermal damages, fall out of synchronism of power generators, electromagnetic impulse resulting in false response of communication and automation systems, etc. By this why, in the event of short-circuit the faulty subsystem must be de-energized as quickly as possible, and accordingly, the response of protection relays is the interruption.

5.2 Short-Circuit Current Parameters

Since the short-circuit fault moment, a complex transient process occurs in the corresponding circuit. Time diagram of short-circuit current, in general case, has the form shown in Figure 5.2. Instantaneous value of short-circuit current usually includes two components: *periodical* (*symmetrical*) *current* i_p and *aperiodic* or *direct current* i_a.

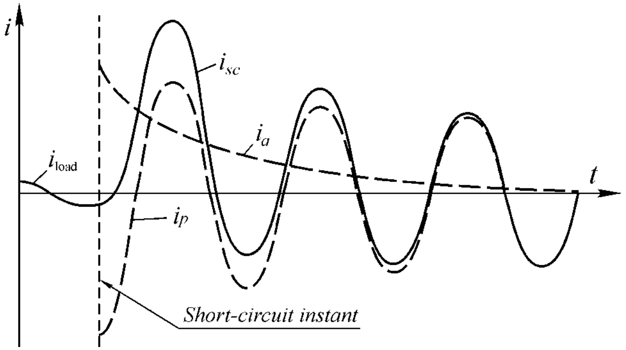

Figure 5.2 – Time diagram of the short-circuit current and its components

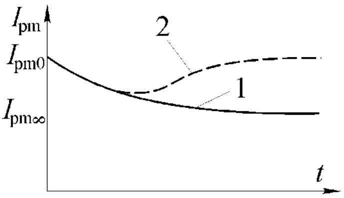

Figure 5.3 – Time-changing symmetrical current amplitude

The symmetrical current component has sine waveform of power frequency. Its amplitude gradually decreases from the initial value I_{pm0} down to steady state value $I_{pm\infty}$. It is resulted from changing the driving voltage of the power generator under increasing load current. At the fault zero-time, the generator EMF accords to the rated conditions, and then gradually decreases according to the value of short-circuit current as shown in Figure 5.3 (curve 1). If the generator is equipped with an automatic excitation controller, the behavior of the symmetrical current amplitude will somewhat differ. Initially, the process will develop at the same manner, and then due to decrease in EMF the excitation current will increase under the action of the controller that will lead to increase in the amplitude of the symmetrical current up to the initial value (see Figure 5.3, curve 2).

If a fault is located at long distance from the generator, the sc current is significantly lower than in the case the fault is located near the generator. In this case, the generator perceives the short circuit as modest overload, and its EMF varies very insignificantly and therefore the change in the symmetrical current amplitude can be neglected. That is, symmetrical current amplitude is considered as invariable in the fault process.

The direct current (dc) component is maximal at the fault zero-time and exponentially decays in further. The duration of decaying the dc component is usually 0.2...0.3 s, when the fault is located in the vicinity of the generator. The initial value of the dc component depends on the power source capacity, remoteness of the fault location and the fault phase. Its magnitude defined as difference:

$$I_{\mathrm{a0}} = I_{\mathrm{p0m}} - I_{\mathrm{load(m)}}, \tag{5.1}$$

where $I_{\mathrm{load(m)}}$ is the amplitude value of the load current (i.e., the current prior to the fault).

Taking into account that usually $I_{\mathrm{p0m}} >> I_{\mathrm{load(m)}}$ the initial value of the dc component will be:

$$I_{\mathrm{a0}} \approx I_{\mathrm{p0m}} = \sqrt{2} I_{\mathrm{p0}} . \tag{5.2}$$

The main parameters characterizing the short-circuit current are the following.

Initial rms symmetrical sc current I_{p0}. This quantity is determined at the instance corresponding to 0.01 s after the start of a fault. Its magnitude defines the selection of electric equipment, more exactly, its verification in respect to short-time withstand current, that is., thermal stability of the equipment under fault conditions. The magnitude of I_{p0} is determined by the aggregate impedance of the resulting shorted circuit, which is generally added of two components:

$$Z_{\mathrm{sc}} = Z_{\mathrm{com}} + Z_{\mathrm{p.sc}} , \tag{5.3}$$

where Z_{com} is the total impedance of the components contained by the resulting shorted circuit, including the impedances of the power sources;

$Z_{\mathrm{p.sc}}$ is the impedance of a fault location (the arc impedance is mainly kept in mind); its value depends on many factor, but at the present time there are not simple and reliable methods to determine it; nevertheless, the longstanding experience states that its value is approximately 10...15% of the total shorted circuit impedance [1, 2, 5, 9, 12].

When practical calculations are performed, the value I_{p0} is usually determined from the condition of the metallic fault (i.e., with no taking into account $Z_{\text{p.sc}}$), and then derived magnitude is decreased by 10...20%, if it is in the range of 60 to 80 kA [1, 2, 5, 9, 12].

The rms symmetrical current at the instant *t* I_{pt}. This quantity is usually determined for the moment when the circuit breaker arcing contacts are started to open. This value is necessary to verify switching devices, mainly circuit breakers, in respect to their interrupting capability.

Peak or **crest value of short-circuit current i_{peak}.** This quantity represents the highest instantaneous value of the short-circuit current. It usually occurs approximately after 0.01 s from the fault zero-time. Its magnitude is determined as the sum of both sc current components at this instant:

$$i_{\text{peak}} = I_{\text{p0m}} + I_{a0}e^{-\frac{0,01}{T}} = \sqrt{2}I_{\text{p0}}\left(1 + e^{-\frac{0,01}{T}}\right), \tag{5.4}$$

where the bracketed expression is usually named *peak factor*

$$\kappa_{\text{peak}} = 1 + e^{-\frac{0.01}{T}}. \tag{5.5}$$

Hence, the peak value of the short-circuit current is:

$$i_{\text{peak}} = \sqrt{2}\kappa_{\text{peak}} I_{\text{p0}}. \tag{5.6}$$

As seen from expression (5.5) the peak factor magnitude is determined by the time constant of decaying the dc component *T*. The task to find the time constant is complex enough, but long-standing experience states that in the first 0.01 s interval after the fault zero-time in high and medium voltage systems the dc component decays approximately by 20%. Accordingly, the magnitude of the peak factor for high and medium voltage systems is 1.8, respectively. In electric installations of low voltage $\kappa_{\text{peak}} = 1.3$; when the fault location is far from power sources, then $\kappa_{\text{peak}} = 1.0$ [1, 2, 5, 9, 12].

5.3 Short-Circuit Current Calculations

The calculation task is to find the main parameters of the sc current: the initial rms symmetrical current I_{p0} and peak value i_{peak}. For the purpose to verify switching devices, providing protection of electrical equipment (breakers clearing the fault), in respect to interrupting capability, it is also necessary to determine the rms symmetrical current at the instant when the breaker main contacts begin to open I_{pt}. Short-circuit currents are calculated for the most severe case, that is, three-phase fault. Despite the fact that the faults of such type are seldom the events (no more than 5% of their total number), the equipment is selected basing upon a three-phase fault, which is the design duty.

For the purpose to simplify short-circuit current calculations, a number of assumptions are accepted. First and foremost, the calculations are performed for the case of a metallic short-circuit when $Z_{\text{p.sc}} = 0$. For high or medium voltage systems, the calculations are performed without taking into account the active resistances of the elements. The magnetization currents of power transformers, as well as saturation of their magnetic systems are also neglected. That is, all the elements included by the shorted circuit are considered as linear ones and electrically coupled. In the calculations, the following two cases are distinguished:

1. **The installation is fed from a system of infinite capacity**. Such a case takes place when the fault location is far from the supply generators. In this case, driving voltage of the generator remains practically unchanging during the fault process. Hence, symmetrical current component amplitude is considered as invariable (i.e., for this case: $I_{\text{pt}} = I_{\text{p0}}$).

2. **The capacity of the system is limited.** Such a case takes place when the fault location is in the neighborhood of the supply generators. In this case, the change of the symmetrical short-circuit current component amplitude should be taken into account.

The parameters of short-circuit current are determined by the aggregate impedance of the resulting shorted circuit from the power sources to the fault location. To determine the initial rms symmetrical short-circuit current component, a *design circuit* corresponding to the normal operation of the subsystem is constructed. All power sources in the circuit are connected in parallel. The design circuit must take into account the impedances of the supplying generators, power transformers, overhead and cable transmission lines, current-limiting reactors etc. In accordance with design circuit, an *equivalent circuit* is drawn up. In the circuit, it should be indicated the impedance magnitudes of denoted elements, as well as stated the points of the fault locations for short-circuit current calculations.

In high and medium voltage systems, only the inductive reactances of the equivalent circuit components are taken into account. Their values are predetermined in the following manner.

- the reactance of synchronous generators is expressed in relative units as the *direct-axis subtransient reactance* x''_d that for turbo-generators is of the order of 0.125, for water-wheel generators with damper winding is of the order of 0.2, without damper winding is of the order of 0.27, for synchronous and asynchronous motors is of the order of 0.2;

- the reactance of power transformers is expressed by its impedance voltage in percent $u_{\text{кз}}\%$;
- the reactance of power transmission lines is expressed in Ohms per unit length x_{o}: for overhead lines, its magnitude is on average about 0.4 Ohm/km; for cable lines it is 0.08 Ohm/km;
- the reactance of current-limiting reactors is expressed as percentage reactance $x_{\text{p}}\%$.

The drawn up equivalent circuit is simplified to elementary one by means of equivalent conversions. It should be pointed out here that due to the available power transformers at the subsystem considered, the initial equivalent circuit will contain sections with different voltages. Therefore, all electrical parameters should be converted to common voltage base by the following expressions:

$$E_{\text{con}} = E \cdot \left(\frac{U_{\text{base}}}{U} \right); \quad x_{\text{con}} = x \cdot \left(\frac{U_{\text{base}}}{U} \right)^2; \quad I_{\text{con}} = I \left(\frac{U}{U_{\text{base}}} \right), \tag{5.7}$$

where E, x, I are EMF, reactance and current, respectively being converted to common voltage base;

U_{base} is the common voltage base chosen; it is usually the voltage of the section, wherein the short-circuit current is calculated;

U is the voltage of the section, wherein values E, x, I are determined.

The application points of the power sources driving voltages are combined, substituting them by one equivalent EMF. When two sources with different driving voltages are available in the equivalent circuit, as shown in Figure 5.4, it is found from the following relationship:

$$E_{\text{eq}} = \frac{E_1 \dfrac{1}{x_1} + E_2 \dfrac{1}{x_2}}{\dfrac{1}{x_1} + \dfrac{1}{x_2}}. \tag{5.8}$$

As their equality takes place, then $E_1 = E_2 = E_{\text{eq}}$.

Short-circuit current calculations can be performed either by real or per-unit values.

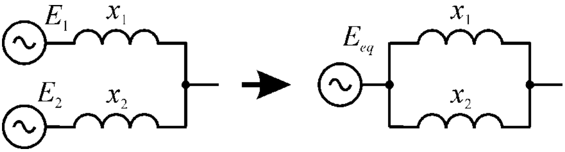

Figure 5.4 – Determination of equivalent driving voltage

Calculations by real values. In this case, the components impedances given in relative units or percentage must be converted into real units (i.e., Ohms).

Inductive reactance of shorted power transformer per one phase in compliance with Ohm's law will be expressed as follows:

$$x_{\mathrm{t}} = \frac{U_{\mathrm{imp}}}{\sqrt{3} \cdot I_{\mathrm{n}}}, \tag{5.9}$$

U_{imp} is the power transformer impedance voltage expressed in volts;

I_{n} is the rated current of the corresponding winding of the transformer.

Note that in the ratings of power transformer its impedance voltage is expressed in % relative to the rated voltage U_{n} of the corresponding winding:

$$u_{\mathrm{imp}} = \frac{u_{\mathrm{imp}}\%}{100\%} \cdot U_{\mathrm{n}}. \tag{5.10}$$

Substituting expression (5.10) into (5.9) and multiplying numerator and denominator by U_{n}, we obtain the inductive reactance of a power transformer expressed through its ratings:

$$x_{\mathrm{t}} = \frac{u_{\mathrm{imp}}\%}{100\%} \cdot \frac{U_{\mathrm{n}}^2}{S_{\mathrm{n}}}, \tag{5.11}$$

where $S_{\text{н}}$ is the total rated power of the transformer.

Similarly, the phase inductive reactance of synchronous and asynchronous generators and motors can be determined:

$$x_{\mathrm{g}} = x_{\mathrm{d}}'' \frac{\left(E_{\mathrm{d}}''\right)^2}{S_{\mathrm{n}}}, \tag{5.12}$$

where. E_{d}'' is the subtransient driving voltage of the generator.

The phase inductive reactance of current-limiting reactors is determined from its percentage reactance:

$$x_{\mathrm{r}} = \frac{x_{\mathrm{r}}\%}{100\%} \cdot \frac{U_{\mathrm{n}}}{\sqrt{3} \cdot I_{\mathrm{n}}}. \tag{5.13}$$

Inductive reactance of overhead and cable transmission lines:

$$x_{\text{line}} = x_0 \cdot l_{\text{line}}, \qquad (5.14)$$

where l_{line} is the line length.

An example **of calculation by real units.** The task is to calculate the parameters of a 3-phase short-circuit current downstream a current-limiting reactor. The fault is fed from two power sources: a system of infinite capacity and a house generator. The design circuit of the subsystem is shown in Figure 5.5.

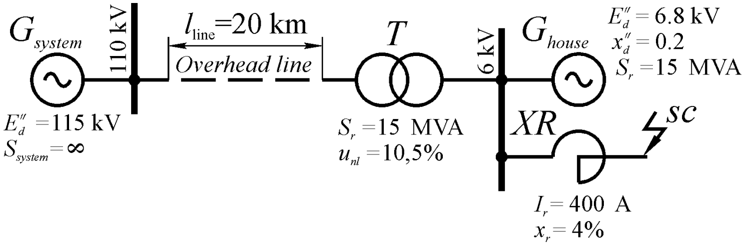

Figure 5.5 – Design circuit

Calculation of short-circuit current is performed in the following order:

1. Equivalent circuit is drawn up. It is shown in Figure 5.6

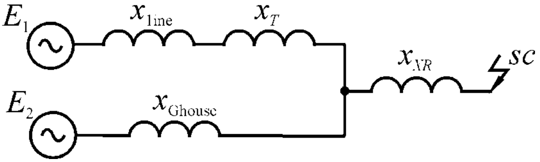

Figure 5.6 – Equivalent circuit

2. The common voltage base is chosen: $U_{\text{base}} = 6\,\text{kV}$.

3. The inductive reactance of the shorted circuit elements in real units are calculated:

- an overhead transmission line with formula (5.14) is:

$x_{\text{line0}} = 0.4 \cdot 20 = 8\,\text{Ohm}$;

- power transformer with formula (5.11) is:

$$x_T = \frac{10{,}5}{100} \cdot \frac{6^2}{15} = 0.252\,\text{Ohm};$$

- current-limiting reactor with formula (5.13) is:

$$x_{XR} = \frac{4}{100} \cdot \frac{6000}{\sqrt{3} \cdot 400} = 0.346\,\text{Ohm};$$

- house generator with formula (5.12) is:

$$x_{\text{Ghouse}} = 0.2\frac{6.8^2}{15} = 0.6165\,\text{Ohm}\,.$$

4. The electrical parameters of the shorted circuit components are converted to the common voltage base with formulas (5.7) as follows:

$$E_1 = E_d^{//}\left(\frac{U_{\text{base}}}{U}\right) = 115\cdot\left(\frac{6}{110}\right) = 6.27\,\text{kV}\,;$$

$$E_2 = E_{\text{Ghouse}} = 6.8\,\text{kV}\,;$$

$$x_{\text{line}} = x_{\text{line0}}\left(\frac{U_{\text{баз}}}{U}\right)^2 = 8\cdot\left(\frac{6}{110}\right)^2 = 0.0238\,\text{Ohm}\,;$$

5. The equivalent EMF is determined with formula (5.8); to do this, the equivalent circuit is transformed to the circuit shown in Figure 5.7, where:

$$x_1 = x_{\text{line}} + x_T = 0.0238 + 0.252 = 0.2758\,\text{Ом}\,;$$

$$x_2 = x_{\text{Ghouse}} = 0.6165\,\text{Ом}\,.$$

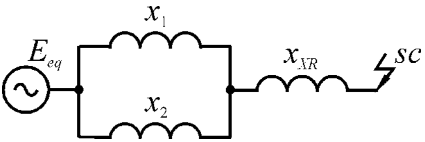

Figure 5.7 – Transformed equivalent circuit

$$E_{\text{eq}} = \frac{6.27\dfrac{1}{0.2758} + 6.8\dfrac{1}{0.6165}}{\dfrac{1}{0.2758} + \dfrac{1}{0.6165}} = 6.43\,\text{kV}$$

6. The circuit is simplified by means of equivalent transformations and the total (equivalent) impedance of the shorted circuit is determined as follows:

$$x_{\text{eq}} = \frac{x_1 x_2}{x_1 + x_2} + x_{XR} = 0.5365\,\text{Ohm}\,.$$

7. The parameters of short-circuit current is determined as follows:

- the initial rms value of the symmetrical component is:

$$I_{\text{p0}} = \frac{E_{\text{eq}}}{\sqrt{3\cdot x_{\text{eq}}}} = \frac{6.43}{\sqrt{3}\cdot 0.5365} = 6.93\,\text{kA}\,;$$

- peak value of short-circuit current is:

$$i_{\text{peak}} = 2.25 \cdot I_{\text{p0}} = 2.25 \cdot 6.93 = 15.6 \text{ kA}$$

Calculations by per-unit method. In using this method, it is not necessary to recalculate the initial impedances represented in relative unis to real ones. In this case, all quantities are converted to a base power and a base voltage. As the base voltage, the voltage of the base step is accepted (see above); as the base power, the power of the system, the transformer power or a conventional unit of power is accepted.

Basing upon the accepted base values, the base current is calculated:

$$I_{\text{base}} = \frac{S_{\text{base}}}{\sqrt{3 \cdot U_{\text{base}}}} . \tag{5.15}$$

The impedances of the elements are also converted to base quantities using the following expressions:

- for power generators and motors:

$$x_{\text{base}} = x''_{\text{d}} \frac{S_{\text{base}}}{S_{\text{n}}} ; \tag{5.16}$$

- for power transformers:

$$x_{\text{base}} = \frac{u_{\text{imp}}\%}{100\%} \cdot \frac{S_{\text{base}}}{S_{\text{n}}} ; \tag{5.17}$$

- for current-limiting reactors

$$x_{\text{base}} = \frac{x_{\text{r}}\%}{100\%} \cdot \frac{U_{\text{n}}}{I_{\text{n}}} \cdot \frac{I_{\text{base}}}{U_{\text{base}}} ; \tag{5.18}$$

- for overhead and cable lines

$$x_{\text{linebase}} = x_0 \cdot l_{\text{line}} \cdot \frac{S_{\text{base}}}{U_{\text{base}}^2} . \tag{5.19}$$

The initial rms value symmetrical short-circuit current component:

$$I_{\text{p0}} = \frac{I_{\text{base}}}{x_{\text{base}\Sigma}} , \tag{5.20}$$

where $x_{\text{base}\Sigma}$ is the total value of the shorted circuit impedance in relative units converted to base quantities.

In the rest, the calculations are performed in the way discussed above.

As already noted, if the fault location is in the neighborhood of the power source (e.g., at a power station), the transient process is more complex in behavior and when calculating the change of the symmetrical current amplitude is to be taken into account. Such necessity arises in the case when there is needed to find the rms symmetrical current at the instant the contacts of the switching device, clearing the fault, start to open in order to verify its interrupting capability.

The most simple and accurate enough method to find this quantity is the employment of design curves. They represent a set of graphical dependencies defining the relationship $I_{\text{pt}}/I_{\text{p0}}$ as a function of the time span from a fault zero-time at different values of the relationship $I_{\text{p0}}/I_{\text{n}}$ [1, 2, 5, 9, 12]. The time span from the beginning of the fault to the start of opening the circuit-breaker contacts is added of the response time of the protection relays and the self-actuation time of the circuit-breaker.

There are frequent cases when the fault is located on the line between synchronous generator and synchronous motor. In this case, the synchronous motor additionally feeds the shorted circuit. Short-circuit currents in this case are calculated with use of relevant design curves for synchronous motors.

The distinctive features that must be taken into account when short-circuit currents are calculated in low voltage electric installations are as follows:

1. The active resistance of some elements is comparable with their reactance; therefore, it is to be taken into consideration.

2. The parameters of short-circuit current are significantly dependent on contact resistances in bus arrangements, in switching devices etc. Therefore, they are also to be taken into account.

3. The main assumption is the installation is fed from the system of infinite capacity.

5.4 Determination of the TRV Parameters at Fault Downstream of a Power Transformer

As already noted (see Section 4), the ability of a switching device to clear a faults does not only depend on the value of current being interrupted. To date, it has been reliably established that the breaking capability of circuit breakers is also determined by the parameters of system transient recovery voltage (TRV), which characterize the switching conditions produced by the network and are normalized by international and national standards. Let us consider practical calculation examples of the TRV parameters.

One of the most typical cases is fault events in the distribution switchboard of an electric power station or substation, shown as a single-line circuit in Figure 5.8.

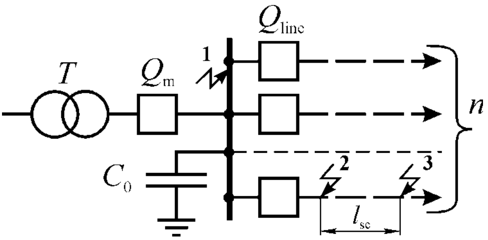

Figure 5.8 – Single-line circuit of power distribution station

The circuit contains a power transformer *T* supplying the switchboard busburs via the incoming feeder with main circuit breaker Q_m; n of outgoing feeders with line circuit breakers Q_{line}, connected to the busbars, serve for further transmission of the power or supplying electric consumers. Let us consider the basic cases of faults downstream of the power transformer.

Case 1. A short circuit has occurred between main circuit-breaker $Q_в$ and busbars or directly on busbars. The equivalent circuit to calculate the TRV parameters for this case is presented in Figure 5.9.

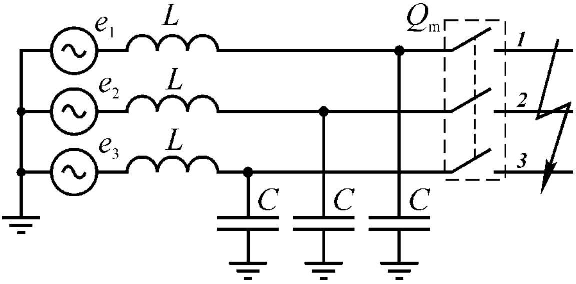

Figure 5.9 – The equivalent circuit to find the TRV parameters (case 1)

In the equivalent circuit: *L* is phase inductance of the short-circuited transformer (leakage inductance); at a power frequency, it is determined from formula (5.11) that, with consideration of angle frequency ω, will be as follows:

$$L_{50} = \frac{u_{imp}\%}{100\%} \cdot \frac{U_n^2}{\omega S_n}. \tag{5.21}$$

Due to eddy currents and other factors, the phase inductance at a high frequency of the TRV will be somewhat different. Its accurate determination is highly difficult, nevertheless the operating experience of power transformers has shown that it reduces by approximately 20–30% [3, 12, 17], and hence:

$$L = (0{,}7...0{,}8) \cdot L_{50}; \tag{5.22}$$

C is the total reduced phase capacitance of electrical equipment connected to the switchboard busburs determined usually by the following expression [17]:

$$C = C_0 + C_{\text{ph}}/2, \tag{5.23}$$

where C_{ph} is the total reduced phase capacitance of the transformer that for actual transformers is usually in the range of 1000 to 5000 pF per one phase, depending on its capacity and the winding nominal voltage [17].

To evaluate the magnitude of the transformer winding capacitance, the Hammarlund's formula is frequently used [3, 17]:

$$C_{\text{ph}} = 70\frac{S_{\text{n}}^{0,35}}{U_{\text{n}}^{0,175}}, \quad \left[\frac{\text{pF}}{\text{phase}}\right], \tag{5.24}$$

where S_{n} is the total capacity of the transformer expressed in kVA;

U_{n} is the nominal voltage of the transformer secondary winding expressed in kV.

Since the line currents are shifted by 120 el. deg., their current-zeros will be non-simultaneous. Calculations show that most heavy duty in terms of the TRV are produced for the circuit-breaker pole in which the current by first passes through zero value usually called the *first pole to clear*. Therefore, the calculations of TRV parameters are mainly performed for this pole [3, 13, 14, 17, 23–27].

Let us suppose that a current is interrupted in pole 1 (see Figure 5.9), while currents in other poles continue to flow due to existence of arc discharges. Since the recovery voltage is calculated with no taking into consideration the switching device properties, the actual switching device is substituted by the ideal switching element. Then, the initial equivalent circuit can be simplified to the circuit represented in Figure 5.10a, i.e. the elementary single-frequency circuit. The value of the PFRV for the first pole to clear is found from the vector diagram shown in Figure 5.10b:

$$U_0 = 1{,}5 \cdot \sqrt{2}U_{\text{ph}} = 1{,}5\frac{\sqrt{2}}{\sqrt{3}}U_{\text{n}} = \sqrt{\frac{3}{2}}U_{\text{n}}, \tag{5.25}$$

where $U_{\text{н}}$ is the nominal rms line-to-line voltage at a given point of the electrical system.

Because of a shunt resistance is absent in this circuit (i.e., $R_{\text{ш}} = \infty$), and the active resistance of the transformer winding is close to zero, then the following condition practically always will be valid:

$$\frac{1}{LC} >> \left(\frac{R}{2L}\right)^2 . \qquad (5.26)$$

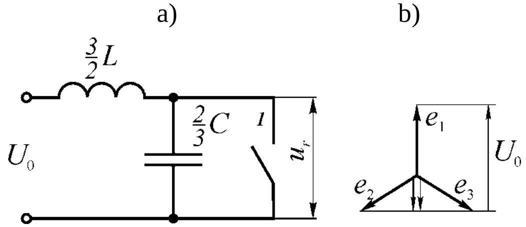

Figure 5.10 – Case 1: a) simplified equivalent circuit; b) vector diagram

Hence, in this case, slightly damped single-frequency oscillatory TRV process will take place:

$$u_r = U_0\left(1 - e^{-at}\cos\omega_0 t\right), \qquad (5.27)$$

where $\omega_0 = \dfrac{1}{\sqrt{\frac{3}{2}L\frac{2}{3}C}} = \dfrac{1}{\sqrt{LC}}; \quad a \approx 0$.

The time diagram of the recovery process for this case is represented in Figure 4.7a. It is featured by the following parameters:

- *the natural frequency* of the TRV :

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} . \qquad (5.28)$$

In actual high and medium voltage electrical systems, its magnitude ranges from 2 to 10 kHz; for low voltage systems the typical magnitudes are from 5 to 100 kHz [3, 17];

- *the maximal value (peak)* of the TRV:

$$u_{r\max} = U_0\left(1 - e^{-at}\right) = \kappa_a U_0 , \qquad (5.29)$$

where κ_a is the peak factor of the TRV; at $a = 0 \quad \kappa_a = 2$; for actual high and medium voltage systems $\kappa_a = 1.4 - 1.5$ are typical; for low voltage systems, it is $\kappa_a = 1.1 - 1.5$ [3, 17];

- for high and medium voltage systems, a vital important parameter is the *average rate of rise* of the recovery voltage (RRRV) that for this case is expressed as follows:

$$\left(\frac{du_r}{dt}\right)_{\text{av}} = \frac{u_{r\max}}{T_0/2} = 2\kappa_{\text{a}} f_0 U_0 , \tag{5.30}$$

where $T_0 = 1/f_0$.

As already noted, in high-voltage systems (of 100 kV and higher) the so-called *double-frequency recovery process* can be take place, when the circuit is formed by power generator and transformer (see Figure 4.8 and 4.9). In this case, the average RRRV has two components defined respectively by the parameters of the power generator and transformer:

$$\left(\frac{du_r}{dt}\right)_{\text{av}} = 2\kappa_a\left(f_{01}U_{01} + f_{02}U_{02}\right). \tag{5.31}$$

Case 2. A fault has occurred directly (in the range from a few tens to several hundred meters) downstream from the line circuit breaker Q_{line} named *terminal fault.* In this case, the fault is cleared by the circuit breaker of the faulty line. As it was noted above, in this case, the line side component of the recovery voltage practically does not effect on the behavior of the TRV. Hence, the equivalent circuit to determine the TRV parameters contains only the parameters of the components located on source side as shown in Figure 5.11.

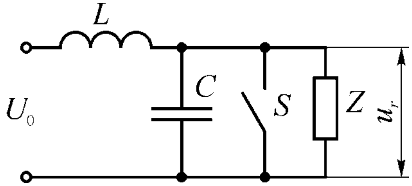

Figure 5.11 – The equivalent circuit for finding TRV parameters (case 2)

The circuit differs from the elementary single-frequency circuit (see Figure 5.10) by the availability of impedance Z connected in parallel with the breaker contacts *S*. The impedance Z results from the available $(n-1)$ healthy transmission lines connected to the switchboard busbars aside from the faulty line. The value Z is equal in magnitude to total surge impedance of healthy lines:

$$Z = \frac{\sqrt{L_0/C_0}}{n-1}, \tag{5.32}$$

where L_0, C_0 are the inductance and capacitance, respectively, per unit length of the line;

n is the number of transmission lines connected to the busbar system.

Healthy lines act like active resistance, i.e. they shunt the breaker contacts and "damp" the recovery process. This is reflected in the fact that a decrease in value of shunt resistance leads to a decrease in the amplitude of the oscillating TRV and its more rapid decaying (see above). The surge impedance of actual transmission lines is relatively small and ranges from 300 to 500 Ohms [3, 17, 22–26]. A value of 450 ohms is usually assumed for single overhead transmission conductors and 360 ohms for bundled conductors. Thus, even at $n = 2$ the transient recovery voltage will behave as aperiodic process (see Figure 4.7d).

If the capacitance C and the active resistance R are neglected in the circuit, then the expression for the TRV will be as follows:

$$u_r = U_0\left(1 - e^{-\frac{z}{L}t}\right). \qquad (5.33)$$

In the process, the initial rate of rise of the recovery voltage will be determined by the following expression:

$$\left(\frac{du_r}{dt}\right)_0 = U_0\frac{Z}{L}. \qquad (5.34)$$

Case 3. Short-circuit fault has occurred at some distance l_{sc} (in the range from a few kilometers to several tens of kilometers) from the line circuit-breaker. In this case, the behavior and parameters of TRV will be defined not only by the processes at the supply side, but also the ones at the line side (see Figure 4.10–4.12).

The line side voltage will be defined by the fault current value, as well as the inductive reactance of the line section between the breaker and the fault point:

$$U_{0\text{line}} = \sqrt{2}I_{\text{p0}}^{(\text{line})}\omega L_{\text{line}} = \sqrt{2}I_{\text{p0}}^{(\text{line})}\omega L_0 l_{\text{sc}}, \qquad (5.35)$$

$I_{\text{p0}}^{(\text{line})}$ is the initial rms value of the symmetrical short-circuit current component under the line fault determined by the following relationship :

$$s = \frac{I_{\text{p0}}^{(\text{line})}}{I_{\text{p0}}}, \qquad (5.36)$$

where I_{p0} is the initial rms value of the symmetrical short-circuit current component under the terminal fault;

s is a value that determines the remoteness degree of line fault; when testing circuit-breakers in short line fault conditions, its magnitude is accepted equal to 0.6; 0.75 and 0.9 [12, 17].

The returning time of reflected wave:

$$t_\text{o} = \frac{2l_\text{sc}}{v}, \tag{5.37}$$

where v is the propagation velocity of the electromagnetic wave in the line, determined in accordance with the following expression:

$$v = \frac{1}{\sqrt{L_0C_0}}. \tag{5.38}$$

Hence, the rate of rise of the line side TRV is:

$$\left(\frac{du_r}{dt}\right)_\text{line} = \frac{2U_{0\text{line}}}{t_0} = \frac{2\cdot\sqrt{2}sI_{\text{p}0}\omega\sqrt{L_0}\,l_\text{sc}}{2l_\text{sc}\sqrt{L_0C_0}} = \sqrt{2}sI_{\text{p}0}\omega Z_\text{line}, \tag{5.39}$$

where $Z_\text{line} = \sqrt{\frac{L_0}{C_0}}$ is the surge impedance of the line.

It should be noted that the rate of rise of the line side TRV in far excess of the one of the supply side TRV. Therefore, the total rate of rise of TRV in the case of the line fault will be defined exceptionally by the line side component of the rate of rise of TRV. As seen from expression (5.39), it will be determined by the fault current value that, in turn, will be determined by the distance of the fault point from the circuit-breaker.

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