Ministry of Education and Science of Ukraine

ZAPOROZHYE NATIONAL TECHNICAL UNIVERSITY

METHODICAL INSTRUCTIONS

for the laboratory works on the discipline:
"Exploitation of Electric and Electronic Apparatuses"

for the students of the specialty
141 – Power, electric and electromechanical engineering
(educational program **«Electric and Electronic Apparatuses»)**

2019

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CONTENT

INTRODUCTION

Traditionally, a significant part of the educational time for the educational program "Electrical and Electronic Apparatuses" is aimed mainly to the study of the theory of electric apparatus, the calculation, design and optimization of their individual elements, the design of apparatus as a whole. Nevertheless, the future specialist studying in specialty 141 "Power, electrical and electromechanical engineering" should insight into the problems related to the exploitation of electric and electronic apparatuses, since the most of specialists in the electrical engineering field in their practical work are aimed to solving just these tasks. The subject presented is in certain degree purposed to overcome such shortcoming. In particular, the proposed cycle of the laboratory works is purposed not only to gain experience of operating conditions analysis of electric equipment, but also to improve experience to use computer technologies. Specifically, it is suitable software for simulation of electric and electronic circuits, which is recently extensively used. [14-16].

To perform each laboratory work successfully and timely, a student must be qualitatively prepared to it beyond of the scheduled study. In the preparing, a student must study theoretical basis, to read the methodical instructions in respect to the subject of the laboratory work as well as to construct the simulating circuit according to the task.

Prior to performing the laboratory work cycle, students must be trained in safety and regulations in the computer class. Students who have not undergone such instruction are not permitted to perform the laboratory works.

Just after beginning of scheduled study, the simulating circuit must be agreed with teacher, which supervises the laboratory works. Once the laboratory work has been performed, the student must agree his findings with the teacher. The findings of the laboratory work must be presented as the report performed in compliance with the requirements of СТП 15-96.

1. LABORATORY WORK №1.
DETERMINATION OF SHORT-CIRCUIT CURRENT PARAMETERS

Duration of scheduled study is 4 hours

1.1 The purpose of the work

The purpose of the laboratory work is to study the methodology and to perform practical work to determine short-circuit current parameters in high-voltage power system with the help of circuit simulation software.

1.2 Subject of study

Short-circuit (fault) is any non-designed electrical connection of lines with the “ground” or between them. The short-circuit (sc) currents flowing in this case through faulty subsystem by tens times in excess of the rated ones and are emergency for electrical equipment; the faulty subsystem therefore must be immediately de-energized. To ensure reliable interruption of the sc current, the interrupting capability of respective switching devices (circuit-breakers) must be agreed with the sc current parameters. That is why their determination is vital important problem solved in the selecting the circuit breakers and other electrical equipment.

A fault, initiating in an electric system, is accompanied with a complex transient process. At this time, the instantaneous value of the sc current consists of two components: periodic (symmetrical current) and aperiodic (dc component).

The periodic component (symmetrical current), in general case, varies according to sine law at a power frequency of 50 or 60 Hz. Its amplitude decreases gradually down to steady-stated value $I_{п\infty}$. It occurs because of varying the power generator’s magnetic field in the fault process. The duration of the symmetric current steadying is typically in the range of 3 to 5 seconds. If the power generator is equipped with automatic excitation controller (AEC), symmetric current amplitude varies in somewhat other manner: initially, the process behaves in the same manner, and then under the action of the AEC the excitation current increases that results in an increase in the symmetric current amplitude. If the fault location is far from power generators, the variation of the symmetrical current amplitude usually does not take place.

The *dc component* is maximal at the fault zero-time and hereafter exponentially decays typically during 0.2–0.3 seconds, if the fault occurs in the vicinity of the power generators. The absolute value of the dc component is dependent on the source power, the fault remoteness and the fault initial instant relative to power voltage wave-shape.

The task of sc current calculations is to determine its basic parameters:

- *initial rms symmetrical sc current* $I_{п0}$ determined in 0.01 second after the fault beginning;
- rms symmetric sc current at the instant when the circuit-breaker main contacts are started to opening $I_{пt}$;
- *peak value of sc current* $i_{уд}$ is maximal instant value of the short-circuit current taking place in approximately 0.01 s after the fault beginning;
- **dc component content** determined by percentage relative to the symmetric current amplitude:

$$\beta = \frac{i_{\text{a}}}{\sqrt{2} \cdot I_{\text{пt}}} 100\% ,$$

where i_{a} is the instantaneous value of the dc component at the instant when the circuit-breaker main contacts are started to open.

Short-circuit current calculations for HV power systems is per-formed for the worst case, that is, the line-to-line fault, although it occurs only in 5% of the fault total events. In calculating, the case of direct (dead) fault is considered, when the fault location impedance is neglected. In the process, the magnetization currents of the power transformers, as well as the saturation of their magnetic systems are also neglected, that is, equivalent circuits are considered as linear and electrically coupled. For high-voltage power systems the calculations are performed without taking into account the resistive components.

The use of the circuit simulation software for the purpose to determine sc current parameters enables us to avoid some assumptions. In particular, the resistances of the components can be taken into ac-count in the equivalent circuit that enables us, firstly, to enhance accuracy of the calculations as well as to determine dc component of the sc current.

1.3 Task

Using the potentialities of circuit simulation software [14–16], it should be found the parameters of sc current for the predetermined fault location and different initial phase relative to power voltage waveform in the power subsystem, illustrated in Figure 1.1. Ratings and other data of the equipment are presented in Table 1.1. Total actuation time of relay protections is to be accepted 0.07 s.

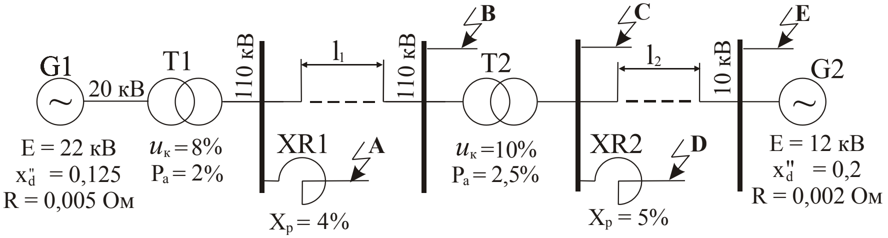

Figure 1.1 – Initial one-line circuit for the laboratory work task

Table 1.1 – Ratings and other data of electrical equipment

№ var.	**S_{G1} MVA**	**S_{T1} MVA**	**l_1 km**	**S_{T2} MVA**	**S_{G2} MVA**	**l_2 km**	**$I_{\text{н}XR1}$, A**	**$I_{\text{н}XR2}$, A**	**Fault location**
1	800	30	100	250	320	3,0	2000	1600	**A**
2	630	250	45	63	150	1,5	1600	630	
3	320	250	50	40	100	0,5	1000	400	
4	250	180	70	100	200	1,0	630	320	
5	500	320	80	100	250	1,5	400	250	
6	100	100	30	80	120	0,8	160	100	**B**
7	150	100	90	50	100	0,9	200	160	
8	200	150	80	25	150	1,2	250	200	
9	400	320	70	32	200	1,4	630	320	
10	180	150	60	75	180	1,8	100	160	
11	800	630	100	250	320	3.0	2000	1600	**C**
12	630	250	45	63	150	1.5	1600	630	
13	320	250	50	40	100	0.5	1000	400	
14	250	180	70	100	200	1.0	630	320	
15	500	320	80	100	250	1.5	400	250	
16	100	100	30	80	120	0.8	160	100	**D**
17	150	100	90	50	100	0.9	200	160	
18	200	150	80	25	150	1.2	250	200	
19	400	320	70	32	200	1.4	630	320	
20	180	150	60	75	180	1.8	100	160	
21	800	630	100	250	320	3.0	2000	1600	**E**
22	630	250	45	63	150	1.5	1600	630	
23	320	250	50	40	100	0.5	1000	400	
24	250	180	70	100	200	1.0	630	320	
25	500	320	80	100	250	1.5	400	250	

1.4 Methodical directions

1.4.1 For a given fault location (see Figure 1.1), construct a one-phase equivalent circuit indicating the active resistances and inductances of its components.

1.4.2 Since the equivalent circuit simulating the fault is one-phase, subtransient line-to-line EMFs of the power sources must be reduced by $\sqrt{3}$ times.

1.4.3 Based upon the ratings of the electrical equipment (see Table 1.1) calculate the resistances and inductances of the equivalent circuit components in the named units, using the following expressions:

a) an inductance per one phase of a power generator:

$$L_{\text{г}} = x''_{\text{d}} \frac{\left(E''_{\text{d}}\right)^2}{\omega \cdot S_{\text{н}}},$$

where ω is the angle frequency of the power voltage, $\omega = 2\pi f$, $f = 50\,\text{Hz}$;

x''_{d} is direct-axis subtransient of power generator;

E''_{d} is the subtransient line-to-line EMF of power generator, kV;

$S_{\text{н}}$ is the total rated power of the generator, MVA;

b) an inductance per one phase relative to primary winding of a power transformer:

$$L_{\text{т}} = \frac{u_{\text{кз}}\%}{100\%} \cdot \frac{U_{\text{н}1}^2}{\omega \cdot S_{\text{н}}},$$

where $u_{\text{кз}}\%$ is the impedance voltage of the power transformer expressed in percentage;

$U_{\text{н}1}$ is the rated voltage of the power transformer primary winding, kV;

$S_{\text{н}}$ is the total rated power of the transformer, MVA;

c) an inductance per one phase of a current-limiting reactor:

$$L_{\text{р}} = \frac{x_{\text{р}}\%}{100\%} \cdot \frac{U_{\text{н}}}{\sqrt{3} \cdot \omega \cdot I_{\text{н}}},$$

де $x_{\text{р}}\%$ is the reactivity percentage of the reactor, %;

$U_{\text{н}}$, $I_{\text{н}}$ are the rated voltage and rated current of the reactor, respectively;

d) an active resistance per one phase relative to the primary winding of a power transformer:

$$R_{\text{т}} = \frac{P_{\text{а}}\%}{100\%}\frac{U_{\text{н}1}^2}{S_{\text{н}}},$$

where $P_{\text{а}}\%$ is the active losses percentage of the power transformer, %;

e) an active resistance of a power generator is predetermined in circuit diagram (see Figure 1.1);

f) an active resistance of current-limiting reactors can be neglected.

1.4.4 The equivalent circuit and its parameters should be agreed with the teacher supervising the laboratory works.

1.4.5 Determine the parameters of sc current with the help of circuit simulation software. That is performed in the following order:

a) turn on the PC;

b) load respective software for circuit simulation: for example, Electronics Workbench;

c) construct simulating circuit with proper parameters of its components;

d) explore the simulating circuit in steady-state and transient condition and determine the sc current parameters according to the task; obtained findings are to be tabulated as follows:

Table 1.2 – Short-circuit current parameters

Ψ, el. deg.	**0**	**30**	**60**	**90**	**120**	**150**	**180**
$I_{\text{п}0}$, kA							
$I_{\text{пt}}$, kA							
$i_{\text{уд}}$, kA							
β, %							

e) change the initial phase of the fault initiation ψ and repeat item d;

f) as an example, print a one of the obtained sc current traces and paste it to the laboratory work report.

1.4.6 Basing upon the obtained findings, plot the graphical dependencies.

1.4.7 The laboratory work report should contain:

a) the name and purpose of the work;

b) simulating circuit (equivalent shorted circuit with pointed up parameters of its components);

c) a table with the sc current parameters and the graphical dependencies;

d) conclusions on the work.

1.5 Self-checking questions

1.5.1 What is a short-circuit (fault)?

1.5.2 How do relay protections operate in event of a fault?

1.5.3 What components does the instantaneous value of sc current consist of?

1.5.4 How do the components of sc current behave?

1.5.5 Name the basic parameters of sc current.

1.5.6 What type of the fault is calculated and why?

1.5.7 What assumptions are accepted in calculating sc current?

2. LABORATORY WORK № 2.

DETERMINATION OF TRANSIENT RECOVERY VOLTAGE PARAMETERS

Duration of scheduled laboratory study is 4 hours

2.1 The purpose of the work

The purpose of the work is to study procedure and to perform a practical work in respect to determining the transient recovery voltage parameters in the short-circuit process downstream a power transformer using circuit simulation software.

2.2 Subject of study

It is known that the contacts of switching devices (except synchronous switches) are started to open at any moment relative to the sine current waveform. At this moment, an arc discharge comes into existence between the contacts, the voltage across the contact gap to the current half-cycle end varies according to the arc volt-ampere characteristic. Just after the current-zero crossing, the arc discharge acquires qualitatively new properties, it is called *residual arc space*. From this moment the dielectric strength, called usually *dielectric recovery*, of the residual arc space increases, at the same time it is stressed by the so-called *recovery voltage*.

If at any moment the recovery voltage will exceed the dielectric recovery, an arc discharge again will come into existence across the contact gap and will exist until the next current-zero crossing. In the case, when the recovery voltage will not be in excess of the dielectric recovery, the electric arc will not come into existence in the contact gap and residual arc space will restore its dielectric strength to the state of “cold strength”. In the process, the voltage across the contact gap will restore to the so-called *power frequency recovery voltage* (PFRV). It should be noted that this process cannot happen instantaneously, because the real components of an electrical system (generators, transformers, power lines, reactors, etc.) possess a capacitance. Therefore, a transient process is initiated called *transient recovery voltage*.

Generally, the transient recovery voltage (TRV) is an instantaneous voltage across the switching device contacts during the restoration of the voltage. TRV is one of the most important factors that determines the process of interrupting ac electric circuits. At the present time, it is reliably recognized that the interrupting (breaking) capability of switching devices (mainly circuit-breakers) should be determined not only by the parameters of the current to be interrupted, but also by the TRV parameters. That is why determination of the TRV parameters is an important problem. It is especially vital for circuit-breakers, which perform protecting function, that is, interruption of a faulty subsystem in the event of short-circuit.

The behavior and parameters of the TRV are determined by the properties of the electric circuit being interrupted, as well as the properties of the switching device. However, the practical significance is the so-called *system TRV* determined without taking into account the properties of the switching device, but only taking into account the properties of the circuit to be interrupted. Such approach allows us to unambiguously evaluate the operating conditions of switching devices, since the *real TRV* observed in interrupting the same circuit by different switching devices will be distinctive, while the operating conditions for these will be identical.

The main parameters of the TRV are the frequency of the proper oscillations, called *free frequency*, and its *peak value* (for the oscillation behavior of the TRV); the most important parameter for medium and high voltage power systems is the *rate of rise of TRV*. At the present time, for medium and high voltage switching devices the TRV is specified by the so-called *normalized limiting curves* [7, 10-12].

Parameters of TRV can be calculated. However, in the case the power system has a complex configuration, contains elements with distributed parameters, the calculation of the TRV parameters is very complicated. In such cases, parameters of TRV are frequently determined experimentally.

The TRV parameters for the simplest circuits are usually calculated with the help of the expressions derived from analytical solution of the describing differential equations [1-3,7,8,13]. In order to calculate the TRV parameters for the circuits having relatively complex configuration, the so-called *counter-current method* is often used. This method is based on Thevenin's theorem, which states that the TRV across the breaker contacts coincides in value and waveform with the voltage that must be applied to the breaker contacts so that it results in the current in this branch equal to the current being interrupted, but oppositely directed to it, at zero driving voltage. Thus, the interrupting process is substituted by insertion into the circuit breaker branch of the conditional power supply, which provides in this branch a current equal to the short-circuit current being interrupted, but opposite to it in the direction at the short-circuited generators. As a result, the current in this branch becomes equal to zero, which is identical to interrupting the short circuit.

The countercurrent method is used in operational notation. The Laplace transform representation the found TRV is as follows:

$$U_{\text{в}}(p) = i(p) \cdot Z(p),$$

where $i(p)$ is the Laplace representation of the current to be interrupted;

$Z(p)$ is the Laplace representation of the impedance seen from the breaker terminals with shorted power generators in the network [13].

In such way, using the Laplace representation of the sc current and impedance of the power system viewed from the breaker terminals, we can find the Laplace representation of the TRV. Then, with the help of reversal Laplace transformation the time notation of the TRV can be found.

Significant advantage of the countercurrent method is the relative versatility that enables us to calculate the TRV for circuits with a relatively complex configuration. However, its significant shortcoming is a complex realization involved with a reversal Laplace transformation, since the resulting operational impedance expressions are frequently very cumbersome.

Application of present-time PC software enables us to determine the TRV parameters using circuit simulation or initial differential equations describing the recovery voltage process. The findings obtained by such a way are more accurate and are well pictorially presented.

One of the most frequent case to find the TRV parameters analysis is the fault downstream the power transformer on a power station or substation illustrated by one-line circuit diagram in Figure 2.1. The subsystem includes power transformer T, main circuit-breaker $Q_{\text{в}}$ supplying the busbar system of the distribution switchboard with (n+1) power feeders with respective line circuit-breakers $Q_{\text{л}i}$. Total capacitance of equipment connected to busbars is C_0. In the subsystem three basic cases of the fault locations are possible:

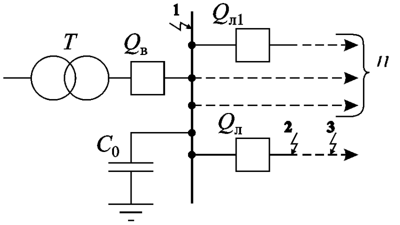

Figure 2.1 – Basic variations of short-circuits downstream a power transformer

- **case 1:** fault is located on the busbar system;
- **case 2:** fault is located in the neighborhood of the line circuit-breaker, called *terminal fault*;
- **case 3:** the fault is located in power line at relatively small distance (2–5 km) from line circuit-breaker, so-called *short-line fault*.

For the case 1 equivalent circuit relative to *first clearing phase* of the main circuit-breaker $Q_в$ is shown in Figure 2.2.

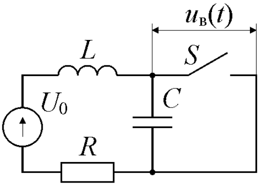

Figure 2.2 – Equivalent circuit for case 1

It includes ideal switch S (its contacts are started to open at arc current-zero moment); R, L, C are parameters of the circuit defined by the ratings of the power transformer and other equipment connected to the busbar system. U_0 is the power frequency recovery voltage; since the TRV progresses very rapidly relative to the PFRV, it is usually accepted as constant determined for this case as follows:

$$U_0 = \sqrt{\frac{3}{2}} U_н,$$

where $U_н$ is the rated line-to-line voltage.

The inductance of the shorted power transformer per one phase relative to power frequency (50 or 60 Hz) is:

$$L_{50} = \frac{u_к\%}{100\%} \cdot \frac{U_н^2}{2\pi f S_н}.$$

where $u_к\%$ is the impedance voltage of the transformer, expressed as a percentage;

$S_н$ is the nominal power of the transformer;

f is the frequency of the supply network.

Due to eddy currents and other factors, the inductance of the transformer at high frequency of the TRV will be approximately 20-30% lower, that is,

$$L = (0{,}7...0{,}8)L_{50}$$

The capacitance of the power transformer per one phase can be determined by the empirical formula proposed by Hammarlund:

$$C_{ф} = 70 \cdot \frac{S_{н}^{0,35}}{U_{н}^{0,175}},\ \frac{\text{pF}}{\text{phase}},$$

where $S_{н}$ is the total rated power of the transformer, kVA;

$U_{н}$ is the rated secondary voltage of the transformer, kV.

The total reduced capacitance of the equipment connected to the busbar system will be:

$$C = C_0 + \frac{C_{ф}}{2}.$$

The reduced pure resistance of the circuit per one phase is determined by the total active losses in copper and iron of the power transformer $P_{а}$.

$$R = P_a \frac{U_{н}^2}{S_{н}^2}.$$

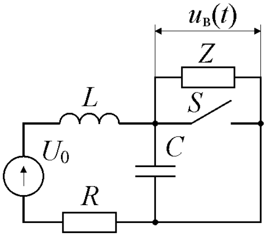

Figure 2.3 – Equivalent circuit for case 2

For the case 2 the equivalent circuit shown in Figure 2.3 differs by the presence of shunting resistor across ideal breaker S. Its value exactly duplicates total surge impedance of non-faulty power lines determined as follows:

$$Z = \frac{Z_{л}}{n}.$$

where $Z_{л}$ is surge impedance of one line that typically ranges from 400 to 500 Ohm;

n is the number of non-faulty power lines.

For the case 3 the equivalent circuit, shown in Figure 2.4, is distinctive by presence of power transmission line connected in series with ideal breaker S.

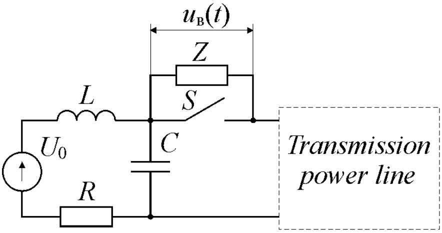

Figure 2.4 – Equivalent circuit for case 3

The power transmission line in the Electronics Workbench program is simulated using respective instrument “Transmission line” predetermined by surge impedance $Z_{\text{л}}$ and TD (time delay) found from the following formula:

$$TD = \frac{1-s}{s} \cdot \frac{L}{Z_{\text{л}}},$$

where s is the remoteness degree of the short-line fault; in switching tests of circuit breakers this quantity is accepted equal to: 0,6; 0,75; 0,9.

The power transmission line may be also simulated with inductive-capacitive circuit train composed, for example, of L-type elements is shown in Figure 2.5.

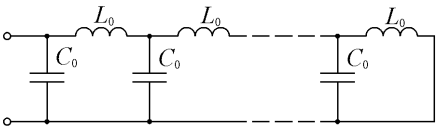

Figure 2.5 – Example of simulation of a power transmission line with the help of a circuit train

The parameters of an element is determined as follows:

$$L_{\text{o}} = \frac{1-s}{s} \cdot \frac{L}{m}; \quad C_{\text{o}} = \frac{L_{\text{o}}}{Z_{\text{л}}^2},$$

where m is the number of the elements predetermined usually in the range from 5 to 10.

2.3 Task

2.3.1 Study the existing methods of calculation of the TRV parameters.

2.3.2 Using possibilities of the circuit simulation software, determine the TRV parameters:

a) for the case 1: interruption of the fault on the busbar system;

b) for the case 2: interruption of the terminal;

c) for the case 3: interruption of the short-line fault.

2.3.3 Compare obtained findings with normalized limiting line and draw corresponding conclusions.

2.4 Methodical directions

2.4.1 Basing upon the power transformer ratings presented in Table 2.1, calculate the parameters of the equivalent circuit using the expressions represented in subsection 2.2.

2.4.2 Item 2.3.2a is performed in the order:

a) turn on the PC and load the required software (for example, Electronics Workbench);

b) enter the simulating equivalent circuit for case 1; ideal switch S in this case can be substituted by active resistor with high resistance (100 kOhm or above);

Table 2.1 – Ratings of power transformers

№ var.	Rated power, $S_{\text{н}}$, MVA	Rated voltage, $U_{\text{н}}$, kV	Total active losses $P_{\text{а}}$, kWt	Impedance volage, $U_{\text{к}}$,%	Total capacitance, C_0, pF
1	1,0	10	14,3	6,5	3500
2	1,6	20	20,2	6,5	4500
3	2,5	10	27,4	5,5	5000
4	6,3	20	55,9	6,5	5500
5	6,3	35	54,5	7,5	2000
6	10,0	35	77,3	7,5	3500
7	40,0	35	196,0	8,5	4500
8	80,0	35	333,0	9,5	5000
9	63,0	115	304,0	10,5	5500
10	80,0	115	580,0	10,5	3500
11	125,0	115	500,0	10,5	4500
12	250,0	121	800,0	10,5	5000
13	25,0	230	176,0	12,5	5500
14	63,0	230	395,0	12,5	2000
15	125,0	230	365,0	11,0	3500
16	250,0	230	670,0	11,0	4500
17	63,0	330	340,0	11,0	5000
18	200,0	347	747,0	10,0	5500
19	400,0	525	1120,0	13,0	4000
20	125,0	500	455,0	10,5	2500

c) determine the TRV parameters: peak value and average rate of rise of the TRV;

d) print the TRV curve and paste it into the report on the laboratory work.

2.4.3 Item 2.3.2b is performed in the same order. The resistance of the substituting resistor in the equivalent circuit calculate as per the expression presented in subsection 2.3. The number of the power transmission lines is to be accepted equal 5.

2.4.4 Item 2.3.2c is performed in the same order using the same data as in item 2.3.2b. In this case the equivalent circuit must be additionally contain the power transmission line according to directions of subsection 2.2. Simulation should be performed for specified values of remoteness degree of a short-line fault: 0,6; 0,75; 0,9.

2.4.5 The report on the laboratory work should contain:
a) the name and purpose of the work;
b) the parameters of the power transformer with noted variant;
c) the equivalent circuit and calculations of its parameters;
d) the obtained findings and recovery voltage traces;
e) conclusions on the work.

2.5 Self-checking questions

2.5.1 What are the methods for determining TRV parameters?

2.5.2 What is the essence of the countercurrent method?

2.5.3 What are the advantages of computer simulation of the voltage recovery process?

2.5.4 What factors affect the parameters of TRV?

2.5.5 Explain the behavior of the TRV curve when clearing the busbar fault of a distribution switchboard.

2.5.6 Explain the behavior of the TRV curve, when clearing the terminal fault.

2.5.7 Explain the behavior of TRV curve, when clearing the short-line fault.

2.5.8 Why the short-line fault is the most heavy duty to clear a short-circuit?

3. LABORATORY WORK №3
DETERMINATION OF OVERVOLTAGES IN INTERRUPTING LOW INDUCTIVE CURRENTS

Duration of scheduled laboratory study is 4 hours

3.1 The purpose of the work

The purpose of the laboratory work is the study of the procedure and performing a practical work of determining overvoltages initiated in interrupting low-inductive currents using computer technologies.

3.2 Subject of study

In the practice of electric equipment exploitation low-inductive currents take place when a power transformer is in no-load operation. The magnitudes of idle currents of high power transformers generally do not exceed 50-100 A, however, interruption of such currents by switching devices with high interrupting capability is usually occurred with the current cutoff prior to its natural zero value called a *current chopping*. It should be pointed out that the current chopping can occur at any moment relative to the current sine waveform, including at its maximum.

At the current chopping moment the recovery voltage process is started that is accompanied with significant overvoltages. Since the circuit is in this case interrupted with no arcing, the electromagnetic energy stored in the transformer inductance practically fully converses into the electrostatic energy dissipating in actually available capacitances. Thus, the overvoltage level can be determined from the energy conservation equation:

$$\frac{CU_{\max}^{2}}{2} = \eta \frac{Li_{\mathrm{ch}}^{2}}{2}, \qquad (3.1)$$

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

L is the idle inductance per one phase of the power transformer;

C is the reduced capacitance per one phase of the circuit;

η is the coefficient taking into consideration the copper and iron losses in the power transformer; it is usually in the range of 0.3 to 0.45.

Thus, equation (3.1) enables us to determine the overvoltage level during the voltage recovery process:

$$U_{\max} = \eta i_{\mathrm{ch}} \sqrt{\frac{L}{C}} \qquad (3.2)$$

If the current chopping occurred at the maximum current, then in this case the value of the overvoltage will be greatest. Thus, the highest expected overvoltage level will be determined in such a way:

$$U_{\max}^{\exp} = \eta I_{0\mathrm{m}} \sqrt{\frac{L}{C}}, \qquad (3.3)$$

where $I_{0\mathrm{m}}$ is the amplitude value of the transformer idle current, which is determined by this expression:

$$I_{0\mathrm{m}} = \frac{U_{\mathrm{m}}}{2\pi f L}, \qquad (3.4)$$

where U_{m} is the amplitude value of the power transformer rated voltage.

Substituting expression (3.4) in (3.3) we obtain:

$$U_{\max}^{\exp} = \eta \frac{U_{\mathrm{m}}}{2\pi f \sqrt{LC}} \qquad (3.5)$$

Taking into account the expression for the free frequency in respect to no-load operation of the power transformer:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \tag{3.6}$$

the overvoltage highest multiplicity will be determined by the multiplicity of the free frequency of the no-loaded transformer in relation to the industrial frequency:

$$\kappa_{\text{exp}} = \frac{U_{\text{max}}^{\text{exp}}}{U_{\text{m}}} = \eta \frac{f_0}{f}. \tag{3.7}$$

Expression (3.7) shows that losses in the transformer significantly reduce the overvoltages resulted from interrupting the no-load current. But they are still quite large and represent a serious danger for the isolation of electrical equipment. The main methods of limiting overvoltages are the use of surge arrests, as well as the shunting the switching devices with active resistance.

The main shortcomings of such approach to determine an overvoltage level are inaccuracies involved in taking into consideration the copper and iron losses in the power transformer in the voltage recovery process. In addition, the properties of the circuit-breakers, interrupting the circuit, as well as of the overvoltage limiters, having frequently non-linear characteristics, are not taken into account. Therefore, to determine the overvoltage level more precisely, sophisticated methods should be used, such as direct solution of the describing differential equations or computer simulation with the help of relevant software (e.g., Electronics Workbench).

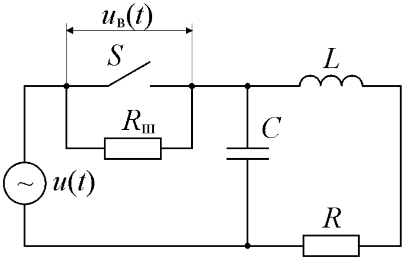

Figure 3.1 – Equivalent circuit to analysis of overvoltages

An equivalent circuit, simulating the process of interrupting a low-inductive current, is shown in Figure 3.1. It contains a switching element S, which opens with no arc, shunted by resistor $R_{\text{ш}}$ with the resistance dependent on the current flowing in the voltage recovery process, as well as inductance L, capacitance C and pure resistance R determined by the parameters of no-loaded power transformer.

The inductance of the no-loaded power transformer per one phase is expressed as follows:

$$L = \frac{100\%}{I_0\%} \cdot \frac{U_{\text{н}}^2}{2\pi f S_{\text{н}}} \tag{3.8}$$

where $S_н$, $U_н$ are the rated total power and rated voltage of the power transformer, respectively;

I_0% is the no-load current of power transformer expressed in percentage;

f is the frequency of the power network.

The capacitance of a power transformer is independent on its load duty and hence can be determined from the Hammarlund's formula (see laboratory work №2). Reduced capacitance is accepted as:

$$C = \frac{C_ф}{2}.$$

The reduced active resistance of a power transformer is determined by the total copper and iron losses in the same manner as in laboratory work №2.

3.3 Task

3.3.1 To study the conventional methods to determine the overvoltage levels for the case of low-inductive currents interruption [1, 8].

3.3.2 Using abilities of the circuit simulation software [14–16], to determine the overvoltage levels at variable resistance value of the shunting resistor and different instants of interruption relative to sine current waveform.

3.3.3 Basing upon the obtained findings, to build graphical dependencies.

3.3.4 To draw conclusions on the work.

3.4 Methodical directions

3.4.1 Basing upon the power transformer ratings represented in table 3.1, calculate the parameters of equivalent circuit using expressions represented in subsection 3.2.

3.4.2 Item 3.3.2 is performed in the following order:

a) turn on the PC and load available circuit simulation software (e.g., Electronics Workbench);

b) construct the simulating circuit and explore it in transient (the time diagram of voltage across switch S should be obtained);

c) basing upon obtained time diagram, determine the overvoltage ratio according to the following expression:

$$\kappa_п = \frac{U_{\max}}{U_m},$$

where $U_{в.макс}$ is the crest value of the recovery voltage across switch S;

U_m is the peak value of the power voltage;

d) sub-items c and d are to be performed for variable values $R_ш$ and $\psi_{ср}$ according to Tables 3.2 and 3.3.

e) print one of the time diagrams as example and paste it to the report.

Table 3.1 – Ratings of the power transformer

№ var.	**Rated total power, $S_н$, MVA**	**Rated voltage, $U_н$. kV**	**Active losses, $P_а$, kWt**	**No-load current $I_{хх}$, %**
1	1,0	10	14,3	1,4
2	1,6	20	20,15	1,4
3	2,5	10	27,4	1,0
4	6,3	20	55,9	0,9
5	6,3	35	54,5	0,9
6	10,0	35	77,3	0,8
7	40,0	35	196,0	0,4
8	80,0	35	333,0	0,3
9	63,0	115	304,0	0,6
10	80,0	115	380,0	0,55
11	125,0	115	500,0	0,55
12	250,0	121	800,0	0,5

Table 3.2 – Dependency the overvoltage ratio vs the value of shunting resistance at constant $\Psi_{ср}$

$R_ш$, kOhm	10	20	50	100	200	500	1000
$u_{в.макс}$, kV							
$\kappa_п$							

Table 3.3 – Dependency the overvoltage ratio vs the instant of the current chopping at constant R_{sh}

$\psi_{ср}$, el. degr.	0	30	60	90	120	150	180
$u_{в.макс}$, kV							
$\kappa_п$							

3.4.3 After the task has been performed, the work with used software is to be completed.

3.4.4 The report on the laboratory work should contain:

a) the name and purpose of the work;

b) the parameters of the power transformer;

c) the equivalent circuit and calculations of its parameters;

d) the obtained findings and the recovery voltage time diagrams;

e) the tables and graphical diagrams of the dependencies the overvoltage ratio vs the shunting resistance value and the current chopping instant;

g) the conclusions on the work.

3.5 Self-checking questions

3.5.1 What the calculation procedures for overvoltages resulted from interrupting low-inductive currents exist?

3.5.2 What advantages does the method based upon the solution of differential equations yield?

3.5.3 What factors affect the value of overvoltage under interrupting low-inductive currents?

3.5.4 What measures are taken to decrease overvoltage level when interrupting low-inductive currents?

3.5.5 What behavior has the recovery voltage curve in interrupting low-inductive current?

4. LABORATORY WORK №4

SELECTION OF HIGH-VOLTAGE CIRCUIT-BREAKER

Duration of scheduled laboratory study is 4 hours

4.1 The purpose of the work

The purpose of the laboratory work is to study methods and to perform the practical work on the selection of high-voltage (HV) circuit-breaker for the distribution plant, as well as to verify its operating ability in respect to basic parameters.

4.2 Subject of study

HV circuit breaker is the main switching device of an electricity distribution plants. Its reliability at large degree defines reliable and uninterrupted power supply. That is why, the selection of HV circuit-breakers is the most responsible stage in the development of electrical distribution and technological plants.

At present time, HV circuit breakers are extensively used in electric power systems with voltage up to 1200 kV and sc currents up to 80–100 kA. In distribution plants of 110 kV and above the application of air blast and sulfurhexafluoride (SF_6) circuit-breakers was mainly taken up. At the same time, there is a clear tendency to supersede the air blast circuit breakers with SF_6 ones. As per estimations of major experts, in the nearest future, SF_6 breakers will occupy dominating positions in distribution plants 220 kV and above. Medium voltage distribution plants (up to 35 kV) are currently equipped with different type of circuit-breakers, such as minimum oil, air magnetic, SF_6 and vacuum ones. It may be pointed out here that the current world market of medium voltage circuit-breakers consists of vacuum breakers to the extent of approximately 80%, SF_6 ones of 20% and minimum oil 1–2%. At the same time, the majority of the electric equipment producers ceased investments into the development of switchgear panels 6–35 kV equipped with minimum oil and air magnetic breakers.

The selection of HV circuit-breakers is carried out, first of all, in regard to nominal values of current and voltage. Then the chosen circuit-breaker is checked for peak and short-time withstand currents (stability under the passage of let-through sc currents) and switching capability according to the functions performed, as well as the requirements imposed.

The selection of HV circuit-breakers as for rated current and voltage is performed in accordance with following inequalities:

$$I_{\text{н}} \geq I_{\text{н.е/у}}\,; \;\; U_{\text{н}} \geq U_{\text{н.е/у}}\,,$$

where $I_{\text{н}}$, $U_{\text{н}}$ are the rated current and voltage of the chosen circuit-breaker, respectively;

$I_{\text{н.е/у}}$, $U_{\text{н.е/у}}$ are the rated current and voltage of given electric installation, respectively.

The chosen circuit-breaker is checked for peak withstand current (electrodynamic stability) as follows:

$$i_{\text{е/д.ст}} \geq i_{\text{уд}} = \sqrt{2}\kappa_{\text{уд}} I_{\text{п0}}\,,$$

and for short-time withstand current (thermal stability) as follows:

$$I_{\text{т.ст}} \geq I_{\text{п0}}\,,$$

under the condition that the time of flowing let-through sc current does not exceed admissible one for the circuit-breaker. If this condition is not fulfilled, then thermal stability can be estimated in respect to thermal action of sc current by the following inequality:

$$I^2_{\text{т.ст}} \cdot t_{\text{доп}} \geq I^2_{\text{п0}} \cdot t_{\text{кз}}\,;$$

where $i_{\text{е/д ст}}$ is the peak withstand sc current of the circuit-breaker;

$I_{\text{т. ст}}$ is the short-time withstand current of the circuit-breaker;

$I_{\text{п0}}$ is the initial rms symmetric sc current;

$\kappa_{\text{уд}}$ is the peak factor.

In regard to switching capacity the circuit-breaker is checked under conditions of reliable breaking the circuit in the event of a fault, as well as reliable making the circuit on existing fault. It is ensured, if the following relationships are fulfilled:

a) $I_{\text{в.ном}} \ge I_{\text{п}0}$; $I_{\text{о.ном}} \ge I_{\text{п}t}$,

where $I_{\text{в.ном}}$ is the rated making sc current of the circuit-breaker;

$I_{\text{о.ном}}$ is the rated breaking sc current of the circuit-breaker;

$I_{\text{п}t}$ is rms symmetric sc current at the instant when the breaker arcing contacts are started to separation; if the fault is located at relatively long distance from the power generators, $I_{\text{п}t}$ practically does not differ from $I_{\text{п}0}$; if the fault is located in the vicinity of power generators, $I_{\text{п}t}$ is substantially different from $I_{\text{п}0}$; in this case, it is determined from engineering curves [2];

b) $\beta \le \beta_{\text{н}}(t_{\text{кз}})$,

where $\beta_{\text{н}}$ is normalized dc component content percentage determined from normalized curve [2]

$t_{\text{кз}}$ is the fault time determined by the total actuation time of protection and proper actuation time of the circuit-breaker chosen;

c) system TRV curve for the given subsystem must lie below normalized limiting curve [7].

4.3 Task

4.3.1 To study procedure of HV circuit-breaker selection.

4.3.2 To select main $Q_{\text{в}}$ and line $Q_{\text{л}}$ circuit-breakers for the distribution plant; its one-line circuit diagram is shown in Figure 4.1.

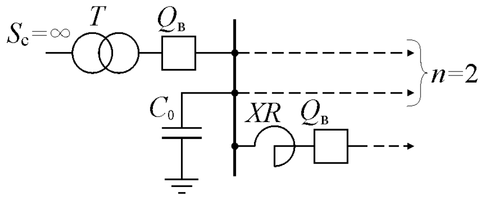

Figure 4.1 – One-line circuit of the distribution plant

Ratings of the power transformer, as well as total capacitance of other equipment connected to the busbar system are represented in Table 4.1. Actuation time of the relay protection is to be accepted as 0.07 s. In calculating, it is to be considered that power transformer is supplied from infinitely powerful system.

4.4 Methodical directions

4.4.1 Calculate the load current for the main circuit-breaker $Q_{\text{в}}$ assuming the power transformer is loaded of 90%, that is:

$$\sqrt{3} \cdot I_{\text{н}} U_{\text{н}} = 0{,}9 \cdot S_{\text{н}}.$$

4.4.2 The load current for the line circuit-breaker $Q_{\text{л}}$ is to be accepted equal to rated current of current limiting reactor XR (see Table 4.1).

Table 4.1 – Ratings of electrical equipment

№ var.	**Transformer**				**Current limiting reactor**			**$C_{о}$, pF**
	$U_{н}$, kV	**$S_{н}$, MVA**	**$U_{к}$,%**	**$P_{а}$, kWt**	**$I_{н}$, A**	**$x_{р}$, %**	**$P_{а}$, kWt**	
1	10	6,3	10,5	62,0	-	-	-	3500
2		10,0		78,8	630	3,5	3,9	2500
3		16,0		116,0	630	2,5	2,5	3000
4		25,0		179,0	630	2,5	2,5	4500
5		32,0		189,0	630	3,5	3,2	1800
6		40,0		237,0	1000	3,5	3,5	4500
7		63,0		308,0	630	3,5	3,2	3800
8		80,0		400,0	3000	3,5	3,5	2800
9	35	32,0	10,4	177	200	6	-	3200
10		40,0		237	500	10	-	2800
11		63,0		260	500	10	-	5000
12		80,0		305	1000	10	-	2000
13		10,0		335	1000	10	-	4000
14		160,0		480	1000	10	-	5500
15	110	80,0	10,5	470	650	15	-	3800
16		125,0		520	650			2500
17		160,0		605	650			4000
18		200,0		720	1350			4500
19		250,0		840	1350			4200
20		400,0		1222	1350			2200
21	220	250,0	12.0	890	325	12	-	3800
22		320,0		1020				2500
23		400,0		1210				4000
24		630,0		1610				4500
25		800,0		2130				3500

4.4.3 Basing upon the rated voltage of the power transformer secondary winding and the load currents, select the main and line circuit-breakers [3,7,10–12] and write the following their parameters: $I_{н}$, $U_{н}$, $I_{т.ст}$, $i_{е/д.ст.}$, $I_{о.ном}$, $I_{в.ном}$.

4.4.4 The parameters of sc current are determined in the following order:

a) construct the equivalent shorted circuits for the cases 1 and 2 (see laboratory work №1) taking the active and reactive resistances of their components into account;

b) calculate the phase inductances and resistances of the shorted circuit components (see laboratory work №1);

c) turn on PC and load the circuit simulation software;

d) construct the simulating circuit and determine sc current parameters: $I_{\text{по}}$, $I_{\text{пt}}$, $i_{\text{уд}}$;

e) print the obtained findings and sc current curve and paste it into the report on the laboratory work.

4.4.5 Draw conclusions about the operating ability of the circuit-breakers selected in regard to peak and short-time withstand current (thermal and electro-dynamic stability);

4.4.6 TRV parameters for the main and line circuit-breakers are determined in the following order:

a) calculate the phase inductance and capacitance (relative to TRV frequency) of the power transformer, as well as the total reduced capacitance of the equipment connected to the busbar system (see laboratory work №2);

b) construct the simulating circuits and determine the TRV parameters for the main and line circuit-breakers (see laboratory work №2);

c) print the TRV curves and paste it into the report on the laboratory work.

4.4.7 Draw conclusions in respect to switching capability of the selected circuit-breakers. Select others circuit-breakers, if it is required.

4.4.8. The laboratory work report should contain:

a) the name and purpose of the work;

b) the one-line circuit of the substation and the power equipment parameters;

c) the types and parameters of the selected circuit-breakers;

d) time diagrams and obtained parameters of sc current;

e) time diagrams and obtained parameters of TRV;

g) conclusions in respect to stability and operating ability in the fault conditions.

4.5 Self-checking questions

4.5.1 In which electrical installations HV circuit-breakers are used?

4.5.2 What functions do HV circuit-breakers perform in electric installations?

4.5.3 What parameters are taken into account in selecting HV circuit-breakers?

4.5.4 What parameters are taken into account in checking HV circuit-breakers?

4.5.5 What is the switching capacity of a circuit-breaker?

4.5.6 By what parameters the stability of the circuit-breaker is evaluated when passing let-through sc currents?

4.5.7 By what parameters is the switching capacity of the switch evaluated?

4.5.8. How switching capacity of circuit breaker is estimated in respect to the TRV parameters?

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