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INTERNATIONAL STUDENT COMPETITION «Electrical Power Engineering–2015» in honor of A.F. Diakov

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Issue 8 of RNC CIGRE bulletin collects the proceedings of International Student Competition on Electrical Power Engineering "Electrical Power Engineering - 2015" in honor of A.F. Diakov among students pursuing their degrees in Electrical Engineering and Electrical Power Engineering. The Competition was organized by RNC CIGRE Youth Section and Ivanovo State Power Engineering University (ISPEU). The event was held on November 17-22, 2015 in Ivanovo.

The main objectives of the Competition are increasing the education effectiveness for Electrical (Power) Engineering students, stirring students' enthusiasm for their chosen field, bringing out talented young people to create a strong pool of potential staff both for businesses and for higher education and research institutions.

The proceedings can be used as a methodological basis for the preparation of similar events. The bulletin presents some of the tasks offered at the competitions on Electrical Power Engineering in 2013-2015, which can be useful for students' self education.

The issue is intended for students and university teachers in the field of electrical power engineering and electrical engineering universities as well as for a wide range of people interested in the topic given.

International Student Competition on Electrical Power Engineering in Honor of A.F. Diakov

In memory of Anatoly Diakov. Instead of a Preface

The annual International Student Competition on Electrical Power Engineering in 2015 was named after outstanding Russian power engineer Anatoly F. Diakov.

The name of Anatoly Dyakov is iconic in the Russian Electrical Power Engineering sector. He had been working in this sphere for more than 55 years.

After his graduation from the Electromechanical Faculty of North-Caucasus Mining and Metallurgical Institute in 1959 he started working as an electrician at the Bashkir copper and sulfur plant and became the Minister of Fuel and Energy of the Russian Federation in 1991. After the reorganization, he was appointed the President of the Russian joint-stock company of energy and electrification (RJSC "UES of Russia") on December 1st, 1992.

He devoted more than 30 years to the active work in International Council on Large Electric Systems (CIGRE). He had been representing Russia in CIGRE Administrative Council and Steering Committee since 1987, as well as headed the Soviet (Russian since 1992) CIGRE National Committee in 1989-2009. Since 2009 Anatoly Diakov had been RNC CIGRE Honorary Chairman and also served as the Chairman of RNC CIGRE Technical Activities Committee.

During all these years, Anatoly Diakov was in charge of scientific and technical activities of the Partnership, and examined promising areas of CIGRE RNC scientific research. He actively attracted Russian scientists and experts to participate in a variety of events organized by CIGRE, where scientists shared their best experience, discussed the most relevant challenges in the development of electric power systems, the design and operation of high-voltage equipment as well as the development and implementation of new control systems. He worked hard in research committees and working groups, symposia, colloquia and CIGRE Sessions. In his scientific work Anatoly Diakov gave much attention to the development and implementation of the system that improves the reliability and survivability of the United Power System of Russia.

In recognition of his outstanding contributions to the global energy community he was awarded the status of "Distinguished Member" in 2000, and in 2014 he was awarded the title of "Honorary Member".

It is difficult to overestimate the contribution of Anatoly Diakov to the preservation and support of research activities in our home electrical engineering. Being the professor, the Doctor of Engineering Sciences, the author of about 400 scientific papers, a lot of patents and copyright certificates, Anatoly Diakov was an active participant in leading Russian electrical power engineering organizations. He had the positions of the Corresponding Member of the Russian Academy of Sciences, the Chairman of the Scientific Council of the Russian Academy of Sciences on the problems of reliability and security of large-scale power systems, the academician (both as a Secretary and a member of the Presidium of the Russian Academy of Electrotechnical Sciences), the Head of the Department of Relay Protection and Automation of Power Systems in Moscow Power Engineering Institute, the Chairman of the Technical Board, the President of non-profit partnership "Scientific Council of United Power System", and the Scientific Director of OJSC "United Power System Engineering Center".

Professor Diakov was actively involved in the life of the industry, carried out successful research, and did a lot of organizational work. His highest level of professionalism, dedication and enthusiasm, lively and inquisitive mind, inexhaustible optimism and energy will always remain in the memory of his colleagues, students, and partners, all those who were fortunate to know Anatoly Diakov and work with him.

Dr. Diakov was also concerned with developing and implementing projects aimed at education and training of a new generation of Russian power sector specialists: young scientists, engineers, designers, managers, and other professionals with international competitiveness who are able to make a significant technological breakthrough in the Russian power engineering industry. He stood at the origins of the program " RNC CIGRE Youth Section " and highly supported its development.

The Competition Preparation and Carrying Out

The International Student Competition on Electrical Power Engineering in honor of A.F. Diakov is held annually under the program of RNC CIGRE Youth Section at the premises of Ivanovo State Power Engineering University (ISPEU). Its main objectives are to promote students' interest in the topics of CIGRE research, develop creative thinking, increase the effectiveness of education, and involve students in research work. The event also helps to bring out talented young people as well as to encourage and support those of them who achieved the best results.

The history of the student competitions on electric power disciplines in ISPEU dates back to the 1960s, when first competitions on Theoretical Basics of Electrical Engineering were organized. In 2010 it was decided to hold a competition on electrical power engineering for senior students under the "Electrical Power Engineering and Electrical Engineering" study program. The tasks were formulated on the basis of those offered in the obligatory courses taught to students. In 2012 the Competition on Electrical Power Engineering in Ivanovo State Power Engineering University took on the All-Russian status, and since 2013 it has been an international-level event.

The Competition is included in the RNC CIGRE Youth Section events plan and is usually held in November. The participants are senior bachelor students and the first-year master's students pursuing their degrees in Electrical Engineering. Detailed information about the Competition is available on the websites of RNC CIGRE and ISPEU, and is also sent out to technical higher education institutions of Russia and former Soviet Republics as well as to other countries. Eighteen universities announced their participation in the Competition in 2015.

In accordance with the Terms and Conditions of the Competition, the lecturers of participating universities were involved in the task preparation. Based on the education standards for teaching electrical engineering disciplines, tasks of two complication levels for each of the following subjects were prepared:

- Theoretical Basics of Electrical Engineering,

- High-Voltage Engineering,
- Relay Protection and Control,
- Electrical Equipment of Power Plants and Substations,
- Electric Grids and Electric Power Systems,
- Electric Power Supply.

The International Student Competition on Electrical Power Engineering in honor of A.F. Diakov was held in November 17-21, 2015.

On the first day of the Competition, after the meeting the participants and helping them with their accommodation, a tour about ISPEU was organized. It included a visit to a full-scale simulator of a nuclear power unit, training and research laboratories for students in the field of electrical and power engineering, libraries, the university sports center and the museum.

The Competition opening ceremony took place on November 18th, 2015 in the main building of ISPEU. A welcoming speech to the participants of the Competition was made by the Vice-Rector of ISPEU Vladimir Tyutikov, the Deputy Head of RNC CIGRE Youth Section Committee Arkady Makarov, the representatives of the administration of the Ivanovo region, and the heads of the participating teams.

The welcoming speech of Vladimir Tyutikov, the Vice-Rector of ISPEU

The welcoming speech of the team of Technical University of Darmstadt (Germany)

The teams of the following higher education institutions took part in the Competition:

1. Belarusian National Technical University (Republic of Belarus);
2. Vologda State University;
3. Vyatka State University;

4. Donetsk National Technical University;
5. Ivanovo State Power Engineering University;
6. Irkutsk National Research Technical University;
7. Kazan State Power Engineering University;
8. National Research University "Moscow Power Engineering Institute";
9. Nizhny Novgorod State Technical University;
10. Peter the Great St. Petersburg Polytechnic University;
11. Novosibirsk State Technical University;
12. The Branch of National Research University "Moscow Power Engineering Institute" in Smolensk;
13. North-Caucasus Federal University;
14. Samara State Technical University;
15. National Research Tomsk Polytechnic University;
16. Ulyanovsk State Technical University;
17. Ural Federal University;
18. National Research South-Ural State University;
19. Technische Universität Darmstadt (Technical University of Darmstadt, Germany).

A total of 120 students took part in the individual championship.

Four hours were given to solve the offered problems. In accordance with the Terms and Conditions, the heads of the teams were included in the jury. A blind review of all the works was carried out by experts from Ivanovo State Power Engineering University and other participating universities.

The Competition participants in room B-301

The Competition participants in room B-316

The Experts are checking the works

Based on the results of the team championship the following higher education institutions achieved the results presented below:

#	Higher education institution	Place
1.	Ivanovo State Power Engineering University	1
2.	Belarusian National Technical University	2
3.	National Research University "Moscow Power Engineering Institute"	2
4.	Peter the Great St. Petersburg Polytechnic University	3
5.	National Research South-Ural State University	3
6.	The Branch of National Research University "Moscow Power Engineering Institute" in Smolensk	3
7.	National Research Tomsk Polytechnic University	4
8.	Vyatka State University	4
9.	Ulyanovsk State Technical University	4
10.	Ural Federal University	4
11.	Irkutsk National Research Technical University	4
12.	Novosibirsk State Technical University	4
13.	Technical University of Darmstadt	5
14.	Kazan State Power Engineering University	5
15.	Vologda State University	5
16.	Nizhny Novgorod State Technical University	5
17.	Samara State Technical University	6
18.	Donetsk National Technical University	6
19.	North-Caucasus Federal University	6

The results of the individual championship are as follows:

Name:	Higher education institution
1st place	
Oleg Soldatkin	Ivanovo State Power Engineering University
2nd place	
Andrey Karpechenko	Belarusian National Technical University
Evgenia Bulicheva	The Branch of National Research University "Moscow Power Engineering Institute" in Smolensk

3^{rd} place	
Evgeny Gorshkov	National Research South-Ural State University
Victor Buslov	Moscow Power Engineering Institute
Aleksandr Habarov	Peter the Great St. Petersburg Polytechnic University

The winners of the Competition in team and individual championships were awarded with the diplomas and cups as well as with scientific books from RNC CIGRE.

Oleg Soldatkin, the student of Ivanovo State Power Engineering University, is receiving his diploma for the 1^{st} place in the Competition

Evgenia Bulicheva, the student of the Branch of National Research University "Moscow Power Engineering Institute" in Smolensk, is receiving her diploma for the 2^{nd} place in the Competition

The trip to the Youth Day of the International Forum on Energy Efficiency and Energy Development "ENES-2015" held in Moscow's Gostiny Dvor was organised for the participants of the Competition on November 20^{th}, 2015. Many of the participants were about to graduate from their universities and will start working at real power engineering objects soon. That is why the visit to the Forum was a great chance for them to meet the representatives of the electrical power engineering industry. At the Forum, the students had the opportunity to address their questions to Anton Inyutsyn, the Deputy Minister of Energy of the Russian Federation, as well as to take part in a round table discussion on the development of electrical power engineering.

The Competition participants at the ENES–2015 Youth Day

Photo of the Competition participants

The International Student Competition on Electrical Power Engineering in honor of A.F. Diakov has become a significant annual event for Russian power engineering universities. The participating institutions have confirmed their desire to send their teams to the Competition in 2016. The representatives of other universities are likely to come to the event as well.

Tasks of the Competition "Electrical Power Engineering" in 2013-2015

1. Theoretical Basics of Electrical Engineering

Task 1.1

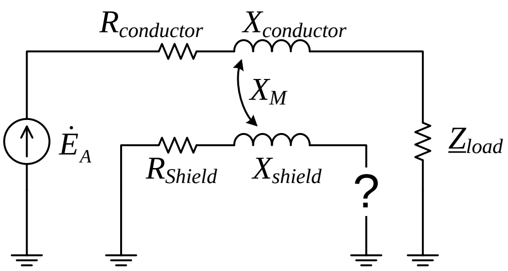


Fig. 1.1

Figure 1.1 shows the single-phase equivalent circuit of a 220 kV three-phase cable line connected to a load with the following impedance: $\underline{Z}_{load}$ = 96.61 + j51.21 Ohm. The cable core conductor and shield have the following parameters: $R_{conductor}$ = 5 Ohm; R_{shield} = 20 Ohm; $X_{conductor}$ = 25 Ohm; X_{shield} = 20 Ohm. The mutual inductance between the core conductor and the shield is X_M = 2.5 Ohm.

Determine whether there is a need to ground the shield on the load side if the potential on the ungrounded end of the shield should not exceed 25 V with respect to ground, and the induced current in the shield must not exceed 10% of the core conductor current. Calculate the active power losses in the three-phase cable line under the chosen method of shield grounding.

Solution

1. To define the induced voltage at the ungrounded end of the shield we first calculate the current in the conductor by using the second Kirchhoff law for the loop made up of the voltage source, conductor and load:

$$\dot{I}_{conductor} = \frac{\dot{E}}{\underline{Z}_{load} + R_{conductor} + jX_{conductor}} = \frac{220000/\sqrt{3}}{96.61 + j51.21 + 5 + j25} =$$

$$= 800 - j600 = 1000e^{j36,87^{\circ}} \text{ A.}$$

Then the induced voltage at the end of shield can be found as:

$U_{shield} = I_{conductor} \cdot X_M = 1000 \cdot 2.5 = 2500$ V, which is more than 25 V.

2. Now it is necessary to find the induced current in the shield when it is grounded on both sides. For this purpose, we denote direction of currents and starts of inductances so that the effect of currents in them was a counter (on the principle of Lenz) (see fig. 1.2).

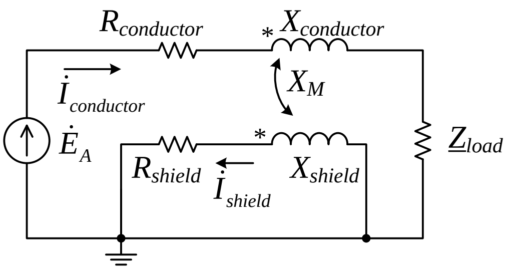


Fig. 1.2

The equation for the second Kirchhoff's law for the circuit with the shield is:

$$0 = \dot{I}_{shield}\left(R_{shield} + jX_{shield}\right) - \dot{I}_{conductor}\, jX_M\,,$$

so $\dot{I}_{shield} = \dfrac{\dot{I}_{conductor}\, jX_M}{\left(R_{shield} + jX_{shield}\right)} \Rightarrow$

$$\Rightarrow I_{shield} = I_{conductor}\frac{X_M}{\sqrt{R_{shield}^2 + X_{shield}^2}} =$$

$= I_{conductor}\dfrac{2,5}{\sqrt{20^2+20^2}} = 0.088 I_{conductor}$, which is less than $0,1I_{conductor}$. So, the shield should be grounded on both sides.

3. We determine the active power losses. For this purpose we should solve a system of equations complying the second Kirchhoff law with respect to the currents in the conductor and shield:

$$\begin{cases} \dot{E} = \dot{I}_{conductor}\left(\underline{Z}_{load} + R_{conductor} + jX_{conductor}\right) - \dot{I}_{shield}\, jX_M\,, \\ 0 = \dot{I}_{shield}\left(R_{shield} + jX_{shield}\right) - \dot{I}_{conductor}\, jX_M\,. \end{cases} \Rightarrow$$

$$\dot{I}_{conductor} = \frac{\dot{E} + \dot{I}_{shield}\, jX_M}{\underline{Z}_{load} + R_{conductor} + jX_{conductor}} \Rightarrow$$

$$\Rightarrow \dot{I}_{shield} = \frac{\dot{E}\cdot jX_M}{\left(R_{shield} + jX_{shield}\right)\left(\underline{Z}_{load} + R_{conductor} + jX_{conductor}\right) + X_M^2}.$$

Hence, $I_{conductor}$ = 999.78 A, I_{shield} = 88.37 A. Then, we can finally determine the active power losses as a sum of losses in the conductor and shield:

$$\Delta P = 3\Delta P_{conductor} + 3\Delta P_{shield} = 3I_{conductor}^2 R_{conductor} + 3I_{shield}^2 R_{shield} =$$

$$= 3\cdot 999{,}78^2\cdot 5 + 3\cdot 88{,}38^2\cdot 20 = 15462062\ \text{W}$$

Answer: the shield should be grounded; ΔP = 15.462 MW.

Task 1.2

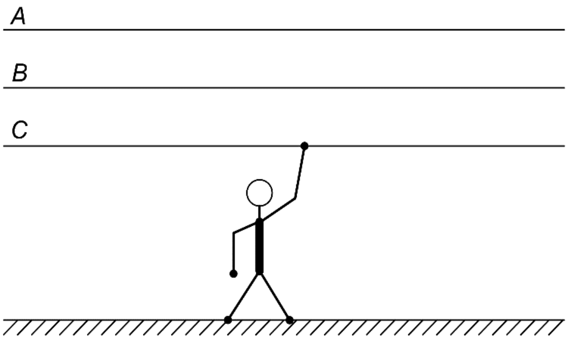


Fig. 1.3

A person touched one wire of a three-phase transmission line rated at 10 kV and 50 Hz (fig. 1.3). The person's resistance is R_{man} = 1000 Ohm, the self-capacitance of each phase with respect to ground is $C_{11} = C_{22} = C_{33} = 0.256$ μF, and the mutual capacitance between phases is $C_{12} = C_{13} = C_{23} = 0.115$ μF.

Calculate the current flowing through the person and determine whether he will die provided that the fatal current is 100 mA or more. The conductivity of insulation between the wire and the ground can be neglected.

Solution

To find the current that will pass through a person, we should create an equivalent circuit that takes into account the partial capacitance of each phase with respect to ground (see fig. 1.4). Mutual partial capacities will not affect the desired current, as they are connected to the three-phase voltage source in parallel with the self-capacities.

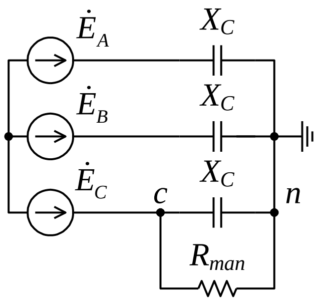


Fig. 1.4

Using the Thevenin's theorem on, we will transform the scheme with respect to the points c and n (Fig 1.5):

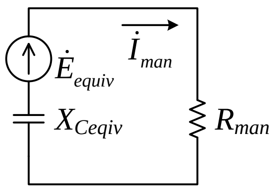


Fig. 1.5

$$\dot{E}_{equiv} = \dot{U}_{noload} = \dot{E}_C = \frac{10000}{\sqrt{3}} e^{j120°} = 5773.5 \text{ V};$$

$$X_{Cequiv} = \frac{X_C}{3} = \frac{1}{2\pi f \cdot C_{11} \cdot 3} = \frac{1}{2\pi \cdot 50 \cdot 0.256 \cdot 10^{-6} \cdot 3} =$$
$$= 4144.7 \text{ Ohm}.$$

The current in the circuit is obtained by the formula

$$I_{man} = \frac{E_C}{\sqrt{R_{man}^2 + X_{Cequiv}^2}} = \frac{5773,5}{\sqrt{1000^2 + 4144.7^2}} = 1.354 \text{ A}.$$

Answer: the deadly current of 1.354 A will pass through a man.

Task 1.3

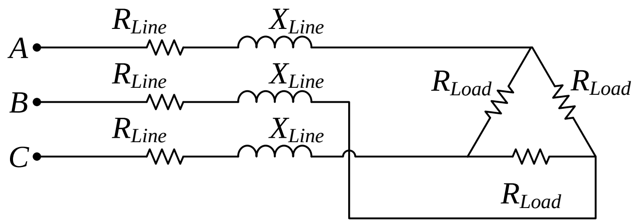


Fig. 1.6

A symmetrical load is connected to a symmetrical three-phase circuit with the line voltage U_{Line}=*380 V* and impedances of $R_{Line}=X_{Line}$=*10 Ohm* (fig. 1.6).

Determine the value of the load resistance R_{Load} causing the maximum power dissipation (P_{Load} = *max*), and find the value of this power.

Solution

We transform the scheme to the following:

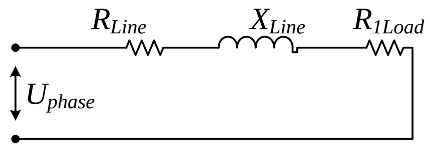


Fig. 1.7

$$R_{Load}/3 = R_{1Load}\ ;\ P_{Load} = 3I_{Line}^{\ 2}\cdot R_{1Load}$$

$$I_{Load} = \frac{U_{phase}}{\sqrt{\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}}}.$$

In order to have the maximum power consumption let us take the derivative of the power with respect to the load resistance, and set it to zero.

$$\frac{dP_{Load}}{dR_{Load}} = \frac{R_{Line}^{\ 2} + 2R_{Line}\cdot R_{1Load} + R_{1Load}^{\ 2} + X_{Line}^{\ 2} - R_{1Load}\cdot 2\left(R_{Line}+R_{1Load}\right)}{\left(\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}\right)^2}$$

$$\frac{dP_{Load}}{dR_{Load}} = \frac{R_{Line}^{\ 2} + 2R_{Line}\cdot R_{1Load} + R_{1Load}^{\ 2} + X_{Line}^{\ 2} - 2R_{Line}\cdot R_{1Load} - 2R_{1Load}^{\ 2}}{\left(\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}\right)^2}$$

$$\frac{dP_{Load}}{dR_{Load}} = \frac{R_{Line}^{\ 2} + X_{Line}^{\ 2} - R_{1Load}^{\ 2}}{\left(\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}\right)^2}\ ;\ \frac{R_{Line}^{\ 2} + X_{Line}^{\ 2} - R_{1Load}^{\ 2}}{\left(\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}\right)^2} = 0$$

$$R_{1Load} = \sqrt{R_{Line}^{\ 2} + X_{Line}^{\ 2}} = 10\sqrt{2}\ \text{Ohm};$$

$$I_{Line} = \frac{U_{phase}}{\sqrt{\left(R_{Line}+R_{1Load}\right)^2 + X_{Line}^{\ 2}}} = \frac{380/\sqrt{3}}{\sqrt{\left(10+10\sqrt{2}\right)^2 + 10^2}} = 8.395\ \text{A};$$

$$P_{Load} = 3\cdot I_{Line}^{\ 2}\cdot R_{1Load}\ ;\ P_{Load} = 8.395^2\cdot 3\cdot 10\cdot\sqrt{2} = 2.990\cdot 10^3\ \text{W}.$$

Answer: $R_{1Load} = 10\sqrt{2}$ Ohm, P_{load}=2990 W.

Task 1.4

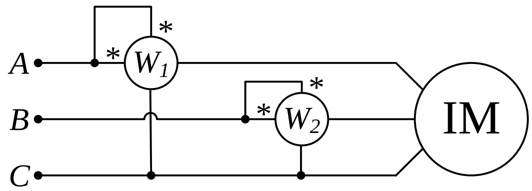


Fig. 1.8

The readings of two identical power meters connected to an induction motor (IM) with the line voltage of 380 V are 2670 and 398 Watts (fig. 1.8).

Determine the resistance and reactance of the IM winding connected in wye.

Solution

The total power is equal to

$$P = P_{W1} + P_{W2} = 2670 + 398 = 3068 \text{ W}$$

$$Q = \sqrt{3}\left(P_{W1} - P_{W2}\right) = (2670 - 398) \cdot \sqrt{3} = 3930 \text{ W}$$

As $P = \sqrt{3} \cdot U_{Line} \cdot I_{phase} \cdot \cos\varphi$, $Q = \sqrt{3} \cdot U_{Line} \cdot I_{phase} \cdot \sin\varphi$

Hence, $\frac{P}{Q} = \text{ctg}\varphi = \frac{3068}{3930} = 0.7806$, $\varphi = 52°$

$$I_{phase} = \frac{P}{\sqrt{3}U_{Line}\cos\varphi} = \frac{3068}{\sqrt{3} \cdot 380 \cdot \cos 52°} = 7.58 \text{ A}$$

$$\underline{Z} = \frac{U_{phase}}{I_{phase}} e^{j52°} = \frac{380/\sqrt{3}}{7.58}(\cos 52° + j\sin 52°) = 17.81 + j22.81 \text{ Ohm.}$$

Answer: $R = 17.81$ Ohm, $X = 22.81$ Ohm.

Task 1.5

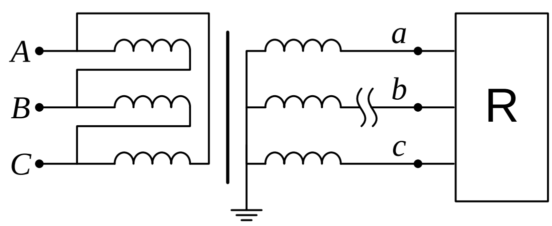


Fig. 1.9

A symmetrical three-phase resistive receiver with the phases connected in a "triangle" is connected to the secondary winding of a transformer (Δ/Y) 6.0/0.38 kV (fig. 1.9). $P_{receiver}$ = 6 kW.

Determine potentials *a*, *b* and *c* relative to the ground if the line conductor from the transformer to point b is broken.

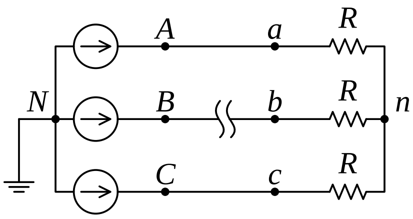


Fig. 1.10

Solution

In case of a wire break in phase B the magnitude of the phase voltage of the transformer secondary winding will not change. Basing on this fact we form the equivalent circuit of the transformer secondary winding (fig. 1.10).

After the break, phases A and C of the receiver will be at the line voltage, which corresponds to the movement of point n to the middle of the vector $\dot{U}_{CA}$ in the vector diagram. (fig. 1.11).

So, if $\dot{\varphi}_N = 0$, then

$$\dot{\varphi}_a = \dot{E}_A = \frac{380}{\sqrt{3}} = 220 \text{ V;}$$

$$\dot{\varphi}_c = \dot{E}_C = \frac{380}{\sqrt{3}} e^{j120^\circ} = 220 e^{j120^\circ} \text{ V;}$$

$$\varphi_b = \dot{U}_{nN} = \frac{1}{2} E_A e^{j60^\circ} = 110 e^{j60^\circ} \text{ V.}$$

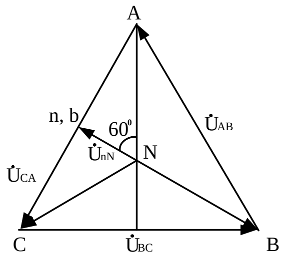


Fig. 1.11

Answer: $\dot{\varphi}_a = 220$ V, $\dot{\varphi}_c = 220 e^{j120^\circ}$ V, $\varphi_b = 110 e^{j60^\circ}$ V.

Task 1.6

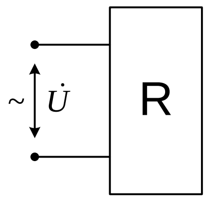


Fig. 1.12

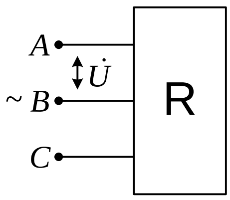


Fig. 1.13

A resistive receiver, which is connected to a single-phase circuit with a voltage *U* is shown in Fig. 1.12. A symmetrical three-phase resistive receiver, which is connected to a three-phase circuit, the line voltage of which is equal to the voltage in the single-phase circuit, is shown in Fig. 1.13. The wire length, the material, and the current density in the wires of single-phase and three-phase circuits are equal.

Determine the ratio between the masses of single-phase and three-phase power supply circuits wires if the capacities of single-phase receiver and three-phase receiver are equal.

Solution

The mass of one wire with cross-section *S*, length *l*, and the material density ρ can be determined by the equation:

$$m = l \cdot S \cdot \rho .$$

Then, the weight of power supply wires of considered receivers is respectively:

$m_1 = 2 \cdot lS_1 \cdot \rho;$ $\qquad m_2 = 3 \cdot lS_2 \cdot \rho.$

Since the current densities in the conductors are equal by the conditions of the task ($\delta_1 = \delta_2 = \delta$), then:

$$\frac{I_1}{S_1} = \frac{I_2}{S_2} = \delta \Rightarrow \frac{I_1}{I_2} = \frac{S_1}{S_2},$$

In order to find the ratio of the currents we form the equivalent circuit (fig. 1.14) and determine the power consumed by the receivers.

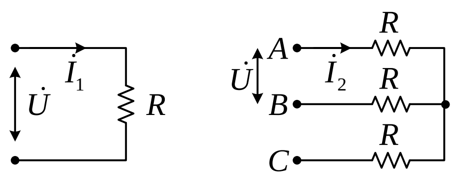


Fig. 1.14

$$P_1 = I_1^2 R_1 = \frac{U^2}{R_1} = P_2 = 3I_2^2 R_2 = 3\frac{U^2}{3R_2},$$

Therefore,

$R_1 = R_2 \Rightarrow I_1 = \sqrt{3} I_2,$

So the ratio is equal to:

$$\frac{I_1}{I_2} = \frac{S_1}{S_2} = \sqrt{3}.$$

Hence, we find the ratio of the masses of wires:

$$\frac{m_1}{m_2} = \frac{2 \cdot lS_1 \cdot \rho}{3 \cdot lS_2 \cdot \rho} = \frac{2\sqrt{3}}{3} = \frac{2}{\sqrt{3}} = 1.155.$$

Answer: $\frac{m_1}{m_2} = 1.155$.

2. Relay Protection and Control

Task 2.1

A three-zone distance protection with the operating circles passing through the origin (see fig. 2.2) is installed on 110 kV transmission line *L1* (fig. 2.1). An equivalent circuit and parameters of the network elements are shown in fig. 2.3 (in Ohm for impedances and kV for voltage sources).

Assume *Z* is equal to *X* for all network elements (all resistances are to be neglected).

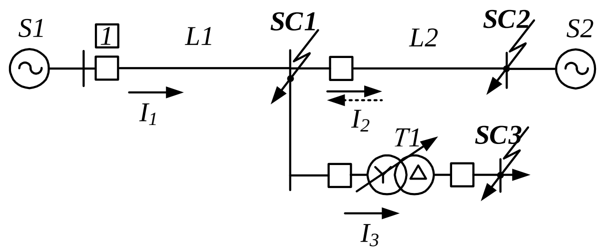


Fig. 2.1

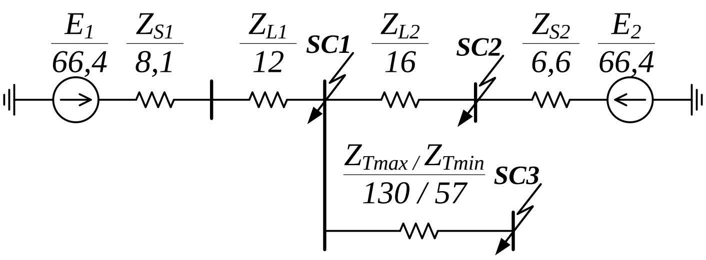


Fig. 2.3

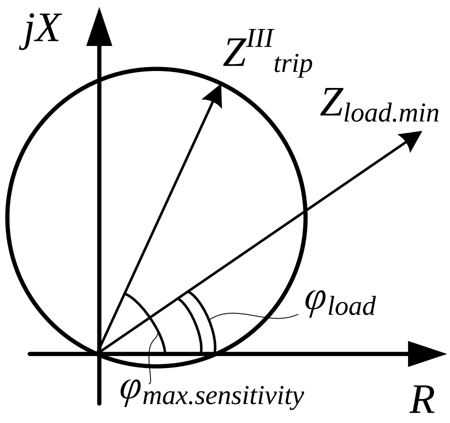


Fig. 2.2

Reference data:

Line impedances: Z_{L1} = 12 Ohm, Z_{L2} = 16 Ohm,

Transformer impedances: $Z_{T\ min}$ = 57 Ohm, $Z_{T\ max}$ = 130 Ohm,

Power system impedances: Z_{S1} = 8.1 Ohm, Z_{S2} = 6.6 Ohm,

Minimum load impedance seen by the protection $Z_{load.min}$ is 287 Ohm,

The relay characteristic angle (maximum sensitivity angle) $\varphi_{max\ sensitivity}$ is 65º,

Power factor angle (load impedance angle) φ_{load} is 30º,

Safety factor *K* is 1.2,

Impedance relay drop off/pick up ratio $K_{dropoff}$ is 1.5,

Minimum sensitivity factors required; on the protected line $K^{III}_{sens\ min\ main}$ is 1.5; in the remote backup zone $K^{III}_{sens\ min\ remote}$ is 1.2.

Goal:

Set the trip value Z^{III}_{trip} for the third zone (providing backup for adjacent components) based on the following criteria:

1) ensure sensitivity for faults on the protected line as well as in the remote backup zone (assume a zero value for the fault impedance);
2) ensure non-operation without faults.

Solution

1. The selection of the trip value to ensure the protection reliability without faults.

In order to ensure non-operation without faults the value of Z_{trip} is selected such that the relay drops off after an external short circuit is cleared causing the motors to accelerate and draw more current from the network:

$$Z_{trip} \le \frac{Z_{load.\min}}{K \cdot K_{dropoff} \cos(\phi_{\max.sensitivity} - \phi_{load})}$$

$$Z_{trip} \le \frac{287}{1.2 \cdot 1.5 \cdot \cos 35°} = \frac{287}{1.2 \cdot 1.5 \cdot 0.819} = 194.7 \text{ Ohm}$$

2. The selection of the trip value to ensure the protection security for faults in zones of remote backup.

2.1. Ensuring the sensitivity at the end of the adjacent line (K2).

$$Z_{trip} \ge K_{sens\,\min\,remote}(Z_{L1} + \frac{Z_2}{K_T})$$

Determine the current distribution coefficient in case of short circuit at K2:

Currents on Fig. 2	Place of short circuit	Expression	Calculation
I_1/I_2	$K_2^{(3)}$	$I_1 = I_2$	$K_T = 1$

$$Z_{trip} \ge 1.2 \cdot (47 + \frac{63}{1}) = 132 \text{ Ohm}$$

2.2. Ensuring the sensitivity after the transformer (K3).

$$Z_{trip} \ge K_{sens\,\min\,remote}(Z_{L1} + \frac{Z_{T\min}}{K_T})$$

Determine the current distribution coefficient in case of a short circuit at K3:

Currents on Fig. 3	Place of short circuit	Expression	Calculation
I_1/I_3	$K_3^{(3)}$	$\frac{1}{1+\frac{Z_{S1}+Z_{L1}}{Z_{S2}+Z_{L2}}}$	$K_T = \frac{1}{1+\frac{8.1+47}{6.6+63}} = 0.558$

$$Z_{trip} \ge 1.2(47 + \frac{57}{0.558}) = 179 \text{ Ohm}$$

2.3. Ensuring the sensitivity in zones of local backup.

$$Z_{trip} \ge K_{sens\,\min\,main} \cdot Z_{L1}$$

$$Z_{trip} \ge 1.2 \cdot 47 = 56.4 \text{ Ohm}$$

3. Choice of the setting.

The maximum value selected as the desired setting is $Z^{III}_{сз} = 194$.

Answer: Z^{III}_{trip} = 194 Ohm.

Task 2.2

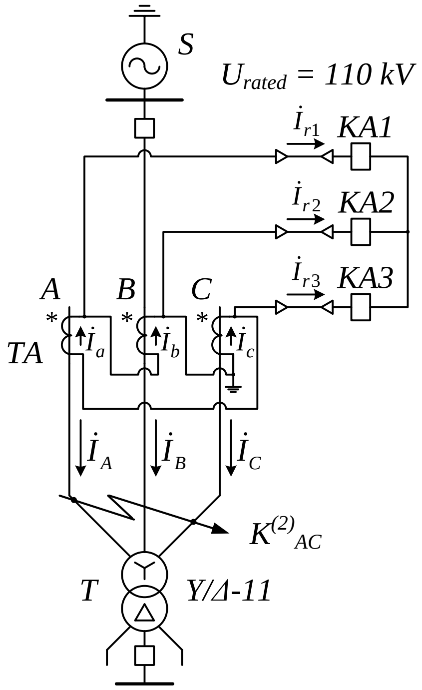


Fig. 2.4

To protect a two-winding step-down transformer T, current transformers TA are connected in delta, and current relays KA in wye (fig. 2.4).

The value of short circuit current seen from the protection side is $I^{(2)}_K$=4200 A.

The transformation ratio of current transformers is K_I = 600/5.

The relay impedance is Z_{relay} = 0.001 Ohm. The current transformer secondary wire impedance is R_{wire} = 1 Ohm.

The positive directions of both the short-circuit currents and currents in the relays are shown in fig. 2.4.

Neglect the influence of transformer T load.

Goal: to draw a phasor diagram of currents in the current transformers and relays in a case of a line-to-line short circuit $K^{(2)}_{AC}$, to determine the currents and to calculate the current transformer load impedance.

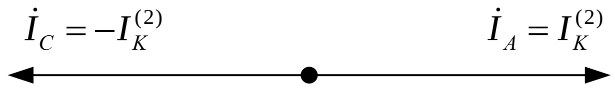
Solution

1. Phasor diagram of short circuit currents (on the protection side):

$$\dot{I}_A = \dot{I}^{(2)}_K$$

$$\dot{I}_B = 0$$

$$\dot{I}_C = -\dot{I}^{(2)}_K$$



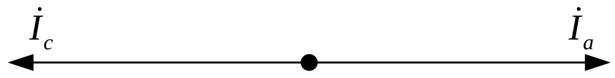
2. Currents magnitudes on the protection side:

$$\left|\dot{I}_A\right| = I^{(2)}_K = 4200\ A$$

$$\left|\dot{I}_B\right| = 0$$

$$\left|\dot{I}_C\right| = I^{(2)}_K = 4200\ A$$

3. Phasor diagram of the CT secondary currents:



4. CT secondary currents magnitude calculation.

With the assumed directions established in the diagram of fig. 1, the CT primary and secondary currents are in-phase, and the secondary current magnitudes are calculated as follows:

$$\left|\dot{I}_a\right| = \frac{\left|\dot{I}_A\right|}{K_I} = \frac{4200}{120} = 35\ A$$

$$\left|\dot{I}_b\right| = 0$$

$$\left|\dot{I}_c\right| = \frac{\left|\dot{I}_c\right|}{K_I} = \frac{4200}{120} = 35\ A$$

5. Phasor diagram of currents in the relays.

If the CTs are connected in delta, and current relays in wye, the currents phasors in the relays follow Kirchhoff's current law:

$$\dot{I}_{p1} = \dot{I}_a - \dot{I}_b$$

$$\dot{I}_{p2} = \dot{I}_b - \dot{I}_c$$

$$\dot{I}_{p3} = \dot{I}_c - \dot{I}_a$$

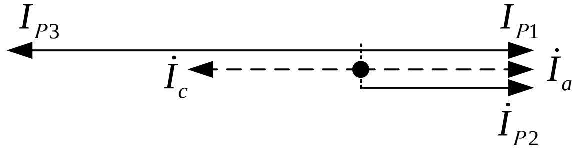
Therefore,

$$\dot{I}_{p1} = \dot{I}_a - \dot{I}_b = \dot{I}_a$$

$$\dot{I}_{p2} = \dot{I}_b - \dot{I}_c = -\dot{I}_c$$

$$\dot{I}_{p3} = \dot{I}_c - \dot{I}_a = \dot{I}_c + \dot{I}_c = 2\dot{I}_c$$

The phasor diagram of currents in the relays is shown below:



The currents magnitudes are:

$$\left|\dot{I}_{p1}\right| = \left|\dot{I}_a - \dot{I}_b\right| = \left|\dot{I}_a\right| = 35\,A$$

$$\left|\dot{I}_{p2}\right| = \left|\dot{I}_b - \dot{I}_c\right| = \left|-\dot{I}_c\right| = 35\,A$$

$$\left|\dot{I}_{p3}\right| = \left|\dot{I}_c - \dot{I}_a\right| = \left|2\dot{I}_c\right| = 70\,A$$

6. Current transformer load impedance.

The load in phase A is determined by the following expression:

$$Z_B = \frac{\dot{U}_a}{\dot{I}_a} = \frac{\dot{I}_{R1}(\mathrm{r}_{wire} + Z_R) - \dot{I}_{R3}(\mathrm{r}_{wire} + Z_R)}{\dot{I}_a} = \frac{3\dot{I}_a}{\dot{I}_a}(\mathrm{r}_{wire} + Z_R)$$

$$Z_B = 3 \cdot (1 + 0.001) = 3.003\,Ohm$$

The load in phase C is equal to that in phase A.

Task 2.3

A restrained differential current protection is installed on a transmission line *L1* (fig.2.5). The operating characteristic is shown in fig. 2.6.

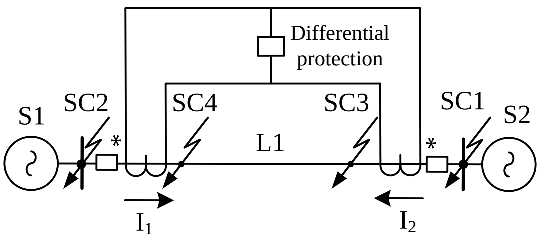


Fig. 2.5

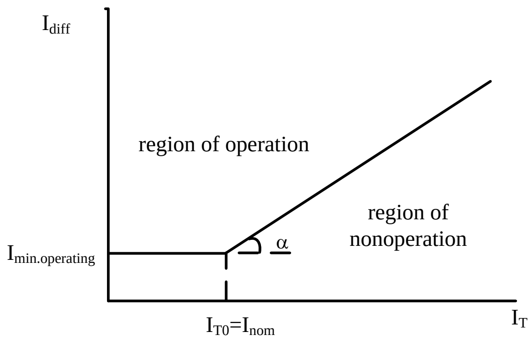


Fig. 2.6

$$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right|,\ I_T = 0{,}5 \cdot \left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right).$$

Rated current I_{rat} is 300 A.

Fault currents, flowing through the protection: I_{SC1max} = 1230 A, I_{SC2max} = 1470 A.

The currents through the protection in system S2 shutdown mode: I_{SC3min} = 1190 A, in system S1 shutdown mode I_{SC4min} = 1340 A.

Depredation factor K_{depr} is 1.5;

coefficient taking into account the transient K_{trans} is 2;

current transformers error ε is 0.1;

current transformers uniformity coefficient K_{uni} is 0.5;

minimum permissible sensitivity factor $K_{min.\ sensitivity}$ is 2.

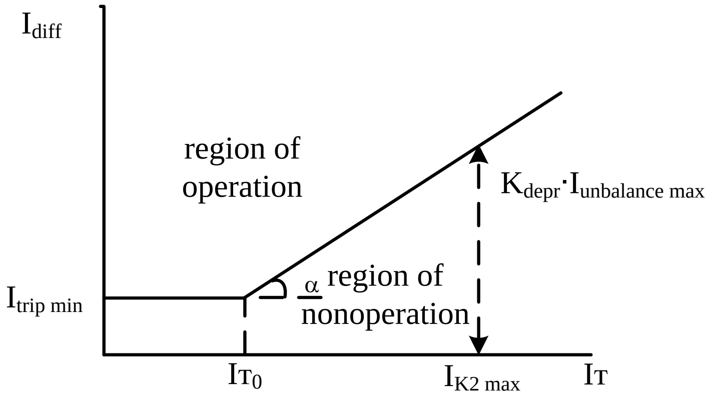
Goal:

1. To calculate the operating characteristic restraining coefficient of transmission line differential current protection.

2. To assess the sensitivity of protection.

Solution

1. The analysis of the operating characteristic:



$$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right| = \left|I_1 - I_2\right| = I_{unbalance\,max}$$

$$I_T = 0{,}5 \cdot \left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right) = 0{,}5 \cdot \left(I_{ext\,max} + I_{ext\,max}\right) = I_{ext\,max}$$

2. The calculated expression of the restraining coefficient

According to fig. 2.6:

$$K_T \geq tg\alpha = \frac{K_{depr} \cdot I_{unbalance\,max(K2)} - I_{trip\,min}}{I_{K2\,max(ext)} - I_{rated}}$$

3. The determination of the unbalance current to calculate the minimum current setting

$$I_{unbalance(I_{rated})} = K_{trans} \cdot \varepsilon \cdot K_{uni} \cdot I_{rated}$$

$$I_{unbalance(I_{rated})} = 2 \cdot 0.1 \cdot 0.5 \cdot 300 = 30 \text{ A}$$

4. The determination of the maximum unbalance current. Since the maximum unbalance current is determined by the maximum current of external short circuit, then we choose I_{K2} as the biggest one:

$$I_{unbalance\,max} = K_{trans} \cdot \varepsilon \cdot K_{uni} \cdot I_{K2}$$

$$I_{unbalance\,max} = 2 \cdot 0.1 \cdot 0.5 \cdot 1470 = 147 \text{ A}$$

5. The determination of the minimum current setting

$$I_{trip\,min} = K_{depr} I_{unbalance(I_{rated})}$$

$$I_{trip\,min} = 1.5 \cdot 30 = 45 \text{ A}$$

6. The determination of the restraining coefficient

$$K_T \ge \frac{1.5 \cdot 147 - 45}{1470 - 300} = 0.15$$

7. The evaluation of the sensitivity of the protection is carried out with a minimum of internal short-circuit current. As $I_{K3} < I_{K4}$, the calculated current is I_{K3}

$$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right| = \left|I_1 - 0\right| = I_{int\ min}$$

$$I_T = 0.5 \cdot \left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right) = 0.5 \cdot \left(I_{int\ min} + 0\right) = 0.5 \cdot I_{int\ min}$$

$$K_{sens} = \frac{I_{SC\ min}}{I_{trip\ min}} \ge K_{min\ sensitivity}$$

$$K_{sens} = \frac{1190}{45} = 26.44 \ge 2.$$

Task 2.4

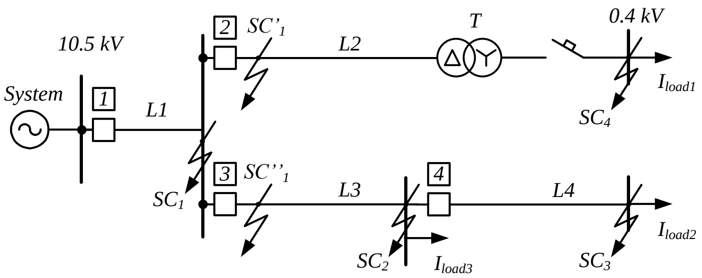


Fig. 2.7

Microprocessor-based inverse time phase protections are installed on 10 kV lines. Inverse time characteristics are determined by the equation:

$$t_{trip} = \frac{k\beta}{I_*^{\alpha} - 1}, \text{ where } I_*^{\alpha} = \left(\frac{I_{SC\ max}}{I_{operating}}\right)^{\alpha}, \ \alpha = 0.02;\ \beta = 0.14.$$

Protections are made in a two-phase design.

Protections 1, 2, 3 have smoothly-dependent characteristics with the following operating currents:

$I_{overcur1} = 253$ A; $I_{overcur2} = 119.2$ A; $I_{overcur3} = 134$ A.

Protection 4 has definite minimum inverse operating time (cut off + overcurrent protection) with the following operating parameters:

$I_{cutoff\ 4} = 1500$ A; $I_{overcur\ 4} = 75$ A; $k_4 = 1$.

A circuit breaker ($I_{cutoffCB}$ = 1000 A) with the following operating characteristic is installed on low voltage side of transformer T (10.5 / 0.4 kV):

$t_{cutoffCB}$ = 0,04 s, if $I \geq 10\ I_{nom}$,

$t_{overcurCB}$ = 8 s, if $I < 10\ I_{nom}$.

Short-circuit currents on 10.5 kV side are:

$I^{(3)}_{SC1max}$ = 3180 A, $I^{(2)}_{SC1min}$ = 1500 A,

$I^{(2)}_{SC2min}$ = 1000 A, $I^{(2)}_{SC3min}$ = 700 A, $I^{(2)}_{SC4min}$ = 350 A.

Load currents on 10.5 kV side are:I_{load1} = 80 A, I_{load2} = 50 A, I_{load3} = 40 A.

Selective time interval Δt is 0.3 s.

Minimum permissible sensitivity factor in local backup protection is $K_{min.\ sensitivity}$ = 1.5; in remote backup protection $K_{min.\ sensitivity}$ = 1.2.

Goal:

1. To coordinate operating characteristics of inverse time overcurrent protections *1, 2, 3*: calculate the coefficients k of the characteristics.

2. To assess the sensitivity of protections *1, 2, 3* in local backup and remote backup zones and the need for schemes with 3-phase relays to increase the sensitivity.

Solution

1. Selecting the operation time characteristics

Protection 2

$$I'_{cutoffCB} = I_{cutoffCB} \cdot \frac{U_{LV}}{U_{HV}} \qquad I'_{cutoffCB} = 10000 \cdot \frac{0,4}{10.5} = 381 \text{ A}$$

$$I_{*2} = \frac{I'_{cutoffCB}}{I_{cз2}} \qquad I_{*2} = \frac{381}{119.2} = 3.2$$

$$t_{trip2} \geq t_{overcurCB} + \Delta t \qquad t_{trip2} = 8 + 0.3 = 8.3 \text{ s}$$

$$k_2 = \frac{t_{trip2}(I_*^{\alpha} - 1)}{\beta} \qquad k_2 = \frac{8.3(3.2^{0.02} - 1)}{0.14} = 1.4$$

Protection 3

$$I_{*4} = \frac{I_{cutoff\,4}}{I_{overcur\,4}} \qquad I_{*4} = \frac{1500}{75} = 20$$

$$t_{trip4} = \frac{k_4 \beta}{I_*^{\alpha} - 1}, \qquad t_{trip4} = \frac{1 \cdot 0.14}{20^{0.02} - 1} = 2.27 \text{ s}$$

$t_{trip3} \geq t_{trip4} + \Delta t$ $\quad$ $t_{trip3} = 2.27 + 0.3 = 2.57$ s

$I_{*3} = \frac{I_{cutoff4} + I_{load3}}{I_{overcur3}}$ $\quad$ $I_{*3} = \frac{1500 + 40}{134} = 11.5$

$k_3 = \frac{2.57(11.5^{0.02} - 1)}{0,14} = 0.92$

Protection 1

Coordination with protection 2:

$I_{*2} = \frac{I^{(3)}_{K1\max}}{I_{covercur2}}$ $\quad$ $I_{*2} = \frac{3180}{119.2} = 26.67$

$t_{trip2} = \frac{1,4 \cdot 0.14}{26.67^{0.02} - 1} = 2.9$ s $\quad$ $t_{trip1} = 2.9 + 0.3 = 3.2$ s

$I_{*1} = \frac{I^{(3)}_{K1\max} + I_{load2} + I_{load3}}{I_{overcur1}}$ $\quad$ $I_{*1} = \frac{3180 + 50 + 40}{253.2} = 12.9$

$k_1 = \frac{3.2(12.9^{0.02} - 1)}{0.14} = 1.2$

Coordination with protection 3:

$I_{*3} = \frac{I^{(3)}_{K1\max}}{I_{overcur3}}$ $\quad$ $I_{*3} = \frac{3180}{134} = 23.73$

$t_{trip3} = \frac{0.92 \cdot 0.14}{23.73^{0.02} - 1} = 2$ s $\quad$ $t_{trip3} = 2 + 0.3 = 2.3$ s

$I_{*1} = \frac{I^{(3)}_{K1\max} + I_{load1}}{I_{overcur1}}$ $\quad$ $I_{*1} = \frac{3180 + 80}{253.2} = 12.9$

$k_1 = \frac{2.3(12.9^{0.02} - 1)}{0.14} = 0.86$

We accept that:

Protection 2 is k_2 = 1.4.

Protection 3 is k_3 = 0.92.

Protection 1 is k_1 = 1.2.

2. The evaluation of sensitivity

The evaluation of sensitivity of local backup protection is made during the fault on the opposite substation busbars and the minimum current through the protection. The evaluation of sensitivity of remote backup protection is made during the fault on the opposite substation busbars of the adjacent element and the minimum current through the protection.

Protection 2

$$K_{sens2} = \frac{I^{(2)}_{K4\min}}{\sqrt{3}I_{overcur2}} \geq K_{\min\ sensitivity} \qquad K_{sens2} = \frac{350}{\sqrt{3}\cdot 119.2} = 1.65 \geq 1.5$$

The required sensitivity of protection 2 of local backup protection is provided.

Protection 3

$$K_{sens3} = \frac{I^{(2)}_{K2\min}}{I_{overcur3}} \geq K_{\min\ sensitivity} \qquad K_{sens3} = \frac{1000}{135} = 7.4 > 1.5$$

$$K_{sens3} = \frac{I^{(2)}_{K3\min}}{I_{overcur3}} \geq K_{\min\ sensitivity} \qquad K_{sens3} = \frac{700}{135} = 5.2 > 1.2$$

The required sensitivity of protection 3 of local and remote backup protection is provided.

Protection 1

$$K_{sens1} = \frac{I^{(2)}_{K1\min}}{I_{overcur1}} \geq K_{\min\ sensitivity} \qquad K_{sens1} = \frac{1500}{253.2} = 5.9 > 1.5$$

$$K_{sens1} = \frac{I^{(2)}_{K2\min}}{I_{overcur1}} \geq K_{\min\ sensitivity} \qquad K_{sens1} = \frac{1000}{253.2} = 3.95 > 1.2$$

$$K_{sens1} = \frac{I^{(2)}_{K4\min}}{\sqrt{3}I_{overcur1}} \geq K_{\min\ sensitivity} \qquad K_{sens1} = \frac{350}{\sqrt{3}\cdot 253.2} = 0.798 < 1.2$$

Three relays protection scheme:

$$K_{sens1} = \frac{2\cdot 350}{\sqrt{3}\cdot 253.2} = 1.6 > 1.2$$

The required sensitivity of protection 1 of local backup protection is provided. The required sensitivity of protection 1 of remote backup will be provided with the usage of three relays protection scheme.

Task 2.5

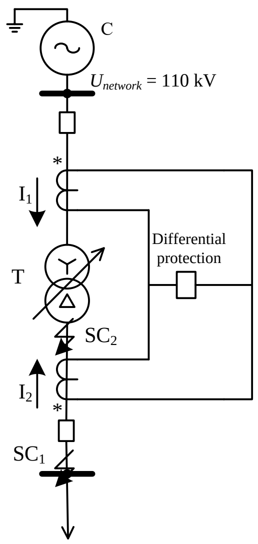


Fig. 2.8

A restrained differential current protection is installed on a transformer (fig. 2.8). The operating characteristic is shown in fig.2.9.

Calculate the operating characteristic restraining coefficient and assess the sensitivity of protection.

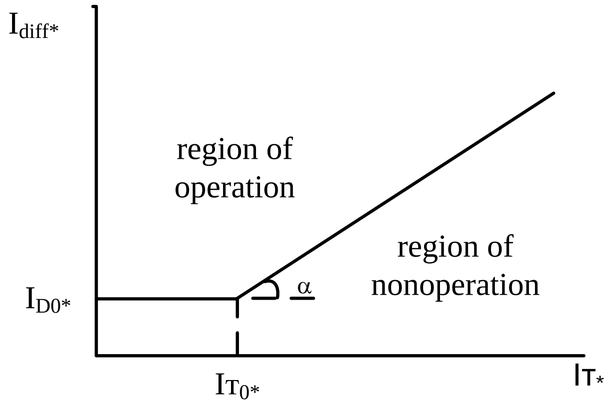


Fig. 2.9

Reference data:

$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right|$, $I_T = 0.5 \cdot \left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right)$

Minimum operating current I_{D0*} is 0.3 pu.

Restraining start current I_{T0*} is 1 pu.

Maximum external through fault current $I_{ext.max*}$ is 3.5 pu.

Minimum internal through fault current $I_{int.min*}$ is 2.5 pu.

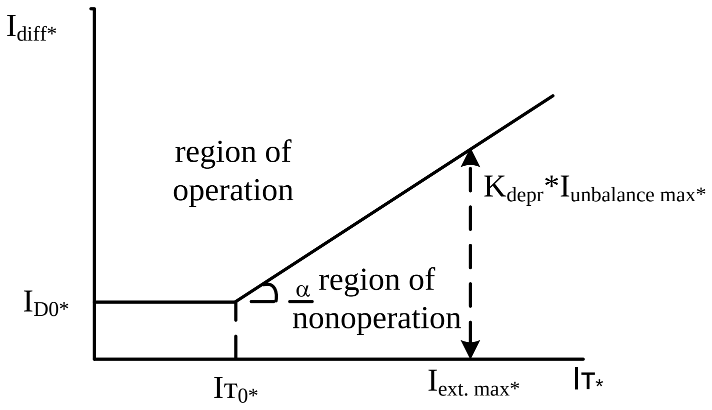
Depredation factor K_{depr} is 1.3, the coefficient taking into account the transient K_{trans} is 2, current transformers error ε is 0.1, current transformers uniformity coefficient K_{uni} is 1, the under voltage control error ΔU_* is 0.16 pu, the error of fitting Δf_{fit} is 0.02, $K_{min.\ sensitivity}$ is 2.

Goal:

1. To calculate the restraining coefficient of operating characteristic;
2. To assess the protection sensitivity.

Solution

1. The analysis of the operating characteristic



$$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right| = \left|I_1 - I_2\right| = I_{unbalance\,max}$$

$$I_T = 0.5\cdot\left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right) = 0.5\cdot\left(I_{ext.max} + I_{ext.max}\right) = I_{ext.max}$$

2. The calculated expression of the restraining coefficient

According to fig. 1:

$$K_T \geq tg\alpha = \frac{K_{depr}\cdot I_{unbalance\,max*} - I_{D0*}}{I_{ext.max*} - I_{T0*}}\ ;$$

3. The determination of the unbalance current 30%

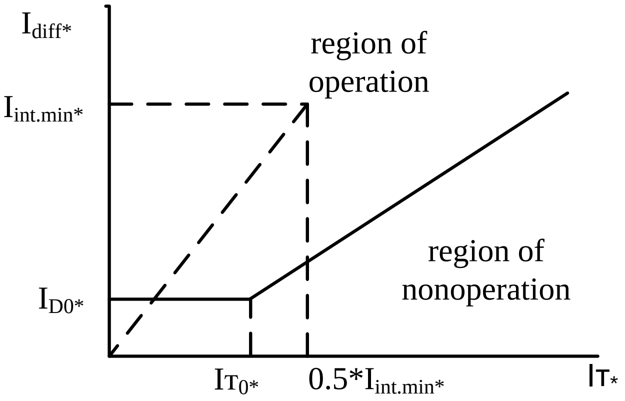
$$I_{unbalance\,max*} = \left(K_{trans}\cdot\varepsilon\cdot K_{uni} + \Delta U_* + \Delta f_{fit*}\right)\cdot I_{ext.max*}$$

$$I_{unbalance\,max*} = \left(2\cdot 0.1\cdot 1 + 0.16 + 0.02\right)\cdot 3.5 = 1.33$$

4. The determination of the restraining coefficient

$$K_T \geq \frac{1.3\cdot 1.33 - 0.3}{3.5 - 1} = 0.57$$

5. The evaluation of the protection sensitivity



$$I_{diff} = \left|\dot{I}_1 + \dot{I}_2\right| = \left|I_1 - 0\right| = I_{int.min}$$

$$I_T = 0.5 \cdot \left(\left|\dot{I}_1\right| + \left|\dot{I}_2\right|\right) = 0.5 \cdot \left(I_{int.min} + 0\right) = 0.5 \cdot I_{int.min}$$

$$K_{sensitivity} = \frac{I_{int.min*}}{I_{D0*}} \geq K_{min.sensitivity}$$

$$K_{sensitivity} = \frac{2}{0.3} = 6.67 \geq 2$$

Task 2.6

The directed and undirected definite time stepped current protections are installed on 35 kV lines (fig. 2.10).

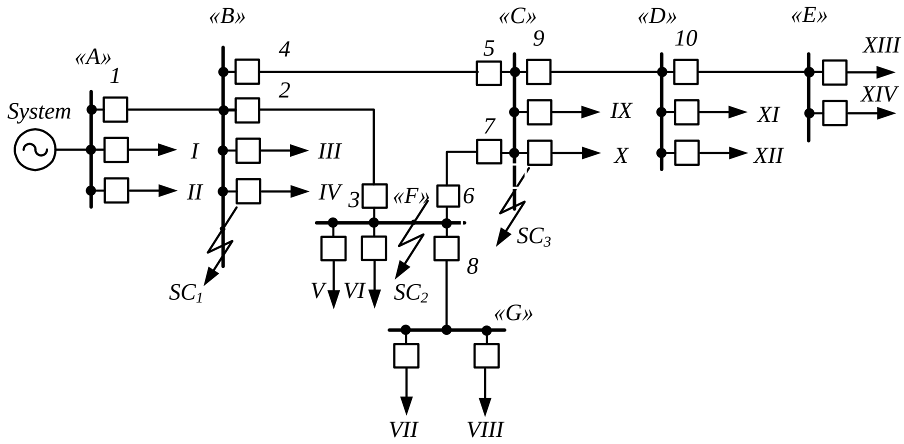


Fig. 2.10

Reference data: $I^{(3)}_{SC1max}$ = 2.8 kA; $I^{(2)}_{SC1min}$ = 1.8 kA; $I^{(2)}_{SC2min}$ = 1.2 kA; $I^{(2)}_{SC3min}$ = 0.63 kA; $I_{dynamic\ current\ max}$ = 0.2 kA.

For protection: Δ*t*. = 0.5 s; $K_{re\text{-}acceleration}$ = 1.5; K_{reset} = 0.95; $K_{overcurrent}$ = 1.2; K_{cutoff} = 1.3.

Time settings for outgoing lines I –XIV:

t_I	t_{II}	t_{III}	t_{IV}	t_V	t_{VI}	t_{VII}	t_{VIII}	t_{IX}	t_X	t_{XI}	t_{XII}	t_{XIII}	t_{XIV}
1	1.1	0.9	2.7	0.5	2.1	0	0.5	2.2	1.5	1.8	0.8	1.5	1

Goal:

1. To determine which protections should be directed.
2. To select the time settings for *1, 2, 3, 4, 5, 6, 7, 8, 9, 10* overcurrent protections.
3. To select $I_{cutoff1}$ and $I_{overcurrent1}$. Write an approach for setting choice
4. To assess the sensitivity of overcurrent protection 1.

Solution

1. The following protections should be directional ones: 3, 5, 6, 7.

2. The selection of 1, 2, 3, 4, 5, 6 overcurrent protections time settings

Since the overcurrent protection performs remote backup, the operating time of each protection is calculated as the sum of the operating time of the adjacent (previous) element and the selective interval Δ *t*. If there are several adjacent elements, the biggest operating time of these elements is chosen.

Task to be carried out	Calculated condition	Calculated expression	Calculation	Assumed value
				$t_3 = 0$
				$t_5 = 0$
Non-operation during external faults	Offset from the time of adjacent elements protection operation	$t_{10} = t_{XIII} + \Delta t$	1.5+0.5=2	t_{10}=2 (5%)
		$t_{10} = t_{XIV} + \Delta t$	1+0.5=1.5	
		$t_9 = t_{XII} + \Delta t$	0.8+0.5=1.3	t_9=2.5 (5%)
		$t_9 = t_{XI} + \Delta t$	1.8+0.5=2.3	
		$t_9 = t_{10} + \Delta t$	2+0.5=2.5	
		$t_8 = t_{VIII} + \Delta t$	0.5+0.5=1	t_8=1 (5%)
		$t_8 = t_{VII} + \Delta t$	0+0.5=0.5	
		$t_7 = t_{VI} + \Delta t$	2.1+0.5=2.6	t_7=2.6 (5%)
		$t_7 = t_V + \Delta t$	0.5+0.5=1	
		$t_7 = t_3 + \Delta t$	0+0.5=0.5	
		$t_7 = t_8 + \Delta t$	1+0.5=1.5	

		$t_6 = t_X + \Delta t$	1.5+0.5=2	t_6=3.0 (5%)
		$t_6 = t_{IX} + \Delta t$	2.2+0.5=2.7	
		$t_6 = t_5 + \Delta t$	0+0.5=0.5	
		$t_6 = t_9 + \Delta t$	2.5+0.5=3	
		$t_4 = t_X + \Delta t$	1.5+0.5=2	t_4=3.1 (5%)
		$t_4 = t_{IX} + \Delta t$	2.2+0.5=2.7	
		$t_4 = t_7 + \Delta t$	2.6+0.5=3.1	
		$t_4 = t_9 + \Delta t$	2.5+0.5=3	
		$t_2 = t_{VI} + \Delta t$	2.1+0.5=2.6	t_2=3.5 (5%)
		$t_2 = t_V + \Delta t$	0.5+0.5=1	
		$t_2 = t_6 + \Delta t$	3+0.5=3.5	
		$t_2 = t_8 + \Delta t$	1+0.5=1	
		$t_1 = t_{IV} + \Delta t$	2.7+0.5=3.2	t_1=4 (10%)
		$t_1 = t_{III} + \Delta t$	0.9+0.5=1.4	
		$t_1 = t_4 + \Delta t$	3.1+0.5=3.6	
		$t_1 = t_2 + \Delta t$	3.5+0.5=4	

2. The selection of $I_{cutoff1}$ and $I_{overcurent1}$

The cutoff current setting is calculated to ensure non-operation during external faults, so it offsets from maximum current through the protection during the fault on the opposite substation busbars:

$$I_{cutoff\,1} = K_{cutoff} \cdot I^{(3)}_{SC1max}$$

$$I_{cutoff\,1} = 1.3 \cdot 2.8 = 3.64\ kA$$

In order to non-operate during the modes without faults the overcurrent protection time setting is chosen from the condition of immediate sustainable return of protection to its initial state after external short circuit clearance by previous line protection:

$$I_{overcurrent1} = \frac{K_{overcurrent} \cdot K_{re-acceleration}}{K_{reset}} \cdot I_{operating\,max}$$

$$I_{overcurrent1} = \frac{1.2 \cdot 1.5}{0.95} \cdot 0.2 = 0.379\ kA$$

3. The evaluation of the sensitivity of overcurrent protection 1.

3.1. The evaluation of sensitivity of local backup protection is made during the fault on the opposite substation busbars and the minimum current through the protection:

$$K_{sensitivity} = \frac{I^{(2)}_{SC1min}}{I_{overcurrent1}} \geq K_{min.sensitivity}$$

$$K_{min.sensitivity} = 1.5$$

$$K_{sensitivity} = \frac{1.8}{0.379} = 4.75 \geq 1.5$$

3.2. The evaluation of sensitivity of remote backup is made during the fault on the adjacent element opposite substation busbars i.e. in the case, when the fault occurs at the points *K2* and *K3* and the minimum current through the protection:

$$K_{sensitivity} = \frac{I^{(2)}_{SC2min}}{I_{overcurrent1}} \geq K_{min.sensitivity}$$

$$K_{min.sensitivity} = 1.2$$

$$K_{sensitivity} = \frac{1.2}{0.379} = 3.2 \geq 1.2$$

$$K_{sensitivity} = \frac{I^{(2)}_{SC3min}}{I_{overcurrent1}} \geq K_{min.sensitivity}$$

$$K_{min.sensitivity} = 1.2$$

$$K_{sensitivity} = \frac{0.63}{0.379} = 1.68 \geq 1.2$$

The calculations showed that the required sensitivity of overcurrent protection 1 is provided.

3. Electric Power Supply

Task 3.1

A substation is equipped with two two-winding transformers TDN-16000/110.

Voltage deviations at the 110 kV bus were V1 = - 5.63 % during on-peak hours and V2 = - 0.18 % during off-peak hours.

The corresponding voltage losses in the transformers were ΔU_{T1} = 4.5 % and ΔU_{T2} = 1.54 %.

The transformer reference data are:

$U_{rated\ HV}$ = 115 kV;

$U_{rated\ LV}$ = 11 kV;

Load tap changer has a regulation range of ± 9 × 1.78%.

Determine the transformer ratios for the on-peak and off-peak periods if counterload voltage control (voltage level control based on load current) is used at the 10 kV side.

Solution

On-peak conditions

1. The voltage on 110 kV substation busbars at on-peak conditions is

$$U_1 = 110 - 5.63 \cdot 110/100 = 103.8 \text{ kV}$$

2. The voltage losses in transformers are equal to

$$\Delta U_{T1} = 4.5 \cdot 103.8/100 = 4.67 \text{ kV}$$

3. The voltage on 10 kV busbars, corrected to higher voltage side, is

$$U_{21} = U_1 - \Delta U_{т1} = 103.8 - 4.67 = 99.13 \text{ kV}$$

4. The number of transformer-tap under $U_{2desired}$ is 1.05·10 = 10.5 kV

$$n_1 = 100\ [\ (U_{21} \cdot U_{LV\ rated} / U_{HV\ rated} \cdot U_{2desired}\ ) - 1] / \Delta K =$$
$$= 100\ [(99.13 \cdot 11/ 115 \cdot 10.5) - 1] /1.78 = -5.5$$

We assume $n_1 = -6$.

5. The tap voltage is

$$U_{1tap} = 115\ (1 - 6 \times 1.78/ 100) = 102.7 \text{ kV}$$

6. The voltage on 10 kV busbars if n_1 is –6, K_t is 102.7 /11 = 9.336,

hence, U_{2real} is U_{21}/ K_t= 99. 13 / 9.336 = 10.62 kV.

Off-peak conditions

7. The voltage on 110 kV substation busbars at off-peak conditions is:

$$U_1 = 110 – 0.18·110/100 = 109.8 \text{ kV}$$

8. The voltage losses in transformers is equal to

$$\Delta U_{T1}= 1.54 ·109.8/100 = 1.69 \text{ kV}$$

9. The voltage on 10 kV busbars, corrected to higher voltage side is

$$U_{21} = U_1 – \Delta U_{T1} = 109.8 – 1.69 = 108.11 \text{ kV}$$

10. The number of transformer-tap under $U_{2desired}$ is 1.05·10 = 10.5 kV

$$n_1= 100 ·[(U_{21} · U_{LV\ reated} / U_{HV\ rated}·U_{2desised}) –1]/ \Delta K =$$
$$= 100 [(108.11·11/ 115·10) – 1] /1.78 = 1.92$$

We assume n_1 = +2.

11. The tap voltage is

$$U_{1tap}= 115 (1 +2\times 1.78/ 100) = 119.1 \text{ kV}$$

12. The voltage on 10 kV busbars if n_1 = +2, K_T= 119.1 /11 = 10.827

$U_{2real}= U_{21}/ K_T$= 108.11 / 10.827 = 9.99 kV ≈ 10 kV.

Answer: at on-peak conditions K_T = 9.336; at off-peak conditions K_T = 10.827.

Task 3.2

A factory is fed through a 110 kV double circuit transmission line. The type of the phase conductors is ACSR with the steady-state thermal rating (ampacity) of I = 380 A corresponding to the maximum wire temperature of T = + 70 ˚C and the ambient temperature of T_{air} = + 25 ˚C. The maximum load of the factory P_{max} is 40 MW, tgφ is 0.5.

Determine:

- Whether one circuit of the transmission line can carry the full load current in a case of an accident on the other circuit i.e. determine the transmission line thermal capacity (maximum active power that can be transmitted and wires will not be overheated) in case of an emergency shutdown of one circuit;

- The steady-state temperature (T) of the wires of one circuit in the post-emergency operation mode (with only one of the two circuits is in service).

Solution

1. The transmission line current capacity:

$$I = \frac{S_{max}}{\sqrt{3} \cdot U_{ном}} = \frac{\sqrt{P_{max}^2 + Q_{max}^2}}{\sqrt{3} \cdot U_{ном}} = \frac{\sqrt{40^2 + (40 \cdot 0,5)^2}}{\sqrt{3} \cdot 110} \cdot 10^3 = 235 \text{ A.}$$

Check the line cross section for heating

$I_{admissible}$= 380 A, which is more than I = 235 A.

2. The transmission capacity of one circuit of double-circuit line

$P_{admissible} = \sqrt{3} \cdot U_{rated} \cdot I_{admissible} \cdot \cos\varphi = \sqrt{3} \cdot 110 \cdot 380 \cdot 0.894 = 64.725$ MW.

The operation under such post-fault conditions is *admissible*, because $P_{admissible}$= 64,725 MW is more than P_{max}= 40 MW.

3. The conductor temperature in the post-fault conditions is determined by the expression:

$$T = [I^2 (T_{admissible} – T_{air}) + I^2_{admissible} \cdot T_{air}] / I^2_{admissible} =$$
$$= [235^2(70 – 25) + 380^2 \cdot 25] / 380^2 = 42.21 \text{ degrees.}$$

or $T = T_{air} + I^2 \cdot (T_{admissible} – T_{air}) / I^2_{admissible} = 25 + 235^2 \cdot (70 – 25)/380^2 = 42.21$ degrees.

Answer: $P_{admissible}$ = 64.725 MW; T =42.21 degrees.

Task 3.3

It is necessary to connect electric arc furnace (EAF) with the transformer with capacity of S_{nom} = 4 MVA to an existing main step-down substation (fig. 3.1), and to find the operation mode of main step-down substation transformers so that voltage fluctuations caused by the operation of furnace would not exceed the permissible. The permissible peak-to-peak amplitude of voltage change $\delta U_{t\ perm}$ is 1.6 %. ($S_1 = S_2 = S_3 = S_4$).

Goal:

1. To determine the peak-to-peak amplitude of voltage change δU_t at the connection point of EAF, if it is connected to one of the split secondary windings of the transformer T1 if transformers T1 and T2 and their split secondary windings operate separately, assume windings splitting ratio K_{split} = 4;

2. To determine the peak-to-peak amplitude of voltage change (δU_t), if EAF is connected to 10 kV busses and transformers T1 and T2 and their split secondary windings operate in parallel;

3. To select the working mode of main step-down substation transformers to reduce voltage fluctuations in 10 kV net.

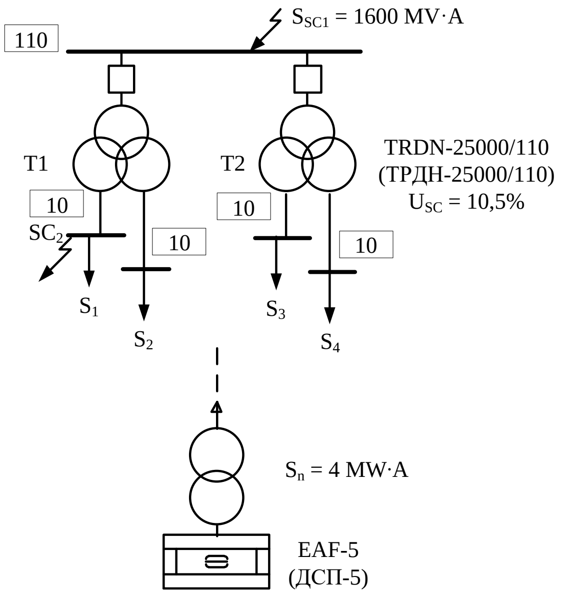


Fig. 3.1. The network scheme

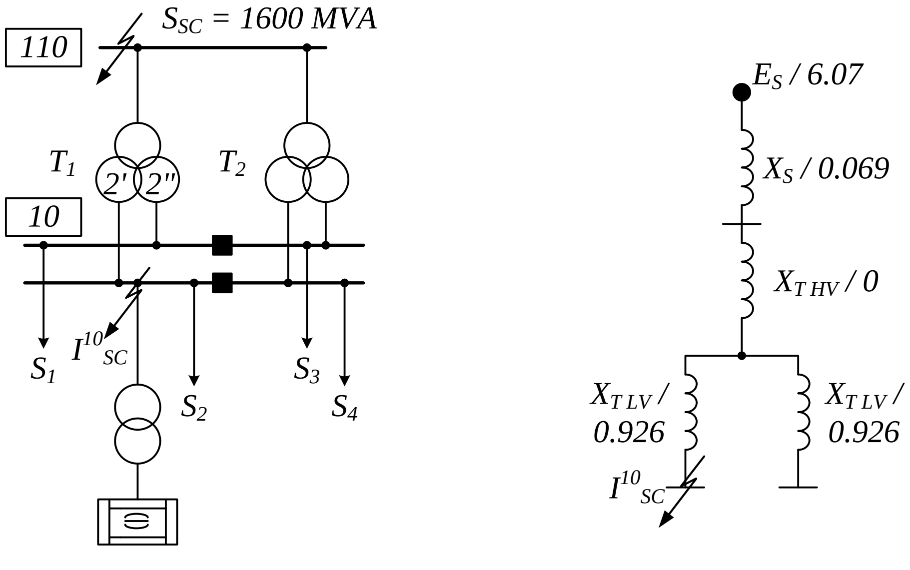
Solution

The peak-to-peak amplitude of voltage change is determined by the equation:

$$\delta U_t = \frac{S_n}{S_{SC}^{10}} \cdot 100\%$$

The scheme of separate operation of transformers T1 and T2

The equivalent circuit for computation of I_{SC}^{10} and its computation



The parameters of the equivalent circuit are

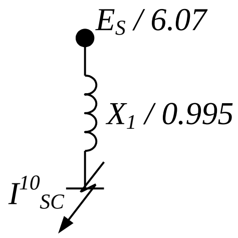
$U_{base} = 10.5$ kV

$$E_S = \frac{U_{base}}{\sqrt{3}} = \frac{10.5}{\sqrt{3}} = 6.07 \text{ kV}$$

$$x_S = \frac{U^2{}_{base}}{S_{SC}} = \frac{10,5^2}{1600} = 0.0689 = 0.069 \text{ Ohm}$$

$$x_{T\,HV} = \frac{U_{SC}}{100} \cdot \frac{U^2{}_{base}}{S_{SC}} \cdot \left(1 - \frac{K_{split}}{4}\right) = 0 \text{ Ohm}$$

$$x_{TLV} = \frac{U_{SC}}{100} \cdot \frac{U^2{}_{base}}{S_{SC}} \cdot \left(\frac{K_{split}}{2}\right) = \frac{10.5}{100} \cdot \frac{10.5^2}{25} \cdot \frac{4}{2} = 0.926 \text{ Ohm}$$



$$x_1 = x_S + x_{T\,LV} = 0.069 + 0.926 = 0.995 \text{ Ohm}$$

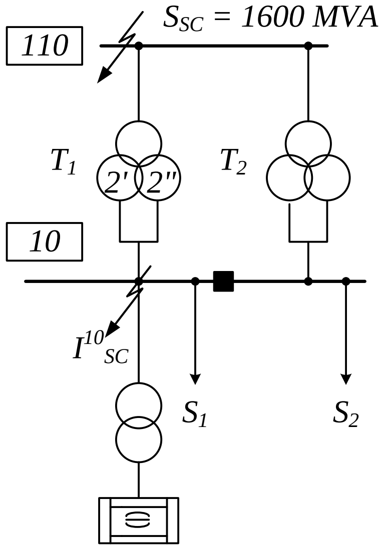
$$I_{SC}^{10} = \frac{E_S}{x_1} = \frac{6,07}{0,995} = 6.1 \text{ kA}$$

$$S_{SC}^{10} = \sqrt{3} \cdot U_{base} \cdot I_{SC}^{10} = \sqrt{3} \cdot 10.5 \cdot 6.1 = 110.8 \text{ MVA}$$

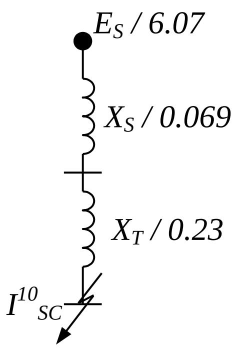
The peak-to-peak amplitude of voltage change:

$$\delta U_t = \frac{S_n}{S_{SC}^{10}} \cdot 100\% = \frac{4}{110.8} \cdot 100\% = 3.6\%$$

The scheme of the second mode.



The equivalent circuit and parameters:

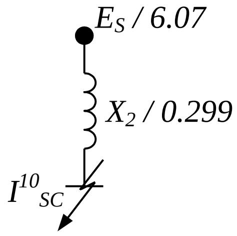


$$U_{base} = 10.5 \text{ kV}$$

$$E_S = \frac{U_{base}}{\sqrt{3}} = \frac{10,5}{\sqrt{3}} = 6.07 \text{ kV}$$

$$x_S = \frac{U^2{}_{base}}{S_{SC}} = \frac{10.5^2}{1600} = 0.0689 = 0.069 \text{ Ohm}$$

$$x_T = \frac{1}{2} \cdot \frac{U_{SC}}{100} \cdot \frac{U^2{}_{base}}{S_{SC}} = \frac{1}{2} \cdot \frac{10.5}{100} \cdot \frac{10.5^2}{25} = 0.23$$



$$x_2 = x_S + x_T = 0.069 + 0.23 = 0.299 \text{ Ohm}$$

$$I_{SC}^{10} = \frac{E_S}{x_2} = \frac{6.07}{0.299} = 20.3 \text{ kA}$$

$$S_{SC}^{10} = \sqrt{3} \cdot U_{base} \cdot I_{SC}^{10} = \sqrt{3} \cdot 10.5 \cdot 20.3 = 368.8 \text{ MVA}$$

The peak-to-peak amplitude of voltage change:

$$\delta U_t = \frac{S_n}{S_{SC}^{10}} \cdot 100\% = \frac{4}{368.8} \cdot 100\% = 1.08\%$$

Task 3.4

The substation is supplied by 10 kV power transmission line 5 km in length. The line wire is AC-50/8 (r_0 = 0.603 Ohm/km; x_0 = 0.388 Ohm/km). Transmitted over the transmission line power is 1200 + j·1050 kVA.

Determine the capacity of the capacitor bank, which must be installed on the substation 10 kV side to decrease the voltage loss to a value of 5% of the rated voltage.

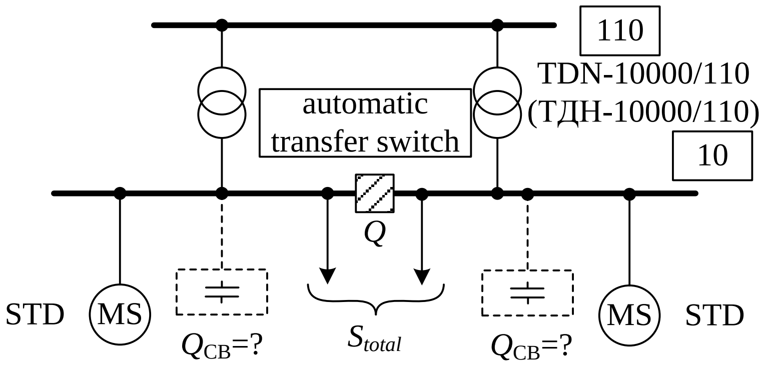


Fig. 3.2. The network scheme

Solution

1. The line voltage loss without installing a capacitor bank:

$$\Delta U_{Line} = \frac{P_{Line} \cdot R_{Line} + Q_{Line} \cdot X_{Line}}{U_1} = \frac{1200 \cdot 0.603 \cdot 5 + 1050 \cdot 0.388 \cdot 5}{10} = 565.5\,V$$

As a percentage of the nominal voltage:

$$\Delta U_{Line\%} = \frac{\Delta U_{Line}}{U_{nom}} = \frac{565.5}{10000} \cdot 100\% = 5.65\,\% > 5\%$$

2. The desired voltage loss is:

$$\Delta U^{desired} = 0.05 \cdot U_{nom} = 0.05 \cdot 10000 = 500\,V$$

3. The power of the capacitor bank to provide the desired voltage loss should be:

$$Q_{CB} = \frac{\left(\Delta U_{Line} - \Delta U^{desired}\right)\cdot U_{nom}}{X_{Line}} = \frac{(565.5-500)\cdot 10}{0.388\cdot 5} = 337.6\ kvar$$

We choose capacitor banks UKL56-10.5-450 (УКЛ56-10.5-450) with Q_{CB} = 450 kvar.

4. The line voltage loss after installing the capacitor bank:

$$\Delta U_{Line} = \frac{P_{Line}\cdot R_{Line} + (Q_{Line} - Q_{CB})\cdot X_{Line}}{U_1} = \frac{1200\cdot 0.603\cdot 5 + (1050-450)\cdot 0.388\cdot 5}{10} = 478.2\,V$$

As a percentage of the nominal voltage:

$$\Delta U_{Line\%} = \frac{\Delta U_{Line}}{U_{nom}} = \frac{478.2}{10000}\cdot 100\% = 4.782\,\% < 5\%$$

Answer: after installing the capacitor bank UKL56-10,5-450 (УКЛ56-10,5-450) with the power of 450 kvar line voltage the loss will be less than 5% of nominal voltage.

Task 3.5

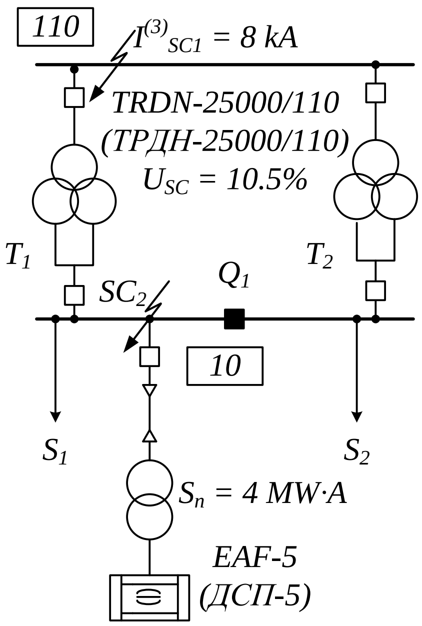


Fig. 3.3

A new electric arc furnace DSP-5 is connected to the main step-down substation 10 kV buses (fig. 3.3).

Goal:

- to determine the range of voltage variation at DSP-5 connection point (10 kV bus section) for operating mode of transformers T_1 and T_2, shown in fig.3.3;
- to draw a conclusion on the admissibility of voltage fluctuations if the length of the melt period is 10 min and the rate of the occurrence of voltage changes is 0.3 c^{-1}.

Solution

1. The equivalent circuit for the calculation of the short-circuit current at the main step-down substation 10 kV bus section at point SC_2 is shown in Fig. 3.4.

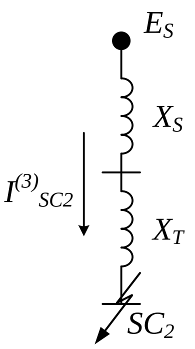


Fig. 3.4

The parameters of the equivalent circuit (fig. 3.4) in actual values (U_{base} = 10.5 kV) are:

$E_S = 10.5$ kA

$$X_S = \frac{U_{base}^2}{S_{SC}} = \frac{U_{base}^2}{\sqrt{3}\cdot I_{SC1}\cdot U_S} = \frac{10.5^2}{\sqrt{3}\cdot 8\cdot 115} = 0.069 \text{ Ohm}$$

$$X_T = \frac{U_{SC}}{100}\cdot\frac{U_{base}^2}{S_{rated}} = \frac{10.5}{100}\cdot\frac{10.5^2}{25} = 0.463 \text{ Ohm}$$

The parameters of the equivalent circuit in relative units (S_{base} = 1000 MV·A; U_{base} = 10,5 kV) are: $E_S = 1$ p.u.

$$X_S = \frac{S_{base}}{S_{SC}} = \frac{S_{base}}{\sqrt{3}\cdot I_{SC1}\cdot U_S} = \frac{1000}{\sqrt{3}\cdot 8\cdot 115} = 0.628 \text{ p.u.}$$

$$X_T = \frac{U_{SC}}{100}\cdot\frac{S_{base}}{S_{rated}} = \frac{10.5}{100}\cdot\frac{1000}{25} = 4.2 \text{ p.u.}$$

2. The calculation of the short-circuit current at the main step-down substation 10 kV buses:

$$I_{SC2} = \frac{E_S}{\sqrt{3}\cdot X_\Sigma} = \frac{E_S}{\sqrt{3}\cdot(X_S + X_T)} = \frac{10.5}{\sqrt{3}\cdot(0.069+0.463)} = 11.4 \text{ kA, or}$$

$$I_{SC2} = \frac{E_S}{X_\Sigma}\cdot I_{base} = \frac{E_S}{(X_S + X_T)}\cdot\frac{S_{base}}{\sqrt{3}\cdot U_{base}} = \frac{1}{(0.069+0.463)}\cdot\frac{1000}{\sqrt{3}\cdot 10.5} = 11.4 \text{ kA}$$

Then, short circuit power is equal to

$$S_{SC2} = \sqrt{3}\cdot U_{base}\cdot I_{SC2} = \sqrt{3}\cdot 10.5\cdot 11.4 = 207.326 \text{ MVA}$$

3. The calculated range of voltage fluctuation:

$$\delta U_t = \frac{S_n}{S_{SC2}}\cdot 100\% = \frac{4}{207.326}\cdot 100\% = 1.93\ \%.$$

The rate of voltage changes occurrence

$F = 0.3\cdot 60 = 18$ min^{-1}

4. The permissible peak-to-peak amplitude of voltage change is determined in accordance with GOST 13109-97 (ГОСТ 13109-97). The permissible peak-to-peak amplitude of voltage change depending on repetition voltage variations frequency is $\delta U_{t\ permiss} = 1.6$ %.

5. The assessment of the admissibility of voltage fluctuations is

$\delta U_{t\ permiss} > \delta U_t$, (1.6 % < 1.93 % - fluctuations are not permissible).

Answer: voltage fluctuations are not permissible as $\delta U_{t\ permiss} < \delta U_t$,.

4. Electric Grids and Electric Power Systems

Task 4.1

It was decided to install a capacitor bank (CB) with the capacity of 400 kvar on the 0.4 kV bus of a substation with a flat load profile (fig. 4.1). The cost of the CB is 120 000 rubles.

The transformer (T) operates 5000 hours per year, and the price of electricity P_w is 3 rubles per kWh.

Determine the costs caused by additional losses of electricity in the transformer before the CB installation. Calculate the CB payback period. Battery heating can be neglected.

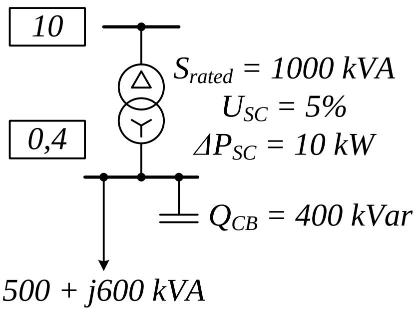


Fig. 4.1

Solution

1. The load power losses in the transformer before the installation of the capacitor bank:

$\Delta P = \Delta P_{SC} \cdot (S / S_{rated})^2 = 10 \cdot (781 / 1000)^2 = 6.1$ kW,

where $S = \sqrt{P^2 + Q^2} = \sqrt{500^2 + 600^2} = 781$ кВ·А.

2. The load power losses after the installation of the capacitor bank:

$\Delta P = \Delta P_{SC} \cdot (S1 / S_{rated})^2 = 10 \cdot (538{,}5 / 1000)^2 = 2.9$ kW,

where $S = \sqrt{P^2 + Q^2} = \sqrt{500^2 + 200^2} = 538{,}5$ кВ·А.

3. The loss reduction is equal to

dP = 6.1 – 2.9 = 3.2 kW.

4. The annual power consumption reduction is equal to

dW = dP·T = 3.2 · 5000 = 16 000 kWh/year.

5. The cost of power losses compensation in the transformer is

$C_{\Delta w} = dW \cdot Pr_w = 16000 \cdot 3 = 48000$ rub.

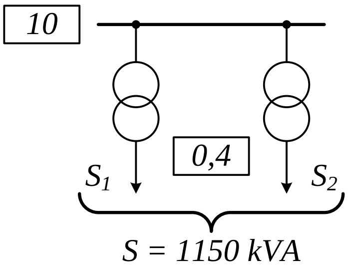
6. The capacity bank payback period is

$T_{pp} = K / C_{\Delta w} = 120\,000 / 48000 = 2.5$ years.

Answer: $C_{\Delta w} = 48000$ rub, $T_{pp} = 2.5$ years.

Task 4.2

Two transformers T1 (S_{rated} =1600 kVA) and T2 (S_{rated} = 630 kVA) operate separately, their total load is 1150 kVA under cos φ = const (fig. 4.2). Determine loads S_1 and S_2 such that the sum of the active power losses in the two transformers is minimal.



	T_1	T_2
S_{rated}, kVA	1600	630
$\Delta P_{no\text{-}load}$, kW	3.65	1.9
ΔP_{SC}, kW	18	7.6

Fig. 4.2

Solution

Method 1

1. The sum of the load losses in two transformers is

$$\Delta P = \left(\frac{S - S_2}{S_{rated1}}\right)^2 \cdot \Delta P_{SC1} + \frac{S_2{}^2}{S_{rated2}{}^2} \cdot \Delta P_{SC2}$$

2. We equate the first derivative to zero:

$$-2\frac{S - S_2}{S_{rated1}{}^2} \cdot \Delta P_{SC1} + 2\frac{S_2}{S_{rated2}{}^2} \cdot \Delta P_{SC2} = 0$$

3. We transform the expression to the following:

$$\frac{S - S_2}{S_2} = \frac{\Delta P_{SC2}}{\Delta P_{SC1}} \cdot \frac{S_{rated1}{}^2}{S_{rated2}{}^2} = \frac{7.6}{18} \cdot \frac{1600^2}{630^2} = 2.723$$

4. Then the loads of transformers will be equal to

T2: S_2 = 308,86 kVA ≈ 309 kVA.

T1: $S_1 = S - S_2$ = 1150 – 309 = 841 kVA.

Method 2

1. It is known that the load losses will be minimal when the transformers operate in parallel. The currents in this mode of operation are distributed inversely proportional to the active resistance of the transformers:

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \text{ or } \frac{I_1}{I_2} = \frac{S_1}{S_2} = \frac{S - S_2}{S_2}, \ \frac{R_2}{R_1} = \frac{\Delta P_{SC2}}{\Delta P_{SC1}} \cdot \frac{S_{rated1}{}^2}{S_{rated2}{}^2} = \frac{7.6}{18} \cdot \frac{1600^2}{630^2} = 2.723$$

2. Then the loads of transformers will be equal to

T2: S_2 = 308,86 kVA ≈ 309 kVA.

T1: $S_1 = S - S_2$ = 1150 – 309 = 841 kVA.

Answer: S_1 = 841 kVA, S_2 = 309 kVA.

Task 4.3

Calculate the power flow in a ring network taking into account power losses in a given operating mode (fig. 4.3). Check the current capacity of A-3 power transmission line cross-section when you turn off A-2 power transmission line, if the air temperature is 40^0C. Charge capacity of power transmission lines can be neglected.

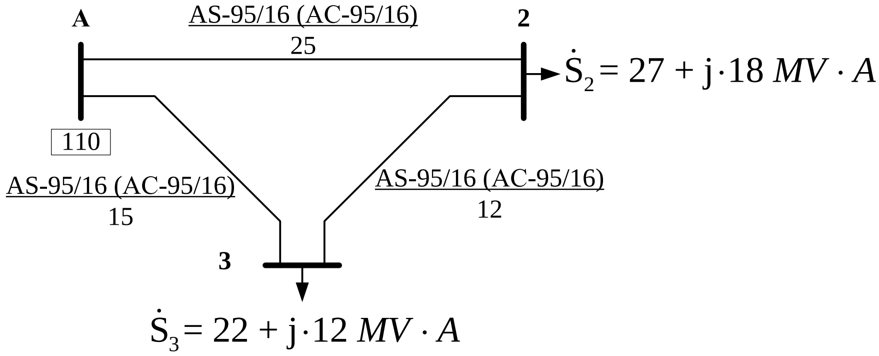


Fig. 4.3

The reference data for the power transmission line are:
r_0 = 0.301 Ohm/km; x_0 = 0.434 Ohm/km; $b_0 = 2.611\cdot10^{-6}$ mho/km.
Admissible continuous current at the temperature of 25^0C $I_{admissible}$ is 330 A.

Solution

1. Let us open the ring network (fig. 4.4).

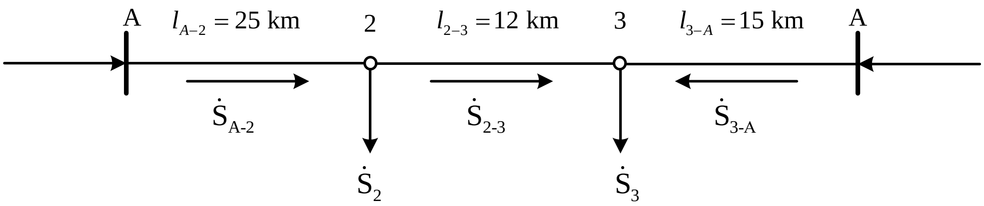


Fig. 4.4

We define the power flow in the ring network using lines length because cables cross-section are the same:

$$S_{A-2} = \frac{S_2\cdot(l_{2-3}+l_{3-A})+S_3\cdot l_{3-A}}{l_{A-2}+l_{23}+l_{3-A}} = \frac{(27+j\cdot18)\cdot(12+15)+(22+j\cdot12)\cdot15}{25+12+15} =$$

$$= 20.365 + j\cdot12.808 \text{ MVA}$$

$$S_{3-A} = \frac{S_3\cdot(l_{2-3}+l_{A-2})+S_2\cdot l_{A-2}}{l_{A-2}+l_{23}+l_{3-A}} = \frac{(22+j\cdot12)\cdot(12+25)+(27+j\cdot18)\cdot25}{25+12+15} =$$

$$= 28.635 + j\cdot17.192 \text{ MVA}$$

$$S_{2-3} = S_{A-2} - S_2 = (20.365+j\cdot12.808)-(27+j\cdot18) = -6.635 - j\cdot5.192 \text{ MVA}$$

Node 2 is power partition node.

2. We form the equivalent circuit (fig. 4.5) and define the parameters of transmission lines:

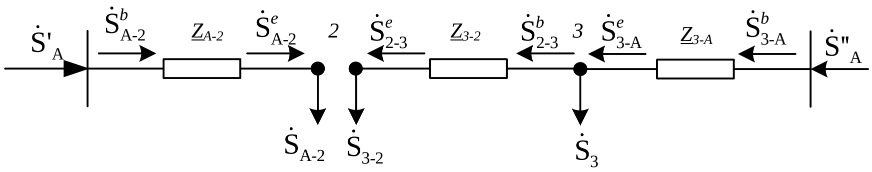


Fig. 4.5

- transmission lines impedance:

$\underline{Z} = R_0 \cdot l + j \cdot x_0 \cdot l;$

$\underline{Z}_{A\text{-}2} = R_0 \cdot l_{A\text{-}2} + j \cdot x_0 \cdot l_{A\text{-}2} = 0.301 \cdot 25 + j \cdot 0.434 \cdot 25 = 7.525 + j \cdot 10.85$ Ohm;

$\underline{Z}_{3\text{-}2} = R_0 \cdot l_{3\text{-}2} + j \cdot x_0 \cdot l_{3\text{-}2} = 0.301 \cdot 12 + j \cdot 0.434 \cdot 12 = 3.612 + j \cdot 5.208$ Ohm;

$\underline{Z}_{3\text{-}A} = R_0 \cdot l_{3\text{-}A} + j \cdot x_0 \cdot l_{3\text{-}A} = 0.301 \cdot 15 + j \cdot 0.434 \cdot 15 = 4.515 + j \cdot 6.51$ Ohm.

3. We determine the power flow taking into account power losses:

- line A-2 ($U_2 = U_{rated} = 110$ kV)

$$\dot{S}^e_{A-2} = \dot{S}_{A-2} = 20.365 + j \cdot 12.808 \text{ MVA}$$

$$\Delta \dot{S}_{A-2} = \frac{\left(P^e_{A-2}\right)^2 + \left(Q^e_{A-2}\right)^2}{U_2^2} \cdot \left(R_{A-2} + j \cdot X_{A-2}\right) =$$

$$= \frac{(20.365)^2 + (12.808)^2}{110^2} \cdot (7.525 + j \cdot 10.85) = 0.36 + j \cdot 0.519 \text{ MVA}$$

$$\dot{S}^b_{A-2} = \dot{S}^e_{A-2} - \Delta \dot{S}_{A-2} = 20.365 + j \cdot 12.808 \ + 0.36 + j \cdot 0.519 = 20.725 + j \cdot 13.327 \text{MVA}$$

$$\dot{S}'_A = \dot{S}^b_{A-2} = 20.725 + j \cdot 13.327 \text{ MVA}$$

- line 3-2 ($U_2 = U_{rated} = 110$ kV)

$$\dot{S}^e_{3-2} = \dot{S}_{3-2} = 6.635 + j \cdot 5.192 \text{ MVA}$$

$$\Delta \dot{S}_{3-2} = \frac{\left(P^e_{3-2}\right)^2 + \left(Q^e_{3-2}\right)^2}{U_2^2} \cdot \left(R_{3-2} + j \cdot X_{3-2}\right) =$$

$$= \frac{(6.635)^2 + (5.192)^2}{110^2} \cdot (3.612 + j \cdot 5.208) = 0.021 + j \cdot 0.031 \text{ MVA}$$

$$\dot{S}^b_{3-2} = \dot{S}^e_{3-2} - \Delta \dot{S}_{3-2} = 6.635 + j \cdot 5.192 \ + 0.021 + j \cdot 0.031 = 6.656 + j \cdot 5.223 \text{ MVA}$$

– line 3-A ($U_3 = U_{rated} = 110$ kV)

$$\dot{S}^e_{3-A} = \dot{S}^b_{3-2} + \dot{S}_3 = 6.656 + j \cdot 5.223 + 22 + j \cdot 12 = 28.656 + j \cdot 17.223 \text{ MVA}$$

$$\Delta \dot{S}_{3-A} = \frac{\left(P^e_{3-A}\right)^2 + \left(Q^e_{3-A}\right)^2}{U_3^2} \cdot \left(R_{3-A} + j \cdot X_{3-A}\right) = 0.417 + j \cdot 0.601 \text{ MVA}$$

$$\dot{S}^b_{3-A} = \dot{S}^e_{3-A} - \Delta \dot{S}_{3-A} = 28.656 + j \cdot 17.223 \ + 0.417 + j \cdot 0.601 = 29.073 + j \cdot 17.824 \text{ MVA}$$

$$\dot{S}''_A = \dot{S}^b_{3-A} = 29.073 + j \cdot 17.824 \text{ MVA}$$

– power supply capacity

$$\dot{S}_A = \dot{S}'_A + \dot{S}''_A = 20.725 + j \cdot 13.327 + 29.073 + j \cdot 17.824 = 49.798 + j \cdot 31.151 \text{ MVA}$$

4. Let's check current transmission capacity of line A-3 cross-section.

- We determine power flow in line A-3 when line A-2 is not in operation (fig. 4.6):

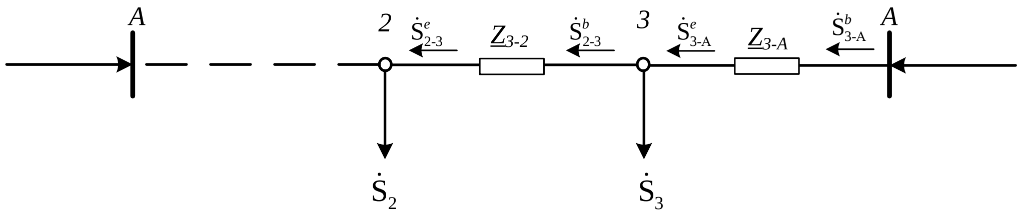


Fig. 4.6

$$\dot{S}^e_{3-2} = \dot{S}_2 = 27 + j \cdot 18 \text{ MVA}$$

$$\Delta\dot{S}_{3-2} = \frac{\left(P^e_{3-2}\right)^2 + \left(Q^e_{3-2}\right)^2}{U_2^2} \cdot \left(R_{3-2} + j \cdot X_{3-2}\right) =$$

$$= \frac{(27)^2 + (18)^2}{110^2} \cdot (3.612 + j \cdot 5.208) = 0.314 + j \cdot 0.453 \text{ MVA}$$

$$\dot{S}^b_{3-2} = \dot{S}^e_{3-2} - \Delta\dot{S}_{3-2} = 27 + j \cdot 18 \ + 0.314 + j \cdot 0.453 = 27.314 + j \cdot 18.453 \text{ MVA}$$

$$\dot{S}^e_{3-A} = \dot{S}^b_{3-2} + \dot{S}_3 = 27.314 + j \cdot 18.453 + 22 + j \cdot 12 = 49.314 + j \cdot 30.453 \text{ MVA}$$

$$\Delta\dot{S}_{3-A} = \frac{\left(P^e_{3-A}\right)^2 + \left(Q^e_{3-A}\right)^2}{U_3^2} \cdot \left(R_{3-A} + j \cdot X_{3-A}\right) =$$

$$= \frac{(49.314)^2 + (30.453)^2}{110^2} \cdot (4.515 + j \cdot 6.51) = 1.253 + j \cdot 1.807 \text{ MVA}$$

$$\dot{S}^b_{3-A} = \dot{S}^e_{3-A} - \Delta\dot{S}_{3-A} = 49.314 + j \cdot 30.453 \ + 1.253 + j \cdot 1.807 = 50.567 + j \cdot 32.26 \text{ MVA}$$

- We determine current in line ($U_A = U_{rated} = 110$ kV):

$$I_{line} = \frac{\sqrt{\left(P^b_{line}\right)^2 + \left(Q^b_{line}\right)^2}}{\sqrt{3} \cdot U_A \cdot n} = \frac{\sqrt{50.567^2 + 32.26^2}}{\sqrt{3} \cdot 110 \cdot 1} = 0.315 \text{ kA} = 315 \text{ A}$$

- We determine the permissible current at the temperature of +40°C:

$$I'_{permiss} = I_{permiss} \cdot \sqrt{(T_{permiss} - T_{real}) / (T_{permiss} - T_0)} = 330 \cdot \sqrt{(70-40)/(70-25)} = 269.4 \text{ A}$$

- We determine the transmission capacity of line A-3 cross-section:

$I_{line} > I'_{permiss}$, so we should increase the cross-section of line A-3.

Task 4.4

The substation is supplied by 10 kV power transmission line 5 km in length. The line wire is AS-50/8 (AC-50/8) (r_0 = 0.603 Ohm/km; x_0 = 0.388 Ohm/km). The power transmitted over the transmission line is 1200 + j·1050 kVA.

Determine the capacity of the capacitor bank, which must be installed on the substation 10 kV side to decrease the voltage loss to the value of 5% of the rated voltage.

Solution

1. The line voltage loss without installing the capacitor bank:

$$\Delta U_{Line} = \frac{P_{Line} \cdot R_{Line} + Q_{Line} \cdot X_{Line}}{U_1} = \frac{1200 \cdot 0.603 \cdot 5 + 1050 \cdot 0.388 \cdot 5}{10} = 565.5\,V$$

As a percentage of the nominal voltage, they are:

$$\Delta U_{Line\%} = \frac{\Delta U_{Line}}{U_{nom}} = \frac{565.5}{10000} \cdot 100\% = 5.65\,\% > 5\%$$

2. The desired voltage loss is:

$$\Delta U^{desired} = 0.05 \cdot U_{nom} = 0.05 \cdot 10000 = 500\,V$$

3. The power of the capacitor bank to provide the desired voltage loss should be:

$$Q_{CB} = \frac{\left(\Delta U_{Line} - \Delta U^{desired}\right) \cdot U_{nom}}{X_{Line}} = \frac{(565.5 - 500) \cdot 10}{0.388 \cdot 5} = 337.6\,kvar$$

We choose capacitor banks UKL56-10.5-450 (УКЛ56-10.5-450) with Q_{CB} = 450 kvar.

4. The line voltage loss after installing the capacitor bank is:

$$\Delta U_{Line} = \frac{P_{Line} \cdot R_{Line} + (Q_{Line} - Q_{CB}) \cdot X_{Line}}{U_1} = \frac{1200 \cdot 0.603 \cdot 5 + (1050 - 450) \cdot 0.388 \cdot 5}{10} = 478.2\,V$$

As a percentage of the nominal voltage, they are:

$$\Delta U_{Line\%} = \frac{\Delta U_{Line}}{U_{nom}} = \frac{478.2}{10000} \cdot 100\% = 4.782\,\% < 5\%$$

Answer: that after installing the capacitor bank UKL56-10.5-450 (УКЛ56-10.5-450) with power of 450 kvar line the voltage losses will be less than 5% of nominal voltage.

Task 4.5

Two transformers TDN-16000/110 (ТДН-16000/110) (ΔP_{SC} = 85 kW, ΔP_{noload} = 19 kW), operating in parallel are installed on a substation. The graph of load changes during the year is shown in fig. 4.9. The maximum load of the substation P_1 is 20 MW. During the year, the lowest load P_2 is $\alpha \cdot P_1$, value α varies in the range of 0.3 ÷ 0.6. The power factor is not changed during the year and is equal to 0.9.

Goal:

1. To determine the values of α when it is economically feasible to disconnect one of the transformers at the lowest load;

2. To determine the active power and the electricity losses in the transformers for the year if you disconnect one of the transformers at the lowest load (α = 0.3).

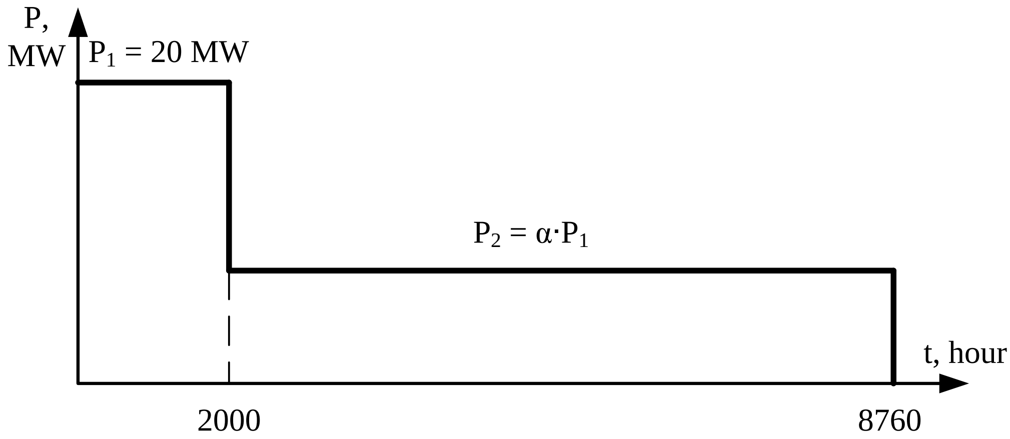


Fig. 4.9. Graph of active load behavior

Solution

1. The load ($S_{critical}$), whereby the power losses during operation of the substation with one and two transformers are equal, is calculated as follows:

$$S_{Load} = S_{critical} = S_{nom} \cdot \sqrt{\frac{2 \cdot \Delta P_{no-load}}{\Delta P_{SC}}} = 16 \cdot \sqrt{\frac{2 \cdot 19}{85}} = 10.7\ MV \cdot A$$

Then, the active power of the load, whereby the power losses during operation of the substation with one and two transformers are equal, can be calculated as follows:

$$P_{Load} = P_{critical} = S_{critical} \cdot \cos\varphi = 10.7 \cdot 0.9 = 9.63\ MW$$

The coefficient α is then equal to:

$$\alpha = \frac{P_{critical}}{P_1} = \frac{9.63}{20} = 0.48$$

I.e. when α is from 0.3 to 0.48 it is economically feasible to disconnect one of the transformers as power losses will be less.

2. We determine the active power losses in transformers:

- The active power losses in a transformer are determined as follows:

$$\Delta P_T = \Delta P_{no-load} + \Delta P_{SC} \cdot \left(\frac{S_{Load}}{S_{nom}} \right)^2$$

- The active power losses in two transformers in parallel operation are determined as follows:

$$\Delta P_T = 2 \cdot \Delta P_{no-load} + \frac{1}{2} \cdot \Delta P_{SC} \cdot \left(\frac{S_{Load}}{S_{nom}} \right)^2$$

In on-peak conditions the active power losses in the transformers will be:

$$\Delta P_T = 2 \cdot 0.019 + \frac{1}{2} \cdot 0.085 \cdot \left(\frac{20/0.9}{16} \right)^2 = 0.12\ MW \ \left(\Delta P_{var\,2\,transformers} = 0.082\ MW \right)$$

In off-peak conditions (α = 0.3) the active power losses in transformers will be:

$$\Delta P_T = 0.019 + 0.085 \cdot \left(\frac{0.3 \cdot 20/0.9}{16} \right)^2 = 0.34\ MW \ \left(\Delta P_{var\,1\,transformer} = 0.015\ MW \right)$$

3. We determine energy losses in the electrical network:

- the constant losses of electricity:

$$\Delta W_{const} = \Delta P_{const} \cdot t_{working} = \Delta P_{no-load} \cdot t_{working1} + 2 \cdot \Delta P_{no-load} \cdot t_{working2} =$$
$$= 0.019 \cdot 6760 + 2 \cdot 0.019 \cdot 2000 = 204.44\ MW \cdot h$$

- the variable losses of electricity:

$$\Delta W_{var} = \Delta P_{var} \cdot t_{working} = \Delta P_{var\,2\,transformers} \cdot t_{working2} + \Delta P_{var\,1\,transformer} \cdot t_{working1} =$$
$$= 0.082 \cdot 2000 + 2 \cdot 0.015 \cdot 6760 = 265.4\ MW \cdot h$$

- the total losses of electricity:

$$\Delta W_{total} = \Delta W_{const} + \Delta W_{var} = 265.4 + 204.44 = 469.84\ MW \cdot h$$

Answer: 1) when α is from 0.3 to 0.48 it is economically feasible to disconnect one of the transformers as power losses will be less;

2) the active power losses in on-peak conditions are equal to 0.012 MW;

3) the active power losses in off-peak conditions are equal to 0.034 MW;

4) the total electricity losses are equal to 469.84 MW·h.

5. High-Voltage Engineering

Task 5.1

500 kV power transmission line wire-tower body clearance has an average discharge voltage of 1350 kV under ordinary atmospheric conditions. How will the dielectric strength of the clearance change if the power transmission line is located in a mountainous area at the altitude of 1100 m above the sea level?

While calculating, assume that the temperature and humidity corresponds the normal conditions, and the air pressure depends on the altitude according to the barometric formula:

$$P = P_0 e^{-\frac{Mgh}{RT}},$$

where P_0=101.3 [kPa] is the sea level pressure (normal atmospheric pressure); M = 0.029 [kg / mole] is the molar mass of dry air; g = 9.81 [m/s²] is the acceleration of gravity; R = 8.31 [J / mole K] is the absolute gas constant; T = t + 273 [K] is the air temperature, where t is the temperature in ^{0}C; h is the altitude above the sea level [m].

Solution

The influence of temperature and air pressure on the spark-over voltage (discharge voltage) of the gaps is recognized by the relative density of air:

$$\delta = \frac{T_0 \cdot P}{P_0 \cdot T}.$$

While $U_{sov} = U_{sov0} \cdot \delta$.

Let's evaluate the air pressure at the altitude of 1100 m above the sea level by the given dependency:

$$P = 101.3e^{-\frac{0,029 \cdot 9,81 \cdot 1100}{8,31 \cdot 293}} = 89.08 \text{ [kPa]}.$$

So, $\delta = \frac{293 \cdot 89.08}{101.3 \cdot 293} = 0.879$

The sparking-over voltage is calculated by the formula $U_{sov} = 1350 \times 0.879 = 1186.65$ [kV]

Answer: the sparking-over voltage of the gap decreases to 1186.65 kV.

Task 5.2

While designing the insulator the following requirements on the electrical conductivity were imposed: the specific cubic conductance should be no more than 10^{-12} Sm/m, and the specific surface conductivity is not more than 10^{-11} Sm. We consider three samples of insulators: varnished cloth, electric-grade cardboard and glass textolite. Resistances of materials samples were measured by the three-electrode circuit (fig. 5.1, fig. 5.2). The diameter of the central (measuring) electrode $d_1 = 66 \cdot 10^{-3}$ m, ring electrode $d_2 = 70 \cdot 10^{-3}$ m. The thickness of the samples for varnished cloth h_{varn} is $0.1 \cdot 10^{-3}$ m, for electric-grade cardboard $h_{el.card}$ is $0.2 \cdot 10^{-3}$ m, for glass textolite h_{gtext} is $0.5 \cdot 10^{-3}$ m.

The measurement results are:

1. varnished cloth full cubic resistance $R_{cub\ varn} = 30 \cdot 10^{9}$ Ohm, electric-grade cardboard $R_{cub\ el.card} = 60 \cdot 10^{10}$ Ohm, glass textolite $R_{cub\ gtext} = 15 \cdot 10^{8}$ Ohm.

2. varnished cloth full surface resistance $R_{s\ varn} = 12 \cdot 10^{8}$ Ohm, electric-grade cardboard $R_{s\ el.card} = 10 \cdot 10^{7}$ Ohm, glass textolite $R_{s\ gtext} = 8 \cdot 10^{10}$ Ohm.

Goal:

1. Choose any megger from the proposed types of devices and write its designation into the given measurement circuits (Fig. 5.2 – 5.4). Connect the device terminals with the electrode system on circuits for the dielectric cubic and surface resistances measurement.

2. Determine which of the proposed insulating materials may be used in accordance with the conditions of the task.

Note: While calculating dielectrics surface resistances, assume that the surface resistance measurement with the use of ring electrodes is equivalent to the measurement when a planar electrode with a width equal to the circumference of the electrodes of the central (measuring) electrode is used.

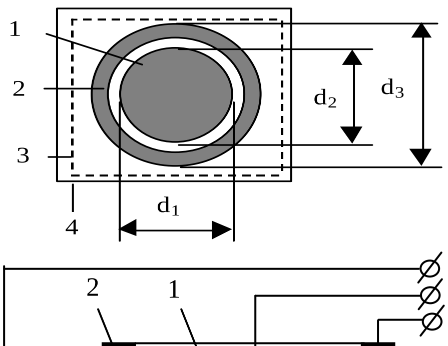


Fig. 5.1. Sketch of a sample of solid dielectric Foil electrodes pasted on the sample: a) above: 1 – a central (meter) disk electrode; 2 – a ring electrode; b) below: 3 – an electrode in the form of a square or a circle having a diameter of at least d_3. 4

Fig. 5.2. Diagram of dielectric cubic resistance measurement:
1, 2, 3 – electrodes; 4 – dielectric

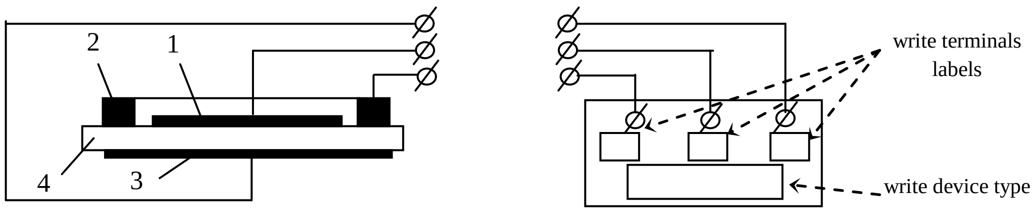


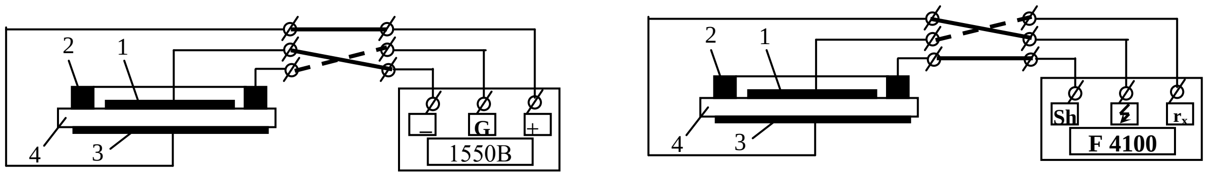
Fig. 5.3. Diagram of dielectric surface resistance measurement:
1, 2, 3 – electrodes; 4 – dielectric

Fig. 5.4. Megger terminal designation diagrams: a – FLUKE 1550B; b – F 4100;
1 – high voltage output; 2 – test lead; 3 – protective lead (shield)

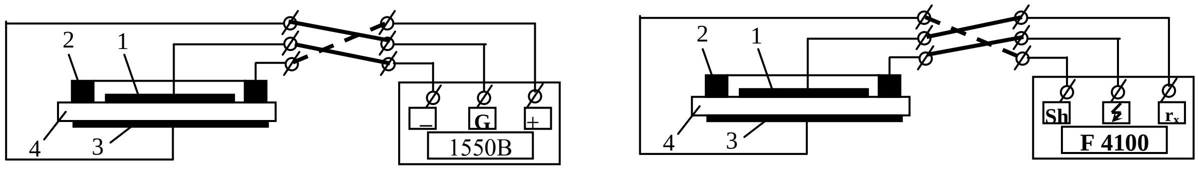
Solution

Measurement design

FLUKE 1550B F 4100 (Ф 4100)



Measuring of the dielectric bulk resistance



Measuring of the dielectric surface resistance

For the three-electrode system the dielectric bulk resistance is:

$$\rho_v = R_v \frac{S_{electrode}}{h} = R_v \frac{\pi d_1^2}{4h} = R_v \frac{3.14 \cdot \left(66 \cdot 10^{-3}\right)^2}{4h} = \frac{3.42 \cdot 10^{-3} R_v}{h},$$

where $S_{\text{electrode}}$ is an area of the measuring electrode

The dielectric surface resistance is:

$$\rho_s = R_s \frac{2\pi}{\ell n(d_2 / d_1)} = R_s \frac{2 \cdot 3.14}{\ell n(70 \cdot 10^{-3} / 66 \cdot 10^{-3})} = 106.7 \cdot R_s$$

In the approximate calculation the dielectric surface resistance is:

$$\rho_s = R_s \frac{2 \cdot l}{d2 - d1} = R_s \frac{2 \cdot \pi \cdot d1}{d2 - d1} = 103.6 \cdot R_s,$$

where *l* is a perimeter of the central (measuring) electrode circle.

The specific conductions are: bulk $\gamma = \frac{1}{\rho_v}$, surface $\gamma = \frac{1}{\rho_S}$.

The calculated values are summarized in the table:

Testing sample	ρ_V, Ohm·m	ρ_S, Ohm	γ_V, mho/m	γ_S, mho
varnished cloth	$10.3\cdot10^{11}$	$12.8\cdot10^{10}$	$9.75\cdot10^{-13}$	$7.81\cdot10^{-12}$
electric-grade cardboard	$10.3\cdot10^{12}$	$10.7\cdot10^{9}$	$9.75\cdot10^{-14}$	$9.37\cdot10^{-11}$
fiber-glass plastic	$10.3\cdot10^{9}$	$8.54\cdot10^{12}$	$9.75\cdot10^{-11}$	$1.17\cdot10^{-13}$

Answer: in accordance to the statement of problem the varnished cloth satisfies the requirements.

Task 5.3

High-voltage inputs of three-phase 35 kV electrical installation have a form of a coaxial cylindrical system with two-layer insulation. The first layer is Bakelite (ε=3.5), the second one is silicone rubber (ε=7).

Calculate the value of the electric field at the boundaries of the insulating layers and in the middle of insulation layers of high voltage inputs when exposed to the rated voltage of industrial frequency.

Reference data:

the radius of the current-carrying rod is 4 mm;

the outer radius of the first layer is 14 mm;

the outer radius of the second layer is 20 mm.

Solution

For multilayer cylindrical capacitor electric field strength in the *i*-th layer is determined as:

$$E_{ri} = \frac{U_{\text{work}}}{r \cdot \ln\frac{r_{2i}}{r_{1i}} \sum\limits_{k=1}^{n} \frac{C_i}{C_k}} \qquad \text{or} \qquad E_{ri} = \frac{U_{work}}{\varepsilon_i \cdot r \sum\limits_{k=1}^{n} \frac{\ln\frac{r_{2k}}{r_{1k}}}{\varepsilon_k}}$$

where r_{2i}, r_{2k}, are the outer radii of layers, r_{1i} r_{1k} are the inner radii of layers, ε_i, ε_k are inductivities of layers, U_{work} is the voltage applied to the insulation.

In installations with rated voltage of 35 kV the phase voltage is applied to the insulation inputs

$$U_{work} = \frac{U_{rated}}{\sqrt{3}} = \frac{35}{\sqrt{3}} = 20.2 \quad \text{(kV)}$$

Hence, for the first layer:

$$E_{r1} = \frac{20.2}{3.5 \cdot r \left(\frac{\ln \frac{14}{4}}{3.5} + \frac{\ln \frac{20}{14}}{7} \right)} = \frac{14.12}{r}$$

For the second layer:

$$E_{r2} = \frac{20.2}{7 \cdot r \left(\frac{\ln \frac{14}{4}}{3.5} + \frac{\ln \frac{20}{14}}{7} \right)} = \frac{7.06}{r}$$

The result is the following:

	the 1st layer			the 2nd layer		
r, mm	4	9	14	14	17	20
E_r, kV/mm	3.53	1.57	1.01	0.5	0.42	0.35

6. Electrical Equipment of Power Plants and Substations

Task 6.1

Figure 6.1 shows the one-line diagram of a network.

Reference data:

1. S_{max} = 22 MVA is the maximum power of the load connected to the 10.5 kV busbar;
2. $I_{init\ forced}$ = 32 kA is the initial (at t=0) RMS value of the forced current after a three-phase fault has occurred at point K1 (right before the reactor in fig. 1);
3. $I_{init\ forced\ desired}$ = 15 kA is a desired initial RMS value of the forced current after a three-phase fault has occurred at point K2 in fig. 1;
4. $t_{clearance}$ = 0.2 s is clearing time for a three-phase fault at point K2 (at the 10.5 kV busbar);
5. T = 0.25 s is the time constant describing the exponential decay of the natural response current after a three-phase fault at point K2.

Goal:

Choose a dual current limiting reactor for internal installation in the circuit after the step-down transformer (as shown in fig. 6.1).

Check if the selected reactor can withstand electrodynamic forces and thermal stresses.

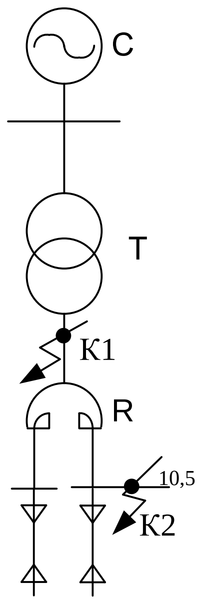


Fig. 6.1. One-line diagram of the network under study

Solution

1. We determine the maximum load current at the 10.5 kV output of power transformer (common terminal of coupled reactor):

$I_{msx} = S_{max}/\sqrt{3}U_{rated} = 22000/\sqrt{3}10.5=1211.1$ (A)

2. We determine the maximum current in one branch of coupled reactor:

$I_{max\ branch} =0.5\ I_{max} =1211.1/2 =605.6$ (A)

3. We pre-select the coupled reactor RBSG-10-2x630 (РБСГ-10-2x630) according to the rated voltage and maximum current.

$I_{rated\ \ branch} \geq I_{max\ branch}$

$630 \geq 605.6$

4. We determine the resulting impedance in case of short-circuit before the reactor (point K1):

$X_{result} = U_{mean}/\sqrt{3}I_{periodic0} = 10.5/\sqrt{3}x32 =0.19$ (Ohm)

5. We determine the desired impedance value to reduce the short-circuit current to the desired value (point K2):

$X_{result\ desired} =U_{mean}/\sqrt{3}I_{periodic0\ desired} =10.5/\sqrt{3}x15 = 0.405$ (Ohm)

6. We determine the desired impedance of reactor:

$X_{desired} = X_{result\ desired} – X_{result} = 0.405 – 0.19 = 0.215$ (Ohm)

7. We choose the reactor according to impedance: RBSG-10-2x630-0.25 (РБСГ-10-2x630-0.25),

$X_{rated\ branch} \geq X_{desired;}$ $0.25 \geq 0.215$

The parameters of the selected reactor are: $i_{dynamic}$ = 40 kA is short time electrodynamic current; $I_{thermal}$ =15.75 kA is short-time thermal current; $t_{thermal}$ = 8 s is short-time thermal current flow time.

8. We determine the initial RMS value of the short circuit periodic current after the reactor (point K2):

$I_{periodic0} = U_{mean}/\sqrt{3}(X_{result} + X_{rated\ branch}) = 10,5/\sqrt{3}(0.19 + 0.25) = 13.5$ (kA)

9. We check the selected reactor:

- for electrodynamic stability: $i_{dynamic} \geq i_{shock}$;

$i_{shock} = \sqrt{2}I_{periodic0}K_{shock} = \sqrt{2}x13.5x1.9 = 36.16$ (kA)

$40 \geq 36.16$

- for thermal stability: $I^2_{thermal}t_{thermal} \geq B_k$

$B_к = I^2_{periodic0}(t_{trip} + T_a) = 13,5^2(0.2 + 0.25) = 82.01$ (kA^{2}s)

$I^2_{thermal}t_{thermal} = 15.75^2x8 = 1984.5$ (kA^{2}s)

$1984.5 \geq 82.01$

Answer: the coupled reactor RBSG-10-2x630 (РБСГ-10-2x630) selected according to the voltage and the maximum current is suitable under the terms of the electrodynamic and thermal stability.

Task 6.2

Determine the acceptability of the daily load curve for a transformer by estimating the rate of deterioration of the winding insulation. The transformer operates in accordance with the daily load profile outlined in the figure. The transients are to be neglected (assume that the temperatures at all points inside the transformer undergo step changes to their steady-state values corresponding to a given power level). The ambient temperature is constant and equal to $+10^0$C. The power factor is constant and equal to cosφ=0.8.

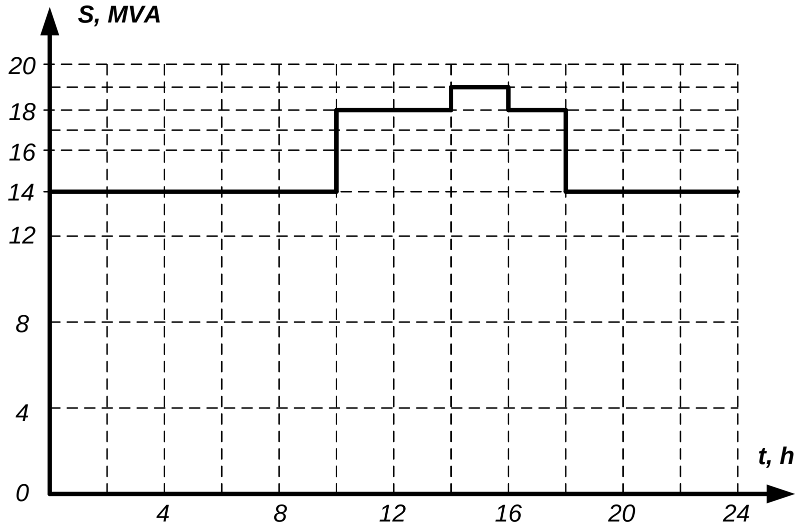


Fig. 6.2

The transformer parameters are:

1. the type is TDN-16 000/110-U1
2. the rated power is 16 MVA.
3. the rated voltage of the high voltage winding is 115 kV.
4. the rated voltage of the low voltage winding is 11 kV.
5. the no-load losses are $P_{No\text{-}load}$=18 kW.
6. the short circuit losses are P_{SC}=85 kW.
7. the short circuit voltage is U_{CS}=10.5 %.
8. the no-load current is $I_{No\text{-}load}$=0.7 %.

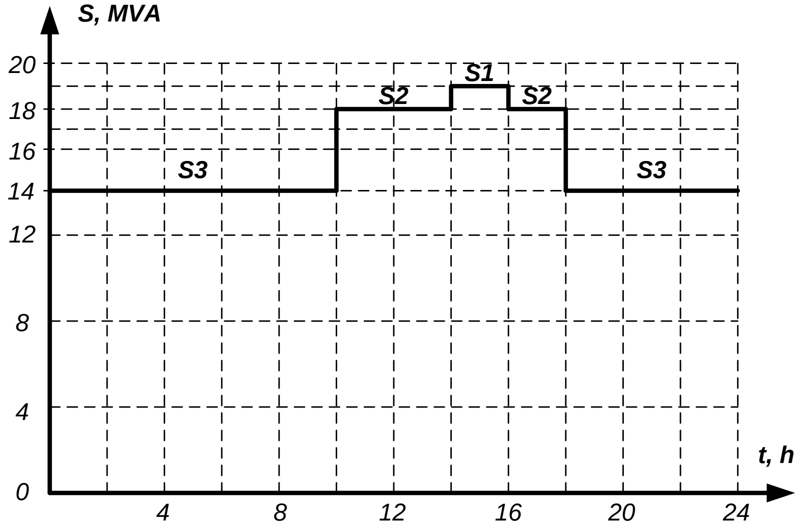
Solution

The load diagram parameters:

The load S1=19 MVA, duration t_1=2 h.

The load S2=18 MVA, duration t2=6 h.

The load S3=14 MVA, duration t3=16 h.



The capacity factors are:

$$K_1 = \frac{S_1}{S_{rated}} = 19/16 = 1.1875$$

$$K_2 = \frac{S_2}{S_{rated}} = 18/16 = 1.125$$

$$K_3 = \frac{S_3}{S_{rated}} = 14/16 = 0.875$$

The ratio of the transformer losses are:

$$d = \frac{P_{SC}}{P_{No-Load}} = \frac{85}{18} = 4.72$$

The oil temperature exceeding on the ambient temperature in three modes will be:

$$\vartheta_{O1} = \vartheta_{O.nom} \cdot \left(\frac{1 + d \cdot K_1^2}{1 + d} \right)^x = 55 \cdot \left(\frac{1 + 4.72 \cdot 1.1875^2}{1 + 4.72} \right)^{0.9} = 71.5 \ {}^\circ\text{C}.$$

$$\vartheta_{O2} = \vartheta_{O.nom} \cdot \left(\frac{1 + d \cdot K_2^2}{1 + d} \right)^x = 55 \cdot \left(\frac{1 + 4.72 \cdot 1.125^2}{1 + 4.72} \right)^{0,9} = 65.74 \ {}^\circ\text{C}.$$

$$\vartheta_{O3} = \vartheta_{O.nom} \cdot \left(\frac{1 + d \cdot K_3^2}{1 + d} \right)^x = 55 \cdot \left(\frac{1 + 4.72 \cdot 0.875^2}{1 + 4.72} \right)^{0,9} = 45.33 \ {}^\circ\text{C}.$$

The winding temperature exceeding at the hottest point on the oil temperature in three modes will be:

$$\vartheta_{HP1} = \vartheta_{HP.nom} \cdot K_1^y = 23 \cdot 1.1875^{1.6} = 30.28 \ {}^\circ\text{C}.$$

$$\vartheta_{HP2} = \vartheta_{HP.nom} \cdot K_2^y = 23 \cdot 1.125^{1,6} = 27.77 \ {}^\circ\text{C}.$$

$$\vartheta_{HP3} = \vartheta_{HP.nom} \cdot K_3^y = 23 \cdot 0.875^{1,6} = 18.56 \ {}^\circ\text{C}.$$

The absolute temperature at the hottest point is:

$\Theta_{HP1} = \Theta_{amb} + \vartheta_{O1} + \vartheta_{HP1} = 10 + 71.5 + 30.28 = 111.78$ °C.

$\Theta_{HP2} = \Theta_{amb} + \vartheta_{O2} + \vartheta_{HP2} = 10 + 65.74 + 27.77 = 103.51$ °C.

$\Theta_{HP3} = \Theta_{amb} + \vartheta_{O3} + \vartheta_{HP3} = 10 + 45.33 + 18.56 = 73.9$ °C.

The wear of turn insulation during S1, S2, S3 loads are:

$$F_1 = \frac{t1}{24} \cdot 2^{\frac{(\Theta_{HP1} - 98)}{6}} = \frac{2}{24} \cdot 2^{\frac{(111.78-98)}{6}} = 0.409$$

$$F_2 = \frac{t2}{24} \cdot 2^{\frac{(\Theta_{HP2} - 98)}{6}} = \frac{6}{24} \cdot 2^{\frac{(103.51-98)}{6}} = 0.472$$

$$F_3 = \frac{t3}{24} \cdot 2^{\frac{(\Theta_{HP3} - 98)}{6}} = \frac{16}{24} \cdot 2^{\frac{(72.9-98)}{6}} = 0.041$$

The general wear of insulation per day is:

$$F = F_1 + F_2 + F_3 = 0.409 + 0.472 + 0.041 = 0.923$$

It is less than a unit. Such load diagram is acceptable for the transformer.

Answer: such load diagram is acceptable for the transformer.

Task 6.3

Select the conductive part between the generator and the main transformer of the unit. The unit diagram is shown in fig. 6.8.

Note: 1) the unit power is 300 MW; 2) the short-circuit power of the system is 6.500 MVA; 3) the auxiliary transformer power is 25 MVA.

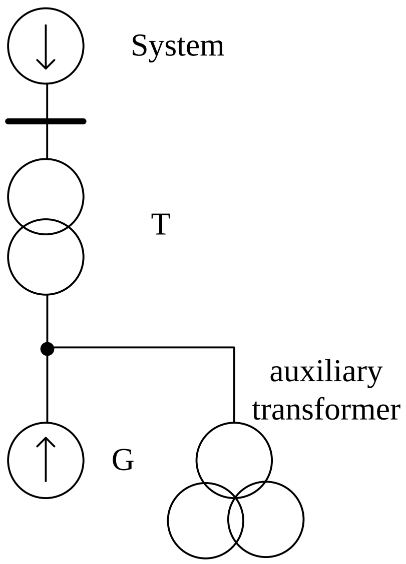


Fig. 6.8. The unit diagram

Solution

The short-circuit current from the generator is

$$I^{(3)}_{p0g} = \frac{E''_g}{X''_{d*}} I_6 = \frac{1.13}{0.2} \cdot \frac{376}{\sqrt{3} \cdot 20} = 61 \text{ kA}$$

The short-circuit current from the system is

$$I^{(3)}_{p0s} = \frac{E''_s}{X_1} I_6 = \frac{1.0}{0.44} \cdot 28.9 = 65.7 \text{ kA}$$

The impedance $X_1 = X_s + X_T = \frac{1000}{6500} + \frac{11,5}{100} \cdot \frac{100}{400} = 0.44$ p.u.

The generator rated current is 11 kA.

The shock current is: $i_{sh} = \sqrt{2} K_{sh} \cdot I_{p0s}^{(3)} = \sqrt{2} \cdot 1.9 \cdot 65.7 = 176$ kA

The heat impulse is $B_k = \left(I_{p0s}^{(3)} \right)^2 \cdot 4 = 17266$ kA^{2}c

Answer: we choose the current-conducting wire TEKNE 20-12500-400 U1 (ТЭКНЕ 20-12500-400 У1), B_k =76800 kA^{2}s.

Task 6.4

Figure 6.9 shows the power circuit of the motor M.

Reference data:

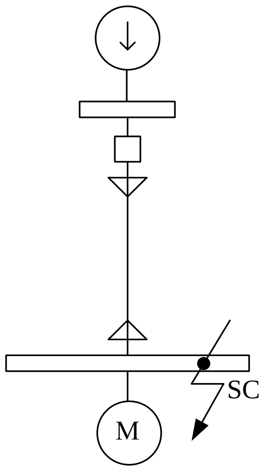


Fig. 6.9. The scheme of power plant power distribution

- The initial RMS value of the periodic component of the three-phase short-circuit current at the point is equal to $I^{(3)}_{periodic0}$ =15 kA.
- The time constant of the aperiodic component of the three-phase short-circuit current at the point T_a is 0,06 s.
- A cable with aluminum conductors with paper-oil impregnated insulation without armor with q = 95 mm^2 section is selected under the terms of the continuous mode.
- Operation time for the primary relay protection is equal to 0.1 s, for the backup protection is 0.8 s.

The circuit-breaker total break time $t_{totalBreak}$ is 0.07 s.

- The reciprocal value of the resistance temperature coefficient a is 228 °C.
- The constant characterizing the thermal properties of aluminum b is 45.25 mm^4/(kA^2 s).
- The initial temperature of the cable (pre-load) $\Theta_{initial}$ is 65°C.

Check out the pre-selected cable on thermal stability and noncombustibility conditions.

Solution

The criteria for testing cables on thermal stability and noncombustibility conditions are:

$$\Theta_{SC\ permissible} \geq \Theta_{SC}\ ,$$

where Θ_{SC} is the temperature of conductor at the moment of short circuit clearance; $\Theta_{SC\ permissible}$ is the maximum temperature under the terms of thermal stability, either noncombustibility.

1. Thermal stability.

Solution can be accomplished in two ways.

The first way

Determination of the minimum heat resistant cross section is:

$$q_{\min} = \frac{\sqrt{B_k}}{C},$$

where B_k is Joule integral , determined at operation of the main relay protection; C is the parameter, depending on the thermal properties of conductors.

For cables with paper insulation and aluminum core it is $C = 90\frac{A \cdot s^{0.5}}{mm^2}$, and $B_k = I_{p0}^2 \cdot (t_{totalBreak} + T_a)$; $B_k = 15^2 \cdot (0.1 + 0.07 + 0.06) = 51.75$ kA^{2}s.

$$q_{\min} = \frac{\sqrt{51.75 \cdot 10^6}}{90} = 80 \text{ mm}^2.$$

$q_{\min} < q$, so the cable has thermal stability.

The second way

$$\Theta_{SC} = \Theta_{initial} \cdot e^k + a \cdot (e^k - 1). \qquad k = \frac{b \cdot B_k}{q^2}.$$

B_k is determined at the operation of the main relay protection $B_k = 51.75$ kA^{2}s.

$$k = \frac{45.65 \cdot 51.75}{95^2} = 0.26. \qquad \Theta_{SC} = 65 \cdot e^{0,26} + 228 \cdot (e^{0,26} - 1) = 152.9 \ {}^\circ\text{C}.$$

200>152.9, $\Theta_{SC\ permissible} > \Theta_{SC}$ so, the cable has thermal stability.

2. Noncombustibility.

Joule integral B_k is determined at operation of the backup relay protection:

$B_k = 15^2(0.8 + 0.07 + 0.06) = 209.25$ kA^{2}s.

$$k = \frac{b \cdot B_k}{q^2} = \frac{45.65 \cdot 209.25}{95^2} = 1.06 \quad \Theta_{SC} = 65 \cdot e^{1.06} + 228 \cdot (e^{1.06} - 1) = 615.8\ {}^\circ\text{C}.$$

$\Theta_{SC} > \Theta_{SC\ permissible}$, 615.8>350, so the cable is not resistant to combustion.

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