Z. KHUDYAKOV

REPAIR OF POWER TRANS-FORMERS

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ИЗДАТЕЛЬСТВО · МИР ·

З. И. ХУДЯКОВ

РЕМОНТ ТРАНСФОРМАТОРОВ

ИЗДАТЕЛЬСТВО «ВЫСШАЯ ШКОЛА» · МОСКВА

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The Greek Alphabet

Α α Alpha	Ι ι Iota	Ρ ρ Rho
Β β Beta	Κ κ Kappa	Σ σ Sigma
Γ γ Gamma	Λ λ Lambda	Τ τ Tau
Δ δ Delta	Μ μ Mu	Υ υ Upsilon
Ε ε Epsilon	Ν ν Nu	Φ φ Phi
Ζ ζ Zeta	Ξ ξ Xi	Χ χ Chi
Η η Eta	Ο ο Omicron	Ψ ψ Psi
Θ θ ϑ Theta	Π π Pi	Ω ω Omega

The Russian Alphabet and Transliteration

А а a	К к k	Х х kh
Б б b	Л л l	Ц ц ts
В в v	М м m	Ч ч ch
Г г g	Н н n	Ш ш sh
Д д d	О о o	Щ щ shch
Е е e	П п p	ъ ″
Ё ё e	Р р r	ы y
Ж ж zh	С с s	ь ′
З з z	Т т t	Э э e
И и i	У у u	Ю ю yu
Й й y	Ф ф f	Я я ya

На английском языке

Contents

Preface

The rapid growth of the capacity of power stations and supply networks, and their integration into power systems by means of long-distance, high- and super-high-capacity transmission lines, require reliable and uninterrupted operation of every piece of electrical equipment, power transformers included.

On its way from the generating station to the consumer, electric power is transformed several times. Today, when hardly a single electrical installation can do without a power transformer, the uninterrupted operation of the transformers, whose total capacity is several times the installed generating capacity, cannot be overestimated.

Year after year, transformer-building works raise their output of increasingly perfect transformers, and the unit capacity of power transformers grows higher in line with this rise. At present, the maximum unit capacity of three-phase transformers is 630 MV A at 500 kV on the high-voltage side; that of autotransformers is to come to 1 million kV A in the near future.

Transformers are sufficiently reliable in operation, but as the pool of operating power transformers grows larger, so does the number of transformers which, for one reason or another, stand in need of repair. Old, unreliable transformers have to be repaired as well. Besides, there are cases where their characteristics can no longer meet the more stringent technical requirements of the day, hence the need for modernization.

Low- and medium-capacity transformers are usually repaired at specialized works, while high-capacity ones, directly on site. Some transformer parts are repaired at transformer-building works.

In-situ repairs require highly skilled personnel capable of organizing their workplace correctly. It is especially important that the workers should be skilled in several trades—electrician and winder, electrician and welder, etc.

For a timely and efficient repair work it is essential that the personnel have a high standard of technical knowledge. This book outlines the amount of technical knowledge necessary for electricians specializing in transformer repairs and is intended for training at vocational schools or on the job.

CHAPTER ONE

An Outline of Transformers

1.1. Application of Transformers

Electrical energy generated by fuel-fired (thermal) power stations usually located near large fuel deposits and by hydro-electric stations built in regions where water power resources are available has to be transmitted to industrial centres which may lie hundreds and thousands of kilometres away from the stations, hence the need for vast transmission lines between the generating plants and the consumers.

It is a well-known fact that when current is transmitted over a line, some of the power it carries is dissipated as heat in the line conductors. This loss grows higher as the current and the resistance of the conductors are increased. It is not economical to try to reduce the loss by solely decreasing the conductor resistance, because this would require a substantial increase in the cross-sectional area of the conductors, entailing a large consumption of costly nonferrous metals.

It is precisely to reduce the power loss and consumption of nonferrous metals that the transformer is used. The transformer, while leaving the transmitted power unchanged, decreases current by increasing voltage, and the loss which is proportional to the square of the current (I^2R loss) is thus sharply reduced. For example, a ten-fold increase in the supply voltage reduces the power loss by a factor of 100.

At the beginning of a power transmission line the voltage is raised by step-up transformers, and at the end of the line it is lowered by step-down transformers to a value convenient for the consumers (from 127 V to a few kilovolts). Electric power is distributed among the consumers (works, factories, residential areas, etc.) through transformer substations.

The prime role in the present-day power engineering is played by power transformers, i.e., transformers used to raise or lower voltages in the supply networks of power systems which serve to transmit electric power over great distances and distribute it among the consumers. Power transformers are notable for their high power capacity and operating voltage.

Since electricity has to be conveyed over thousands of kilometres — to the integrated power grid, the load centres, and directly to numerous minor consumers — it has to be transformed four or even five times, hence the need to install a large number of step-up and step-down transformers. Also,

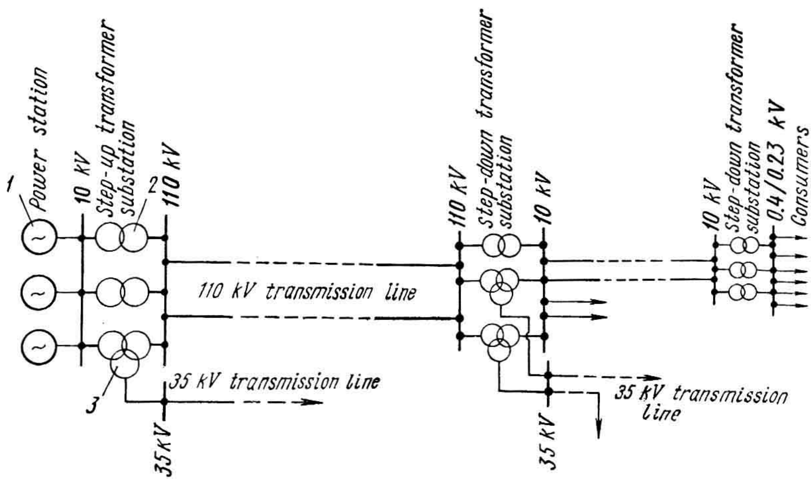

Fig. 1.1. Single-line diagram of a transmission and distribution network

1—generator; *2*—two-winding transformer; *3*—three-winding transformer

it should be noted that at each transformation stage operating at progressively lower voltage the total capacity of power transformers is usually greater than that at the preceding stage. Therefore, in any power system the installed transforming capacity is six or seven times the installed generating capacity. As an example, Fig. 1.1 shows the layout of a transmission and distribution network.

Supply networks operating at a voltage of 220 kV and higher make wide use of autotransformers. Such transformers have two or more windings conductively connected so that there is some winding portion common to both the primary and the secondary circuits.

Besides power transformers and autotransformers, there are a great variety of special transformers, including electric-furnace, rectifier, welding, regulating, testing, traction, marine, mining, and instrument transformers. Numerous types of transformers find application in communications equipment, automatic and telecontrol systems, domestic appliances, and so on. Today, there is hardly a single electrical installation operating without a transformer. The capacities and voltages of existing transformers vary over a very wide range — from a few fractions of a kilovolt-ampere to hundreds of thousands of kilovolt-amperes and from a few fractions of a volt to hundreds of kilovolts.

Autotransformers and some special transformers will be onsidered in greater detail later in the text.

1.2. Principle of Operation of the Transformer and Basic Definitions

The transformer is an electromagnetic apparatus consisting of two or more independent electric circuits (windings) linked by a common magnetic circuit (core), which, by electromagnetic induction, converts one or more alternating-current systems to one or more other alternating-current systems without the use of rotating parts, and, in particular, is intended for transforming electric power at one voltage to electric power at some other voltage. For its operation the transformer depends on the phenomenon of electromagnetic induction which is the generation of an electromotive force (emf) in a closed conductive circuit by a change in the magnetic flux linking that circuit.

Figure 1.2 shows a schematic diagram of a simple single-phase transformer. Core *3* made up of thin, insulated laminations of electrical-sheet steel carries two windings (coils) *1* and *2* which are insulated from each other. If one of the windings, say winding *1*, is supplied with alternating voltage V_1, current I_x will flow in it, producing magnetic flux Φ which varies at the same frequency as voltage V_1 does.

Since the permeability of steel is 800 to 1000 times that of air, a major part of the magnetic flux, which is called the main flux, has its path through the core. The other part of the flux (referred to as the leakage flux $\Phi_{l,1}$), much smaller in magnitude than the main one, does not link magnetically with winding *2* and has its path through air. The leakage flux takes no part in voltage (energy) transformation.

According to the law of electromagnetic induction, the periodically varying main magnetic flux Φ linking both windings *1* and *2* induces an emf in each. Let us designate

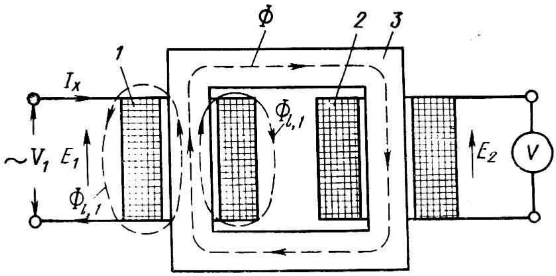

Fig. 1.2. Simple single-phase transformer

1—primary winding; *2*—secondary winding; *3*—core

these emf's as E_1 and E_2. Electromotive force E_2 can be measured with a voltmeter connected across winding *2*. If winding *2* is connected across some load, this will give rise to a flow of current through the load, and this current will cause an increase in the current flowing in winding *1*.

Thus, the apparatus considered transforms the electrical energy supplied to winding *1* first to electromagnetic energy and then to the electrical energy consumed by the load circuit connected across winding *2*.

The transformer winding to which the a.c. power being transformed is supplied is referred to as the *primary winding*, while the other, from which the transformed a.c. power is drawn, is called the *secondary winding*.

Electromotive Forces Induced in the Transformer Windings

The magnitudes of emf's E_1 and E_2 induced in the primary and secondary windings (see Fig. 1.2) are measured in volts and may be calculated by the following formulas:

$$E_1 = 4.44fn_1\Phi_m \text{ (volts)}$$

$$E_2 = 4.44fn_2\Phi_m \text{ (volts)}$$

where f = frequency of alternating current, Hz
n_1 and n_2 = number of turns in the primary and secondary windings
Φ_m = peak (maximum) value of magnetic flux, Wb

Electromotive force E_1 induced in the primary winding is practically equal to the applied voltage; the magnitude of secondary emf E_2 depends on the number of turns in the secondary winding. An increase in the number of turns on the secondary side causes an increase in the secondary emf, and vice versa. In practice, to calculate the *emf*'s induced in the transformer windings use is made of a formula in which frequency is taken at 50 Hz (mains frequency). Then

$$E = 222nA_{core}B_{core} \times 10^{-4} \text{ (volts)}$$

where n = number of winding turns
A_{core} = net cross-sectional area of the core limb, cm^2
B_{core} = magnetic induction in the core limb, T

The net cross-sectional area of the core is the area of the core steel less the lamination insulation.

The emf per turn, e_t, is given by

$$e_t = 222A_{core}B_{core} \times 10^{-4} \text{ (volts)}$$

The voltage induced per turn (e_t) is the same for both the primary and secondary windings since they are linked by one and the same flux. This is a very important transformer characteristic which is widely used in calculations. For example, if e_t (volts) and A_{core} (square centimetres) are known, it is an easy matter to calculate the magnetic induction in the core:

$$B_{core} = (e_t \times 10^4)/222A_{core} \text{ (teslas)}$$

The units of measurement here are given in accordance with the SI system (USSR Standard 9867—61). In this system the unit of magnetic flux is the weber (Wb) having the dimension of volt-second (V s), and the unit of magnetic induction, the tesla (T) with the dimension of volt-second per square metre (V s/m^2).

To convert magnetic flux in maxwells (the cgs system) to webers, one should use the following relation:

$$1 \text{ Wb} = 1 \text{ V s} = 10^8 \text{ Mx}$$

A conversion factor of 10^4 should be used to convert induction in gausses (the cgs system) to teslas:

$$1 \text{ T} = 10^4 \text{ Gs}$$

Transformation Ratio

A very important characteristic of the transformer is the transformation ratio (k) which is the ratio of the emf induced in the high-voltage (HV) winding to that induced in the low-voltage (LV) winding, so, it is always greater than unity. The transformation ratio is widely used in calculations.

Under no-load conditions, it may safely be assumed that the *emf*'s induced in the transformer windings are equal to the voltages across these windings, i.e.,

$$E_1 = V_1 \text{ and } E_2 = V_2$$

Hence, if, say, the primary winding having n_1 turns is the HV winding and the secondary with n_2 turns, the LV winding we then may write

$$k = E_1/E_2 = V_1/V_2 = n_1/n_2$$

whence

$$V_1 = kV_2 \text{ and } n_1 = kn_2$$

Thus, knowing the transformation ratio and the voltage on the secondary side of a transformer, we can easily find the voltage on the primary side, and vice versa. This equally applies to the numbers of turns in the windings.

Basic Definitions

According to their operating voltage, transformers are divided into classes. The transformer winding of a higher voltage class is referred to as the *high-voltage* (HV) *winding*, and that of a lower voltage class, as the *low-voltage* (LV) *winding*. The winding of a voltage class intermediate between those of the HV and LV windings is called the *medium-voltage* (MV) *winding* (in three-winding transformers).

A transformer whose core carries two independent windings is called the *two-winding* transformer, while that with three independent windings on its core is referred to as the *three-winding* transformer. High-capacity power transformers often have three windings — HV, MV, and LV. One of these is the *primary*, and the two others are the *secondaries*.

A transformer whose primary is the LV winding is called the *step-up* transformer, and that with the HV primary is known as the *step-down* transformer.

A transformer with a single-phase magnetic field produced in its magnetic circuit (core) is referred to as the *single-phase* transformer, while the *three-phase* transformer is the one in whose magnetic circuit a three-phase magnetic field is produced.

To improve the electrical insulation of the current-carrying components of a transformer and its cooling conditions, the transformer windings, together with the core, are placed in a tank filled with transformer oil. Such transformers are called *oil-immersed* or *oil-cooled*. Some special transformers use an incombustible synthetic liquid — askarel — instead of the oil. Transformers operating in air (not immersed in oil) are called the dry-type or air-cooled.

Each transformer has a nameplate on which the rated values defining its operating conditions are indicated.

The *rated* values, or ratings, are the numerical values of electrical quantities, such as capacity, voltages, currents, frequency, etc., assinged to the transformer by the designer to define its working in conditions specified by a pertinent standard. These values form the basis for the manufacture, testing and operating of the transformer.

The rated capacity of the transformer is usually expressed as its apparent power in kilovolt-amperes (the kV A rating). Transformers are built for certain standard rated capacities and voltages. The rated primary voltage is the one for which the primary winding of the transformer is designed. The rated secondary voltage is the voltage developing across the secondary winding when the transformer primary is supplied with the rated voltage under conditions of no load. The rated currents are determined by the corresponding rated voltages and the kV A rating of the transformer. In the USSR, the rated frequency for transformers is 50 Hz.

1.3. Power Transformer Performance

No-Load (Open-Circuit) Characteristics. No-Load Current and Losses

If rated alternating voltage V_1 is impressed on a transformer winding, say, the primary winding $A—X$ having n_1 turns (Fig. 1.3*a*) whilst the secondary winding is open-circuited, the transformer is said to be operating under conditions of no load.

Current $I_{no-load}$ flowing in the primary of the transformer on no load is known as the *no-load current*. Its magnitude is small in comparison with that of the rated primary current: 2-3.5% in low-capacity power transformers and 0.5-1.5% in high-capacity transformers of Soviet make.

The reactive component of the no-load current produces the main magnetic flux Φ in the core and a weak leakage flux $\Phi_{l,1}$ which causes an inductive reactance to come into play in the primary circuit. The resistive component of the no-load current, amounting to not more than 10% of the reactive component, has but a negligible effect on the latter and causes only a resistance voltage drop across the primary winding. Therefore, the no-load current is customarily called the *exciting current*.

The no-load transformer transfers no electrical energy since the secondary winding having n_2 turns is open-circuited. The active power consumed by the transformer is dissipated as heat in the core steel and partially in the primary winding. These power losses as a whole are referred to as the *no-load losses* of the transformer and designated as $P_{no-load}$.

The I^2R loss (copper loss) in the primary winding due to the no-load current is low because the current is small, therefore, this loss is disregarded and the active power consumed by the transformer under no-load conditions is considered to be dissipated only as losses in the core steel, i.e.,

$$P_{no-load} = P_{core}$$

The power losses in the core steel are caused by its cyclic magnetization (reversal of magnetic field sense at twice the supply frequency) and by eddy currents. The reversal of magnetization is accompanied by the generation of heat in