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LOSSES IN MEDIUM VOLTAGE CURRENT TRANSFORMERS

ZTRÁTY VE VYSOKONAPĚŤOVÝCH TRANSFORMÁTORECH PROUDU

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Popište historii a principy operace.
Proveďte teoretickou analýzu transformátoru.
Proveďte měření ztrát a jejich analýzu.
Vypočítejte ztráty daného transformátoru.

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ABSTRAKT

Tato bakalářská práce umožňuje nahlédnout do problematiky ztrát u přístrojových transformátorů proudu vysokého napětí. Přístrojové transformátory proudu představují velmi důležitou součást elektrických zařízení, slouží k transformování měřených proudů na standardní hodnoty, které měřicí a jisticí přístroje mohou zpracovat. Je důležité, aby tyto proudy byly převáděny s co nejvyšší přesností.

Teoretická část práce se zaměřuje na popis přístrojových transformátorů proudu a analýzu jednotlivých ztrát u transformátoru. Praktická část je obsažena v deváté kapitole, má za cíl ověřit teoretické poznatky práce a popisuje laboratorní měření.

KLÍČOVÁ SLOVA

přístrojový transformátor proudu; princip činnosti transformátoru; feromagnetické materiály; ztráty v transformátoru; ztráty v železe; ztráty v mědi; měření ztrát v přístrojovém transformátoru proudu

ABSTRACT

The bachelor’s thesis is intended to provide insight into the current transformer losses phenomenon. Current instrument transformers represent very important part of electrical systems, they are used to transform measured currents to standard values that measuring and protection devices can handle. It is important to transform these currents with the highest accuracy.

The theoretical part is focused on the description of the current instrument transformers and particularly on the transformer losses analysis. The practical part included in the ninth chapter describes laboratory measurement and aims to verify the theoretical knowledge.

KEYWORDS

current transformer; transformer principle of operation ; ferromagnetic materials; losses in transformer; core loss; copper loss; current transformer losses measurement

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PROHLÁŠENÍ

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V Brně dne ....

(podpis autora)

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INTRODUCTION

The only transformer having 100 % efficiency is the ideal one. The ideal transformer has the input power equal to the output power. However, since nothing is ideal in reality in the world, there is a difference between the input and output power. As in all electrical machines, the losses occur in transformer too. They are in the form of heat. Unfortunately, it is not possible to neglect them. Nevertheless, the transformer is considered as the most efficient electrical machine since it is a static device and there are no mechanical losses. In the case of current transformer, the emphasis is put on the transformation ratio, so the losses should be as low as possible. Firstly, it is necessary to acquaint with instrument transformers.

The instrument transformers represent one of the most important components of electric systems, since the reliable production operation, energy distribution and consumption are secured by them. Not only would it be virtually impossible to measure produced and supplied electric energy without them, but primarily to run electricity supply system safely. Therefore, the knowledge of instrument transformers is essential for many electrical engineers working in the field of electrical and power engineering.

The electricity supply system is characterized by a significant range of electric quantities, for example current can reach the values in units of amperes to kilo-amperes. Nevertheless, measuring, protecting and control devices are only able to work in specific range and it would be technically and economically inconvenient to adjust them. Therefore, these devices are connected indirectly through the instrument transformers that are specifically designed for these purposes.

Firstly, the instrument transformers can be divided according to the transformed quantity into: *voltage transformers* and *current transformers*. The division is due to the fact that the transformer can only transform one of the quantities (voltage or current) with convenient accuracy.

Secondly, from the function point of view and according to what device will be connected to the secondary output it is distinguished between: *measuring transformers* and *protective transformers*. However, they are often constructed to work in both ways, so they are provided with more secondary outputs.

Thirdly, if the placement of transformers is concerned, the transformers are divided into*: indoor transformers* and *outdoor transformers*. [2]

Primarily, instrument transformers are used in medium or high voltage electricity supply systems or in other electrical systems. However, they can be applied in low voltage systems or in laboratories as well. Instrument transformers are used to perform the functions mentioned below:

1) To transform the values of current and voltage to the values that are suitable for power supply of current and voltage coils of measuring and protecting devices.

2.) To insulate MV circuits (electricity supply system) from LV circuits (for example circuit of protective devices).

3.) To eliminate negative influence of strong magnetic and electric field on connected devices by receding the devices from the field influence.

4.) To determine sums and differences of voltages or currents in mutually isolated circuits for protection purposes.

5.) To centralize measuring and protective devices, for example in control center, outside a distributing point, and so to facilitate operational control of distributing point and the whole mains.

6.) To protect systems of measuring and protective devices against heating and dynamic effect of over-current during failure state by its design. [1]

The aim of the thesis is to acquaint theoretically with the current transformers so as to understand the principle of operation and the current transformer function and to describe the current transformer design and materials. With understanding of the basic transformer theory, the further aim is to theoretically analyse the losses in the transformer. In the practical part, the losses will be measured in a given transformer and their value will be determined.

1 HISTORICAL DEVELOPMENT

This chapter is written on the basis of information contained in [7, 8].

The invention of transformer represented an important part of electrical engineering since the transformer is essential for electric transmission. Transformer development started after the Industrial Revolution that brought many changes into everyday life.

The demonstration of electromagnetic induction was the first step to invent the transformer. The phenomenon of electromagnetic induction was discovered by Michael Faraday in 1831 when his experiments were carried out. Faraday found that a current of electricity flowing in a coil of wire wound around a piece of iron would convert the iron into a magnet and that, if this magnet were inserted into another coil of wire, a galvanometer connected to the terminals of the second coil would be deflected. [6] A few years later, in 1836, Rev. Nicholas Callan from Ireland invented an induction coil and was the first one who realized that if a secondary winding has more turns than a primary winding, induced voltage is larger. Pavel Yablochkov connected the induction coils to create a lighting system in 1876, and the system basically functioned as the transformer. A toroidal shaped transformer appeared in the period of 1878-83 when the Ganz Company in Budapest used it in lighting systems. Another step in the development was a device called "secondary generator" that had an open iron core, and was invented by Lucien Gaulard and John Dixon Gibbs in 1882. However, the transformer design with the open iron core was not practical due to a bad voltage regulation. Thus, Károly Zipernowsky, Ottó Bláthy and Miksa Déri who were connected with the Ganz factory, designed a transformer with a closed magnetic circuit in 1884. The Gaulard and Gibbs' patents were sold to Westinghouse. William Stanley working for Westinghouse improved the Gaulard and Gibbs' design, and this improved transformer was commercially used in the U.S.A. in 1886.

Generally, this is how the first transformer was developed, the instrument transformers were started to be manufactured around 1919 and were insulated with oil. Transformers with epoxy insulation have been produced since 1952. The innovations in materials and design have often appeared.

2 THEORETICAL ANALYSIS OF CURRENT TRANSFORMERS

The same physical laws of power transformers are applied on the current transformers. The current transformers only differ in the application in electric circuits. They are non-rotary electric machines working on the electromagnetic induction principle and transform the value of alternating current to the other selected value. Frequency remains constant. Unlike power transformers, the instrument transformers have negligible power. However, it is necessary to keep a required transformation ratio and accuracy in the certain range of transformed quantity.

2.1 Important terminology according to standard

Firstly, it is necessary to define some basic terms which are related with the current transformers. Following definitions are taken directly from the standard [15].

Instrument transformer - “a transformer intended to supply measuring instruments, meters, relays and other similar apparatus.” [15]

Current transformer - “an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections.” [15]

Primary winding - “the winding through which flows the current to be transformed.” [15]

Secondary winding - “the winding which supplies the current circuits of measuring instruments, meters, relays or similar apparatus.” [15]

Rated primary current - “the value of the primary current on which the performance of the transformer is based.” [15]

Rated secondary current - “the value of the secondary current on which the performance of the transformer is based.” [15]

Rated transformation ratio - “the ratio of the rated primary current to the rated secondary current.” [15]

Burden - “the impedance of the secondary circuit in ohms and power-factor.” [15]

Rated output - “the value of the apparent power (in voltamperes at a specified power-factor) which the transformer is intended to supply to the secondary circuit at the rated secondary current and with rated burden connected to it.” [15]

Measuring current transformer - “a current transformer intended to supply indicating instruments, integrating meters and similar apparatus.” [15]

Protective current transformer - “a current transformer intended to supply protective relays.” [15]

2.2 Principle of operation

Since the transformers are based on the electromagnetic induction, it is necessary to understand it. Generally, a time-varying magnetic field is the source of electric field and the electric field is the source of time-varying magnetic field as well. Michael Faraday formulated two laws of electromagnetic induction based on his experiments.

The first one is defined as follows: “Any change in the magnetic field of a coil of wire will cause an electromotive force to be induced in the coil. This electromotive force induced is called induced electromotive force and if the conductor circuit is closed, the current will also circulate through the circuit and this current is called induced current.” [9] Faraday also described how to change the magnetic field:

“- By moving a magnet towards or away from the coil

- By moving the coil into or out of the magnetic field.

- By changing the area of a coil placed in the magnetic field

- By rotating the coil relative to the magnet.” [9]

The second law is formulated as follows: “The magnitude of electromotive force induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of number of turns in the coil and flux associated with the coil.” [9] Thus, the electromotive force can be expressed mathematically as

$$\varepsilon = -N\frac{d\Phi}{dt}. \tag{1}$$

It is obvious from Faraday's Law that the electromotive force is induced when the magnetic flux changes in time.

Lenz's law is indicated by the negative sign in (1) and it is defined as: “When an emf is generated by a change in magnetic flux according to Faraday’s Law, the polarity of the induced emf is such, that it produces an current that’s magnetic field opposes the change which produces it.” [3]

Thus, the transformer function can be characterized in general as follows: If a primary winding is connected to an AC voltage source V_1, the magnetic flux Φ in a transformer core is caused by magnetizing current I_1 that flows through the primary winding. The magnetic flux will have the same frequency as the voltage V_1 and will have effect on a secondary winding. The electromotive force will be induced in the secondary winding because of the change of magnetic flux in time. The electromotive force corresponds to Lenz's law. The current excited by the electromotive force in the secondary winding will act against the original magnetic flux.

In a real transformer, the finite magnetic permeance of magnetic circuit is applied. The magnetic flux is not only in the magnetic core but the part of magnetic flux is outside of magnetic core in an air gap. This flux is called leakage flux and results in leakage inductance. Thus, all the flux does not pass through the secondary turns.

2.3 Basic theory of current transformer

The current transformer connection in a circuit is depicted in the Figure 1. The current transformers are connected in the circuit in the same way as an ammeter in series. This is considered to be the main difference from the power and voltage transformers that are connected in parallel. The primary winding is connected in series with a circuit, the current I_1 flows through the primary winding and is transformed into the secondary winding where individual devices are connected in series. It is obvious from the Figure 1 that the current I_1 is determined by impedance Z. On the contrary, the current I_2 passes through the secondary winding and can be calculated from the rated transformation ratio. The number of turns of primary winding N_1 and the number of turns of secondary winding N_2 are determined by the ratio of primary current I_{1n} to secondary current I_{2n}.

$$k_n = \frac{I_{1n}}{I_{2n}} = \frac{N_2}{N_1} \tag{2}$$

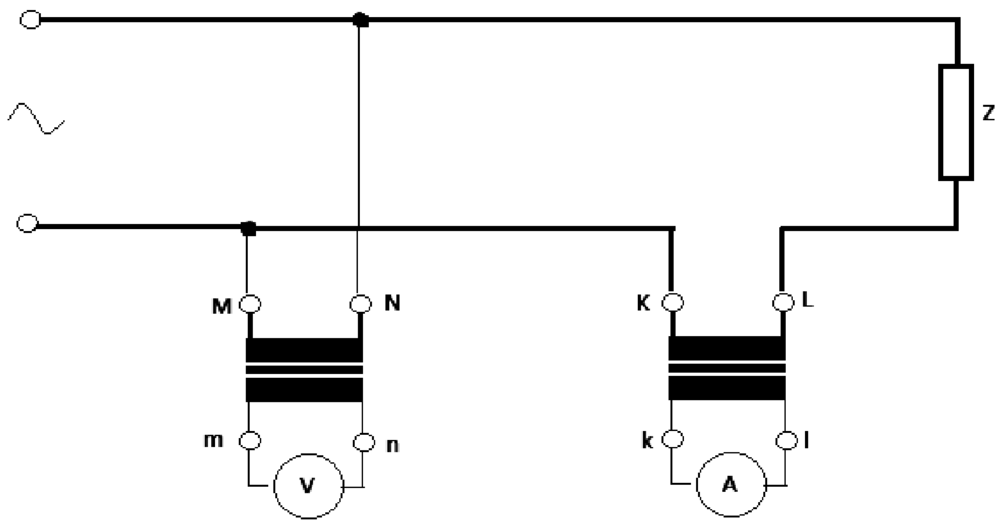

Figure 1: Current and voltage transformer connection into a circuit [5]

However, voltage across both windings is expressed as the product of current and impedance.

The measuring, protecting and control devices are supplied by the current transformers. These devices connected to secondary terminals comprise an outer electric circuit which is called a burden. The burden is determined as impedance of connected devices and cable entries connected from the transformer to the devices which is mathematically expressed as [1]

$$Z = \sqrt{R^2 + X^2} \tag{3}$$

where R is resistance, and X is reactance.

The transformer load can be calculated using the burden

$$P = V_2 \cdot I_2 = Z \cdot I_2^2 \tag{4}$$

where V_2 is secondary voltage, and I_2 is secondary current.

If the burden is equal to $Z = 0$, the secondary terminals k, l are short-circuited. If the burden increases, the voltage $V_2 = Z \cdot I_2$ and so voltage V_{20} and the V_1 increase over limits, for example if the secondary winding becomes disconnected, a failure state will arise. In this case, the whole primary current becomes the magnetizing current, and the magnetic circuit will be saturated quickly. [1] The voltage across disconnected secondary winding is very dangerous for the transformer and its operation, because it can reach the values of tens of kilo-volts.

Generally, there are two working areas in which the current transformer can be. The first one is called an operational area in which the transformer works during a normal operation in the mains. The second one comes when an overload and failure state occurs in the mains and then the working area is called an overload area. There are different requirements for the measuring and protecting transformers in the overload area. [2]

Owing to the assumption that a ferromagnetic material is saturated slightly which is ensured by the mutual voltage compensation of input and output winding at a state close to a short-circuit operation, the output circuit cannot be disconnected, since the voltage across input winding would oversaturate the magnetic circuit. Therefore, the high voltage would occur, for which insulation is not dimensioned, and the transformer would be destroyed. [11]

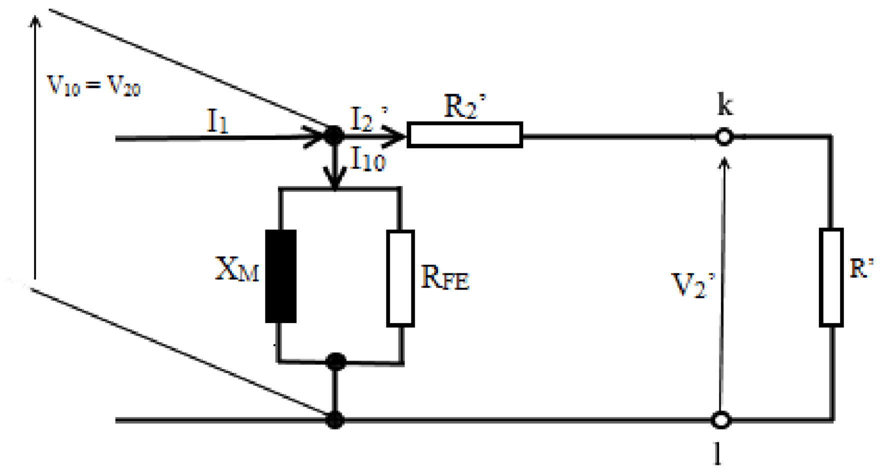

Figure 2: Equivalent circuit diagram of current transformer [5]

In the Figure 2, the current transformer is depicted in its equivalent circuit diagram. It is assumed that the components X_m and R_{FE} are linear. If the secondary winding is spread over a toroid core, it is assumed that there is no leakage reactance. Moreover, to determine the quantities easily, there are another assumptions introduced: the load connected to the secondary winding is active and the number of primary and secondary turns is equal to $N_1 = N_2$. The voltage across the secondary winding V_2 is determined as

$$V_2 = I_2 \cdot R \tag{5}$$

where R is the load connected to the secondary winding.

The induced voltage V_{20} is calculated as

$$V_{20} = I_2(R + R_2) \tag{6}$$

where R_2 is the load of secondary winding.

Further, the induced voltage can be expressed as

$$V_{20} = 4{,}44 \cdot f \cdot \Phi \cdot N_2 \tag{7}$$

where f is frequency, Φ is magnetic flux, and N_2 is the number of secondary winding.

The secondary current I_2 can be calculated using the transformation ratio (1) as

$$I_2 = \left(\frac{N_1}{N_2}\right) I_1 \tag{8}$$

where I_1 is primary current, and N_1 is the number of primary turns.

Magnetic voltage V_m required to the magnetic flux Φ passes through the magnetic circuit is

$$V_m = N_1 \cdot I_{10} = H \cdot l_m \tag{9}$$

where I_{10} is exciting current, H is magnetic field strength, and l_m is median magnetic length.

2.4 Conversion of output quantities to the number of turns of primary winding

In the Figure 3, the real current transformer is depicted where the leakage reactance is assumed compared to the Figure 2.

Assuming that the losses are neglected, the input power is equal to the output power

$$P_1 = P_2, \tag{10}$$

$$V_1 \cdot I_1 = V_2 \cdot I_2. \tag{11}$$

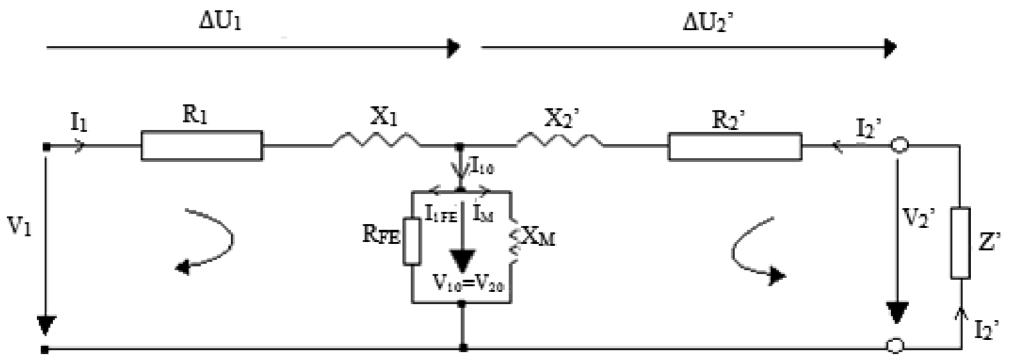

Figure 3: Equivalent circuit diagram of real current transformer [2]

The transformation ratio is expressed as

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}. \tag{12}$$

The number of volts per turn has to remain the same during the transformation, the ratio of original voltage V_2 to the original number of turns N_2 is equal to the ratio of referred voltage V_2' to the new number of turns N_1

$$\frac{V_2}{N_2} = \frac{V_2\prime}{N_1}. \tag{13}$$

Using the formulae above, the output voltage V_2' converted to the number of turns of primary winding is calculated as

$$V_2' = V_2 \frac{N_1}{N_2}. \tag{14}$$

The input voltage V_1' converted to the number of turns of secondary winding

$$V_1' = V_1 \frac{N_2}{N_1}. \tag{15}$$

Further, it is assumed that powers are equal for the calculation of currents

$$V_2 \cdot I_2 = V_2' \cdot I_2'. \tag{16}$$

The current I_2 passing through the secondary winding with the number of turns N_2 is equal to referred current I_2' passing through the primary winding with the number of turns N_1

$$I_2 \cdot N_2 = I_2' \cdot N_1. \tag{17}$$

The secondary current I_2' converted to the number of turns of primary winding is then calculated as

$$I_2' = I_2 \frac{U_2}{U_2{}'}, \tag{18}$$

$$I_2' = I_2 \frac{N_2}{N_1}. \tag{19}$$

Thus, the current I_1' is computed as

$$I_1' = I_1 \frac{N_1}{N_2}. \tag{20}$$

Using Ohm's law, the resistance R_2' of secondary winding converted to the number of turns of primary winding is calculated as

$$R_2' = \frac{U_2{}'}{I_2{}'} = V_2' = \frac{V_2 \frac{N_1}{N_2}}{I_2 \frac{N_2}{N_1}} = R_2 \left(\frac{N_1}{N_2}\right)^2. \tag{21}$$

Similarly, the resistance of primary winding R_1' converted to the number of turns of secondary winding is expressed as

$$R_1' = R_1 \left(\frac{N_2}{N_1}\right)^2. \tag{22}$$

In the same way, the impedances and reactances could be calculated.

The induced voltage is determined by equality

$$\hat{V}_{10} = \hat{V}_{20}. \tag{23}$$

If the first node is assumed, the equation is according to Kirchhoff's current law expressed as

$$-\hat{I}_1 - \hat{I}_2{}' + \hat{I}_{10} = 0. \tag{24}$$

Modifying the equation above (24)

$$\hat{I}_{10} = \hat{I}_1 + \hat{I}_2{}', \tag{25}$$

$$\hat{I}_1 = \hat{I}_{10} - \hat{I}_2{}'. \tag{26}$$

Similarly, the voltage V_1 and V_2 can be determined using Kirchhoff's voltage law

$$\hat{V}_1 = R_1\hat{I}_1 + jX_1\hat{I}_1 + \hat{V}_{10}, \tag{27}$$

$$\hat{V}_2{}' = R_2{}'\hat{I}_2{}' + jX_2{}'\hat{I}_2{}' + \hat{V}_{20}. \tag{28}$$

The equations (27) and (28) can be converted to determine the voltage V_{10} and V_{20}

$$\hat{V}_{10} = \hat{V}_1 - R_1\hat{I}_1 - jX_1\hat{I}_1, \tag{29}$$

$$\hat{V}_{20} = \hat{V}_2{}' - R_2{}'\hat{I}_2{}' - jX_2{}'\hat{I}_2{}'. \tag{30}$$

Modifying the both equations (27 and 28), the voltage V_1 is expressed

$$\hat{V}_1 = \hat{V}_2{}' + \hat{I}_{10}(R_1 + jX_1) + \left(-\hat{I}_2{}'\right)(R_1 + R_2{}' + jX_1 + jX_2{}'). \tag{31}$$

3 FERROMAGNETIC MATERIALS

This chapter is written on the basis of information contained in [10, 12, 13].

Ferromagnetic materials are the most important materials in the field of electrical engineering. They are characterized by high permeance enabling the high magnetic flux Φ to be reached. Relative permeability is not constant, but is dependent on magnetic field strength H. The relationship between magnetic flux density B and the magnetic field strength H is not linear, so it is not possible to express it in a mathematical way and it has to be determined for every material by a measurement.

The theory of ferromagnetic materials was published by a French physicist Pierre-Ernest Weiss in 1906. The theory is based on the existence of molecular field inside the ferromagnetic materials. The molecular field aligns individual magnetic moments with one another, i.e. it produces saturation magnetization below the Curie temperature. The saturation magnetization arises without an external impulse and is called spontaneous magnetization.

Every ferromagnetic material is divided into small regions that are called magnetic domains. The molecular field causes that the magnetic domains are magnetized individually and spontaneously until the saturation during which the magnetic moments are organized in parallel in one direction.

If there is no external field, the magnetic moment of domain is larger than the magnetic moment of atom. The magnetic moments are spread randomly and cancel each other. The material will act as non-magnetic which is depicted in the Fig. 4. When the external magnetic field is present, the magnetic moments of domains are gradually oriented in the direction of field which can be seen in the Fig. 5.

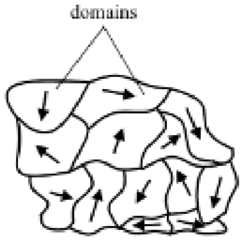

Figure 4: Domain structure - without the magnetic field [10]

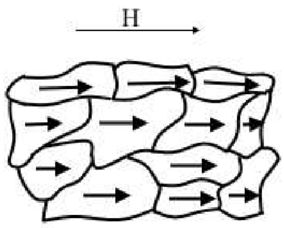

Figure 5: Domain structure - in the magnetic field [10]

3.1 Initial magnetization curve

The dependence of magnetic flux density *B* and magnetic field strength *H* is expressed by a magnetization curve that is nonlinear. The magnetization curve is often called as the initial magnetization curve, because it is valid solely for the first material magnetization. The typical shape is depicted in the Fig. 6 where three regions can be described.

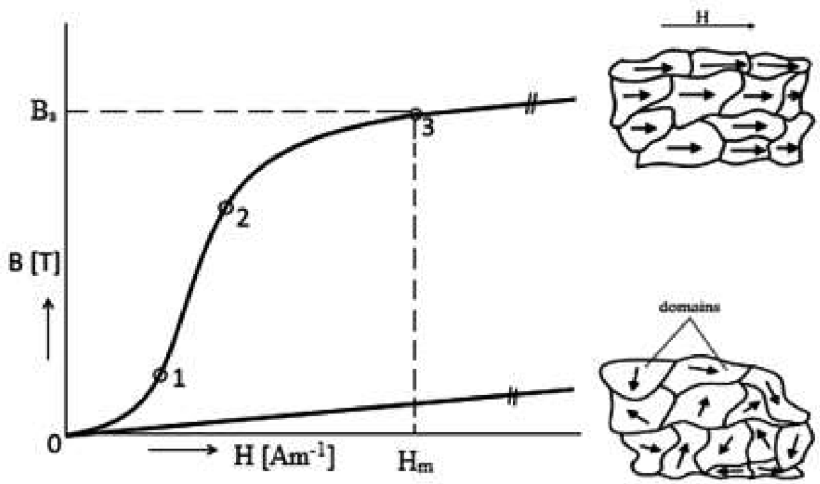

Figure 6: Initial magnetization curve

3.1.1 Region 0 – 1

The magnetic flux density *B* increases slowly with the small values of magnetic field strength *H*. The relative permeability μ_r increases rapidly from the initial value.

3.1.2 Region 1 – 2

The region is highly used in practice, it is nearly linear. The magnetic flux density *B* and the relative permeability μ_r increase more rapidly, because more domains are oriented in the direction of field.

3.1.3 Region behind the point 2

The magnetic flux density *B* increment decreases considering dependence on the magnetic field strength *H*. The ferromagnetic material is saturated when $H > H_m$ (behind the point 3) and the most of material is magnetized.

3.2 Hysteresis loop

The hysteresis loop, depicted in the Fig. 7, is a magnetization curve expressing the dependence $B = f(H)$ during the slow, fluent change of magnetic field strength *H* from $+H_m$ to $-H_m$. The name of loop comes from the meaning of hysteresis (hysteresis – retardation) and indicates that the magnetic flux density *B* is not only dependent on the magnetic field strength *H* representing current inputs, but is dependent on past inputs (the preceding material state) as well.

3.2.1 Hysteresis loop description

The hysteresis loop is obtained if one "magnetization cycle" is performed.

Firstly, assuming an unmagnetized material, the magnetic flux density *B* and magnetic field strength *H* are zero (the point zero in the Fig. 7). The magnetic field strength *H* is increased fluently from the zero by increasing magnetization current, thus the magnetic flux density *B* increases to the point 1 (corresponding to the saturation) as well according to the magnetization curve. Now if the current (at the point 1) is reduced, the magnetic field strength *H* decreases from H_{max} to zero. Although exciting current is equal to zero, the magnetic flux density *B* has magnitude equal to a distance 0 - 2. This magnetic flux density *B* remaining during $H = 0$ is called remanent flux density B_r. If the remanent flux density B_r should be cancelled, the orientation of exciting current has to be changed to change the magnetic field strength *H*. The magnetic field strength *H* needed to cancel the remanent flux density B_r is called coercive field strength H_c corresponding to a distance 0 - 3. If the exciting current was disconnected after reached coercive field strength H_c, the magnetic flux density B would increase to the value given by the point 7.

Secondly, if the magnetic field strength H is increased again, the saturation is reached at the point 4, but in the opposite direction. By decreasing the exciting current and so magnetic field strength H again, remanent flux density B_r is present at the point 5 with the same value as previous one, but in a reverse direction. To cancel the remanence, the orientation of current has to be changed and the coercive field strength H_c has to be reached at the point 6, but with the opposite sign as in the case of remanence.

3.2.2 Hysteresis loop area

The remanent flux density B_r is dependent on the magnitude of coercive field strength H_c. The ferromagnetic materials can be divided into *magnetically hard materials* and *magnetically soft materials*.

The magnetically hard materials are characterized with the high remanent flux density B_r as well as with the high coercive field strength H_c. The hysteresis loop is wide and has a large area. Moreover, they are used in permanent magnets.

Materials with the small coercive field strength H_c and the narrow hysteresis loop are the magnetically soft materials. They can be easily magnetized and have high initial and maximum permeability. The alloys of iron with silicon and iron with nickel are classified into the magnetic soft materials.

The hysteresis loop area is proportional to energy that has to be supplied during the one "magnetization cycle". The supplied energy is converted into heat and the losses, which are caused by the conversion, are called *hysteresis losses*.

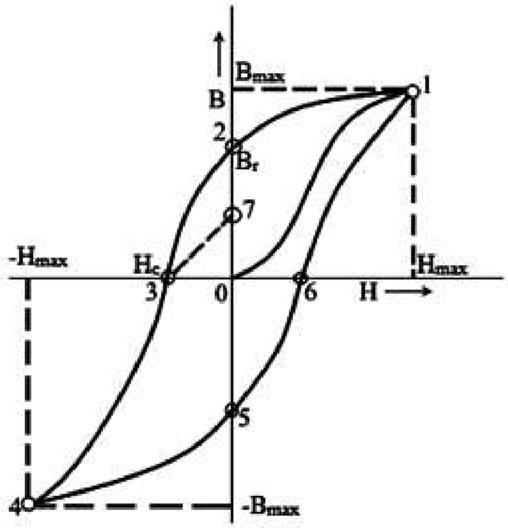

Figure 7: Hysteresis loop

4 LOSSES IN CURRENT TRANSFOMES

The information used in the chapter are taken over from the sources [12, 13, 14].

Generally, loss is the difference between the input power and the output power. Losses are present in every electrical machine, they arise from the supplied energy changed in the heat that is no longer used. Since the transformers are static devices, mechanical losses do not have to be considered, but electrical losses are important in the transformers. Although the losses arising during the transformer operation cannot be entirely removed, the aim is to suppress them as much as possible. The losses are always source of heat that is necessary to conduct away in order not to influence the winding insulation and the whole transformer. The losses in the transformer can be divided into two categories: *winding losses* and *core losses*.

4.1 Core losses/Iron losses

Core losses or iron losses represent losses in the magnetic circuit that is made from the ferromagnetic material and through which the time-varying magnetic flux passes. The hysteresis and eddy currents cause the heat losses, therefore the iron losses are comprised of *hysteresis losses* and *eddy current losses*. Both losses are not dependent on the load, but on the material magnetic properties.

4.1.1 Hysteresis losses

The hysteresis losses can be considered as a scale of work that is consumed on alternating magnetization. When the magnetic field is reversed, there is some amount of lost energy for every cycle. As it was already mentioned in 3.2.2 chapter, the lost energy is proportional to the hysteresis loop area. It is necessary to do work that is given by a horizontally dashed area (Fig. 8 a.) during the magnetization from H = 0 to the saturation. When the magnetic field strength H is reduced to zero, energy density is reduced too, the energy is gained in the field given by a vertically dashed area (Fig. 8 b.) and is passed on to the source. The Fig. 8 c. and Fig. 8 d. show values during the reversed magnetization.

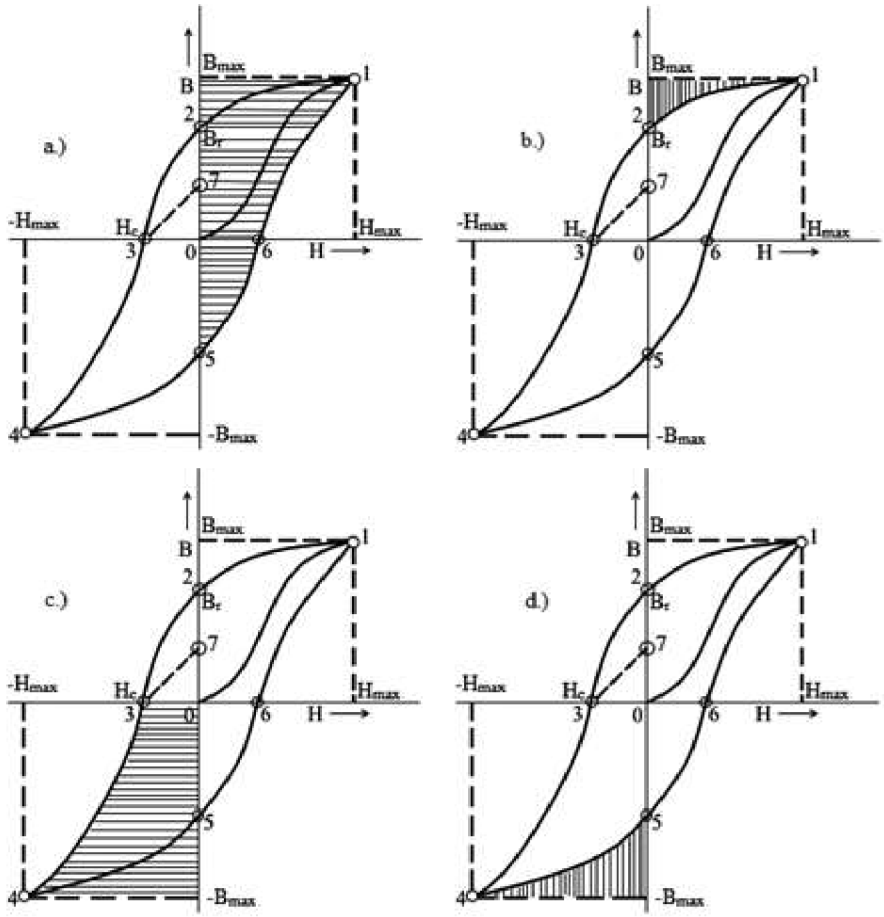

Figure 8: To determine the work during magnetization [13]

The smaller is the hysteresis loop area (the smaller is coercive field strength H_c), the smaller the hysteresis losses (changed into idle heat). During the constant alternating magnetization the lost energy is proportional to the area of one hysteresis loop and the number of loops created per second. To determine the hysteresis loss the following formula is used

$$P_h = K_h \cdot f \cdot B_m^n \qquad (32)$$

where P_h is hysteresis loss, K_h is hysteresis constant, f is frequency, B_m is maximum amplitude of magnetic flux density, and n is Steinmetz constant generally 1, 6 or 2 for magnetic flux density above 1, 2 T.

Hysteresis constant K_h holds for certain frequency, the values for frequency 50 Hz and magnetic circuit mass 1 kg are written in the Table 1.

Table 1: The values of constant Kh [14]

K_h	Material	Figure of loss (W/kg)
2,2	Lamination with THKNS 0,5 mm	3,6 W/kg
1,5	Lamination with THKNS 0,5 mm	2,6 W/kg
1,2	Transformer sheet with THKNS 0,35 mm	1,25 W/kg

4.2 Eddy current losses

The eddy currents arise during the ferromagnetic material magnetization by the time-varying alternating magnetic flux Φ. The magnetic field strength H and magnetic flux density B are time-varying too. The time-varying magnetic flux Φ creates an electrical field whose lines of force produce close tracks around the magnetic flux Φ and they are perpendicular to the direction of magnetic flux density B. Since the environment is electrically conductive, there could be current.

According to Lenz's law, the induced currents oppose the change which produced it, therefore induced currents weaken the exciting alternating magnetic flux. The largest weakening is obtained in the middle of cross-section, since it is surrounded by all the induced currents. The induced currents are called the eddy currents. The reduction of the whole magnetic flux and of the magnetic flux density in the middle of cross-section has an impact on the relative permeability decrease in ferromagnetic material. Generally, owing to the current passes through a conductor, the heat losses arise. Thus when eddy currents pass through, the losses are produced as well. The part of energy that is supplied for the magnetization is transformed to the heat (Joule heat). The eddy current losses are significantly dependent on frequency, they are expressed mathematically as

$$P_e = K_e \cdot f^2 \cdot B_m^2 \qquad (33)$$

where P_e is eddy current loss, K_e is eddy current loss constant, f is frequency, and B_m is maximum amplitude of magnetic flux density.

The values of eddy current loss constant K_e are mentioned below in the Table 2.

Table 2: The values of K_e

K_e	Material	Figure of loss (W/kg)
1,4	Lamination with THKNS 0,5 mm	3,6 W/kg
1,1	Lamination with THKNS 0,5 mm	2,6 W/kg
00,1	Transformer sheet with THKNS 0,35 mm	1,25 W/kg

Generally, the eddy current losses can be reduced by:

1.) Using mutually insulated laminations that leads to core distribution

2.) Using a material with high resistance

3.) Reducing induced voltage

The magnetic circuit is constructed from thick laminations. It is not possible to reduce the losses by increasing resistance (by increasing silicon) from the practical point of view, because the laminations will be too fragile. Thus, oriented laminations are used, the laminations are cold-rolled in the direction where the magnetic flux passes.

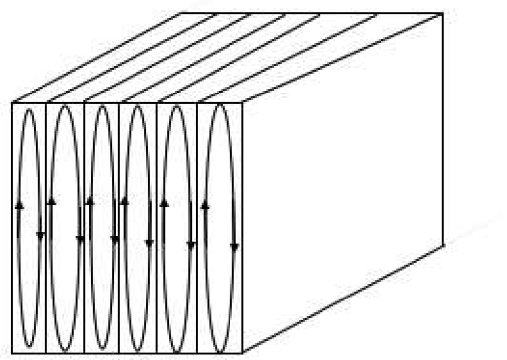

Figure 9: Eddy current losses in magnetic circuit made of laminations [14]

4.3 Winding losses/Copper losses

The winding losses or copper losses arise in the primary and secondary winding. They vary with the load, so they increase as the load increases. They are given by the individual wire resistance of winding. The magnitude of winding resistance is not only dependent on the winding material, but also skin effect and proximity effect represent an important part, since the transformers work with alternating current.

The current is not uniformly distributed along a wire cross-section because it flows with higher density through the surface of wire (through the skin of wire) than in the centre of wire. The reduction of conductivity and the increase of winding resistance will appear. This described phenomenon is called the skin-effect. Moreover, if there are other adjacent conductors where the current passes through, they influence each other and then the proximity effect arises. The skin effect and proximity effect cause the loss to increase.

Copper loss is calculated simply as

$$P_c = R \cdot I^2 \tag{34}$$

where P_c is copper loss, R is winding resistance, and I is current.

5 TEMPERATURE RISE

The chapter is written on the basis of information contained in [1, 15].

Active losses in the winding, magnetic circuit, and dielectric are presented on the outside in the form of heat and they cause the temperature rise of mentioned transformer parts or adjacent parts. A steady state in which the heat resulting from the effect of whole losses in transformer is conducted into its surroundings, occurs at steady temperature rise. The permissible value of steady temperature rise is given by permissible, permanent temperature of insulation that is adjacent to the heat source and the temperature of surroundings.

Moreover, insulation materials are classified into classes Y, A, E, B, F, and H according to thermal stability. There is maximum temperature rise given for each class which can be seen in the Table 3.

Table 3: Limits of temperature rise of the windings [15]

Class of insulation (in accordance with IEC 60085)	Maximum temperature rise K
All classes immersed in oil	60
All classes immersed in oil and hermetically sealed	65
All classes immersed in bituminous compound	50
Classes not immersed in oil or bituminous compound:	
Y	45
A	60
E	75
B	85
F	110
H	135

5.1 Temperature rise of winding

The temperature rise of winding is given solely by the current and is not dependent on the magnitude of burden. Owing to small current density, the steady temperature rise is often small, but it is high in the case of the lowest transformer short-circuited classes where higher current density can be chosen. The temperature rise of primary winding should be checked in the case of medium voltage current transformers with epoxy insulation, because the significant temperature drop could occur in an insulation barrier. Higher temperature rise occurs during the overcurrent in the mains, and has to last for a short time.

Owing to the temperature rise of winding, the mechanical and electrical properties are worsening with the time. The increased temperature rise, for example during short circuits in the mains, speeds up the ageing process, and naturally, the process is faster if the short circuits are more frequent. This fact has to be taken into account in the case of mains where the short circuits often occur.

5.2 Temperature rise of ferromagnetic material

The temperature rise of magnetic circuit is dependent on the burden and load, because the magnetic flux density, on which the core losses are dependent, is proportional to the load. When the burden is increased at the given current, the magnetic flux density and as well as the core losses increase and they are highest if the secondary circuit is disconnected.

5.3 Temperature rise of constructional parts

In the current transformer with the high primary current, the eddy currents can be induced in close conductive parts due to the magnetic field of primary winding and terminals, and cause the temperature rise in these parts. The magnitude of temperature rise is dependent on many factors, for example: on the magnetic field strength, magnetic field orientation, electric conductance of part that is affected by the magnetic field, part dimensions, and etc. It is not possible to derive the equations to compute this temperature rise, thus it has to be examined on an appropriate prototype.

5.4 Temperature rise of dielectric

If the epoxy resin is the dielectric, the temperature change causes mechanical stress created by various thermal expansions of dielectric and materials casted in the dielectric. The mechanical stress can lead to the mechanical damage of insulation body. It is important to assume not only the losses causing the temperature rise and usually do not exist in the epoxy resin, but in the materials casted in the epoxy resin, but to assume a temperature drop due to a low temperature.

6 CURRENT TRANSFOMER MATERIALS

The current transformer design is based on the transformer operation principles and the properties of used magnetic materials. The selected magnetic material influences achieved properties as well as production technology.

6.1 Magnetic circuit

The soft ferromagnetic alloys containing a large amount of nickel are selected as the magnetic circuit material. The magnetic properties of alloy are changed according to ratio of nickel and iron which can be seen in the Figures 10, 11, 12. The Fig. 10 shows that an alloy with 27 % nickel is not magnetic. It obvious from the Fig. 11 that initial permeability is dependent on the ratio of alloy elements as well. Resistivity shown in the Fig. 12 is highest at 30 - 35 % of nickel and is important in the case of eddy current losses. [1]

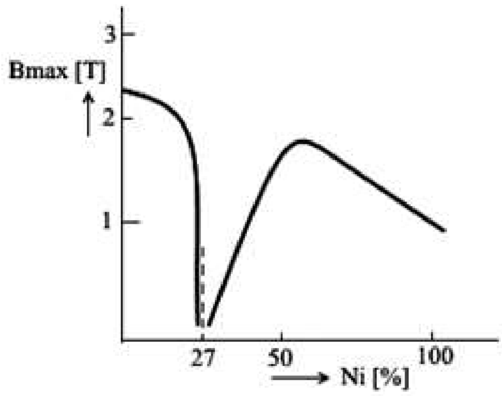

Figure 10: Ferromagnetic alloys properties according to materials used a.) Maximum saturation [1]

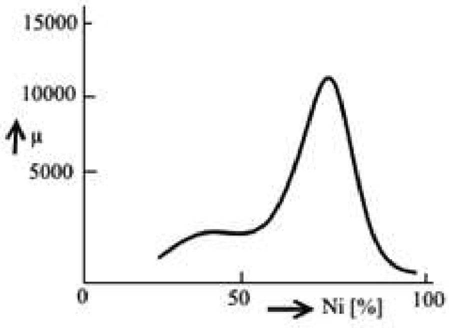

Figure 11: Ferromagnetic alloys properties according to materials used b.) Initial permeability [1]

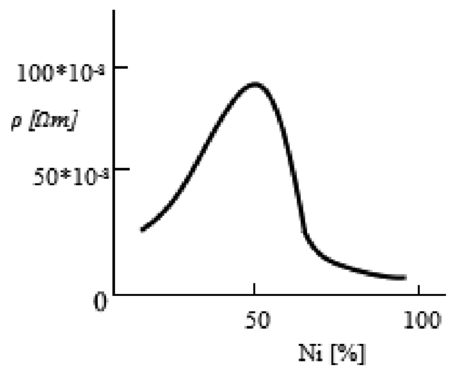

Figure 12: Ferromagnetic alloys properties according to materials used c.) Resistivity [1]

The soft ferromagnetic alloys containing more than 76 % of nickel are used as the magnetic circuit material in the current transformers. The initial and maximum permeability is high in the case of these alloys, but the saturation comes around 0, 6 – 1, 1 T. Some per cent of chromium and molybdenum is added in order to reduce the eddy current losses and to improve the magnetic properties. [1]

Permalloy (Py) which belongs to the group of soft ferromagnetic alloys is often used as the magnetic core material. It is the alloy composed of nickel and iron. It is distinguished between permalloy with contain max. 50 % of nickel and permalloy with content over 50% of nickel and the rest is iron. The Permalloy is characterized by the high maximum and initial permeability and is considered to be one of highest-quality soft magnetic materials. The initial permeability is around 10^4 and the maximum permeability around 10^5. Saturation induction is relatively small, usually around 0, 6 to 1, 2 T.

Moreover, the magnetic circuits need to be encased due to the influences of epoxy insulation.

6.2 Insulation

The insulation quality is very important in the medium – voltage current transformers 1 - 35 kV in comparison with low-voltage current transformers.

The insulation can be divided into inner and outer insulation. The outer insulation is influenced by outer effects, for example, rain, dust, and humidity. The inner insulation includes the inner winding insulation, for instance, wire insulation, coil insulation, and winding insulation (the primary winding against the secondary winding). The significant part of inner insulation is called the insulation barrier which divides primary circuit from the secondary one. [2]

Solid insulating materials connect and insulate individual parts against voltage. The solid insulating material is for example the electrical insulation paper. Cellulose is often used to insulate the winding between individual layers.

Porcelain is another insulator and is classified into ceramic insulators. Transformer shells, bushings, covers, and terminal plates are made from the porcelain.

Epoxy resin is mainly used at medium voltage instrument transformers production. The whole transformer or solely some parts (usually winding) are encased in the epoxy resin. The epoxy resin is characterized by excellent mechanical and electrical properties and it can function as the insulator and constructional material. The epoxy resin cast instrument transformers are small, less material is used and it is relatively simple to manufacture them. It is possible to adjust the transformer proportions for convenient installation and to install them in any position without atmospheric influences. The moisture absorption of epoxy resin is minimal and the transformers can be used in tropical environment. [1]

There are three main constructional ways in which the transformers can be designed:

1.) The primary winding is casted-in the resin, the secondary winding and magnetic circuit are not casted or the other way around
2.) The primary and secondary winding is casted-in, the magnetic circuit is not casted-in
3.) All function parts are casted-in

The transformer production is not too complicated with respect to the casting technology according to the first point as in the case of second and third point. When the insulation barrier is damaged, it is possible to remove the parts which were not casted-in and use them again. However, the first technology disadvantage lies in the fact that the parts which are not casted-in have to be protected against the environment and the dimensions do not differ from the transformers with porcelain insulation.

In the third case, the all functional parts are casted-in, so they are protected against the environment influence. The dimensions are smaller than in the first and second case and the insulation levels are increased by one level up to two levels. The higher requirements are placed on the casting technology. [1]

6.3 Winding

The winding is usually made from copper. Enamel, cotton, paper, or the combinations of them are used to insulate the winding. The primary winding is usually made from copper strips or wires.

7 CURRENT TRANSFORMER DESIGN

Sources [1, 2, 15] were used to write the chapter.

Current transformers can have various designs given by some aspects, for example, by rated values, construction, used materials, the operational environment, and the installation way.

7.1 Rated values

According to IEC 60044-1 [15], the standard values of rated primary currents are: <u>10</u> – 12, 5 – <u>15</u> – <u>20</u> – 25 – <u>30</u> – 40 – <u>50</u> – 60 – <u>75</u> A, and their decimal multiples or fractions. The underlined values are preferred in practice. [15]

The standard values of rated secondary currents are 1 A, 2 A and 5 A. The preferred value is 5 A. The secondary current 1 A is used in transformers with small output and if a distance between transformer and measuring device is long. [15]

The standard values of rated output up to 30 VA are: 2, 5 – 5, 0 – 10 – 15 and 30 VA. [15]

7.2 Current transformer types

The current transformers can be divided according to the primary winding into single-turn current transformers and wound current transformers.

The wire of primary winding passes through the magnetic circuit solely once in single-turn current transformers. However, wound current transformers are equipped with several primary turns passing through the magnetic circuit.

The basic shapes are described below:

7.2.1 Single-turn current transformer

Supporting type

Primary terminals are situated at the top of insulating body. The insulating body is anchored to an earthed vessel. The transformer is depicted in the Fig. 13.

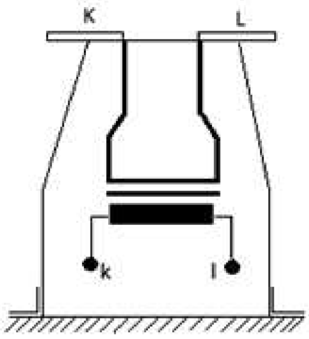

Figure 13: Single turn current transformer - Supporting type [1]

The following types can be designed either as a bushing type or as a window type. There is a slight difference between these two types, and differentiation is given by an arrangement during installation.

Bar primary type

A built-in primary conductor is bar-shaped and is insulated with a bushing. The transformer can be seen in the Fig. 14.

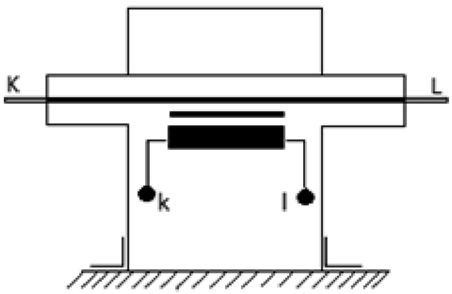

Figure 14: Bar primary type current transformer, bushing type [1]

Bus type

There is no built-in primary conductor. The transformer is equipped with the magnetic circuit with solely the secondary winding.

Toroidal type

The magnetic circuit is ring-shaped and the secondary winding is spread over the whole circuit. The built-in primary conductor is absent and the transformer is used as the bus-type. The Fig. 15 shows the toroidal transformer.

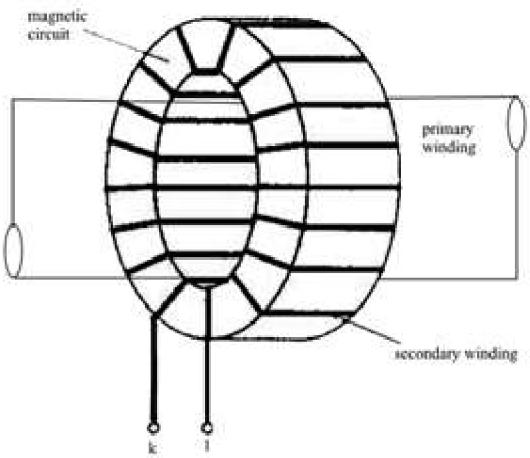

Figure 15: Toroidal type, bushing type

7.2.2 Wound current transformers

Supporting type

The outer design remains the same as in the case of single-turn transformer, but the primary winding has several turns.

Window type

The primary terminals are placed on the opposite sides of insulating body.

Bushing type

The type is the same as the window-type transformer, but is used simultaneously as a bushing.

7.3 Transformer with several secondary outputs

Current transformers with several secondary outputs are used to supply several separated secondary circuits with different working requirements. Such current transformer design enables to save costs as well as space in a switchgear. There are several independent magnetic circuits with the secondary winding and one common primary winding, so every output is supplied from the secondary winding of individual magnetic circuit. Medium voltage current transformers are usually made with two cores – the first core is used for measuring and the second for protection (Fig. 16). [1]

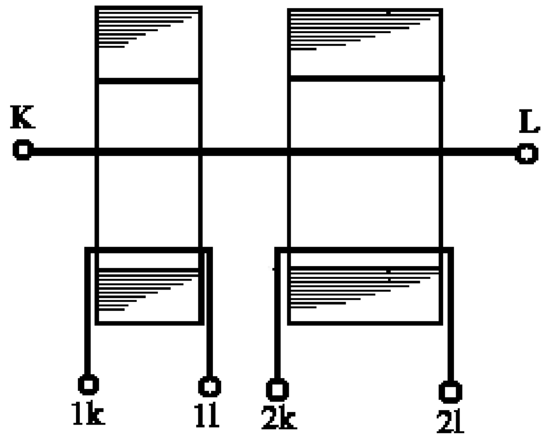

Figure 16: Current transformer with two cores: 1k - 1l output for measuring, 2k – 2l output for protection [1]

8 NO–LOAD AND SHORT-CIRCUIT CONNECTION

The chapter is written with regard to the bibliography [14].

The no–load and short–circuited connection are used during the transformer measurement in laboratories and testing labs. The measurement is used to determine the fundamental transformer parameters that are important during its operation.

8.1 No–load measurement

During the no-load transformer condition, the primary winding is supplied by rated voltage V_n and the secondary terminals are disconnected (without the load). The transformer takes from the mains only no-load current I_0 that is given by the vector sum of magnetizing current and current covering the iron losses. Therefore, the equivalent circuit diagram of transformer can be simplified into the one that is depicted in the Fig. 18. No-load losses are basically only iron losses (represented by input P_0), because the rated current passing through the winding is small.

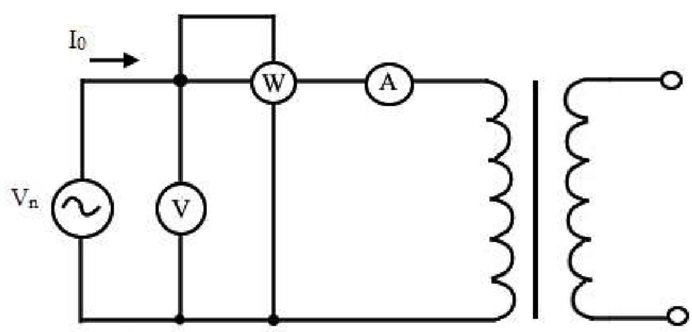

Figure 17: No-load measurement [14]

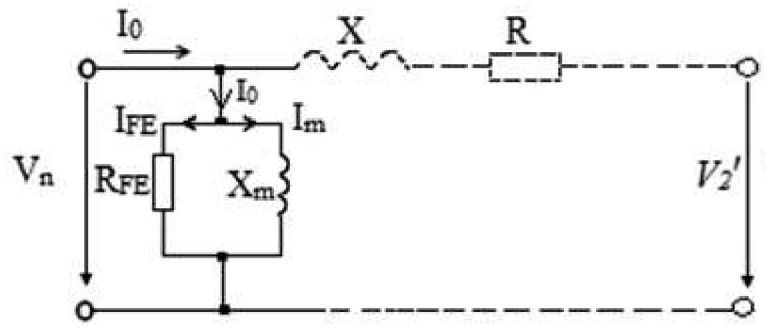

Figure 18: Simplified circuit diagram of no-load transformer

8.2 Short–circuit measurement

During the short-circuit transformer condition the transformer is supplied from the high-voltage side and the secondary terminals are short-circuited. The transformer is supplied by such reduced V_{sc} (called short-circuit voltage) that the rated current I_n passes through the winding. The secondary voltage is zero, therefore the whole primary voltage has to be used in impedances of the primary and secondary winding. The magnetic flux Φ in the core is small, the current I_0 is negligible considering the rated current I_n. Therefore, a magnetization branch can be neglected (see the Fig. 20). The input P_{sc} represents the winding losses.

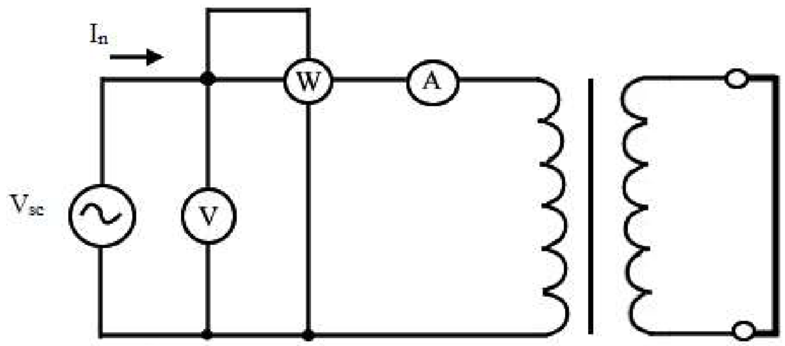

Figure 19: Short-circuit measurement [14]

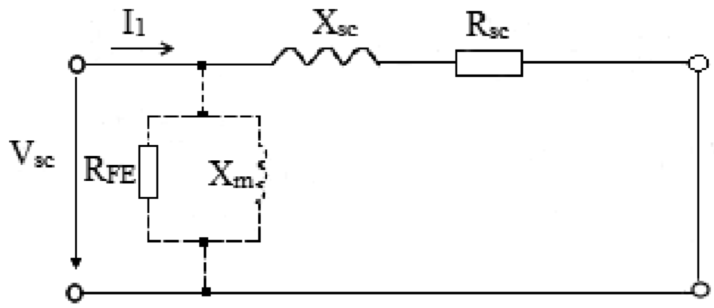

Figure 20: Simplified circuit diagram of short-circuit transformer

9 LOSSES MEASUREMENT

The losses were measured in the current transformer with the transformer ratio 600//5 A, rated output 15 VA, rated insulation levels 12/28/75 kV, and rated frequency 50 Hz using the three methods:

1.) Winding resistances measurement to determine the copper losses
2.) Short-circuit measurement to determine the copper losses
3.) No-load measurement to determine the iron losses

9.1 Transformer winding resistance measurement

The winding resistance of primary and secondary winding was measured using an ohmmeter. The measured values of primary and secondary winding resistance can be seen below in the Table 4.

Table 4: Primary and secondary winding resistance

Rated primary current I_p:	600 A
Rated secondary current I_s:	5 A
Primary winding resistance R_p:	0,23 mΩ
Secondary winding resistance R_s:	198,31 mΩ

9.2 Short–circuit measurement

The transformer was supplied from the high voltage side by such voltage that the rated current 600 A passed through the winding. The connection can be seen in the Fig. 19 and the measured values are written in Table 5.

Table 5: Measured values during short-circuit measurement

Short-circuit voltage V_{sc}:	100, 9 mV
Short-circuit current I_{sc}:	592,2 A
Power factor cos φ:	0,8157

9.3 No–load measurement

The transformer was supplied from the low-voltage side and the primary terminals were opened at the high-voltage side. The rated voltage was set to 3 V, since the rated output was 15 VA and the secondary current was 5 A. The connection is depicted in the Fig. 17 and the measured values are written in the Table 6, 7.

Table 6: No-load current I_0 and input P_0 with the frequency 50 Hz

Frequency f:	50 Hz
No -load current I_0 :	0,09 A
No-load input power P_0:	95 mW

Table 7: No-load current I_0 and input P_0 with the frequency 60 Hz

Frequency f:	60 Hz
No-load current I_0 :	0,07 A
No–load input P_0:	90 mW

9.4 Losses calculations

The total loss is the sum of all transformer losses:

$$\Delta P = \Delta P_j + \Delta P_{Fe}, \quad (35)$$

$$\Delta P = \Delta P_{jp} + \Delta P_{js} + \Delta P_{Fe} \quad (36)$$

where ΔP is total loss, ΔP_{jp} primary winding loss, ΔP_{js} secondary winding loss, and ΔP_{Fe} core loss.

9.4.1 Losses calculation using values from winding resistances measurement and no-load measurement

Firstly, the primary winding loss is calculated using the measured primary winding resistance R_p and the rated primary current I_p:

$$\Delta P_{jp} = R_p \cdot I_p^2$$

$$\Delta P_{jp} = 0{,}00023\ \Omega \cdot 600^2\ A$$

$$\Delta P_{jp} = 82{,}8\ W$$

Secondly, the secondary winding loss is expressed using the measured secondary winding resistance R_s and the rated secondary current I_s:

$$\Delta P_{js} = R_s \cdot I_s^2$$

$$\Delta P_{js} = 0{,}19831\ \Omega \cdot 5^2\ A$$

$$\Delta P_{js} = 4{,}96\ W$$

Finally, if the primary winding loss, the secondary winding loss and core loss are substituted into one formula, the total losses ΔP are determined:

$$\Delta P = 82{,}8\ W + 4{,}96\ W + 0{,}095\ W$$

$$\Delta P = \mathbf{87{,}86\ W}$$

9.4.2 Losses calculation using values from short – circuit measurement and no-load measurement

Firstly, the quantities Z_{sc}, R_{sc}, X_{sc}, and R_1 can be determined from the measured values, the impedance Z_{sc} can be expressed:

$$Z_{sc} = \frac{U_{sc}}{I_{sc}}$$

$$Z_{sc} = \frac{0{,}1009\,V}{592{,}2\,A}$$

$$Z_{sc} = 0{,}170\,m\Omega$$

The resistance R_{sc} and reactance X_{sc} can be calculated:

$$R_{sc} = Z_{sc} \cdot \cos\varphi$$

$$R_{sc} = 0{,}000170\,\Omega \cdot 0{,}8157$$

$$R_{sc} = 0{,}139\,m\Omega$$

$$X_{sc} = Z_{sc} \cdot \sin\varphi$$

$$X_{sc} = 0{,}000170\,\Omega \cdot 0{,}0142$$

$$X_{sc} = 0{,}00242\,m\Omega$$

The resistance R_1 is calculated

$$R_{1=} \frac{R_{sc}}{2}$$

$$R_1 = \frac{0{,}000139\,\Omega}{2}$$

$$R_1 = 0{,}0695\,m\Omega$$

After the determination of resistance R_1, it is obvious that R_1 differs considerably from the primary resistance R_p that was measured by the winding resistances measurement method. The primary resistance measured according to the first method is 0, 23 mΩ and the determined primary resistance from the measured quantities in the short-circuit method is 0, 0695 mΩ. The second value 0, 0695 mΩ can be considered as more accurate. The reason for the difference in resistances may lie in the measurement error and selected method error.

Secondly, the measured winding losses P_{sc} are calculated

$$P_{sc} = U \cdot \mathrm{I} \cdot \cos\varphi$$

$$P_{sc} = 0{,}1009\,V \cdot 592{,}2\,A \cdot 0{,}8157$$

$$\Delta P_{sc} = 48{,}74\,W$$

Thirdly, the winding losses ΔP_j are expressed

$$\Delta P_j = P_{sc} \cdot \left(\frac{I_n}{I_{sc}}\right)^2$$

$$\Delta P_j = 48{,}74\,W \cdot \left(\frac{600\,A}{592{,}2\,A}\right)^2$$

$$\Delta P_j = 50{,}03\,W$$

Finally, total loss ΔP can be determined

$$\Delta P = \Delta P_j + \Delta P_{Fe}$$

$$\Delta P = 50{,}03\,W + 0{,}095\,W$$

$$\Delta P = \mathbf{50{,}13\,W}$$

10 CONCLUSION

In conclusion, the aim of the thesis was to describe the transformer history and the working principle of transformer, to provide the theoretical analysis of instrument transformer and losses analysis, to conduct the losses measurement, and to measure and calculate the transformer losses of a given transformer.

The theoretical part prevails in the thesis. Firstly, the transformer development is described briefly. The second chapter deals with the theoretical analysis of current transformers. The important terms, which are used in the thesis, are defined using the standard, the principle of operation and the basic theory of current transformer are also described. To analyse the transformer losses, it was necessary to find out information about the ferromagnetic properties and about the behaviour of ferromagnetic materials. Thus, I have characterized the initial magnetization curve and hysteresis loop to follow up with the description of transformer losses. The losses, which represent the source of heat, are classified into the iron/core losses and the copper/winding losses in the fourth chapter. Furthermore, the iron losses are divided into the hysteresis losses and the eddy current losses and all the losses are analysed. The sixth chapter analyses the materials used in the magnetic circuit, winding and how the current transformer can be insulated. The used materials in the magnetic circuit are very important for the iron losses since they are dependent on magnetic material properties. The seventh chapter determines the current transformer rated values, and provides the description of current transformer types and the description of transformer with several secondary outputs.

In the practical part, the losses were measured. Firstly, the transformer winding resistance measurement method was used to measure the primary and secondary winding resistances and to calculate the winding losses. Secondly, the short-circuit measurement method was used to verify the previous method and to express the winding losses too. Thirdly, the no-load measurement method was used to measure the no-load input power and so to determine the core losses. After the primary resistance determination with the use of the measured values in the short-circuit measurement, the primary resistances obtained from two different methods have been compared. On the basis of the comparison, I have found out that the short – circuit measurement method is more accurate and that the difference may lie in the measurement error and in selected measurement method. Therefore, for the current transformer total loss determination, the second calculated value 50, 13 W, which is introduced as more accurate one, can be used. The value 50, 13 W represents the sum of the measured core losses 0, 095 W and the winding losses 50, 03 W. It is demonstrated that the winding losses are given by the winding resistance. It is obvious the winding losses dominate significantly. Since the core losses are only 0,095 W, they can be neglected, the material magnetic properties were excellent.

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LIST OF SYMBOLS AND ACRONYMS

Symbol	Description	Unit
B	Magnetic flux density	[T]
B_r	Remanent flux density	[T]
f	Frequency	[Hz]
H	Magnetic field strength	[A/m]
H_c	Coercive field strength	[A/m]
I	Current	[A]
I_0	No – load current	[A]
I_n	Rated current	[A]
I_p	Primary current	[A]
I_s	Secondary current	[A]
N	Number of turns of wire	[-]
P	Electric power	[W]
P_0	No – load input power	[W]
P_{Fe}	Losses in core	[W]
P_{jp}	Losses in primary winding	[W]

P_{js}	Losses in secondary winding	[W]
P_{sc}	Short-circuit losses	[W]
R	Resistance	[Ω]
R_p	Primary winding resistance	[Ω]
R_s	Secondary winding resistance	[Ω]
R_{sc}	Short-circuit resistance	[Ω]
t	Time	[s]
THKNS	Thickness	[m]
V	Voltage	[V]
V_n	Rated voltage	[V]
V_{sc}	Short–circuit voltage	[V]
X	Reactance	[Ω]
X_{sc}	Short-circuit reactance	[Ω]
Z	Impedance	[Ω]
Z_{sc}	Short-circuit impedance	[Ω]
ε	Electromotive force	[V]
Φ	Magnetic flux	[Wb]