The Transformer

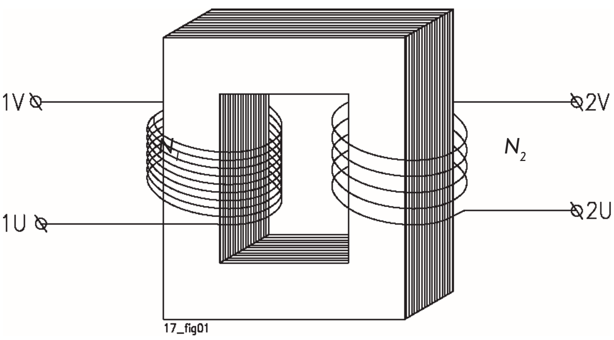
A transformer is an electrical machine without moving parts. It works on the induction principle and can only be connected to alternating current. Its main task is to transmit electrical AC energy, often from one voltage level to another.

The transformer is an important and efficient electrical apparatus, and it is widely used in electricity supply, electrical equipment and instruments where voltages other than those provided by the supply system are required.

Principle

In principle the single-phase transformer consists of a closed laminated iron core with two main parts: the yoke and the limbs.

One or more electrical conductors of insulated copper or aluminium are wound around each limb **N** times.



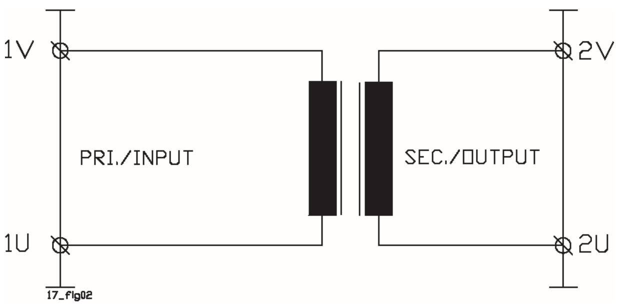
Schematic diagram of a single-phase transformer

The electrical conductors are magnetically coupled in that they surround a common magnetic circuit in the transformer core. Energy can be transmitted through this electrical/ magnetic coupling. Energy is supplied to one of the windings (**primary**), while energy can be tapped from the other winding (**secondary**). The number of turns of the primary winding, or the number of times the conductor is wound round the limb, is referred to as $\mathbf{N_1}$, while the number of turns of the secondary winding is referred to as $\mathbf{N_2}$.

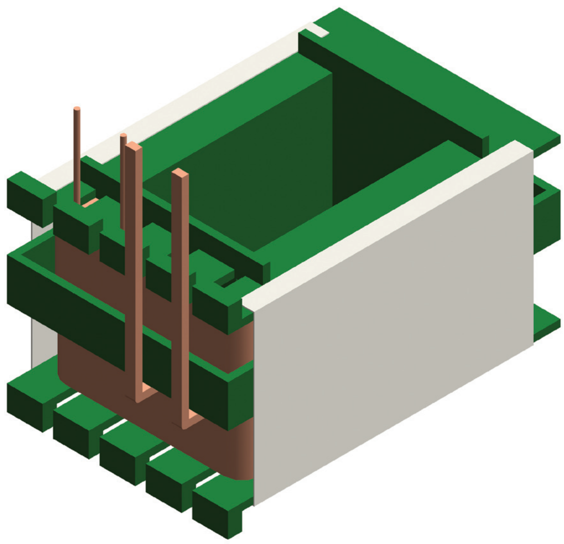
If an AC voltage $\mathbf{U_1}$ is applied to the transformer's primary winding, an AC voltage $\mathbf{U_2}$ with the same frequency occurs in the secondary winding by induction. The ratio between the voltages at no load is equal to the ratio between the number of turns of the coils.

i.e.: $$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

All transformers with separate primary and secondary windings are called **separating or isolating transformers**. Common to all such transformers is that they generate "a new system", with any earth faults on the supply side being eliminated on the delivery side.



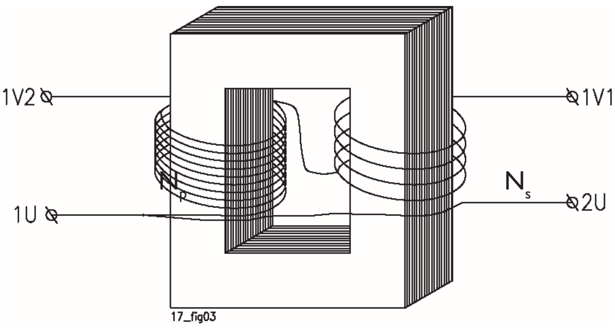
Connection diagram for a single-phase transformer. The primary and secondary windings are galvanically separated.



The drawing shows a transformer with a two-chamber coil form. Here we can clearly see that there are two separate windings (separating/isolating transformer). There is also insulation on the outside of those parts of the winding which are enclosed by the iron core. This is often use for reinforced insulation in class II transformers.

Autotransformer

In cases where there is no need for such galvanic separation between the primary and secondary windings, a transformer like that shown in the below figure can be built in principle. A design of this type is called an **autotransformer**. Here the entire coil functions as the primary winding and part of the coil functions as the secondary winding. The shared part of the winding can be called the common winding (**N_p**), while the other part is called the series winding (**N_s**).



Schematic diagram of an autotransformer

The ratio between the primary and secondary sides is expressed as follows:

$$\frac{U_1}{U_2} = \frac{N_p}{N_s}$$

The difference between the maximum and minimum voltage determines the dimensions and weight of the autotransformer. This design is particularly profitable when it comes to transformation ratios of less than 1:2. There is little financial gain to be had from using an autotransformer for ratios larger than this.

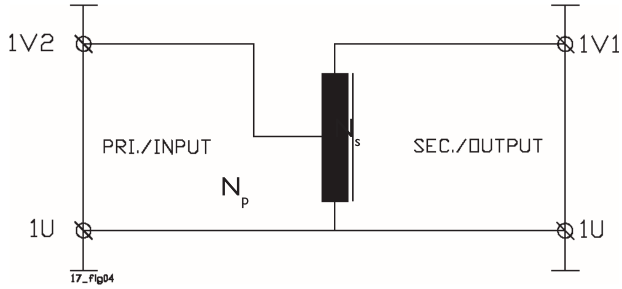
Example:

Transformer requirement for autoconnection:
Voltage transformation: 220/240 V
Transformer requirement: 1500 VA

$$\left(1 - \left(\frac{220\,V}{240\,V}\right)\right) \times 1500 = 125\,VA$$

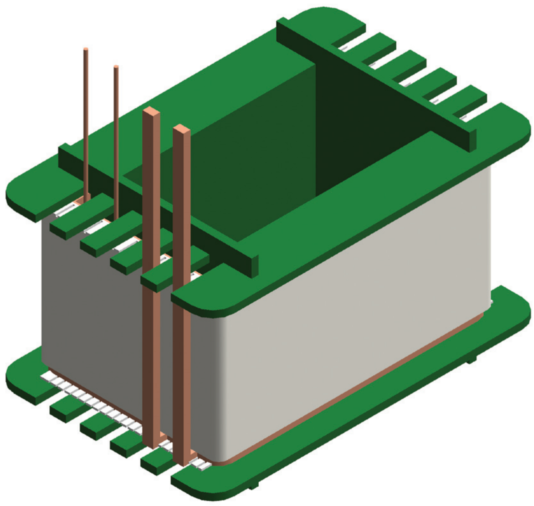
In this case an autotransformer with a core size equivalent to a 125 VA conventional transformer will be sufficient.

In practice an autotransformer will be smaller, lighter and cheaper than a conventional transformer with equivalent voltages and power.

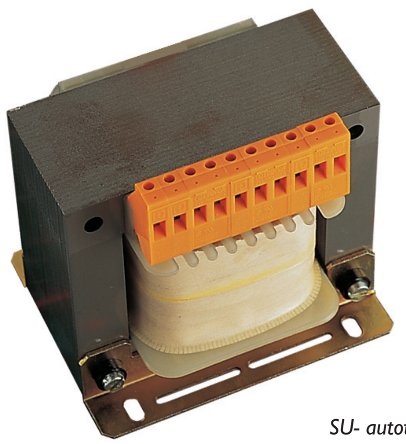


Connection diagram for a single-phase autotransformer. There is no galvanic separation between the primary and secondary sides. The example shows self-excitation.

The problem with an autotransformer design is that the secondary and primary sides will have the same voltage to earth in the event of an earth fault. In other words, autotransformers are not able to eliminate earth faults from the secondary side. All the earth fault problems in the power station's system would be propagated through the autotransformer, resulting in a considerable risk to safety. The use of autotransformers is therefore not permitted in boats and medical installations, etc.



The drawing shows an autotransformer with a single-chamber coil form. A single-chamber transformer does not have to be an autotransformer. The primary and secondary windings can be separated with other satisfactory forms of insulation.



SU- autotransformer

Voltage drops

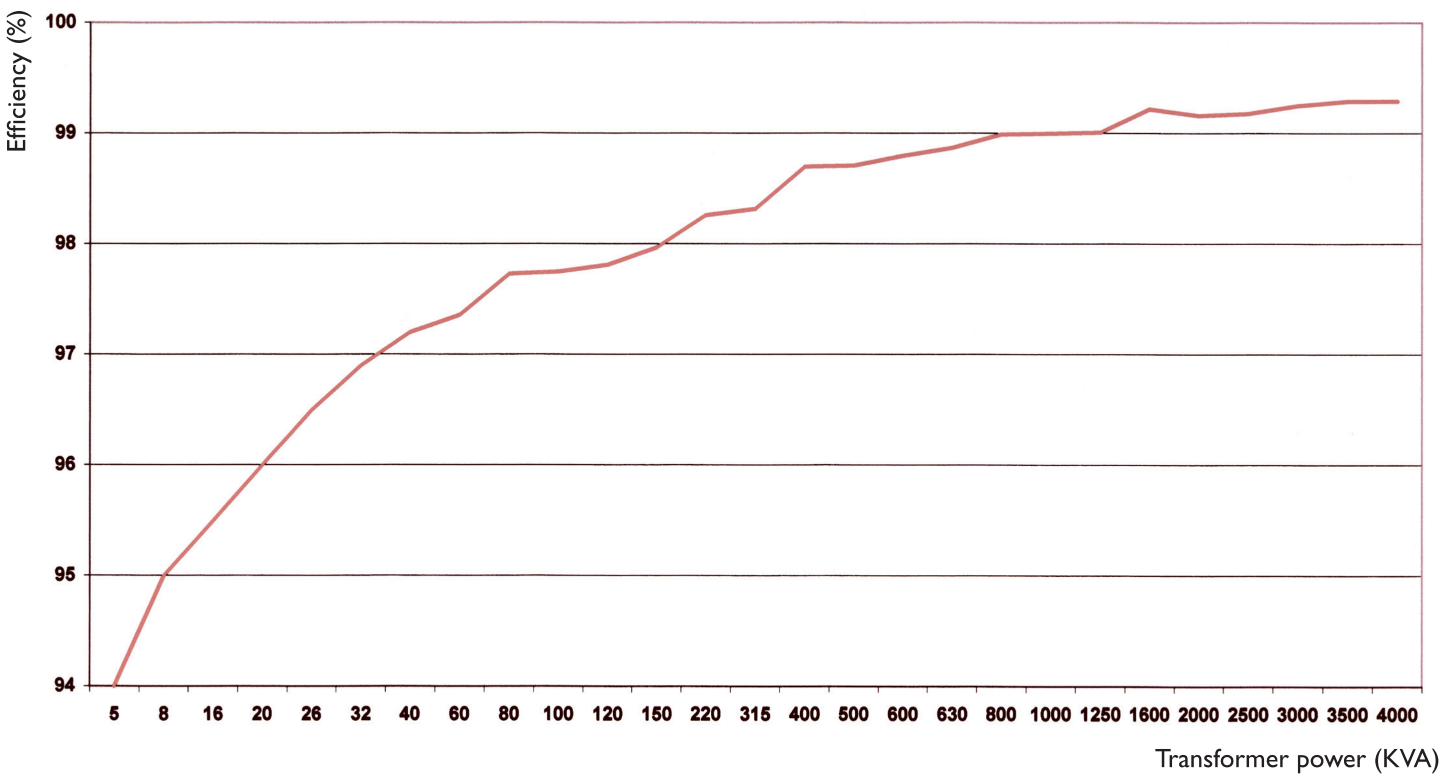
A transformer with no load normally has such a small primary current that we can ignore voltage drops. But in small transformers where the no-load current is a substantial component the secondary voltage will actually drop slightly from the theoretical transformation owing to the component IR^2. In this case the no-load current causes a copper loss, which in turn reduces the induced voltage. Under load the transformers primary and secondary currents are substantial, and we have to take account of voltage drops. The voltage drop in the transformer also varies according to the type of load. The short-circuit resistance and reactance will affect the voltage drop individually. That is to say, the voltage drop of an inductive load will be different to that of a purely resistive load. Both the primary and the secondary voltage drops are roughly proportional to the current. The voltage drops are specified by means of the short-circuit resistance (e_r), short-circuit reactance (e_x) and short-circuit impedance (e_z) at rated current in the form of relative or percentage values with reference to the rated voltage. Small transformers have bigger voltage drops than large ones.

Losses

All transformers, regardless of type or make, have a loss when put into operation. The most efficient large transformers have an efficiency of approx. 99-99.5%. There are largely two types of loss to be taken into account: no-load loss and load loss. The no-load loss, also known as the magnetisation loss, occurs because the iron in the magnetic circuit is exposed to a changing magnetic field, resulting in the consumption of reactive power. This loss can be calculated as constant if voltage is connected to the transformer. The no-load loss is measured at rated frequency with full voltage without load.

The load loss is made up of a heat loss owing to current, caused by the current having to flow through a resistance in the windings, and what is called the supplementary loss, which is due, among other things, to the leakage field around the windings. The total loss developed under load changes in proportion to the load squared.

Typical efficiency of dry-type transformers



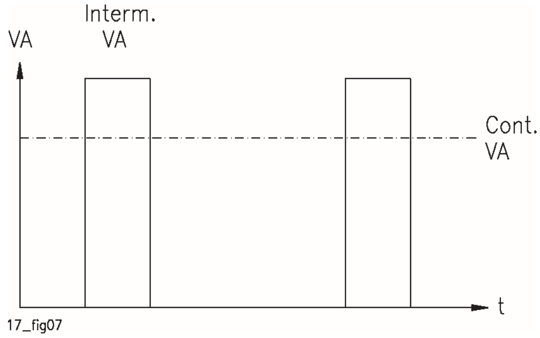
The graph shows the typical efficiency in % of dry-type transformers from Noratel. Power 5 to 4000 KVA.

Normal operating temperatures

By virtue of the fact that energy conversion in the transformer is not ideal, a small part of the supplied energy is lost in the form of heat. When building a transformer the aim is to minimise losses and therefore heat generation, but technical and economic factors set limits. The below graph gives typical values for the surface temperature of LF transformers from Noratel. It shows that it is completely normal for transformers to have a surface temperature of between 70 and 85°C in operation. The specified power of a transformer is often quoted for an ambient temperature of 40-45°C. If a transformer is put in a cabinet, the ambient temperature will increase. In practice this means that the transformer can be loaded less than the rated power would indicate. The larger the sealed box/cabinet, the smaller the power reduction.

Intermittent operation

The heat produced by the transformer is partly stored in its mass and partly given off to its surroundings. In the case of intermittent operation, the temperature will not be as high as for continuous operation at the same load owing to thermal inertia. If the periods with load are short in relation to the periods without load, the temperature rise will be modest in relation to continuous operation. Owing to thermal inertia, the heat given off will remain constant, and more of the stored heat will be given off, causing the temperature to drop. This means that the transformer can be overloaded for short periods.



Transformer in intermittent operation. Typical load is elevator, compressor or a crane.

Necessary transformer power (VA_{nom}) at intermittent operation:

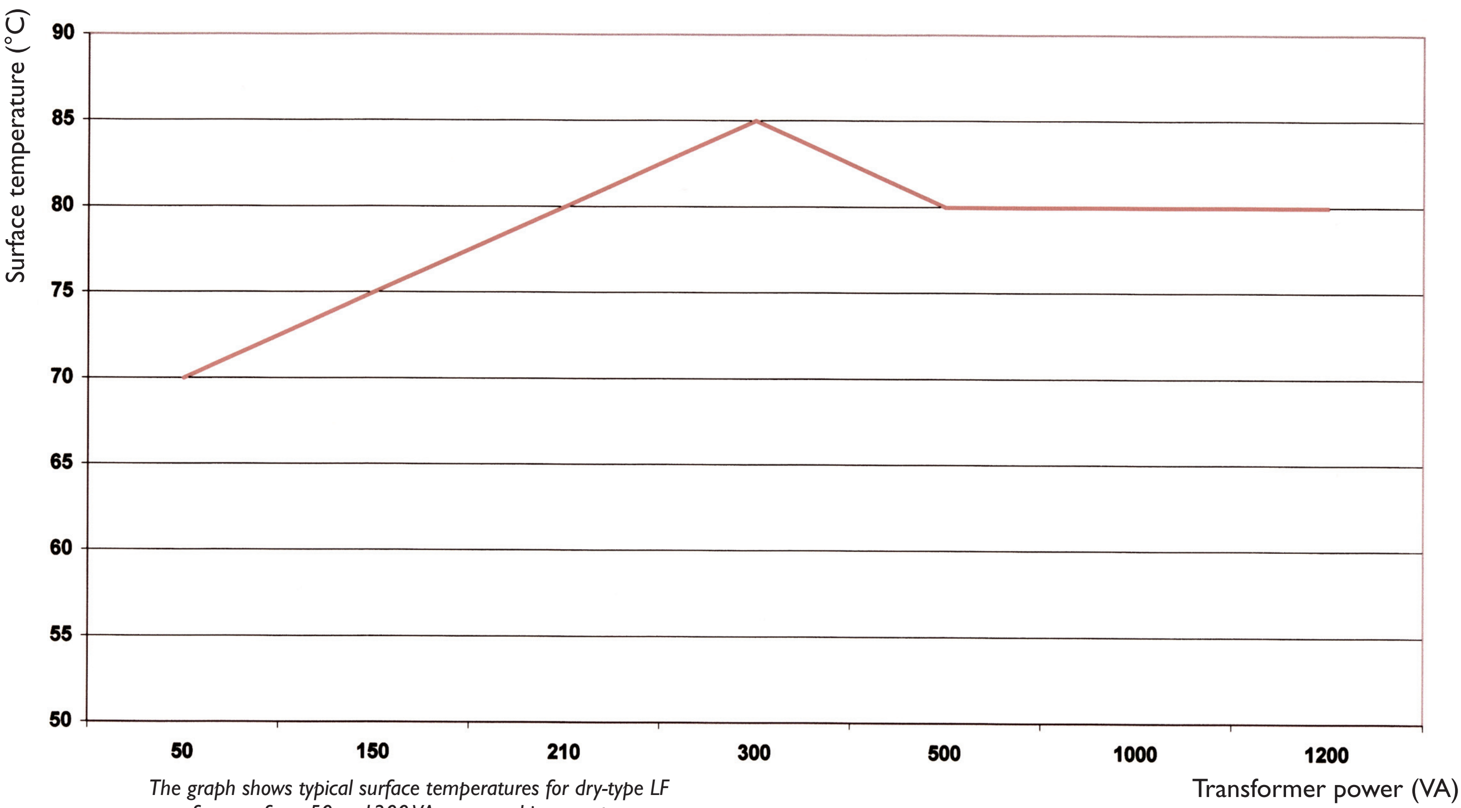
$$VA_{nom} = \sqrt{\frac{VA_{int}^{2} \times T_{int}}{T}}$$

Example:

Necessary transformer power when:
Load (VA_{int}) = 1000 VA
in 5 min/hour time interval (T_{int}):

$$VA_{nom} = \sqrt{\frac{1000^2 \times 5}{60}} = \underline{289\,VA}$$

Surface temperatures at t_a = 40 °C (LF-models)



The graph shows typical surface temperatures for dry-type LF transformers from 50 to 1200 VA at an ambient temperature of max. 40°C.

Cooling and cooling systems

To achieve effective heat release and reduce losses, the transformer enclosure and cooling system are designed with a view to carrying as much heat away from the transformer as possible. This can be achieved by making the heat-emitting surface large enough or providing for effective heat release by other means. The design of the transformer enclosure and cooling system is also dependent on the power of the transformer.

Load / ambient temperature

The size of the load is determined by the temperature in the transformer windings. The rated power of the transformer relates to a maximum ambient temperature (t_a max.), frequently 40°C or 45°C. This is the maximum temperature at which the transformer has the specified characteristics and can supply the specified power. The load must be reduced at higher temperatures. On the other hand, the load on the transformer can only be increased slightly at a temperature lower than t_a max. It is therefore important to take account of whether the transformer is to be installed in a sealed cabinet with other heat-generating equipment, for example, or whether ventilation will be possible.

The below graph shows transformer power/rated power as a function of ambient temperature for the two commonest temperature classes, class B (130°C) and class F (155°C).

Examples based on the graph:

Example 1:

What is the maximum permitted load for a class B, 250 VA (t_a = 40°C) transformer at an ambient temperature of 70°C?
From the table we can see that the power is reduced to 84% of rated power at t_a = 70°C.

This produces:

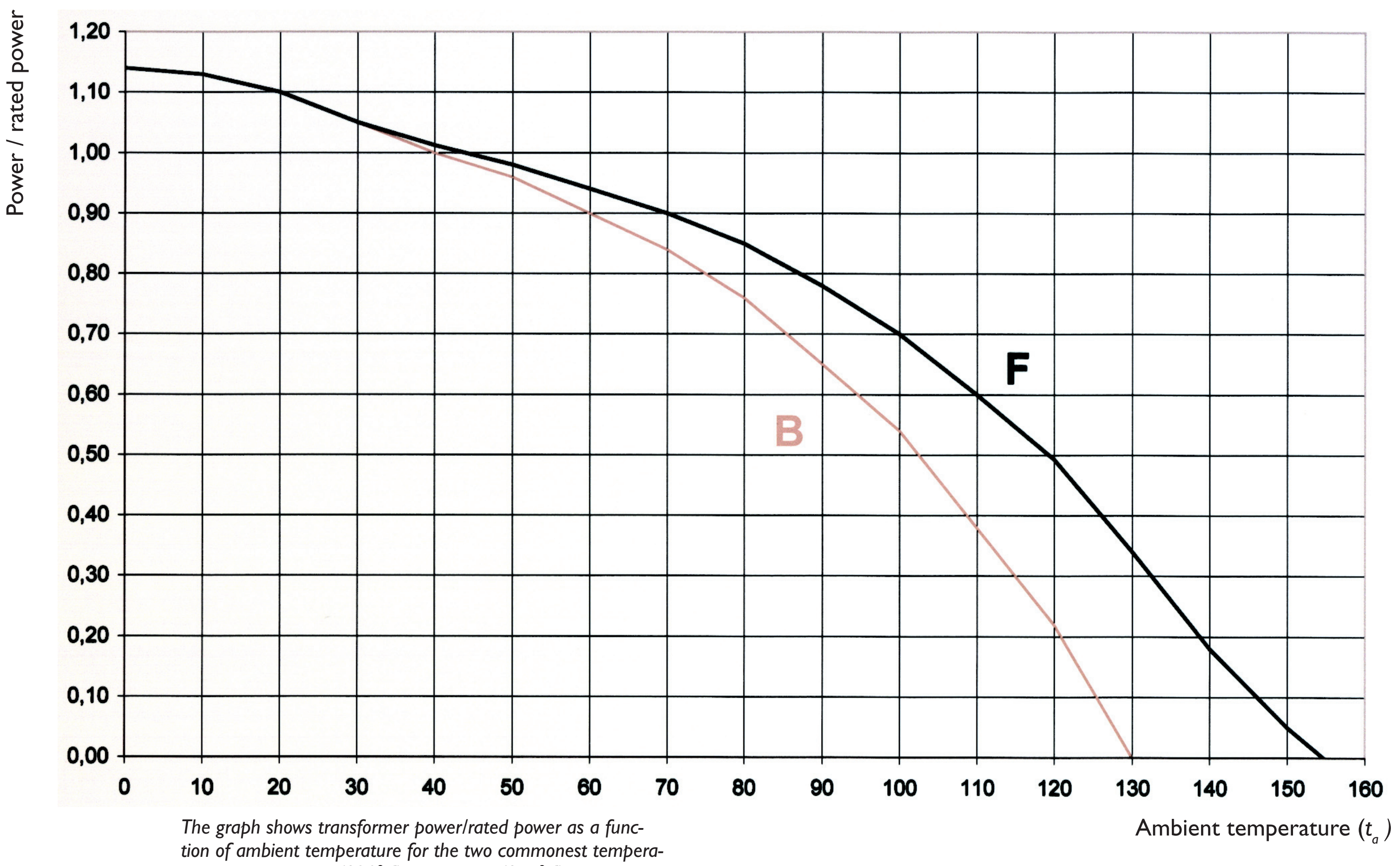
P = 250 x 0.84 = <u>210 VA</u>

Example 2:

Necessary transformer power: 180 VA
Ambient temperature: 70°C
How large does the transformer have to be?
(class B transformer, t_a = 40°C)

P_{max} = 180 / 0.84 = <u>214 VA</u>

Load / ambient temperature



The graph shows transformer power/rated power as a function of ambient temperature for the two commonest temperature classes, class B (130°C) and class F (155°C).

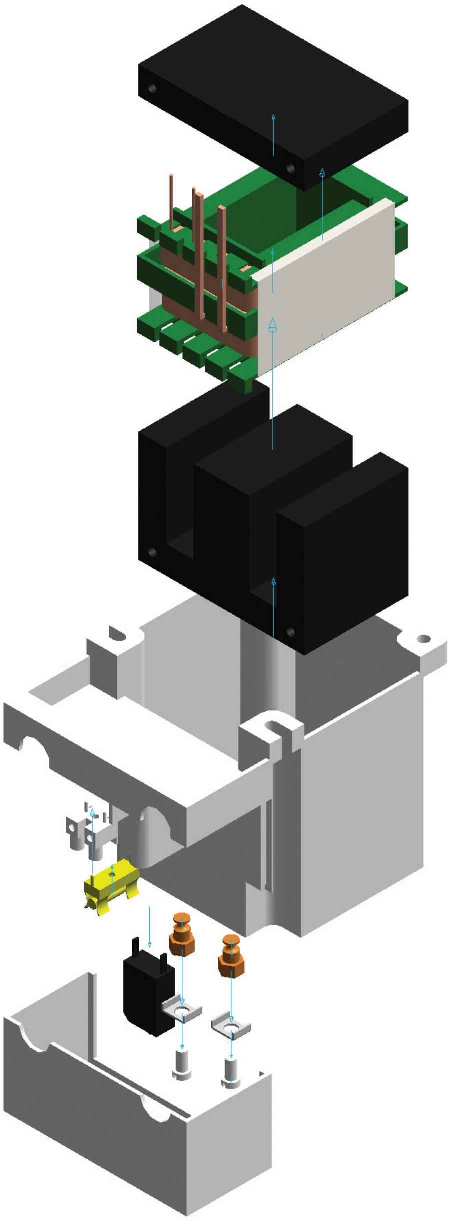
Structure / Choice of materials

The main parts in a dry-type transformer are the core material, steel, copper/aluminium and insulating materials. The quality and stability of these materials is vital in terms of losses, ability to withstand overloading and the transformer's operating temperature and service life.

The transformer core is often made up of iron or ferrite. In large transformers the iron core consists of very thin (0.3 mm), cold-rolled, laminated sheets insulated from each other by an insulating material which withstands tempera-tures in excess of 800°C.

In small transformers strip-wound cores, powder cores and ferrite cores are also used.

There are many different types of sheet quality with different parameters. High-quality sheet metal is more expensive, so the sheet quality is evaluated precisely on the basis of frequency, iron loss, overall size, etc.



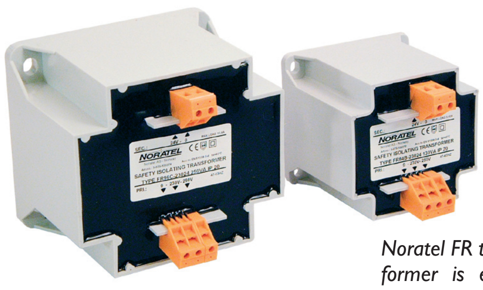
Typical structure of a safety transformer of the LF type with a two-chamber coil form. The whole construction is encapsulated in self-extinguishing polyurethane in the plastic enclosure.

In large transformers the corners are normally cut at an angle of 45° to reduce the losses and no-load current. The core cross-section is also made roughly circular. Depending on the size of the transformer, insulating tape, yoke bolts or adhesive can be used to hold the sheets together. The core and steel construction have a virtually unlimited service life in the temperature range in question.

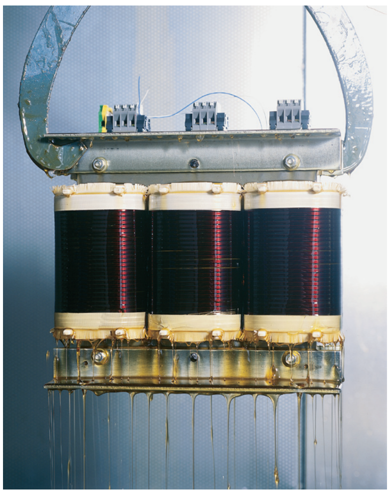
The windings generally consist of coils of insulated copper or aluminium conductors and are put on the transformer limbs using various methods. The choice of copper or aluminium conductors is made during the construction process on the basis of sphere of use, technical requirements and transformer size.

Aluminium is most usual in the case of high powers if a foil winding is to be used. Aluminium has to have a larger cross-section than copper, something which will increase the size of the transformer core by 5-8%.

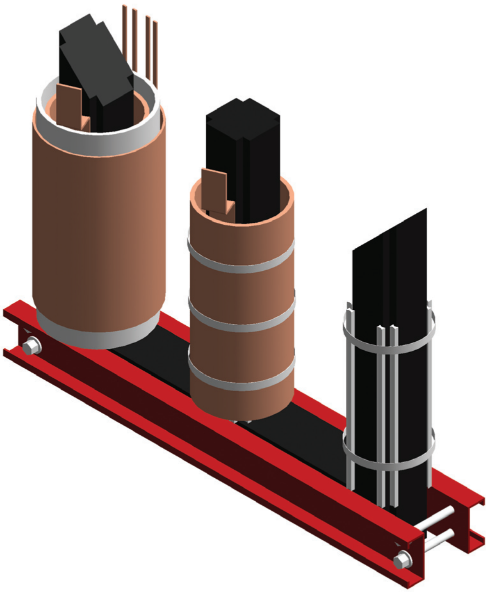
The most vulnerable parts of the transformer are the insulating materials. These are the materials that are placed between the windings, and between the windings and the transformer core. The insulation is made up of organic materials such as paper, cotton, pressboard, plastic, etc., which become brittle and lose their mechanical stability with the passage of time. These degradation processes are affected by voltage, temperature, humidity and other operating conditions. To give a transformer an acceptable noise level and increase insulation capacity (and therefore service life), the entire transformer can be impregnated with a varnish. This is done using dip or vacuum impregnation with air or hot-hardening varnish. Another option is to encapsulate the transformer in a plastic compound, e.g. polyurethane.



Noratel FR transformer. The transformer is encapsulated in self-extinguishing polyurethane in a plastic-like enclosure which is also self-extinguishing.



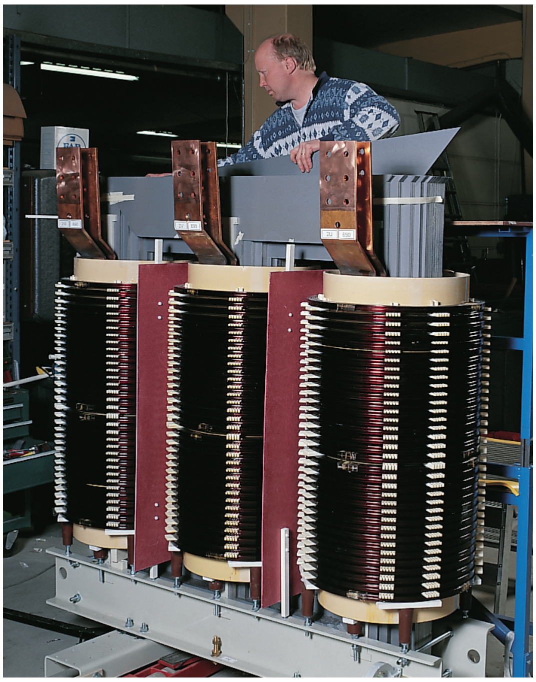
Open transformers are impregnated with hot-hardening varnish.



Different stages of construction of a large three-phase transformer. Schematic structure of a transformer.

Transformer service life

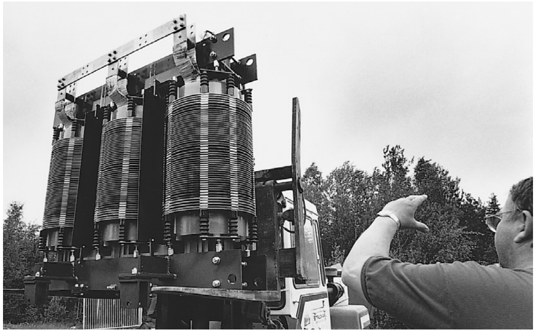
The service life of a transformer is closely linked to the stability of the materials used in its construction.
The insulating material in the transformer is the limiting factor with regard to service life. It is broken down by temperature, dust and humidity. Normally a service life for dry-type transformers of 30-40 years can be expected with normal use and maintenance.



Installation of a three-phase 2000 kVA transformer. The transformer is built for high voltage. The outermost coil on each limb is divided into discs. Disc windings are used to achieve greater resilience to overvoltages and fault conditions in high-voltage transformers.

Transport, handling and storage

Any transformer with unprotected windings is exposed to impacts and contact. Direct impacts on the windings and fittings can cause insulation faults or winding short-circuits. Care is required, and when it comes to transporting, handling and storing transformers we recommend the following rules, which are particularly important in the case of high-voltage transformers:



Great care is required when transporting large high-voltage transformers.

- Transformers should be loaded and unloaded by means of cables or chains secured to the eye nuts provided. The weight of the transformer is specified on the rating plate.
- Avoid sudden movements which might lead to impacts or contact with the windings and fittings.
- Avoid exposing the transformer to humidity or rain.
- The transformer should be stored in a dry place at between 0 and 40°C and a max. relative humidity of 80%.
- Keep the plastic packaging on as long as possible, even during installation.

Great care is required when transporting large high-voltage transformers

In the case of open, unenclosed, high-voltage transformers care must be taken that burrs from the rest of the installation do not drop into the windings. This can generate flashovers at start-up. As a general rule, open transformers should always be covered during installation work.