TRANSFORMERS

1. Basics of transformers

A transformer consists of two or more magnetically coupled windings. Electrical energy is fed to the primary. The secondary supplies electrical energy to the load. An ideal transformer will supply the same amount of real power to the load as it accepts in the primary:

$$P_p = P_s$$

P_p *= primary (input) power*
P_s *= secondary (output) power*

The voltages in all windings are proportional to their number of turns:

$$\frac{U_p}{U_s} = \frac{N_p}{N_s}$$

U_p *= primary (input) voltage*
U_s *= secondary (output) voltage*
N_p *= number of turns on primary (input) winding*
N_s *= number of turns on secondary (output) winding*

For the same amount of power the current is always inverse proportional to the voltage and therefore also inverse proportional to the number of turns (N).

Since the power is assumed to be the same on both sides of the transformer, the winding with less turns has to carry the higher current.

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

I_p *= primary (input) current*
I_s *= secondary (output) current*
N_p *= number of turns on primary (input) winding*
N_s *= number of turns on secondary (output)winding*

Combining the first and the second equation we get for the resistance ratio of the transformer:

$$\frac{R_p}{R_s} = \frac{N_p^{\,2}}{N_s^{\,2}}$$

R_p *= primary (input) resistance*
R_s *= secondary (output) resistance*
N_p *= number of turns on primary (input) winding*
N_s *= number of turns on secondary (output)winding*

All of these relationships consider the ideal transformer. The practical transformer will produce power losses, therefore not all of the primary power is transferred to the secondary. These losses range between 5% (large transformers) and 40% (small transformers).
Therefore the relationships above will only serve as rough estimation for the voltages, currents and numbers of turns in practice.

2. Applications of transformers

Transformers are used for many different purposes in electronic circuits. Different applications will produce different requirements to transformers:

Transforming electrical quantities: current, voltage, resistance.

1) Mains transformer to convert 220 V to other ac voltages as used in electronic equipment.

2) Resistance transformation, e.g. to match an output stage (of an amplifier) of high resistance to a loudspeaker of low resistance: Power matching.

3) Input transformer of an amplifier: To step up the source voltage to overcome noise at the input of an amplifier.

Isolating

Transformers provide a non-galvanic transfer of electrical power. This is used in isolation transformer. They provide an earth-free supply for safety reasons. Voltage, current and resistance are not changed by the transformer. But also all other mains transformer make use of this principle to increase the safety for the user.

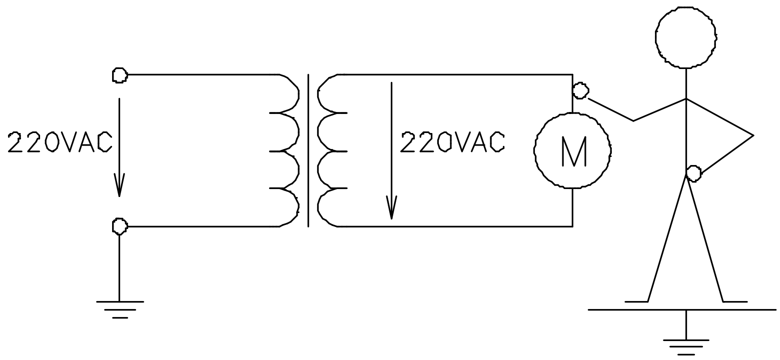


Fig. 2.1.
When isolation transformers are used, touching any ONE point of the secondary is not dangerous.

Example:
Operation of electric hand tools used by workmen standing on a wet ground.

Balancing transformers

In broadcasting studios and during outdoor broadcasting, great care must be taken to prevent interference coming into signal lines, either by capacitive coupling or by induction. For this reason all signal lines are balanced. In a balanced line both leads have no or the same potential to earth. Interfering fields are practically always "unbalanced", i.e. they have a potential against earth. When such fields induce a voltage into a balanced signal line, the same voltage is induced in phase in both wires. With reference to the wanted signal, such induced voltages therefore cancel out. The effect is basically the same as in a bifilar winding.

A balanced line is safe against interference by induction even without any screen. Such line is usually twisted so as to avoid that one lead (wire) may run closer to earth (or another potential) than the other wire.

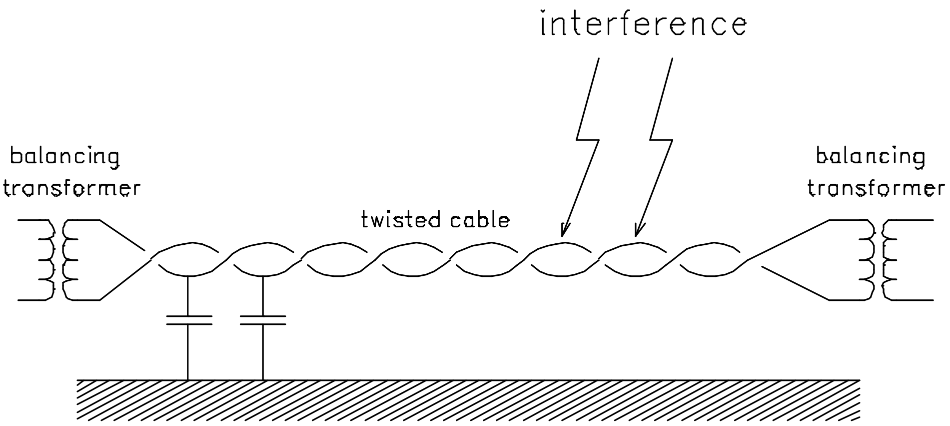


Fig. 2.2.
Balanced lines with twisted cables are safe against interference. They require balancing transformers at either side.

In broadcasting all units are usually provided with input- and output transformers. This is to achieve balanced (symmetrical) inputs and outputs. If such transformers are to serve only this one purpose then they will have a turns ratio of 1:1.

In many cases these transformers serve at the same time other purposes. The voltage may be stepped up or down, or the resistance (impedance) can be changed.

3. Types of transformers

Transformers may have very different constructions depending on the following conditions:

The power to be transferred

The power has a direct influence on the size of the transformer. The more power to be transferred, the larger the transformer. In audio electronics transformers for powers of up to 200 W may be found.

The frequency range

The frequency range has an influence on the core material used. Basically the same material as for inductors are in use:

- laminated cores for mains frequencies (50 Hz/60 Hz)
- special thin laminated cores for audio frequencies
- ferrites for high frequencies.

Generally the transformer will be the larger, the lower the frequency. Thus the smaller, the higher the frequency.)

The dc loading

When d.c. current flows through any winding of the transformer, the core has to have an air gap to avoid saturation of the core. This will require a larger core.

Insulation between the windings.

If no insulation between the primary and the secondary is required, the primary and the secondary may share the same windings (auto transformer). This will reduce the dimensions and the costs of a transformer considerably.

3.1. Mains Transformers

Mains transformers are standard circuit elements, which can be bought off the shelf for many different power ratings and many different secondary voltages.
Mains transformer are characterised by the following design data:

- the power rating(in VA)
- the primary voltage
- the secondary voltage
- the secondary current.

The cores are of laminated and insulated (oxide) iron sheets. For small and medium power today mainly M and EI-type sheets are used.

These core sheets are basically square shaped. The length of the side in millimetres gives the type. E.g. the type M74 has a side length of 74 mm.

Mains transformer may not have an air gap, therefore the sheets are to be assembled interleaved.

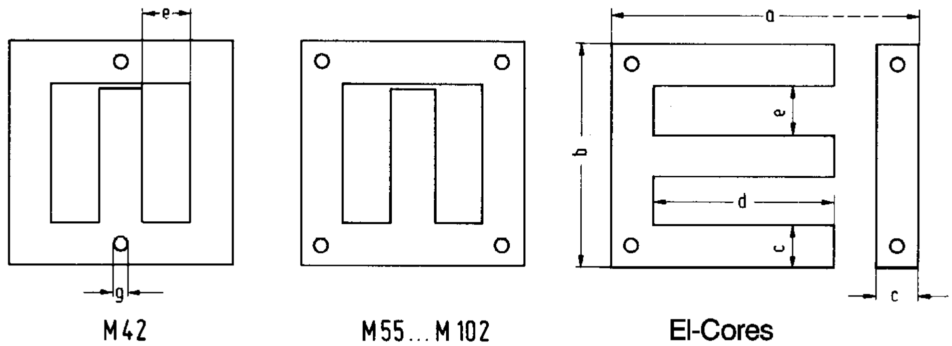
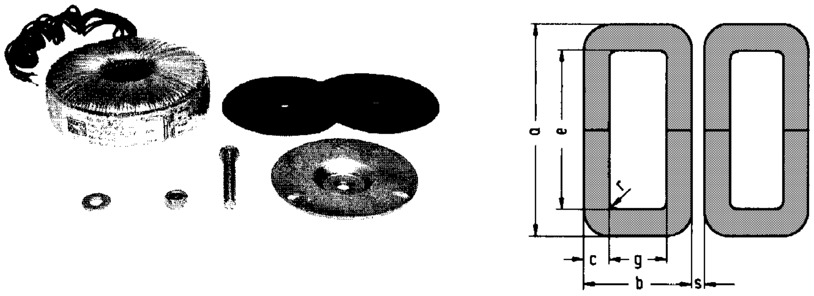


Fig. 3.1.1.
Types of transformer sheets in use. The sheets have to be mounted interleaved to close the air gap.

In addition there are ring core transformers. Its core is made of a closed ring wound of iron laminates. Due to the high quality core with its homogeneous magnetic path they have very low losses and very small stray fields. They will also be smaller and lighter than other transformers of same power. The production of the transformers is difficult and requires special machines. Therefore they are expensive and are only used in high quality equipment. It is almost impossible to wind them manually.

The C-core transformer is closely related to the ring core transformer, but it is easier to produce. The core is also made of a ring wound of iron laminates. The ring is then cut in two half rings (forming C-shaped packages), the cut surfaces are carefully grinded to give good contact when assembling the halves afterwards. The windings are wound on bobbins similar to other transformers. The halves of the core are then assembled into the bobbin and are tightly pressed together by a steal ribbon. These transformers also have very low stray losses.



ring core transformer C-core

Fig. 3.1.2.
Example of a ring core transformer and of C-cores.

The coil may be wound on a single section or double section bobbin. Single section bobbins give better coupling and therefore less losses, double section bobbins provide better insulation between primary and secondary and are used for safety transformers. Usually the primary is the first layer (innermost), secondary the outermost winding. This provides best dissipation of heat losses from the secondary to the core and protects the thin wires of the primary better.

Between primary and secondary a screen layer may be wound. The screen is to be grounded.

When a suitable transformer is not available, they can be designed using standardised transformer cores. Also transformer kits with a ready wound primary winding are available. Alternatively an existing transformer may be modified for a different secondary voltage.The design procedure will be described in chapter 1.5.

3.2. Audio transformers

They are designed for the audio frequency range between 20 Hz and 20 kHz. We find them in amplifiers but also in oscillators (sine) and ac/dc converters (e.g. 3 V dc to 600 V dc in electronic flash).

In professional studios they are widely used as balancing transformers in the inputs and outputs of the equipment.

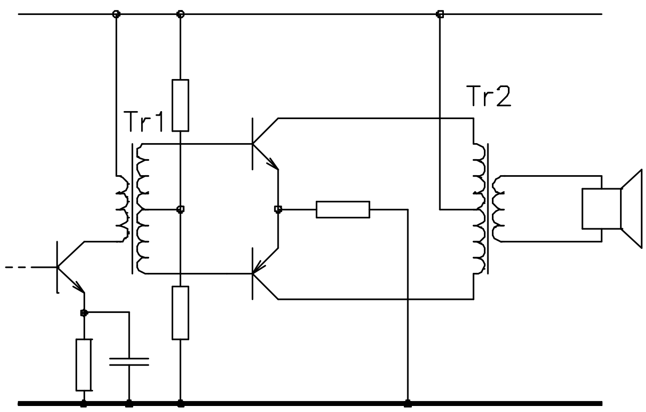


Fig. 3.2.1.
Transistor audio amplifier
with push-pull output stage.
Tr1 = driver transformer (dc loaded)
Tr2 = output transformer (no dc load)

Audio transformers must be designed to the requirements of the circuit.

Therefore there is nothing like "standard audio transformers". They are always ordered for a special application. They are normally very expensive.

Design considerations for audio transformers:

1) Lamination iron cores of 0.35 mm are nearly always used. There is a big variety of different shapes of cores.

2) The core area must be larger than for mains transformers of the same power rating because:

   - the low frequencies require higher flux and thus a larger core area
   - only 0.8 T (Tesla) density are usually permitted to avoid distortion due to saturation
   - if also dc flows through a winding an even larger core area is necessary to avoid saturation.

3) Rough rule for the core area of audio transformers with dc and a maximum current density of 1.5 A/mm²:

$$A_{fe} = 10 \times \sqrt{\frac{2P}{f_l}}$$

A_{fe} *effective c.s.a of the core (in cm²)*
P *maximum transmission power (in W)*
f_l *lowest operation frequency*

4) The inductance of the primary (L_p) forms a high pass filter with the output resistance of the preceding stage and the transformed resistive load to the secondary. Its critical frequency should be lower than the lowest frequency of the signal.

   The inductance of the primary should then be:

$$L_p = \frac{R_p}{2\mathbf{p} \times f_l}$$

L_p *primary inductance of the transformer*
R_p *total resistance composed of the output resistance of the previous stage in parallel with the transformed load resistance.*
f_l *lower critical frequency (-3dB).*

5) The wire size (diameter) depends on the available core window:

$$d = 0.8 \times \sqrt{\frac{A_w}{2N}}$$

d *diameter of wire including its insulation (in mm)*
A_w *window area of the core (in mm²)*
N *number of turns of a winding*

This formula is a rough rule considering space for insulating layers.

6) Stray fields increase with frequency. To reduce stray losses, audio transformers are wound interlaced and in sections.

7) Very careful and intensive magnetic screening is necessary for low power transformers to avoid interference with magnetic fields, especially hum from mains transformers.

3.3. HF Transformers

Such transformers are often parts of tuned circuits working at resonance. The losses of the transformer will affect the resonant circuit. Therefore various soft ferrites are used, they have sufficiently low losses at high frequencies.

No general rules can be given for the construction and the design of such transformers. At very high frequencies transformers may even be built without core (air coils).

In HF circuits full coupling (k=1) is not always required (e.g. in band filters). The coupling factor will be set to achieve the required frequency response.

3.4. Auto transformers

They consist of one winding with one or more tappings. The partial windings are magnetically coupled through the core. Input and output are electrically connected (galvanic connection).

The input circuit and the output circuit both use the winding with the lower voltage as a common winding. In this common winding only the difference of the two currents I_1 and I_2 flows (I_d). This requires less c.s.a. for this part of the winding and therefore saves coil space and allows the use of smaller cores.

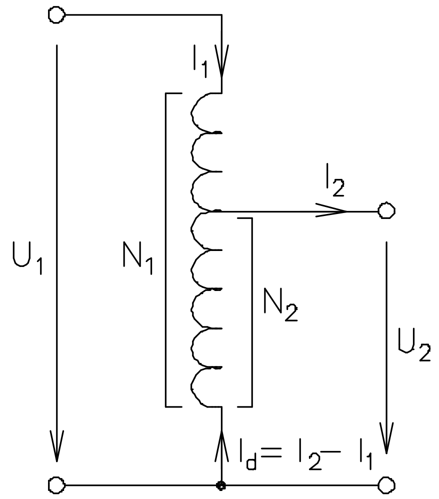


Fig. 3.4.1.
Principle of the auto transformer, showing the voltage and currents.

For a step down transformer the current in the lower voltage winding will be:

$$I_d = I_2 - I_1 = I_1 \times \left(\frac{N_1}{N_2} - 1 \right) = I_2 \times \left(1 - \frac{N_2}{N_1} \right)$$

I_1	*primary (input) current*
I_2	*secondary (output) current*
I_d	*difference current flowing in winding N_2*
N_1	*number of turns of primary (total) winding*
N_2	*number of turns of secondary (output) winding*

The voltages are proportional to their number of turns. The relationships are the same as for normal transformers.

$$\frac{U_1}{U_2} = \frac{N_1}{N_2}$$

U_1 *= primary (input) voltage*
U_2 *= secondary (output) voltage*
N_1 *= number of turns on primary (input) winding*
N_2 *= number of turns on secondary (output) winding*

Auto transformers are especially economical when the difference between input voltage and output voltage is small, e.g. 210 V and 240 V. But even for 115 V to 230 V transformation (or vice versa) the savings in material and losses are considerable.

For low voltage transformers (e.g. 220 V/24 V) auto transformers are not used, because here the savings do not justify the disadvantage of missing galvanic insulation from primary to secondary.

4. Losses in transformers

The losses in transformers have the same physical reasons as losses in coils (see "Inductors", Chapter 4). Basically we distinguish three different types of losses:

- Core or iron losses, they are independent of the output loading
- Coil or copper losses, they increase with increasing loading
- Stray losses, they increase with increasing loading.

The losses in transformers have two practical aspects which have to be considered:

- They cause heating of the transformer
- They cause a loss in voltage at the secondary.

Losses in transformers cause loss of energy or power between input and output. Therefore the losses will result in an efficiency of the transformer of less than 100%.

$$h = \frac{P_s}{P_p}$$

P_s *= primary (input) voltage*
P_p *= secondary (output) voltage*
h *= efficiency*

The efficiency of a transformer will depend on its power rating and its actual power loading.

Efficiencies of different transformers at full power loading:

Small transformers (5 W to 20 W) approximately	60%
Medium size transformers (20 W to 100 W) approximately	80%
High power transformers (>100 W) approximately	90%
Transformers for power engineering up to	98%
Unloaded transformer always	0%

The coil losses of a transformer will increase with increasing power loading. Therefore the efficiency of a transformer increases, if the load is reduced. The efficiency is highest at approximately half of the power rating.

The losses in a transformer will cause a reduction of the secondary voltage compared to the ideal transformer. This can be compensated by increasing the number of turns of the secondary, or by reducing the number of turns in the primary. In practice both will be done, the compensation for the losses is partly done in the primary and partly in the secondary.

The turns ratio considering the losses is calculated by the formula

$$\frac{N_p}{N_s} = \frac{U_p}{U_s} \times \sqrt{h}$$

U_p *= primary (input) voltage*
U_s *= secondary (output) voltage*
N_p *= number of turns on primary (input) winding*
N_s *= number of turns on secondary (output) winding*
h *= efficiency*

This will produce the required secondary voltage under full load. When the transformer is not loaded, the secondary voltage will be higher.

5. Design of Standard Mains transformer.

Standard mains transformers use industrially produced laminated cores and bobbins. When designing a transformer the following quantities will be given:

- Primary voltage
- Secondary voltages
- Secondary currents.

To make the transformer we need the following information:

- The suitable core type
- the number of turns for the primary
- the wire diameter for the primary
- the number of turns for the secondaries
- the wire diameters for the secondaries.

There are three different ways to design standard transformers:

1) Use a table which gives all required information. There is such a table for transformers up to 120 VA as appendix.
2) Use a computer programme which does all necessary calculations.
3) Use the following steps to calculate all required information from formulas.

Note that all of these are practical rules of thumb. If they are based on different assumptions (e.g. about the losses) they will lead to different results. Nevertheless all approaches will result in reasonable transformers.

Step 1: the required secondary voltage.
Normally transformers are used in d.c. power supplies. The secondary voltage will be rectified and smoothed. The rectifier diodes will cause a voltage drop, while smoothing will rise the voltage to 1.4 times the effective value.
The required secondary voltage is thus:

$$U_s \approx 0.7 \times U_{dc} + 2V$$

U_s *= secondary (output) voltage of the transformer*
U_{dc} *= anticipated d.c. output voltage of the power supply*

Step 2: the required secondary current
When the secondary voltage is rectified and smoothed, the effective transformer current will be different from the d.c. current. The precise relationship is difficult to determine, because it depends on too many factors.
As a rule of thumb the following relationship can be used:

$$I_s \approx 1.5 \times I_{dc}$$

I_s = *max. secondary (output) current of the transformer*
I_{dc} = *anticipated d.c. output current of the power supply*

Step 3: the required power rating
The primary power rating of the transformer is equal product of the maximum total secondary voltages and currents increased by the rate of the efficiency:

$$P_p = \frac{U_{s1} \times I_{s2} + U_{s2} \times I_{s2} + \ldots\ldots\ldots + U_{sn} \times I_{sn}}{h}$$

P_p = *primary power rating of the transformer*
U_{sn} = *secondary (output) voltage of output winding n*
I_{sn} = *max. secondary (output) current of output winding n*

Step 4: the required core size
A certain power requires a certain size of the core. The important characteristic of the core is the c.s.a. of the inner leg. The required area A can be found from the relationship:

$$A \text{ (in cm}^2\text{)} > \sqrt{P_p} \text{ (in Watt)}$$

A = *cross sectional area of the inner leg of the iron core*
P_p = *primary power rating of the transformer*

Select a standard core with the required area A.

Type of M-core	M42/10	M55/20	M65/27	M74/32	M85/32a	M85/45b	M102/35a	M102/52b
Core area A (cm²)	1.8	3.4	5.4	7.36	9.43	13.05	12.1	17.9
Max. power rating (VA)	5	15	30	50	70	95	120	180

Type of EI core	30/10	48/16	54/18	60/20	66/22	78/26	84/28	84/42	105/35	105/45	130/45
Core area A (cm²)	1	2.56	3.24	4	4.84	6.76	7.84	11.8	12.25	15.75	15.75
Max. power rating (VA)	<10	<10	10	15	20	35	50	75	100	140	290

Step 5: number of turns per volts
The following formula gives a good approximation:

$$N_V \approx \frac{42}{A}$$

A = *cross sectional area of the selected iron core*
N_v = *number of turns per volt*

Step 6: The number of primary turns
The number of the primary turns can now be calculated from the turn per volts N_V considering the losses. Remember that half of the losses will be considered in the primary and half in the secondary.

The correction factor K_L to consider the losses can be calculated from the efficiency by the relationship:

$$K_L = \sqrt{1 - \frac{(1 - \boldsymbol{h})}{2}}$$

K_L *= correction factor for the calculation of number of turns*
h *= efficiency of the selected core (see table)*

The number of primary turns is then:

$$N_p = U_p \times N_V \times K_L$$

N_p *= number of turns of the primary winding*
U_p *= required primary voltage*
N_v *= number of turns per volt of the selected core*
K_L *= correction factor of the selected core*

Step 7: Diameter of primary wire
To determine the primary wire, the primary current must be calculated first. It can be found from the total power of the transformer:

$$I_p = \frac{P}{U_p}$$

I_p *= primary (input) current*
P *= power rating of the transformer*
U_p *= primary (input) voltage*

For a transformer winding a current density of 2 to 3 A/mm² can be allowed.
The wire diameter can be calculated by the simplified formula:

$$d_p \approx \sqrt{\frac{I_p}{2}}$$

d_p *= diameter (in mm)of the wire of the primary winding*
I_p *= primary (input) current*

Step 8: Number of secondary turns
This is calculated similar to the number of primary turns. The correction factor K_L will appear in the denominator, because the number of turns must be increased to compensate for the losses.

$$N_s = \frac{U_s \times N_V}{K_L}$$

N_s *= number of turns of the secondary winding*
U_s *= required secondary voltage*
N_v *= number of turns per volt of the selected core*
K_L *= correction factor of the selected core*

Step 9: Diameter of secondary wire

$$d_s = \sqrt{\frac{I_p}{2}}$$

d_s *= diameter (in mm)of the wire of the secondary winding*
I_s *= secondary (output) current*

The primary and the secondary windings will normally require each half of the bobbin space. Note that the diameters of the primary and the secondary wires may not be selected too large, else the windings will not fit on the bobbin.

Table for the design of M-core transformers								
	Standard Cores M-shapes							
Quantities	Units	M 42	M 55	M 65	M 74	M 85	M 102a	M 102b
Max. power (single bobbin)	VA	4.5	12	26	48	62	120	180
Max. power (double bobbin)	VA	3	9	21	40	52	100	160
Voltage per turn	mV	44.6	84.4	134	183	230	298	447
turns per volt	turns/V	22.4	11.8	7.4	5.5	4.3	3.6	2.2
Turns for 220V (unloaded)	turns	4940	2610	1650	1200	956	740	494
Primary turns for 220 V at full load	turns	4300	2400	1550	1150	920	718	482
Secondary turns for 220 V at full load	turns	6400	2980	1790	1280	1010	770	506
Secondary turns for 6,3 V at full load	turns	190	87	52	37	29	22	14,5
Core losses	W	0.8	1.9	3.5	3.8	5.6	8.5	13
Efficiency	%	60	70	77	83	84	87.5	88.5
Thickness of sheet	mm	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Current density (inner winding)	A/mm²	4.5	3.8	3.3	3.0	2.9	2.4	2.3
Current density (outer winding)	A/mm²	5,2	4,3	3,6	3,3	3,3	2,8	2,7
Coil losses at full load	W	2	3	4	5	6	8	9
Usable bobbin height	mm	6,6	7,5	9,2	10,4	9,3	12,2	12,2
Usable bobbin length	mm	24	30	35	43	46	58	58
Width of core	mm	12	17	20	23	29	34	34
Thickness of core	mm	15	20	27	32	32	35	52
Core c.s.a	cm²	1.8	3.4	5.4	7.4	9.3	12	18
C.s.a. of core window	cm²	2.7	4.0	5.6	7.1	7.5	11.5	11.5
Weight of core	kg	0.14	0.33	0.62	0.88	1.3	2.0	3.0
Weight of coil	kg	0.04	0.09	0.16	0.28	0.3	0.55	0.65
length of one turn (inner winding)	cm	7.3	9.6	12.1	14.2	15.1	17.1	20.6
length of one turn (outer winding)	cm	9,8	12,4	15,2	17,9	18,6	21,4	24,9