POTENTIAL TRANSFORMERS

Instrument transformers are transformers of low rated power. They transform high voltages and high currents in an electrical power grid to low voltages and low currents in order to supply measuring instruments, electricity meters, protection relays, or similar equipment. This is necessary because high voltages and high currents cannot be directly processed by measuring devices.

Figure 1 shows one phase of an electrical power grid with the operating voltage U_b and current I_b to be measured. The primary winding of an instrument transformer is connected to the power grid, and the secondary winding is connected to measuring respectively control instruments. The equipment connected to the secondary winding plus the used leads are called "burden" or "load" (Fig. 1).

Voltage transformers supply low secondary voltages U_2 which are proportional to the high primary voltages U_1. Current transformers supply low secondary currents I_2 which are proportional to the high primary current I_1. In the case of higher voltage levels it can be an advantage to combine voltage and current transformers in one common apparatus. In addition to the transformation of the voltages and currents to lower values, instrument transformers have the important task to isolate the potential of the electrical power grid from that of the measuring instruments.

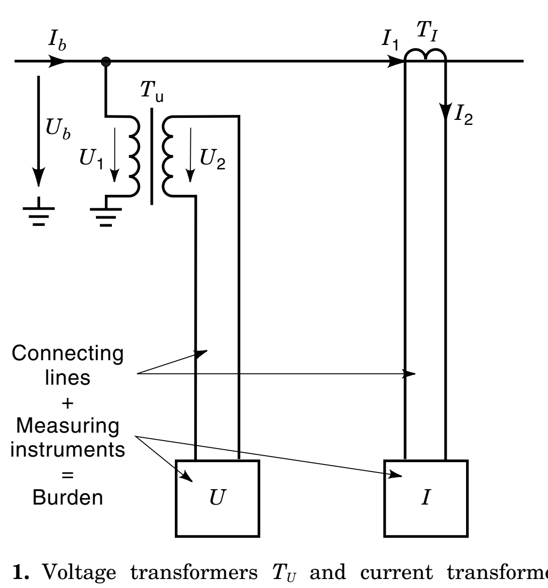

Figure 1. Voltage transformers T_U and current transformers T_I transform the high operating voltage U_b and high current I_b in the electric power grid to lower values U_2 and I_2.

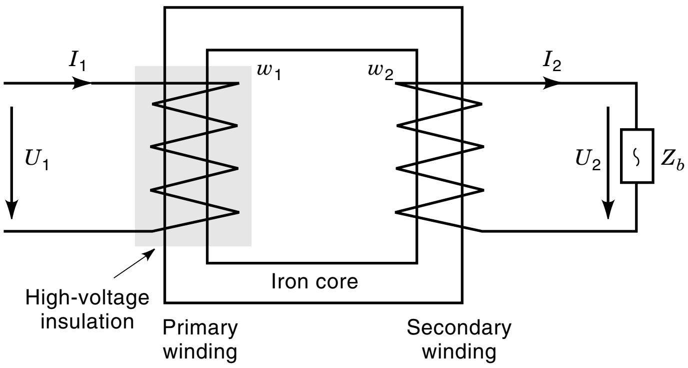

Figure 2. Basic design of an instrument transformer.

Figure 2 shows the basic design of an instrument transformer. The primary winding and the secondary winding are mounted on an iron core which links both windings magnetically. The windings are made of an electric conductor which is wound a certain number of turns w_1 and w_2. The number of turns determines the instrument transformer's performance:

Voltage transformer: $w_1 > w_2 \rightarrow U_1 > U_2$ and $I_1 < I_2$
Current transformer: $w_1 < w_2 \rightarrow I_1 > I_2$ and $U_1 < U_2$

Since the primary winding is directly connected to the power grid, the primary winding has to be insulated against the iron core and against the secondary winding. The insulation level is defined by the basic insulation level (BIL) of the relevant power grid.

The secondary measuring signals U_2 or I_2 supplied by instrument transformers are used for three main purposes:

1. Protection
2. Control
3. Calculation of electrical energy for billing

Instrument transformers are not ideal transformers. They cause measuring errors. Depending on the measuring purpose, a certain measuring accuracy is necessary. Instrument transformers used for billing meet high accuracy requirements. The quantity needed for billing is electrical energy. The multiplication of voltage, current, and time results in the electrical energy. So the measuring error not only of the voltage transformer but also of the current transformer contributes to the total energy error and consequently in an error in billing. A simplified calculation may clarify the meaning of 1% measuring error in terms of money for a country like Germany. Purchasing the country's annual electrical energy equivalent to 80 billion DM (about 50 billion US$) includes a billing inaccuracy of 800 million DM (about 500 million US$).

In some countries there are legal calibration regulations for commercially used measuring instruments. These calibration regulations demand a verification and documentation of the accuracy of certain instrument transformers used for billing performed by qualified and licensed organizations. Though based on the same physical background, these regulations are quite different and vary from country to country, so details cannot be described here. The basic requirements for the accuracy of instrument transformers can be found in the international standard IEC 60044.

Instrument transformers used for control and protection purposes need less accuracy. In general, these instrument transformers have sufficient measuring accuracy in the range needed for the detection and location, respectively, of electrical faults in the grid.

The measuring accuracy is expressed by the accuracy class rating:

$$F_U = \frac{k_U U_2 - U_1}{U_1} \times 100 \text{ (voltage transformer)}$$
$$F_I = \frac{k_I I_2 - I_1}{I_1} \times 100 \text{ (current transformer)}$$

(k_U, k_I: transformation ratio).

International standards specify the following accuracy classes for instrument transformers (Table 1).

There are numerous types of voltage and current transformers depending on measuring purpose, voltage level, and type of switchgear and substation, respectively, to which the instrument transformer is scheduled to be applied. The specifications for voltage transformers are described in the international standard IEC 60044-2 (former IEC 185), and those for current transformers are described in IEC 60044-1 (former IEC 186).

INSULATION OF INSTRUMENT TRANSFORMERS

The materials used for insulation strongly depend on the voltage which has to be withstood. In general, three voltage ranges are distinguished.

High Voltage, Extra-High Voltage, and Ultra-High Voltage (100 kV up to 1200 kV)

For this voltage range the most common insulation system used for the insulation of the transformer windings is still a combination of paper and oil. Tapes of a special paper are wound around the parts which have to be insulated so that a necessary number of paper layers is formed. Care must be taken that the paper is dried extremely well—that is, contains a very low residual amount of water. Finally the paper layers are impregnated with dried transformer oil. Since the insulation is a combination of solid and liquid materials, a housing is needed. A portion of the housing is made of metal. Metal parts on a high potential must be insulated from grounded metal parts. This is accomplished by shedded or ribbed porcelain cylinders or cones, which are the main visi-

Table 1. Accuracy Classes for Instrument Transformers

	Voltage Transformers (IEC 60044-2)	Current Transformers (IEC 60044-1)
Accuracy class:	0.1, 0.2, 0.5, 1, or 3 (at rated voltage and with rated burden)	0.1, 0.2, 0.5, 1, 3, 5 (within 25% to 100% of rated burden)
Accuracy class (P: protection purposes):	3P or 6P	5P or 10P

Table 2. Comparison of Different Insulation Systems of Instrument Transformers

Voltage Level (Range of U_m)	Type of Insulation	
Low voltage (<1 kV)	Windings: paper-base laminate, moulding compound Plastic housing (e.g., polycarbonate) For special purposes: cast resin insulation	
Medium high voltage (1–100 kV)	**Indoor Application** Windings: paper Body: Cast resin insulation (epoxy or polyurethane) For special purposes: porcelain	**Outdoor Application** Sheds as a part of the solid body
High voltage (>100 kV)	**Air-Insulated Substation (AIS)** Inner insulation: Oil impregnated paper SF_6 impregnated plastic film Insulator: Porcelain Glass-reinforced plastic tube with silicone rubber sheds	**Gas-Insulated Substation (GIS)** Voltage transformer winding layers insulated with plastic films Main insulation is provided by the SF_6 in the GIS Housing is part of the GIS

ble part of an instrument transformer in the high voltage range. The instrument transformer housing is filled with oil and closed hermetically to keep humidity outside even in the long time range. During operation the oil can warm up and expand. The expansion is compensated by an oil expansion vessel.

Since the 1970s, advanced dry insulation systems have been developed for high-voltage instrument transformers mainly used in gas insulated switchgear (GIS). The insulation layers consist of plastic films instead of paper. Finally the transformer is filled and "impregnated," respectively, with the insulation gas sulfur hexafluoride (SF_6).

In recent years, alternatives for porcelain housings have been established. The housing is a glass-fiber-reinforced tube. Silicon rubber sheds needed for outdoor use are fixed on the surface of that tube.

Medium High Voltage (1 kV up to 100 kV)

The formerly used oil-paper insulation in this voltage range has been almost completely replaced by cast resin insulation. The iron core with the windings is assembled first. Afterwards the instrument transformer is put into a casting tool which is filled with liquid casting resin. The casting resin will be warmed up so that it hardens. As a result, the complete instrument transformer is encapsulated by the solid-state resin insulation. Since resin is a solid material, no extra housing for the instrument transformer is necessary. Adequate resins are those on the base of polyurethane and epoxy. For outdoor use of these instrument transformers, sheds as a part of the solid-state body can be formed during the casting process.

Low Voltage (<1 kV)

The insulation of low-voltage instrument transformers is realized with cylinders made of paper-base laminate or moulding compound. They are assembled in plastic housings. For special demands like high mechanical stress the low-voltage instrument transformers can be casting resin encapsulated.

Table 2 compares the different insulation systems of instrument transformers.

THEORY AND EQUIVALENT CIRCUIT

Instrument transformers consist of a primary winding and a secondary winding mounted on a closed iron core as shown in Fig. 3. The instrument transformer is loaded with a burden $\boldsymbol{Z}_b$. The relevant magnitudes for the measurement with a voltage transformer are $\boldsymbol{U}_1$ and $\boldsymbol{U}_2$, and those for a current transformer are $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$. These currents and voltages are alternating and sinusoidal so that they can be represented by the set of complex numbers and graphically by phasors.

For an ideal transformer there are the following relations between the primary and secondary voltages and currents and the number of turns w_1 of the primary and w_2 of the secondary windings:

$$\frac{\boldsymbol{U}_1}{\boldsymbol{U}_2} = \frac{w_1}{w_2} \tag{1}$$

$$\frac{\boldsymbol{I}_1}{\boldsymbol{I}_2} = \frac{w_2}{w_1} \tag{2}$$

In fact, instrument transformers are not ideal. Losses and stray magnetic fields have to be taken into account. Equations

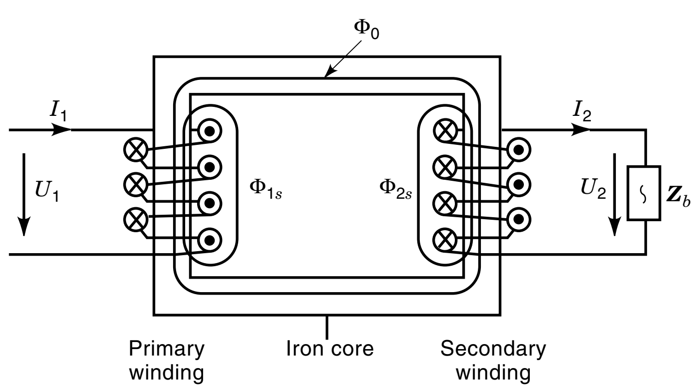

Figure 3. Voltages, currents, and magnetic flux of an instrument transformer with load Z_b.

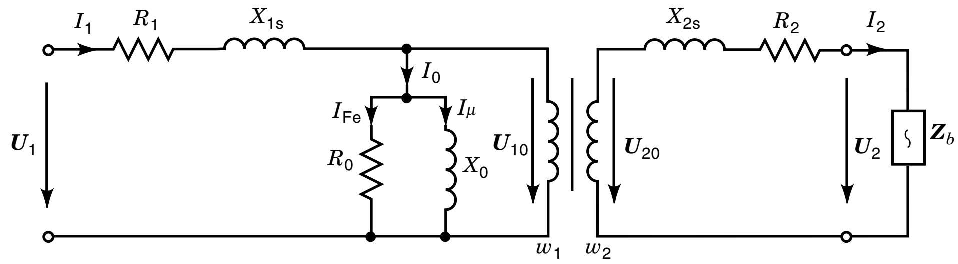

Figure 4. The equivalent circuit describes the terminal performance of an instrument transformer.

(1) and (2) are not valid anymore. The physical relations shown in Fig. 3 can be expressed by an equivalent circuit composed of lumped elements (Fig. 4). This equivalent circuit simulates the instrument transformer's performance at its terminals.

In the following the lumped elements and their physical equivalent are explained. Losses in the instrument transformer are represented by resistances:

1. R_1 represents losses due to the resistance of the wire of the primary winding.
2. R_2 represents losses due to the resistance of the wire of the secondary winding.
3. R_0 represents magnetic hysteresis losses and eddy-current losses in the iron core.

The current in the primary winding causes a magnetic field. As a result, a total magnetic flux $\mathbf{\Phi}_1 = \mathbf{\Phi}_{10} + \mathbf{\Phi}_{1s}$ occurs consisting of (a) the main magnetic flux $\mathbf{\Phi}_0 = \mathbf{\Phi}_{10}$ in the iron core which is linked to the secondary winding and (b) the rather small magnetic stray flux $\mathbf{\Phi}_{1s}$ which is only linked to the primary winding itself. Since this stray flux induces a small voltage in the primary winding caused by the current $\boldsymbol{I}_1$, it can be represented in the equivalent circuit by an inductance L_{1s} or including the frequency f by a reactance $X_{1s} = 2\pi f L_{1s}$ (see Fig. 4). If we consider now the unloaded transformer ($\boldsymbol{Z}_b \to \infty$, $\boldsymbol{I}_2 \to 0$), the transformer performs as follows. The main magnetic flux $\mathbf{\Phi}_0$ induces a voltage $\boldsymbol{U}_{20}$ in the secondary winding and a voltage $\boldsymbol{U}_{10}$ in the primary winding. The ratio between these induced voltages is equivalent to the ratio of the number of turns of the windings:

$$\frac{\boldsymbol{U}_{10}}{\boldsymbol{U}_{20}} = \frac{w_1}{w_2} \tag{3}$$

Equation (3) is represented by an ideal transformer with number of turns w_1 and w_2 in Fig. 4. The current $\boldsymbol{I}_1$ is small. It splits into two parts: $\boldsymbol{I}_{Fe}$ covers the losses in the iron core and $\boldsymbol{I}_\mu$ is responsible for the magnetization of the iron core with the flux $\mathbf{\Phi}_0$. The relation between the voltage $\boldsymbol{U}_{10}$ and the current $\boldsymbol{I}_\mu$ can be represented by an inductance L_0 or a reactance X_0. The voltage $\boldsymbol{U}_{10}$ and the voltage $\boldsymbol{U}_1$ differ only by the voltage drop at the resistance R_1 and the reactance X_1. Since the voltage $\boldsymbol{U}_{10}$ is proportional to the flux $\mathbf{\Phi}_0$, the iron core must be magnetized in a high degree.

At the moment the transformer will be loaded with the burden a current $\boldsymbol{I}_2$ flows in the secondary circuit. The result is a magnetic field in the secondary winding causing a flux $\mathbf{\Phi}_2 = \mathbf{\Phi}_{20} + \mathbf{\Phi}_{2s}$ which is contrary to the magnetic flux of the primary winding. So the effective flux in the iron core is reduced to $\mathbf{\Phi}_0 = \mathbf{\Phi}_{10} - \mathbf{\Phi}_{20}$. This reduced flux $\mathbf{\Phi}_0$ is responsible for a decrease of the induced voltages $\boldsymbol{U}_{10}$ and $\boldsymbol{U}_{20}$. The magnetic stray flux $\mathbf{\Phi}_{2s}$ of the secondary winding is represented by an inductance L_{2s} or a reactance X_{2s} (Fig. 4). The magnetic field in the iron core $\boldsymbol{H}_{Fe}$ and the ampere-windings $w_1 \cdot i\mu$ causing the magnetic field are related by Ampere's law:

$$\oint \boldsymbol{H}_{\mathrm{Fe}} d\boldsymbol{s} = w_1 i_\mu \tag{4}$$

These ampere-windings responsible for the magnetization of the iron core must be in balance with the ampere-windings $w_1 \cdot i_1$ of the primary and $w_2 \cdot i_2$ of the secondary winding:

$$w_1 i_\mu = w_1 i_1 - w_2 i_2 \tag{5}$$

Finally we regard the transformer shorted at its secondary terminals. The secondary voltage $\boldsymbol{U}_2$ becomes zero. Since the current $\boldsymbol{I}_2$ is now bigger the resulting flux $\mathbf{\Phi}_2 = \mathbf{\Phi}_{20} + \mathbf{\Phi}_{2s}$ rises reducing the effective magnetic flux in the iron core $\mathbf{\Phi}_0 = \mathbf{\Phi}_{10} - \mathbf{\Phi}_{20}$. The induced voltages $\boldsymbol{U}_{10}$ and $\boldsymbol{U}_{20}$ become small. This is obvious because the necessary voltage in the secondary circuit to be equalized by $\boldsymbol{U}_{20}$ is at this stage nothing but the voltage drop at the resistances R_2 and the reactance X_{2s}. Regarding Eq. (5) the current $\boldsymbol{I}_2$ has to be supplied by a high current $\boldsymbol{I}_1$.

Voltage transformers are loaded with high impedances $\boldsymbol{Z}_b$ so that their performance resembles the performance of an unloaded transformer. Current transformers perform like shorted transformers because the burden $\boldsymbol{Z}_b$ is rather small.

Figure 5 shows a further developed equivalent circuit. The ideal transformer in Fig. 4 can be omitted if either the values of the primary circuit are recalculated to the magnitude of the secondary circuit or vice versa. In Fig. 5 the latter is shown. The values have been recalculated to the primary side:

$$\boldsymbol{U}'_2 = \boldsymbol{U}_2 \cdot \frac{w_1}{w_2} \tag{6}$$

$$\boldsymbol{I}'_2 = \boldsymbol{I}_2 \cdot \frac{w_2}{w_1} \tag{7}$$

$$\boldsymbol{Z}'_b = \boldsymbol{Z}_b \cdot \left(\frac{w_1}{w_2}\right)^2 \tag{8}$$

$$R'_2 = R_2 \cdot \left(\frac{w_1}{w_2}\right)^2 \tag{9}$$

$$X'_{2s} = X_{2s} \cdot \left(\frac{w_1}{w_2}\right)^2 \tag{10}$$

VOLTAGE TRANSFORMER

According to the equivalent circuit depicted in Fig. 5 the phasor diagram of the voltage transformer can be derived (Fig.

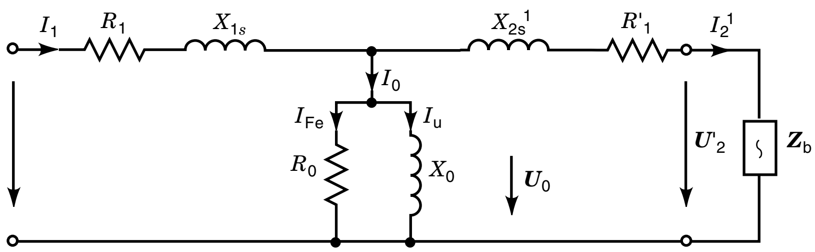

Figure 5. The equivalent circuit can be simplified if the secondary values (index 2) of an instrument transformer are recalculated to the primary values.

6). The diagram is started with the voltage $\boldsymbol{U}_2'$ at the burden. It is shown for a burden with a power factor cos $\beta = 0.8$ and inductive burden characteristic. This means that the voltage $\boldsymbol{U}_2'$ advances the current $\boldsymbol{I}_2'$ by an angle of $\beta = 37°$. The voltage drop $R_2'\boldsymbol{I}_2'$ at the resistance R_2' is in phase with the current $\boldsymbol{I}_2'$. The voltage drop at the stray reactance X_2' caused by $\boldsymbol{I}_2'$ advances this current by 90°. Both voltage drops are added to $\boldsymbol{U}_2'$. The result is the voltage $\boldsymbol{U}_0 = \boldsymbol{U}_{10} = (w_1/w_2)\boldsymbol{U}_{20}$ which is induced by the main magnetic flux in the iron core. The phase angle between $\boldsymbol{U}_0$ and the main flux $\boldsymbol{\Phi}_0$ is 90°. The magnetizing current $\boldsymbol{I}\mu$ which is the cause for the flux is in phase with it. The current $\boldsymbol{I}_{Fe}$ covers the losses in the iron core and is in

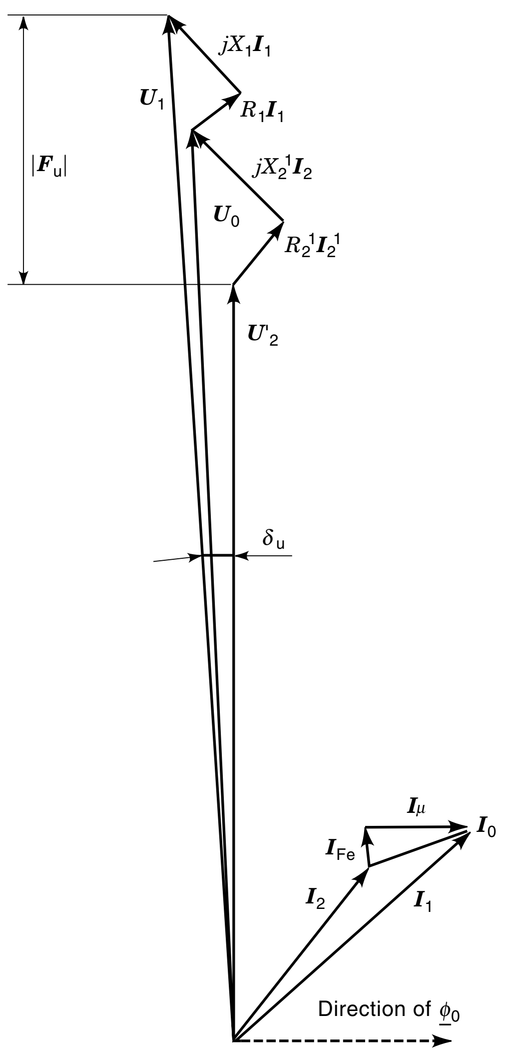

Figure 6. Phasor diagram of a voltage transformer.

phase with the voltage $\boldsymbol{U}_0$. The sum of $\boldsymbol{I}\mu$ and $\boldsymbol{I}_{Fe}$ is the current $\boldsymbol{I}_0$ which, when added to $\boldsymbol{I}_2'$, results in the current $\boldsymbol{I}_1$ in the primary circuit. The current $\boldsymbol{I}_1$ causes the voltage drops $R_1\boldsymbol{I}_1$ and $jX_1\boldsymbol{I}_1$ which, when added to $\boldsymbol{U}_0$, lead to the primary voltage $\boldsymbol{U}_1$.

The phasor diagram explains the measuring error of the voltage transformer. An ideal voltage transformer does not have an error. In the phasor diagram of an ideal transformer the voltages $\boldsymbol{U}_1$ and $\boldsymbol{U}_2'$ are in phase and have the same length. As can be seen in Fig. 6, this is different for the voltage transformer regarding its real characteristics. In its phasor diagram the length of $\boldsymbol{U}_1$ and $\boldsymbol{U}_2'$ is different. Besides there is a phase angle between the primary and secondary voltage. Consequently, the real voltage transformer has an error in magnitude $|\boldsymbol{F}_u|$ as well as in phase δ_U.

In the phasor diagram (Fig. 6) the influence of the voltage drops at R_2', X_{2s}', R_1 and X_{1s} is drawn greater than it is in reality in order to show the voltage transformer's measuring error, which is just a few percent or less.

For this reason there is another construction of a phasor diagram to draw the error of a voltage transformer exactly. This type of phasor diagram has been found by Moellinger and Gewecke. This diagram is shown in Fig. 7. It concentrates on the voltage drops at R_2', X_{2s}', R_1, and X_{1s} and suppresses the full length of $\boldsymbol{U}_2'$ and $\boldsymbol{U}_1$. The measuring error is composed of two parts:

1. F_0: Measuring error of the unloaded voltage transformer ($\boldsymbol{Z}_b \to \infty$).
2. F_b: Measuring error caused by the load $\boldsymbol{Z}_b$.

For the explanation of the diagram according to Moellinger and Gewecke, some further considerations about the measuring error are necessary. The complex measuring error can be expressed in percent:

$$\boldsymbol{F}_U = \frac{\boldsymbol{U}_2' - \boldsymbol{U}_1}{\boldsymbol{U}_1} \times 100\% \tag{11}$$

Defining the voltage drop at R_1 and X_{1s} as

$$\boldsymbol{U}_1 = \boldsymbol{I}_1(R_1 + jX_{1s}) \tag{12}$$

and the voltage drop at R_2' and X_{2s}' as

$$\Delta\boldsymbol{U}_2' = \boldsymbol{I}_2'(R_2' + jX_{2s}') \tag{13}$$

the measuring error can equivalently be expressed as

$$\boldsymbol{F}_U = -\frac{\Delta\boldsymbol{U}_1 + \Delta\boldsymbol{U}_2'}{\boldsymbol{U}_1} \times 100\% \tag{14}$$

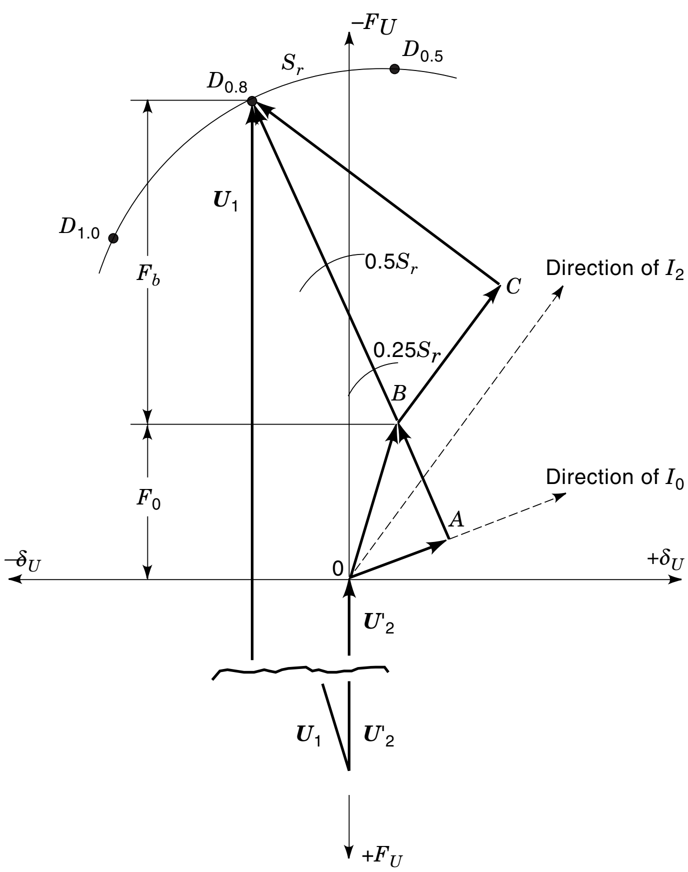

Figure 7. The phasor diagram of the voltage transformer according to Moellinger and Gewecke shows the measuring error for different burden impedances Z_b.

$\boldsymbol{I}_1$ can be replaced by

$$\boldsymbol{I}_1 = \boldsymbol{I}_0 + \boldsymbol{I}'_2 \tag{15}$$

so that

$$\boldsymbol{F}_U = -\frac{\boldsymbol{I}_0(R_1 + jX_{1s}) + \boldsymbol{I}'_2(R_1 + jX_{1s} + R'_2 + jX'_{2s})}{\boldsymbol{U}_1} \times 100\% \tag{16}$$

The measuring error of the voltage transformer is composed of two parts:

1. The error $\boldsymbol{F}_0$ of the unloaded voltage transformer (depending only on $\boldsymbol{I}_0$):

$$\boldsymbol{F}_0 = -\frac{\boldsymbol{I}_0(R_1 + jX_{1s})}{\boldsymbol{U}_1} \times 100\% \tag{17}$$

2. The error caused by the load (depending only on $\boldsymbol{I}_2$):

$$\boldsymbol{F}_b = -\frac{\boldsymbol{I}'_2(R_1 + jX_{1s} + R'_2 + jX'_{2s})}{\boldsymbol{U}_1} \times 100\% \tag{18}$$

We assume a voltage transformer with a constant burden. If the voltage drops caused by the small current $\boldsymbol{I}_0$ are neglected $\boldsymbol{I}'_2$ will be proportional to $\boldsymbol{U}_1$. The impedance $R_1 + jX_{1s} + R'_2 + jX'_{2s}$ can be assumed constant. Thus the error caused by the burden [Eq. (18)] is independent of the primary voltage $\boldsymbol{U}_1$, and proportional to the burden impedance $\boldsymbol{Z}'_b$. Therefore the error $\boldsymbol{F}_b$ can be calculated for any burden if the error $\boldsymbol{F}_b$ has been measured for a certain burden. The error $\boldsymbol{F}_0$ [Eq. (17)] of the unloaded voltage transformer is not independent of the applied primary voltage $\boldsymbol{U}_1$ because the current $\boldsymbol{I}_0$ is dependent on $\boldsymbol{U}_1$. The relation between $\boldsymbol{I}_0$ and $\boldsymbol{U}_1$ is nonlinear due to the magnetization characteristic of the iron core. The phasor diagram of the voltage transformer according to Moellinger and Gewecke is constructed as follows. Figure 7 shows the diagram for a burden power factor of 0.8.

The diagram starts at the top of the phasor $\boldsymbol{U}'_2$ (point 0). The direction of the currents $\boldsymbol{I}'_2$ and $\boldsymbol{I}_0$ must be known. First of all the phasors $R_1\boldsymbol{I}_0$ and $jX_{1s}\boldsymbol{I}_0$ deriving from Eq. (17) are added. Starting at point B the phasors $(R_1 + R'_2)\boldsymbol{I}'_2$ and $j(X_{1s} + X'_{2s})\boldsymbol{I}_2$ of Eq. (18) are added. The result of the sum is the phasor of the primary voltage $\boldsymbol{U}_1$. $\boldsymbol{U}'_2$ and $\boldsymbol{U}_1$ can be drawn as parallel lines because they are long compared to the dimensions of the diagram. A coordinate system is placed into the phasor diagram. The vertical axis is scaled to read the magnitude of the measuring error. The horizontal axis is scaled to read the phase of the measuring error. At first the Moellinger–Gewecke diagram shows the error $\boldsymbol{F}_0$ of the unloaded voltage transformer. Additionally the error $\boldsymbol{F}_b$ due to the burden can be read. The total measuring error is $|\boldsymbol{F}_U| = |\boldsymbol{F}_0| + |\boldsymbol{F}_b|$. The error angle is δ_U. If this diagram has been constructed for a certain burden, the error can be concluded for any other burden. The burden is described by its apparent power S and the power factor $\cos\beta$. If the power factor changes, the direction of the current $\boldsymbol{I}'_2$ related to $\boldsymbol{U}'_2$ changes as well. This means that the triangle B–C–D turns around point B. If the power factor increases, the triangle turns counterclockwise. The point D describes a circle with the radius BD. Figure 7 shows this circle with the points $D_{1.0}$ for a power factor of 1.0 and $D_{0.5}$ for a power factor of 0.5. If the impedance of the burden is raised, the current $\boldsymbol{I}_2$ decreases and the phasors BC and CD become proportionally shorter. So the point D moves on the line BD toward B. So the mentioned circle for the power factor must be drawn with a smaller radius around B. Figure 7 shows the circles' radii for twice and four times the rated burden impedance, which is equivalent to $0.5S_r$ and $0.25S_r$. An inductive and ohmic loaded voltage transformer has always a negative measuring error. The error angle is regarded positive if the voltage $\boldsymbol{U}'_2$ advances $\boldsymbol{U}_1$.

Design of Voltage Transformers

Voltage transformers can be designed with one terminal of the primary winding being earthed or with two unearthed terminals. So the first type can only be used for the measurement of line-to-ground voltages. The latter can also measure the line-to-line system voltage. For the higher-voltage power system, usually earthed voltage transformers are in use. In the design of voltage transformers, usually two types of iron cores are used: (1) the limb-type core and (2) the sleeve core or M-core. Their design is shown in Fig. 8.

The core material used for voltage transformers are sheets of siliconized steel which are cold-rolled. These sheets have a high permeability and low core losses in rolling direction. So the voltage transformer can work with high flux densities to

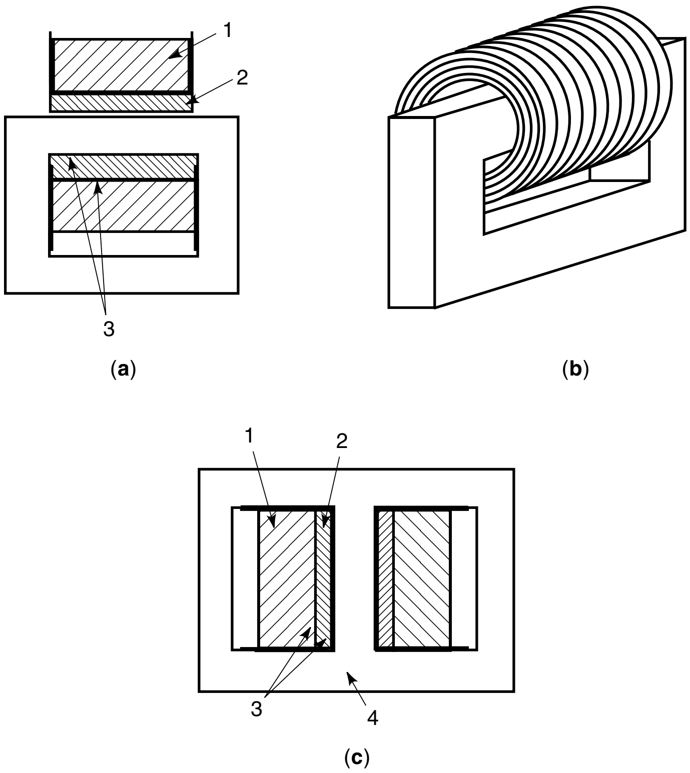

Figure 8. Voltage transformer core types. (a) Limb-type core (sectional view), (b) limb-type core (three-dimensional view), (c) sleeve core (sectional view). 1, Primary winding; 2, secondary winding; 3, isolation; 4, iron core.

keep the number of windings and thus the resistance of the windings low.

The winding of a voltage transformer is carried out as a concentric winding. The secondary winding is wound near the iron core. The primary winding is wound above the secondary winding. Because of the high number of turns the primary winding consists of a certain number of layers.

Voltage transformers can have multiple secondary windings. Some voltage transformers offer the possibility to obtain different secondary voltages. The standard secondary voltages are:

$$100\,\mathrm{V},\ 100/\sqrt{3}\,\mathrm{V},\ 100/3\,\mathrm{V},\ 110\,\mathrm{V},\ 110/\sqrt{3}\,\mathrm{V},\ 110/3\,\mathrm{V}$$

Design Criteria to Reduce the Measuring Error

The measuring error consists of two parts: the error $\boldsymbol{F}_0$ of the unloaded transformer [Eq. (17)] and the error caused by the load [Eq. (18)].

The resistances of the winding conductors R_1 and R_2 contribute to the measuring error. The losses in the windings can be reduced by increasing the conductors' cross section and decreasing the number of turns (total length of the winding) and the current density in the conductor.

Also the stray reactances of primary and secondary winding contribute to the measuring error. The stray flux can be reduced with a large cross section of the iron core, a high core induction, and long core limbs (which means thin windings).

A high core magnetization results in a high magnetizing current. But the magnetizing current which is a part of the no-load current $\boldsymbol{I}_0$ contributes to the measuring error as well. Despite a high core magnetization the no-load current can be reduced by using core materials with high permeability and low core losses.

Some of the above-mentioned design criteria contradict each other so that an optimal compromise has to be found. All design measures taken to reduce the measuring error must result in a voltage transformer which has a handable size and weight and needs a minimum of material.

Finally the measuring error can be optimized by the number of turns of the windings. An unloaded voltage transformer has a negative measuring error. The load has usually an inductive character so that the error becomes even more negative. So a turns correction is made. The number of turns of the primary winding is reduced so that the error of the unloaded transformer becomes slightly positive. The error of the loaded voltage transformer is not as negative as without turns correction and is consequently smaller.

The Capacitor Voltage Transfer

The capacitor voltage transformer is a special type of voltage transformer used in the high-voltage power grid. The capacitor voltage transformer consists of a capacitive voltage divider C_1 and C_2 and an inductive transformer T as depicted in Fig. 9(a).

The high voltage $\boldsymbol{U}_1$ is applied at the capacitive voltage divider. The divider reduces the power grid voltage to a voltage $\boldsymbol{U}_T$ in the medium high voltage range (10 kV or 20 kV). The voltage $\boldsymbol{U}_T$ is the primary voltage of an inductive voltage transformer T. $\boldsymbol{U}_T$ is transformed to a low-voltage $\boldsymbol{U}_2$ which can be applied to measuring and control instruments.

For the supply of the measuring instruments a certain power is needed. Contrary to the pure capacitive divider

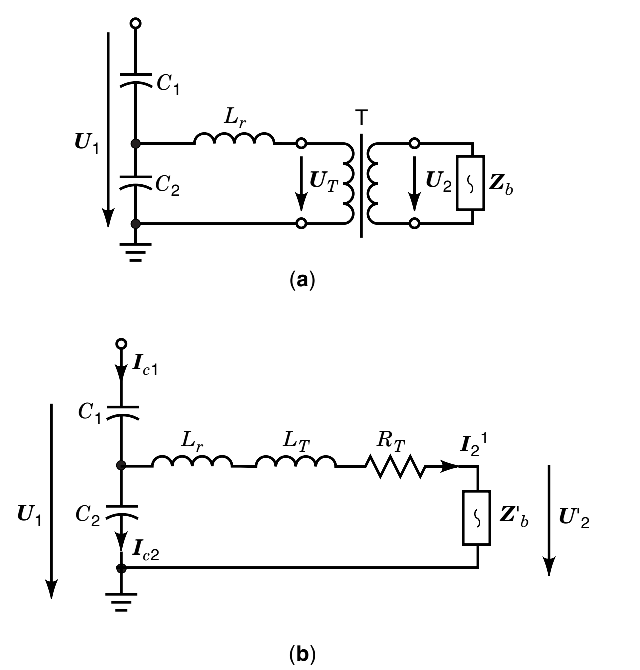

Figure 9. (a) A capacitor voltage transformer consists of a capacitive divider C_1–C_2, an inductive voltage transformer T, and a reactor L_r. (b) The equivalent circuit considers the inductive transformer by R_T and L_T.

which can only supply measuring instruments with a very high input impedance, the capacitor voltage transformer is able to supply the necessary power for measuring and control equipment used in power supply.

Figure 9(b) shows the equivalent circuit for the capacitor voltage transformer. The losses and inductances of the inductive voltage transformer are represented by R_T and L_T. L_r is needed for the resonance tuning. If the capacitor voltage divider is loaded with a burden, the current $\boldsymbol{I}_{C_1}$ is split in $\boldsymbol{I}_{C_1} = \boldsymbol{I}_{C_2} + \boldsymbol{I}_2$. The inductive voltage transformer is an inductive load for the capacitive divider. This means that $\boldsymbol{I}_{C_2}$ becomes greater $\boldsymbol{I}_{C_1}$. Therefore the voltage $\boldsymbol{U}_{C_2}$ is higher than the voltage $\boldsymbol{U}_{C_2}$ at an unloaded capacitive divider. The voltage $\boldsymbol{U}_{C_2}$ rises with the load current $\boldsymbol{I}_2$. To prevent this rise of the voltage $\boldsymbol{U}_{C_2}$ during rated operation, a reactor L_r is used. L_r is rated so that the voltage rise at C_2 is compensated by the voltage drop at $L_r + L_T$. This is achieved by tuning the circuit in resonance. Therefore the following equation must be met:

$$2\pi f(L_r + L_T) = \frac{1}{2\pi f(C_1 + C_2)}$$

Then with a purely resistive load R_b the voltages $\boldsymbol{U}_1$ and $\boldsymbol{U}_2$ are in phase. There is only an error in magnitude which can be reduced by a turns correction in the inductive voltage transformer.

The advantage of a capacitor voltage transformer is that the inductive part of the transformer needs only to be isolated for the medium high voltage $\boldsymbol{U}_T$ instead of the full-power grid voltage $\boldsymbol{U}_1$. The insulation of an inductive voltage transformer for the high voltage range has to handle the nonlinear voltage distribution over the complete winding length during stress with impulse voltages. The impulse voltages at the capacitors of the capacitor voltage transformer distribute almost linearly so that the capacitor isolation is simpler. A capacitor voltage transformer can additionally be used as a coupling device for power-line carrier transmission.

The capacitances of the capacitors C_1 and C_2 are dependent on their temperature, so both capacitors should have the same temperature over the whole operation range to reach a stable transformation ratio.

The phasor diagram is similar to the phasor diagram of the inductive voltage transformer. The accuracy classes and rated power classifications can also be compared to the inductive voltage transformer.

Operating Conditions of Inductive Voltage Transformers

Normal Operation. The usual operation of voltage transformers is at their rated voltage. There is only a small fluctuation of the voltage of a power grid. The maximum voltage fluctuation can be assumed smaller than 20%. The operation voltage stresses the primary winding over its full length. So the insulation of the primary winding must withstand the operation voltage for the voltage transformers' expected full lifetime. The same is for the insulation between the primary winding and all parts in the voltage transformer connected to ground potential. The voltage transformer is specified for a certain rated burden power. IEC 185 offers the following values for the voltage transformer power (in volt-amperes):

<u>10</u> 15 <u>25</u> 30 <u>50</u> 75 <u>100</u> 150 <u>200</u> 300 400 <u>500</u>

(The underlined values are preferred values.) The power factor is cos $\beta = 0.8$ inductive.

Temporary Overvoltages at Rated Frequency. In power systems without solid grounding, a single-phase-to-ground fault leads to a voltage rise in the two phases which are not affected by the fault. The voltage rises from the line-to-ground value in normal operation to the line-to-line value during the fault. This condition can last for hours. This means that the insulation of the voltage transformer is stressed with a voltage $\sqrt{3}$ higher than usual. Beyond that, the induction in the iron core rises by that factor leading to higher losses in the iron core and in the primary winding heating the voltage transformer. It must be able to withstand this voltage and thermal overstress.

Transient Overvoltages. Transient overvoltages occur during switching operations, flashovers, or lightning strikes. They stress the insulation of the voltage transformer, but in a different way from the stress caused by voltages at rated frequency. The primary winding of the voltage transformer is not a homogeneous structure for transient overvoltages compared to rated frequency voltages. The overvoltage does not distribute linearly over the total winding anymore. The main part of the transient voltage drops at the first few turns of the complete primary winding. So the insulation is extremely stressed in the vicinity of the first turns and must be dimensionated for this severe voltage stress.

Ferroresonance. Ferroresonance is a phenomenon which can occur at voltage transformers with one winding terminal earthed. Instable operation conditions can occur which lead to overvoltages. These overvoltages can be transient or last for a long time. They stress the voltage transformer's insulation and may result in a dielectric and thermal overstress of the transformer.

Figure 10(a) shows a simple case to explain the conditions of instability. It shows an iron-cored reactor with a capacitor in series. U_0 is the steady power system voltage. Figure 10(b) depicts the voltage–current characteristic for the capacitor (U_C) and for the reactor (U_L) which has a nonlinear relation between voltage and current. The voltage U_0 drops at the inductance and the capacitor. It is expressed as $\boldsymbol{U}_0 = \boldsymbol{U}_L + \boldsymbol{U}_C$.

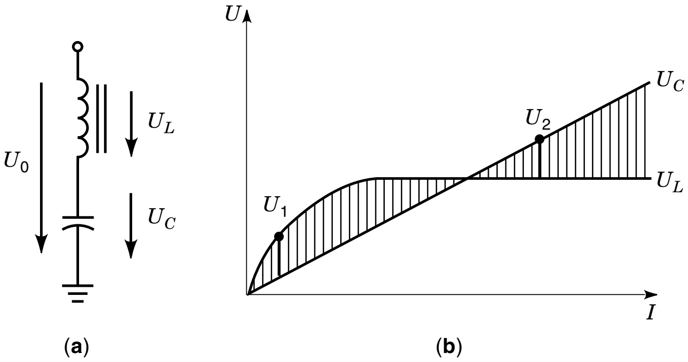

Figure 10. Resonance circuits with an iron-cored inductance can cause instability and transient overvoltages. (a) Equivalent circuit causing instability. (b) Voltages in equivalent circuit depending on an increasing current I.

Since the voltage U_L and U_C are in phase opposition, the magnitudes of the phasors are: $U_0 = U_L - U_C$. So the voltage U_0 is the difference of the curves in Fig. 10(b) marked by vertical lines. Starting at zero the voltage U_0 is raised. The current I rises as well as the voltages U_L and U_C. When the point U_1 is reached, the causal relation of rising U_0, U_L, U_C, and I is not valid anymore because a rising of U_0 seems to be not possible beyond the point U_1. A raising of U_0 is just possible beyond the point U_2. Since U_0 is an independent voltage, a further raise of U_0 must be possible. The consequence is that the state U_1 must jump to the state U_2 because the area in between is an unstable state. According to Fig. 10(b) and the equation above U_0 should be negative. Since U_0 is the independent power system voltage, this is not possible. Consequently, if U_0 cannot become negative, the current I has to become negative. In the end the current magnitude jumps to a higher value and changes its phase by 180°. Such a sudden change must be initiated by power system instabilities or switching operations. It is a transient phenomenon and may result in overvoltages in the power system.

According to the theory explained above, enduring oscillations in the power system can occur if there is another stray capacitance or another inductance contributing to the effect.

Resonance circuits are formed which are able to oscillate for a long time after they have been stimulated by a power system instability or switching operation (Fig. 11). Because of ferroresonance, these enduring oscillations can cause enduring overvoltages at the voltage transformer and result in the saturation of the iron core. So the insulation of the voltage transformer is endangered by voltage and temperature stress.

Shorted Secondary Winding. The voltage transformer is operated with a high burden impedance. If the secondary winding is shorted because of a fault in the secondary lines, a high current flows; this flow is only limited by the voltage transformer's small stray reactances and its winding resistances. The winding conductors and the conductors of the secondary lines cannot withstand the transformer's short-circuit current for a long time because of their small cross section. A voltage transformer according to IEC 185 has to withstand a short circuit for 1 s. Therefore, fuses are sometimes used to protect the secondary circuits. However, these fuses contribute to the burden of the voltage transformer.

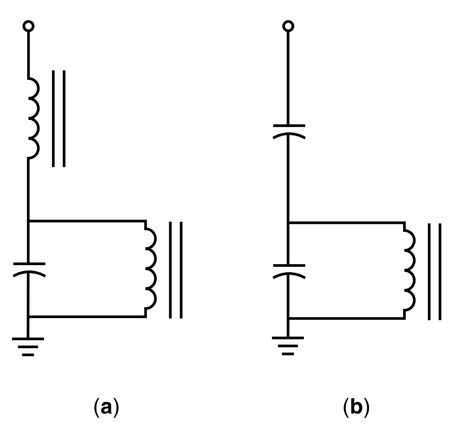

Figure 11. Certain power system configurations can cause ferroresonance. (a) Voltage transformer inductance in parallel to line-to-earth capacitances with stray reactance of power transformer in series. (b) Voltage transformer inductance in parallel to line-to-earth capacitances in series with a capacitance.

Tests of Voltage Transformers

The capability of a voltage transformer to fulfill the requirements derived from the different stresses during its operation in a power grid has to been proved with several tests. Tests of voltage transformers according to IEC 185 are classified in the following:

1. Type tests (for a new type or changed design),
2. Routine tests (for every voltage transformer leaving the factory),
3. Particular tests (only necessary on demand of the client).

Type Tests

- Temperature rise
- Lightning impulse voltage
- Switching impulse voltage
- Wet test for outdoor voltage transformers
- Test of measuring error
- Short-circuit capability

Routine Tests

- Control of terminal assignment
- Alternating-current voltage test at secondary winding
- Alternating-current voltage at parts of windings
- Alternating-current voltage primary winding
- Partial discharge measurement
- Test of measuring error

Particular Tests

- Chopped-wave lightning impulse voltage
- Transient overvoltages at the secondary terminals

CURRENT TRANSFORMER

The current transformer supplies a small current $\boldsymbol{I}_2$ proportional to a high primary current $\boldsymbol{I}_1$. The performance of the current transformer is based on the equivalent circuit in Fig. 5. The current transformer works with a small burden impedances $\boldsymbol{Z}_b$. In principle the phasor diagram of the current transformer can be constructed similar to the phasor diagram of the voltage transformer as described above, starting with the current and voltage phasor at the burden. However, it should be considered that the voltages $\boldsymbol{U}_1$, $\boldsymbol{U}_0$, and $\boldsymbol{U}_2'$ are very small, whereas the measuring values (the currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2'$) are high compared to the voltage transformer. The phasor diagram of the current transformer is centered around the current phasors [Fig. 12(a)].

It can be seen that the current transformer does not behave like an ideal transformer. There is a phase difference between the primary current $\boldsymbol{I}_1$ and the secondary current $\boldsymbol{I}_2'$, the phase error δ_I. The phasors have a different length, the error in magnitude $|\boldsymbol{F}_I|$. The error is determined by the current $\boldsymbol{I}_0$. Also the shorted current transformer ($Z_b = 0$) has a measuring error. In this case the magnetizing current induces

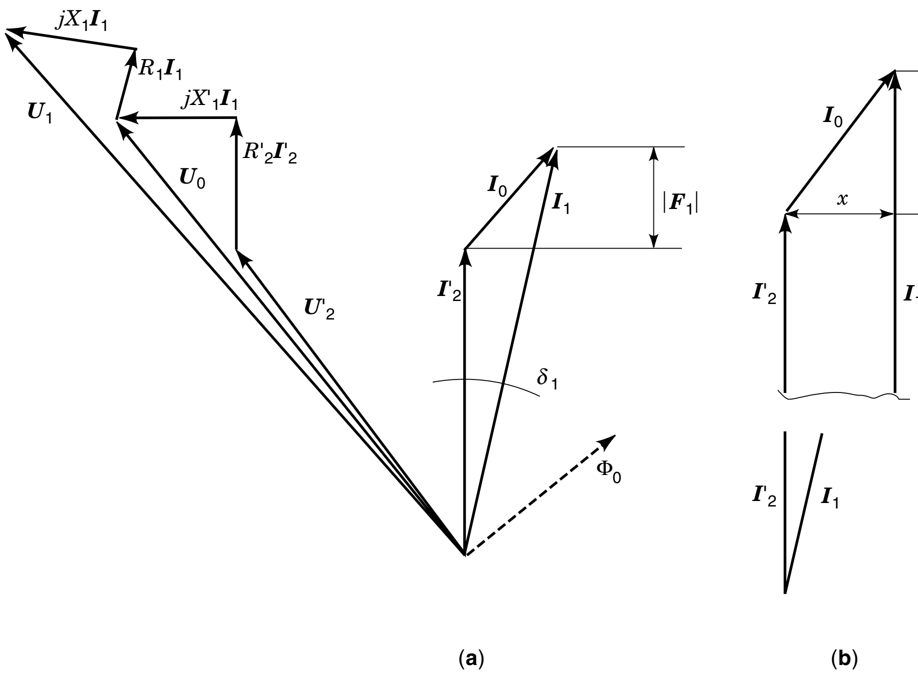

Figure 12. Phasor diagram of the current transformer. (a) Complete phasor diagram. (b) The detail shows the error in magnitude y and in phase x.

the voltage $\boldsymbol{U}_0$ to compensate only the voltage drop at the secondary resistance R'_2 and stray reactance X'_2. If the burden impedance is not zero although it is quite small a higher voltage $\boldsymbol{U}_0$ is necessary to compensate the voltage drop in the secondary circuit. This means a higher current $\boldsymbol{I}_0$ is required so that the measuring error increases.

The phasor diagram in Fig. 12(a) is drawn in a scale different from reality. Since the measuring error of the current transformer is just a few percent and less the phasor $\boldsymbol{I}_0$ is much shorter than $\boldsymbol{I}'_2$ and $\boldsymbol{I}_1$ so that $\boldsymbol{I}'_2$ and $\boldsymbol{I}_1$ are almost parallel as depicted in Fig. 12(b). So the distance x is proportional to the error angle δ_I, and y is proportional to the magnitude $|\boldsymbol{F}_I|$ of the measuring error.

With the following considerations a formula can be derived to understand the measuring error of the current transformer with respect to its geometric design. The measuring error in percent for rated operation of the current transformer is given by the formula

$$\boldsymbol{F}_1 = \frac{\boldsymbol{I}'_2 - \boldsymbol{I}_1}{\boldsymbol{I}_1} \times 100\% = -\frac{\boldsymbol{I}_0}{\boldsymbol{I}_1} \times 100\% \approx -\frac{\boldsymbol{I}_0}{\boldsymbol{I}'_2} \times 100\% \qquad (19)$$

The induced voltage $\boldsymbol{U}_0$ is equal to the voltage drops in the secondary circuit:

$$\boldsymbol{U}_0 = \boldsymbol{I}_2 \cdot (\boldsymbol{Z}'_2 + \boldsymbol{Z}'_\mathrm{b}) \qquad (20)$$

Faraday's law describes the induction of the voltage $\boldsymbol{U}_0$ dependent from the flux $A_{\mathrm{Fe}} \cdot \boldsymbol{B}$:

$$\boldsymbol{U}_0 = j\omega w_2 A_{\mathrm{Fe}} \cdot \boldsymbol{B} \qquad (21)$$

Ampere's law connects the flux density $\boldsymbol{B}$ with the magnetizing current $\boldsymbol{I}\mu$:

$$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} = \mu_0\mu_r \cdot \frac{\boldsymbol{I}_0 \cdot w_2}{l_E} \qquad (22)$$

Combining Eqs. (19)–(22) the result is the magnitude of the measuring error:

$$|\boldsymbol{F}_1| = \frac{l_{\mathrm{Fe}}}{\omega w_2^2 A_{\mathrm{Fe}}\mu_0\mu_{\mathrm{r}} \cdot (\boldsymbol{Z}'_2 + \boldsymbol{Z}'_b)} \qquad (23)$$

Equation (23) shows that the measuring error increases with the length l_{Fe} of the magnetic circuit. The higher the impedance $\boldsymbol{Z}'_2 + \boldsymbol{Z}'_b$ of the secondary circuit, the higher the error.

The error is reduced with increasing cross section A_{Fe} of the core and with higher permeability μ_r. A higher number of turns w_2 of the secondary winding reduces the measuring error even in square.

The considerations above are valid for rated operation of the current transformer—that is, at a low degree of magnetization. When there is a fault in a power grid the current in the primary winding of the current transformer can become many times higher. This will lead to a high magnetization level of the iron core so that the iron core will be saturated. The currents contain harmonics and thus will not be sinusoidal and monofrequent anymore, and therefore the phasor diagram and the error equations above are not valid anymore. So the measuring error in this case is defined by the root-mean-square value:

$$F = \frac{\sqrt{\dfrac{1}{T}\displaystyle\int_0^T (k_I \cdot i_2(t) - i_1(t))^2\,dt}}{I_1} \cdot 100\% \qquad (24)$$

Compared to a voltage transformer whose measuring magnitude, the voltage, stays within 20% of its rated value, the currents to be measured in a power system cover a wider range. The rated currents at a few hundred amperes have to be measured as well as the fault currents up to a few tens of kiloamperes.

If during a fault the iron core is saturated because of the high current amplitudes, the secondary currents are not proportional to the primary currents anymore and remain smaller. This effect is used to protect the secondary equipment against overload, but it is not desired for a distinct detection of a fault in the power system when a reliable secondary current is needed. So a particular design of the current transformer is needed to measure the rated current on the one hand and the fault current on the other hand. This leads to the current transformer with two magnetic circuits, both of which are supplied by the primary winding. One iron core with its own secondary winding is optimized for the measurement of the rated current, while the other is optimized for the measurement of the fault current.

Design of Current Transformers

In the design of current transformers, three different types of iron cores are used Fig. 13:

1. The limb-type core
2. The sleeve core or M-core
3. Toroidal core

The toroidal core offers the advantage that it can be made from one complete strip of iron. In this way the permeability of the material can be used best so that it is applied for current transformers with a high accuracy. The core material based on nickel iron alloy offers the necessary high initial permeability. But also siliconized steel is used. Often different core materials are combined for best performance.

The primary winding can be realized in different ways. The primary winding can consist of several turns, which produces the wound-primary current transformer. But the primary winding can also consist of only a bar—that is, a single turn, which produces the bar-primary current transformer. This type of current transformer can be mounted directly on a conductor which then is the primary winding.

For a flexible application, some wound-primary current transformers have the ability to select the current transformation ratio. This can be realized either with the primary or with the secondary winding. If the selection is done on the primary side, the primary winding consists of different parts. These can be connected in series or in parallel to select the ratio I_1/I_2. Since the rated primary current I_1 changes proportionally to the selection of the ratio, the ampere-windings of the current transformer do not change and the measuring characteristics including the error stay the same. If the ratio selection is realized with different parts of the secondary winding, this is different since a change in the rated primary current in combination with the same number of turns of the primary winding results in a different ampere-winding so that the measuring error will change.

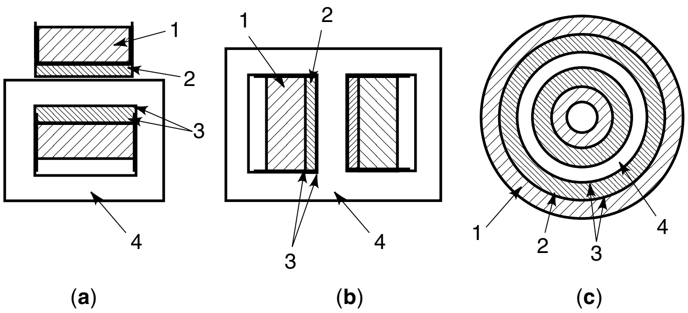

Figure 13. Current transformer core types (sectional view): (a) limb-type core, (b) sleeve core or M-core, (c) toroidal core. 1, primary winding; 2, secondary winding; 3, isolation; 4, core.

Operation Conditions of Current Transformers

Normal Operation and Overvoltages. The current transformer has to insulate the power grid operating voltage for its complete lifetime. The insulation has to withstand the possible overvoltages in the power grid due to switching operations or lightning strikes, specified by the insulation levels for the current transformer's rated voltage.

The current transformer has a rated primary current for long-time operation. The standard primary currents (IEC 186) are

$$\underline{10}\quad 12.5\quad \underline{15}\quad 20\quad 25\quad \underline{30}\quad 40\quad \underline{50}\quad 60\quad \underline{75}\,\text{A}$$

and their decimal multiples. The standard secondary currents (IEC 186) are 1 A, 2 A, and $\underline{5}$ A (the underlined values are preferred).

Maximum Currents. During a fault in the power grid the current can rise enormously compared to the rated current in the power grid. The transient currents can reach amplitudes up to a few tens of kiloamperes. The current transformer must be able to handle these high currents thermically and dynamically. The standard IEC 186 defines three limiting current values:

1. *Rated Short-Time Thermal Current* I_{th}. I_{th} is the maximum root-mean-square value of the primary current which the shorted current transformer is able to withstand for 1 s without damage.
2. *Rated Dynamic Current* I_{dyn}. Amplitude of the primary current so that the current transformer is not damaged electrically and mechanically due to the electrodynamic force caused by the current.
3. *Rated Continuous Thermal Current.* Maximum continuous current in primary winding so that the current transformer does not exceed its maximum temperature if it is loaded with its rated burden.

Open Secondary Circuit. The current transformer must be operated with small burden impedances Z_b. This means that the whole secondary circuit of the current transformer is always closed and the current i_2 can flow. The ampere-windings w_1i_1 and w_2i_2 differ only by the small amount which is necessary for the magnetization of the iron core:

$$w_1 i_\mu = w_1 i_1 - w_2 i_2$$

Opening the secondary circuit has severe consequences. The current i_2 becomes zero so that the balance of ampere-windings is

$$w_1 i_\mu = w_1 i_1$$

The current i_1 does not change so that the ampere-windings $w_1 i_1$ cause a high magnetization of the iron core. On the one hand, this leads to high losses in the iron core so that the maximum temperature of the current transformer can be exceeded. On the other hand, the high flux in the iron core results in a high induced voltage in the unloaded secondary winding. The induced voltage can be dangerous for the operating staff and the current transformer's insulation.

Tests of Current Transformers

The capability of a current transformer to fulfill the requirements derived from the different stresses during its operation in a power grid must be proved with several tests. Tests of current transformers according to IEC 186 are classified as type tests, routine tests, and particular tests.

Type Tests

- Short-time current
- Heating test
- Lightning impulse voltage
- Switching impulse voltage
- Wet test for outdoor current transformer
- Test of measuring error

Routine Tests

- Control of terminal assignment
- Alternating-current voltage test at secondary winding
- Alternating-current voltage test between partial windings
- Induced voltage test
- Alternating-current voltage test primary winding
- Partial discharge measurement
- Test of measuring error

Particular Tests

- Chopped lightning impulse voltage
- Measurement of dielectric loss factor
- Transient overvoltages at the secondary terminals

COMBINED CURRENT AND VOLTAGE TRANSFORMERS

In power grids with higher voltage levels, voltage and current transformers can be assembled in one common apparatus to save space in the substation and reduce production costs and costs during transport, installation, and maintenance. The design and electrical characteristics of the voltage and current transformer separately are as described in the previous sections. But some considerations about insulation and influence between the two parts have to be taken into account. The first question is where the current transformer on the one hand and the voltage transformer on the other hand are placed. A common design is to place the current transformer at the top and the voltage transformer at the bottom of the combined instrument transformer. This means that in the insulator the high voltage potential must be conducted from the top to the bottom parallel to the secondary circuit of the current transformer on ground potential. These two circuits have to be thoroughly insulated against each other. Another problem is the mutual interference of the voltage and current measurement in a combined instrument transformer. The high currents in the current transformer's primary circuit can induce voltages in the voltage transformer if the flux of the current conductor is linked to the coils of the voltage transformer. Since this induced voltage has a phase difference of 90° to the primary voltage, the measuring error can easily become high. So the voltage transformer must be placed so that the flux of the current conductor is not linked to the coils. Moreover, the current measurement can be influenced by the high voltage applied to the combined instrument transformer. Displacement currents through capacitances in the construction of the instrument transformer can add to the measuring currents of the current transformer. A thorough shielding of the current transformer's winding and secondary circuit reduces the effects on an acceptable minimum.

FAST TRANSIENTS IN POWER SYSTEMS AND THEIR EFFECT ON SECONDARY CIRCUITS

In recent years the technology of the secondary measuring and control equipment has rapidly changed. The previously used electromechanical measuring and control devices have been replaced by electronic equipment. The electronic equipment is more sensitive against electromagnetic interference than the older robust electromechanical devices. However, the electronic devices offer many advantages such as high accuracy, solution of complex control problems, flexible usage because of software control, easy installation, and lower costs so that the control of power systems without those electronic equipment is not imaginable anymore. Electronic modules work with low signal voltages in the range of a few millivolts or volts. Thus high interference voltages in the secondary circuits can cause malfunction or destruction of the electronic control devices. In order to understand the rise of interference voltages in secondary circuits, the sources (i.e., fast transient voltages and currents in the high-voltage circuits) as well as the mechanisms responsible for the coupling into the secondary circuits have to be regarded. The characteristics of the interference sources and the coupling mechanisms depend on the kind of substation regarded:

- Air-insulated substations (AIS)
- Gas-insulated substations (GIS)

Besides, the phenomena are a matter of the size and of the voltage level of a substation. Within the same voltage level a different design of a substation influences the rise of interference voltages.

The highest interference voltage amplitudes have been observed in the secondary circuits of high-voltage substations with rated voltages higher than 100 kV so that the interference characteristics there are described first. The most significant interference sources are switching operations with disconnectors or circuit-breakers. Switching operations have the aim to connect energized and de-energized parts of an electrical installation (switching on) or to de-energize parts (switching off). The switching of disconnectors in high-voltage substations is the most frequent operation, and it takes a longer time (up to 2 s) because of the slow movement of a disconnector compared to a circuit-breaker. Disconnectors are not ideal switches. If a disconnector is opened or closed, the arc quenches and restrikes until the gap is completely opened or closed. During the strikes of the arc the capacitances of the substation busbars and lines are charged and discharged depending on the steady voltage of the power system. With every strike, steep voltage changes occur which propagate in the substation. The characteristics of these fast transient phenomena shows differences between air- and gas-insulated substations. The restrike of the arc in air disconnectors takes place within the order of 100 ns, whereas in gas-insulated substations with pressurized SF_6 (sulfur hexafluoride) the breakdown of the insulation is much faster, namely within the order of 10 ns or even less. These steep voltages propagate as traveling waves on the substation conductors and can initiate high frequent oscillations whose frequencies are determined by the design of the substation. This happens with every restrike of the disconnector. The total number of restrikes during a switching operation can be several hundred. Thus the fast transient voltages can be characterized by their rise time, the characteristic oscillation frequencies, the repetition rate, and their amplitude. The fast transient voltages are linked to fast transient currents in the conductors. The voltages and currents cause electric and magnetic fields. If the electric and magnetic fields contain high frequencies compared to the size of the conductors, the radiation of an electromagnetic wave is possible.

The coupling of these fast transient voltages into the secondary circuits occurs in different ways. The most significant ones are depicted in Fig. 14.

As described above, the interference sources are fast transient phenomena (frequencies up to several tens of megahertz). So the secondary circuits behave quite different than they use to do at rated frequency. For example, the equivalent circuit which simulates instrument transformers at the rated frequency described above is not valid anymore. Parasitic capacitances and inductances have to be considered. Also, the grounding grid and secondary cables are no longer ideal conductors with only a resistive component. Frequency-dependent coupling impedances play an important role with regard to fast transient phenomena.

A visible link between the high-voltage circuit and the secondary circuit is an instrument transformer. The fast transient phenomena can couple into the secondary circuits via parasitic capacitances. The voltages and currents are conducted by the secondary circuits to the electronic control equipment where the interfering voltages drop.

The fast transient voltages and currents, however, can couple via nonvisible links. This can be parasitic capacitances between the high-voltage conductors and the ground grid in a substation or the secondary cables. If the transients couple directly into the secondary cables, the currents in the cable lead to a drop of the interference voltages at the electronic equipment. Since the grounding grid in an air insulated substation or the grounding structure of a gas-insulated substation is not an ideal conductor, the coupling of the transient phenomena lead to potential differences in the grounding structure. These potential differences lead to interference currents in the secondary cables and to voltage drops at the electronic equipment. Recent investigations have shown that the inductive coupling between high-voltage conductors and secondary cables plays an important roll as well.

The relations in medium-voltage switchgear are different because they are compared to the high-voltage substations much smaller. A common design is the installation of the switching units into cubicles, and each cubicle has its own electronic control equipment. Since the cubicles are made of metal sheets being a good conductor, potential differences in the cubicles metal structure are low. Thus the transients can only couple directly into the secondary circuits or by the instrument transformers.

It is important to remark that the explanation for interfering voltages has to consider the time characteristics of the transients in the high-voltage circuit as well as the electrical performance of the whole secondary circuit, including instrument transformers, cables, and electronic equipment. Often different coupling mechanisms are superposed.

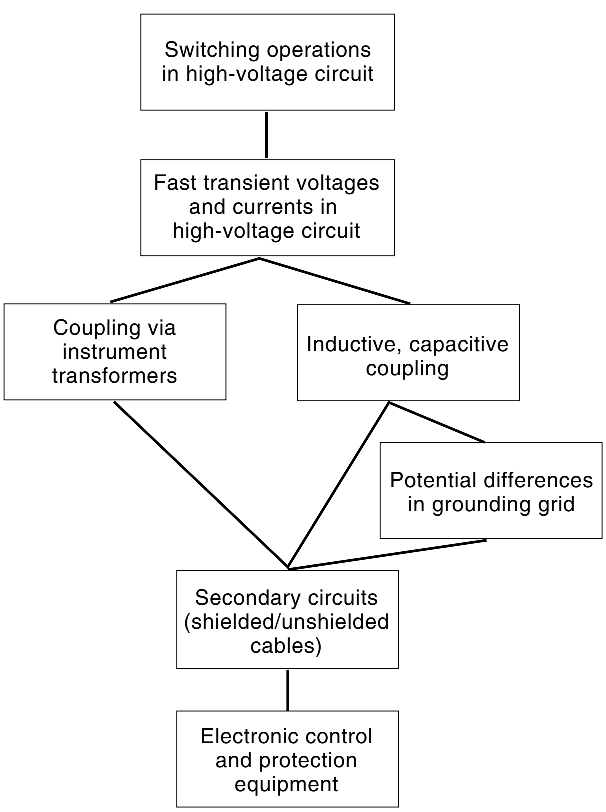

Figure 14. Fast transient voltages can couple into the secondary circuits by different ways.

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