

10.7.6 The mains transformer

The mains transformer generates, from the mains voltage (e.g. 230 V_{eff}, depending on the country), the AC-voltages required in the amp; it also galvanically separates these voltages from the mains line. A transformer typical for a guitar amplifier has, on its secondary side, two filament-windings (5 V and 6.3 V) and a plate-winding with a middle tap (e.g. 2x350 V). The following elaborations refer to the relationships between one primary and *one* secondary winding; further details may be found in textbooks on the subject [e.g. 7, 17, 18, 20].

One main criterion to design or to choose a transformer is the **power** P that needs to be handled. Here, it is not the audio-power (e.g. 50 W) that is meant but the total power necessary to operate the amp (e.g. 140 W). A considerable part of this power taken from the mains line is converted into heat in the amplifier; the power delivered to the loudspeaker usually is the comparably smaller part. The **power required by the filaments** can be easily taken from datasheets; an example would be: 2xEL34 = 19 W, 4xECC83 = 7.5 W, 1xGZ34 = 9.5 W, in total 36 W. Next we get to the power absorbed by the tubes and resistors – that can be estimated only approximately: the **power fed to the triodes** of course depends strongly on the operating point; for an ECC83 we may use 1 W as a first order approximation. The two **output pentodes** absorb about as much power as they make audio-power available: 50 W in our example. This leads to the power-balance: $P = 36\text{ W} + 54\text{ W} + 50\text{ W}$, in total about 140 W. This simple calculation does not include the efficiency of the transformers – for it, about 90% would again be purposeful (although it may be less in individual cases). If the amplifier is to have 50 W audio-power, and the output transformer will dissipate 5 W as thermal energy, the power consumption will be not 50 W but 55 W. Broadly speaking, the power required from the mains transformer will rise to 147 W, and if the mains transformer also has a 90%-efficiency, it will draw 164 W from the mains power. When the power stage is overdriven, this value can increase further; it is therefore recommended to estimate, as a benchmark for the power consumption, the four times the value of the audio output-power. A 50-W amp therefore will require a 200-W-transformer. If saving is an objective, a 150-W-version might also do: an amplifier is not continuously overdriven, is it? Oh, it is?! In that case it is worth the while to go for a few reserves and include a larger transformer right away.

Determining the **transformer-size** is a complicated optimization process: mains transformers are heavy, big, and costly so that any carefree over-dimensioning needs to be under scrutiny. On the other hand, transformer failure will require a complex repair process that might ruin the company-image. A main criterion for the transformer-dependability is (besides adequate proof-voltage – that is taken as a given here) the temperature of the winding. This depends on the build-type and the load, but also on the temperature that develops within the amplifier. If the transformer is operated close to hot tubes (70° C air-temperature are not out of the ordinary), the maximum electrical strain will be lower compared to a fan-cooled amp. Consequently, it is not untypical to find a 250-W-specified transformer in a 50-W-amp. An entirely different question, however, is whether the prices asked for such transformers are justified. The corresponding sums are not always based on special safety-reserves, but on the fact that old (but famous) predecessors from the 1950's and -60's are replicated. Do not let yourself be restrained if you desire to pay 250 € for such an old-school 250-W-mains-transformer; it should be noted, however, that 300-W-toroidal-transformers can be had already from 50 € – and these even meet the present CE- and other international regulations.

A mains transformer constitutes a voltage-source that is defined by its open-loop voltage and its internal impedance. It has been shown in Chapter 10.7.3 that a load-dependent sagging of the supply-voltage depends on the internal impedance of the transformer, among other factors; in that sense it may well be desirable to copy old models. Alternatively, it is however just as possible to increase the internal impedance of the transformer (up to a nominal value) simply by connecting the secondary center tap not directly to ground, but via a resistor.

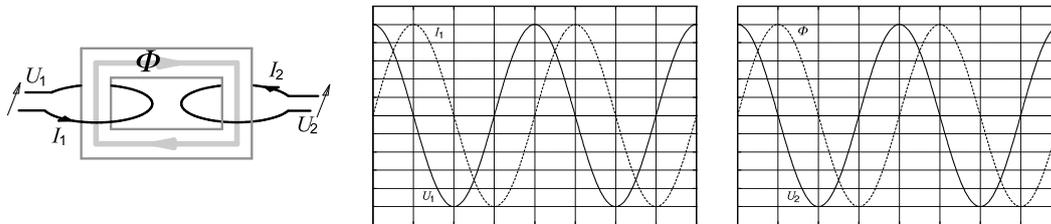


Fig. 10.7.8: The transformer as ideal quadripole. Voltages and currents for secondary open-loop circuit. ($I_2 = 0$).

Fig. 10.7.8 clarifies the principle of operation of a transformer. The primary winding (here represented via merely a single turn) carries the primary current I_1 ; it generates the magnetic flux Φ . First, the secondary circuit shall be considered **without load** ($I_2 = 0$). The magnetic flux is proportional to the primary current (Ampère's circuital law); both shall be purely sinusoidal. Any non-linearity shall be disregarded at this point. The change of magnetic flux over time has the effect that a voltage U_2 is induced in the secondary winding – U_2 is proportional to the flux-amplitude (law of induction: $U_2 = d\Phi/dt$). The secondary voltage and the magnetic flux are shifted in phase by 90° , and so are primary current and primary voltage, because the primary winding represents – for an open-loop secondary circuit – a pure inductance (for the time disregarding the copper-resistance of the windings).

Things change as a **load** is introduced on the secondary side, because now a secondary current is flowing that in itself generates an (additional) magnetic flux. Assuming a stiff *voltage-source* as input (the mains supply is of low impedance), the secondary load must not change the magnetic flux – the primary current and the magnetic flux are interdependent via the law of induction, after all. The temporal course of the magnetic flux can, however, be maintained only if the magnetic flux Φ_2 generated by the secondary current is compensated by a further magnetic flux Φ_1 that is in opposite phase to Φ_2 . Φ_1 needs to be generated by an additional input current. In summary: Φ does not change as a secondary load is connected; an ohmic secondary load will, however, have the effect that a primary active current joins the primary reactive current. This would be the ideal point-of-view. Models that are closer to reality also consider the ohmic resistances, the magnetic leakage, winding-capacitances, and the non-linear behavior of the core material.

The **winding resistances** depend on winding length, turns number, wire-cross-section, and specific (copper-) resistance; these are one cause of transformer losses*, i.e. of the fact that a transformer will convert a part of the received power into heat. For the primary winding of a mains transformer, 6Ω is not an unusual value. This resistance will, however, not be the only component of the primary impedance, because: $230 \text{ V} / 6 \Omega = 38 \text{ A}$ – that input current would be too high an order of magnitude. For a secondary open-loop circuit, the main component of the primary impedance is an inductance*, connected (in the simple equivalent circuit) in series to the winding resistance. With a secondary *active* load, the magnetic field transmits *active* power that is taken from the primary circuit via an additional *active* resistance.

* Losses in the iron will be looked into later.

In the interest of a high efficiency, and as a carrier of reactive and – in particular – active power, the magnetic field generated by the primary winding should completely penetrate the secondary winding as far as at all possible. In order to guide the field, ferromagnetic material (see Chapter 4) that has a much smaller magnetic resistance (relative to air) is used for the transformer core. However, this magnetic resistance is highly **non-linear**: for strong magnetic flux densities, saturation effects occur. As the limit of saturation is exceeded (not a sudden but a gradual process), the ferromagnetic material increasingly loses its good magnetic conductance: for the magnetic flux beyond the limit, the ferromagnetic acts merely with a conductance as bad as the normally much worse conducting air. Moreover, the core material shows the non-linearity not only at high flux densities but very strongly at small drive-levels, as well – this is in sharp contrast to many classic non-linearities. The mains transformer is operated with an AC voltage that will not change significantly (nominal local mains voltage), and it is therefore not purposeful to devise a **small-signal equivalent circuit diagram** – what it would show would be unsuitable for the typical mode of operations.

Fig. 10.7.9 shows the dependency of the primary current on the primary voltage for a mains transformer (EI 105c) without load, and also the dependency of “a kind of impedance” on the voltage. Mind you: the impedance in the classical sense is only defined for sinusoidal signals! The curves shown here are supposed to give an impression of the strong dependency on the voltage; H^* and Ω are the units for non-linear elements.

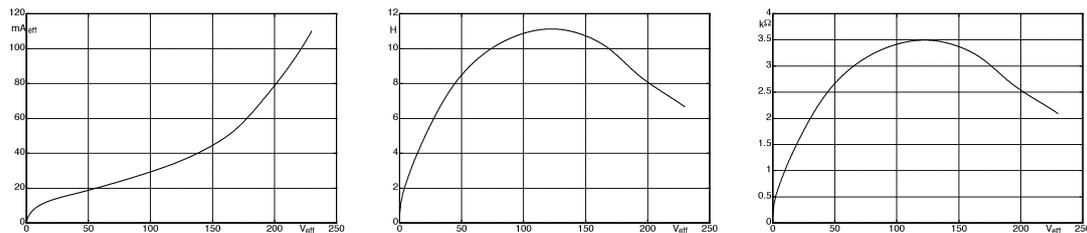


Fig. 10.7.9: Left: primary RMS-current vs. primary RMS-voltage for transformer w/out load; the other two diagrams show the quotient of two RMS-values: $U / 2\pi f I$ and U / I . ($H = \text{Henry}^*$).

In the small-signal equivalent circuit diagram, the primary impedance of the un-loaded transformer would (with $U \rightarrow 0$) result from a series circuit of copper-resistance (6Ω) and inductance $L = 0.4 \text{ H}$. However, already at $U = 1 \text{ V}$, L rises to about 1 H , and further increases up to 11 H with increasing voltage. Already at $U = 1 \text{ V}$ there is a clearly visible non-linearity between current and voltage that increases its influence further with mounting voltage. This system is strongly non-linear and in a sense even **time-variant**: the operating point on the magnetic hysteresis loop depends on the previous drive-levels, and it can run through the curve in one and the same direction (counter-clockwise) only. If switching-off happens at an instant of high field-strength, a different operating point ensues compared to a slow decrease of the AC-field to zero. Currents and impedances measured for small voltages are normally not reproducible if in the meantime a strong field has been present. However, since the mains transformers in guitar amplifiers are not operated at 1 V but at (230 V (or 110 V)), the behavior with strongly varying voltage will not be elaborated on. Specialist literature does offer supplementary information on this.

* The unit Henry (H) must not be confused with the formula symbol of the field strength (H).

Fig. 10.7.10 depicts measurements of a mains transformer that is offered for replica Marshall-amplifiers (TAD-JTM45). First, there is no load; measured are primary current and voltage. While the primary voltages – generated from the mains line via a variac – are approximately sinusoidal, the primary current show voltage-dependent deviations from a sinusoidal curve. With increasing RMS-value of the primary voltage, a bulge emerges in the time-curve of the current, with a maximum close (in time) to the zero-crossing of the voltage. Explanation: at these times, the magnetic flux becomes largest (Fig. 10.7.8), the core material is saturated, $L = U / \dot{I}$ decreases, I increases.

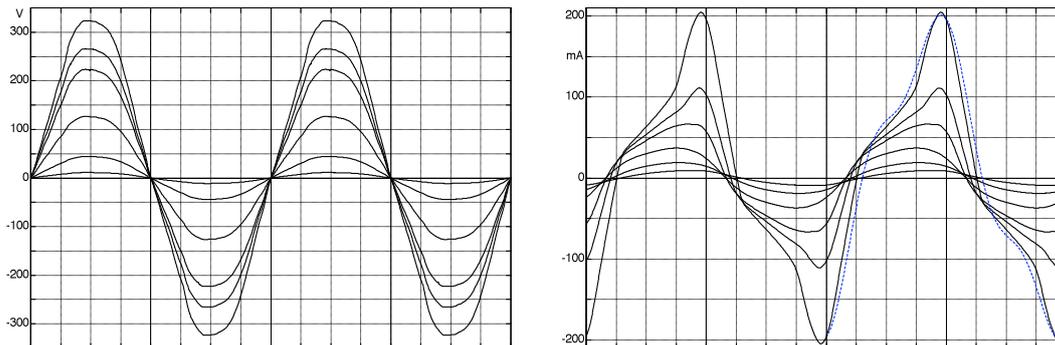


Fig. 10.7.10: Time-curve of primary voltage (left) and current (right) for a mains transformer without load.

Here, the inductance $L = U / \dot{I}$ is not a constant anymore but dependent on the drive-level. The time-course of the current with its non-linear distortion can be dissected into sinusoidal components, and with a few partials, the basic behavior can already be explained: the active power is made up from the sine-voltage cooperating with the sine-component of the current, while the cosine-component of the current forms, together with the sine voltage, the reactive power:

$$u(t) = u_S \cdot \sin(\omega t); \quad i(t) = i_S \cdot \sin(\omega t) + i_{C1} \cdot \cos(\omega t) + i_{C3} \cdot \cos(3\omega t);$$

This simple summation is indicated via a dashed line in the second half of the right hand section of the figure; the basic usefulness can be recognized – if necessary, further partials of higher order must simply be added in. Taken by themselves, the sine-components (u_S , i_S) in combination yield the active part (convolution theorem of the Fourier-transform), while the mean-value of the sine- and cosine-oscillations (orthogonal to each other) always results in zero – these products therefore represent the **reactive power**. Understandably so: the magnetic **leakage-flux** exiting the core includes purely **reactive power** as long as no eddy-currents are generated. The **re-magnetization** of the core sheets, however, requires active power, in the example this would be about 13 W. This power is irreversibly fed to the core and generates heat. Compared to these re-magnetization losses, the copper-losses in the primary winding are, at 0.07 W, insignificant. No heat is generated in the (un-loaded) secondary winding, either. The following holds with good approximation: **in idle, only iron-losses appear**. It should be stressed that a *reactive* current, too, does flow in reality: it generates a co-phase voltage-drop across any ohmic resistance it traverses; this voltage drop implies an active power in conjunction with the reactive current. In the above example, however, the primary copper-resistance is (at 6 Ω) so small that the active power generated at it has no bearing (for secondary open-loop operation). This will change as a load is connected to secondary side. The primary current may now be as high as more than 1 A.

For the following measurements, the transformer received to a secondary load in the form of a 10-k Ω -resistor fed from the series-connected high-voltage windings (2 x 350 V). **Fig. 10.7.11** shows the resulting primary voltages and currents: in contrast to Fig. 10.7.10, the current follows a much more sinusoidal curve because an additional active current joins the magnetizing current – the active power taken from the secondary winding (49 W) needs to be delivered by the primary side as active power, as well. The total active power fed to the primary side is now 63 W, and again about 14 W of this remains in the transformer and is dissipated (into heat). The magnetic flux is approximately independent of the load, and therefore the re-magnetization losses* (here: 13 W) are also load-independent. The copper-losses need to be added – they increase proportionally to the yielded power.

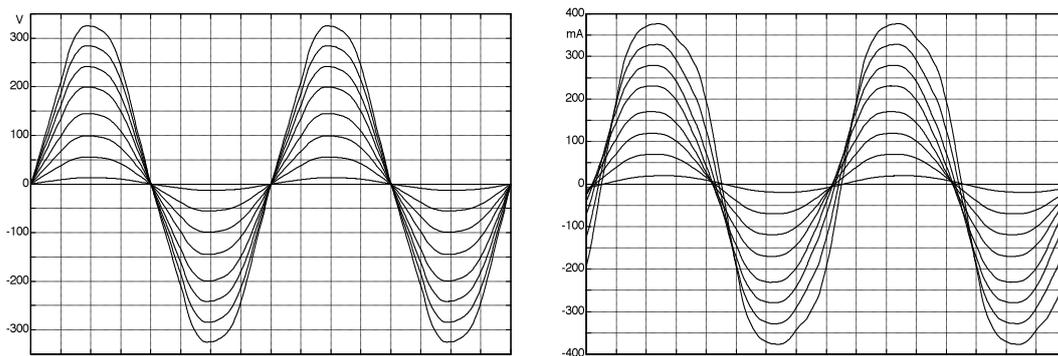


Fig. 10.7.11: Primary voltage (right) and current (left) over time for the mains transformer connected to a load.

Although the superposition-principle is not applicable in non-linear systems, it is still possible in good approximation to separate the primary current into a load-independent magnetization-current and a load-current. **Fig. 10.7.12** gives two examples: the mains transformer mentioned above is given a load of 10 k Ω , and 5 k Ω , respectively, and an active current proportional to the primary voltage is subtracted from the primary overall current. What remains is in all three cases (incl. the condition w/out load) the same amount of magnetization current.

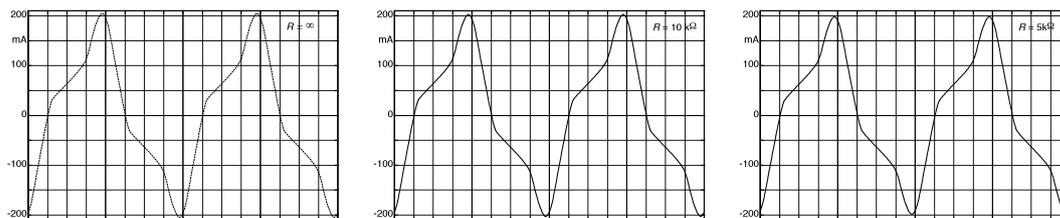


Fig. 10.7.12: Primary magnetization current for three different-sized loads (measurements).

The relationship of primary voltage vs. current may also be depicted as a **Lissajous diagram** – although here we do not directly have the voltage but rather the *integral* of the voltage vs. the current. While the magnetic field-strength H is directly proportional to the current, the law of induction necessitates proportionality between magnetic flux density B and the *integral* of the voltage. This allows for a mental picture of the drive situation in the magnetic circuit, although no exact quantitative scaling is included: the induced voltage corresponds to the product of flux-change and turns-number – the latter is not known for the investigated transformer. That is why the ordinate of the following pictures does not show the flux Φ .

* This simplified discussion does not distinguish between hysteresis- and eddy-current-losses.

Fig. 10.7.13 shows the integrated primary voltage vs. the primary current. With an un-loaded transformer, we would see – for a purely inductive primary winding – a straight line passing through the origin (due to the integration no circle shows), but now the non-linear core material causes the hysteresis loop. With a load present, the active-current-component increases and the curves widen to become more circle-like. Subtracting the voltage-proportional load-current from the total primary current again yields the primary magnetization current with very good agreement. The exact turns-number for the measured transformer is unknown; manufacturer datasheets indicate a value of just short of 400 turns.

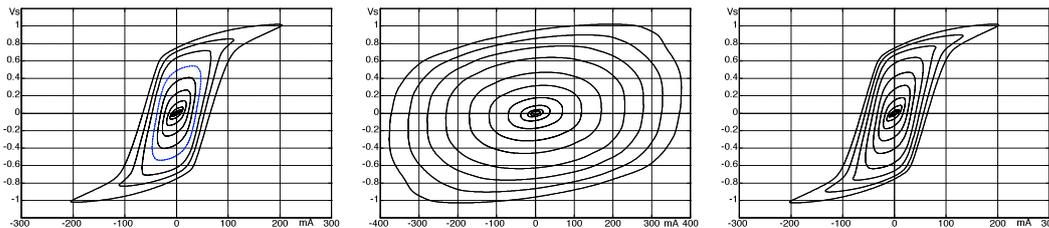


Fig. 10.7.13: Integrated primary voltage vs. primary current. Left: sec. open circuit; center & right: 10 k Ω load. Right: the load current (proportional to the primary voltage) was subtracted from the primary current. The ordinate shows the interlinking flux using the unit Vs, the actual magnetic flux Φ is smaller by a factor of N_1 (N_1 = turns number, about 400).

Summarizing the results so far gives an ambivalent picture: on the one hand, the mains transformer is a complicated non-linear system with inhomogeneous field-distribution, on the other had, it may be rather well **approximated** by a simple voltage-source with internal impedance. For a secondary open-loop circuit, we find at the secondary connections an approximately sinusoidal voltage that drops (sags) as a load is connected. This drop is not dramatic but noticeably: for a secondary current of $I_2 = 300 \text{ mA}_{\text{eff}}$, the RMS-value of the secondary voltage decreases from e.g. $350 \text{ V}_{\text{eff}}$ to $338 \text{ V}_{\text{eff}}$ corresponding to the **source impedance** of $Z_i = 40 \Omega$. This impedance is approximately ohmic; apart from the secondary copper-resistance and the primary copper-resistance transformed via TN^2 , there is also a small (leakage-induced) inductance. The below **table** lists some fundamental parameters of typical transformer-builds; more details can be found in the chapter about output transformers. Complete transformer-design is not the objective of the present discussion: regarding that topic, enough special literature already exists.

Besides size, the **transformer power** probably is the most important parameter in the table. In literature, mention of this power usually refers to the secondary power but occasionally also to the primary power that is about 10% higher. The transformer power i.e. the allowable *maximum* power is directly coupled to the heating-up of a transformer. If the latter becomes too hot, the winding wires may burn through, and/or the insulation may be hurt. Over the last decades, better core materials have become available (less hysteresis and eddy-current-losses, and consequently less heating-up), and the resilience against high temperatures was improved, as well. These reasons are responsible for a power span of as wide as 30 – 57 W in a M-65-mains transformer. Admittedly, this is a pretty considerable range, but again: no recipe without exact information about the ingredients – that holds for transformers, too. The following table includes two values for the power; they may be interpreted as typical limits: the smaller value represents the way the old heroes were constructed back in the day, while the larger value is found in the datasheets of A.D. 2008 (and may be even exceeded by another 10 – 20% using special core materials). For the core data (Fe), the smaller value holds for a fill-factor of 90%, the larger value relates to 100%.

	P / VA	b / mm	h / mm	Cu / cm ²	Cu / cm	Fe / cm ²	Fe / cm	Fe / grams
M20	ca. 0.5	20	5.0	0.33	3.6	0.22 / 0.25	4.6	11 / 10
M30a	ca. 1.5	30	7.0	0.83	5.4	0.43 / 0.49	7.0	33 / 30
M30b	2-3	30	10.5	0.83	6.1	0.65 / 0.74	7.0	45 / 40
M42	5-7	42	14.7	1.75	8.7	1.55 / 1.76	9.8	119 / 108
M55	15-21	55	20.3	2.68	11.3	3.04 / 3.45	12.9	310 / 279
M65	30-50	65	27.0	3.90	13.8	4.75 / 5.40	15.2	560 / 500
M74	60-82	74	32.2	5.17	16.0	6.52 / 7.41	17.3	890 / 790
M85a	79-105	85	32.2	5.29	17.0	8.22 / 9.34	19.8	1240 / 1120
M85b	106-140	85	44.8	5.29	19.6	11.4 / 13.0	19.8	1730 / 1560
M102a	135-180	102	35.0	7.87	19.7	10.5 / 11.9	23.8	1910 / 1770
M102b	193-240	102	52.5	7.87	23.2	15.7 / 17.9	23.8	2880 / 2640
core / mm	P / VA	b / mm	h / mm	Cu / cm ²	Cu / cm	Fe / cm ²	Fe / cm	Fe / grams
EI-30	ca. 1	25	10.0	0.50	6.0	0.9 / 1.00	6.0	45 / 41
EI-42	2.5-4.5	35	13.7	0.95	8.2	1.73 / 1.9	8.4	120 / 108
EI-48	5-9	40	15.7	1.30	9.3	2.25 / 2.5	9.6	180 / 162
EI-54	9-15	45	17.7	1.65	10.5	2.88 / 3.2	10.8	260 / 234
EI-60	14-22	50	19.9	2.06	11.7	3.6 / 4.0	12.0	360 / 324
EI-66a	21-31	55	21.9	2.49	12.8	4.32 / 4.8	13.2	480 / 432
EI-66b	31-46	55	33.5	2.49	15.1	6.63 / 7.4	13.2	733 / 660
EI-75	34-48	62.5	25.2	2.90	14.2	5.67 / 6.3	15.0	710 / 639
EI-78	40-60	65	26.4	3.16	15.1	6.17 / 6.9	15.6	805 / 725
EI-84a	58-80	70	27.9	3.85	16.2	7.03 / 7.8	16.8	985 / 887
EI-84b	75-106	70	41.9	3.85	19.0	10.6 / 11.7	16.8	1480 / 1332
<i>EI-92a</i>	70-91	74	22.9	9.4	16.8	4.7 / 5.3	19.4	770 / 693
<i>EI-92b</i>	95-123	74	31.9	9.4	18.6	6.6 / 7.3	19.4	1070 / 963
EI-96a	100-128	80	34.0	4.9	18.8	9.8 / 10.9	19.2	1567 / 1410
EI-96b	125-170	80	44.0	4.9	20.8	12.7 / 14.1	19.2	2033 / 1830
EI-96c	160-215	80	58.0	4.9	23.6	16.7 / 18.6	19.2	2678 / 2410
EI-105a	120-160	87.5	35.0	5.8	20.3	11.0 / 12.3	21.0	1930 / 1737
EI-105b	150-210	87.5	44.8	5.8	22.3	14.1 / 15.7	21.0	2470 / 2223
EI-105c	190-260	87.5	56.0	5.8	24.5	17.6 / 19.6	21.0	3088 / 2779
<i>EI-106a</i>	135-180	85	31.9	10.6	20.5	8.3 / 9.3	21.8	1520 / 1370
<i>EI-106b</i>	184-239	85	44.8	10.6	23.1	11.7 / 13.0	21.8	2130 / 1920
EI-108	140-180	90	36.1	6.2	21.0	11.7 / 13.0	21.6	2110 / 1900
EI-120a	200-250	100	40.0	7.6	22.9	14.4 / 16.0	24	2889 / 2600
EI-120b	250-320	100	52.2	7.6	25.3	18.8 / 20.9	24	3756 / 3380
EI-120c	320-400	100	72.1	7.6	29.3	25.9 / 28.8	24	5200 / 4680
<i>EI-130a</i>	250-320	105	36.1	16.7	24.2	11.3 / 12.6	27	2570 / 2310
<i>EI-130b</i>	290-400	105	46.1	16.7	26.2	14.5 / 16.1	27	3280 / 2950
<i>EI-150a</i>	340-480	120	40.1	20.9	28.1	14.4 / 16	31	3720 / 3350
<i>EI-150b</i>	430-580	120	50.1	20.9	30.1	18.0 / 20	31	4650 / 4180
<i>EI-150c</i>	500-670	120	60.1	20.9	32.1	21.6 / 24	31	5550 / 5000
EI-150Na	400-510	145	47.9	13.4	28.5	21.5 / 24.0	30	5400 / 4860
EI-150Nb	500-600	145	64.9	13.4	31.9	29.2 / 32.5	30	7300 / 6570
EI-150Nc	630-700	145	90.9	13.4	37.1	40.9 / 45.5	30	10200 / 9180

Table: Transformer-data; b = width, h = height of the metal-sheet-package.

Cu-data: cross section of winding, length of winding.

Fe-data: cross-section of iron; path-length in iron, core-mass (fill-factor 90%.) T'formers in italics: low wastage.

It is customary not to specify the gross-dimensions of a mains transformer, but to give the core-dimensions. The most-often-used **core sheets** either have the M-format, or the EI-format. The core sheets of an M85-transformer feature an edge length of 85 mm (all M-sheets are of a square shape), and usually are of a thickness of 0.35 mm (0.5 mm is also possible). For the thickness (stacking-height) of the whole core, there are two nominal values (designated a or b): M85a = 32.2 mm, M85b = 44.8 mm. In order to minimize the effects of the air gap, the sheets are stacked alternately from opposite directions. With the EI-core, there is – besides the common wastage-free core shape – also the low-wastage shape. Compared to the M-cores, EI-cores have three air gaps, and therefore tend to have higher fringe-losses – but they are easier to assemble. In the wastage-free cut, the punching-out of two E-pieces exactly yields two I-pieces (without clippings). However, the cross-section of the winding is smaller compared to the low-wastage cut. **Fig. 10.7.14** shows all three shapes of core sheets; the table just shown summarizes the dimensions. The geometric and magnetic properties of the core sheets are standardized according to various standards; still, it may not be taken as a given that all manufacturers on the globe produce their transformers according to DIN or EN.

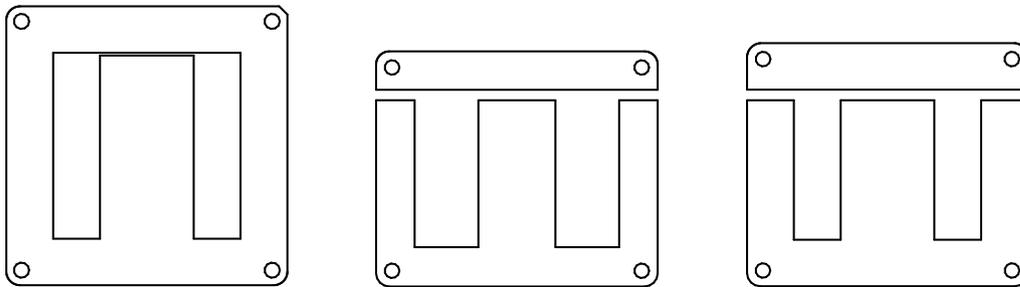


Fig. 10.7.14: Core sheets normalized to equal width: M-core (left), low-wastage EI-core (middle), wastage-free EI-core (right). There are different standards for the mounting holes.

Kühn R.: Der Kleintransformator. C.F. Winter 1964, Prien.

Hanncke W.: Kleintransformatoren und Eisenkerndrosseln, Vogel 1970, Würzburg.

Klein P.: Netztransformatoren und Drosseln, Franzis 1979, Munich.

Feldtkeller R.: Theorie der Spulen und Übertrager, Hirzel 1971, Stuttgart.