## 10.7 Power Supply

The power supply delivers the operating-voltages (and -currents) required by the amplifier to be able to work: plate-voltage, filament-voltage and, if applicable, bias-voltage for the grids. The most important components of the power supply (mains transformer, rectifier, and filter capacitor) will be investigated in the following. Power supplies in guitar amplifiers fitted with tubes generate 500 – 1000 V, and consequently observing pertinent safety regulations is imperative: **touching of live components or wires may be fatal!** For this reason, only trained professionals are allowed to work on such amplifiers. Particular consideration needs to be given to the fact that even devices that are switched off and disconnected from the mains power may be storing deadly voltages for hours. Again: such equipment may be opened by qualified personnel only!

### 10.7.1 Tube filament

The cathode of a tube will emit the required stream of electrodes only as it glows. A dedicated secondary winding of the mains transformer delivers the necessary power (2 – 16 W depending on the tube) for the associated heating. Most tubes are heated with 6.3 $V_{\sim}$ , rectifier tubes with 5.0 $V_{\sim}$, as well. DC-heating is possible but uncommon. In order to minimize the effects of capacitive coupling between filament-circuit and signal-circuits, the heating voltage often is of symmetric configuration, either via a middle tap in the filament-winding of the mains transformer, or via two resistors or a potentiometer.

The connections to the tube-filaments are mostly designated with *f* (from the Latin filum) in the socket-diagrams; in the actual circuit diagrams, they are not included to keep the drawings neat. Filaments are positive-temperature-coefficient (PTC) resistors – their resistance increases by a factor of 7 – 8 when heated. It can therefore be beneficial to a long tube-life to limit the switch-on current – but this is not mandatory. On the other hand, the **filament voltage** should be neither too high nor too low: ±5% is stated as acceptable tolerance and ±10% would already be too much. The reason is that at too high a voltage, part of the cathode material evaporates, and at too low a voltage, undesirable intermediate layers form.

The filament circuits carry large AC-currents, possibly upwards of 5 A. At a distance of 2 cm from a wire subject to such a current, we find a magnetic flux-density of 50 µT, i.e. there will be 100 µT between two wires positioned at a distance of 4 cm. This magnetic field will induce, into a conductor loop of 3 $cm^2$, a hum-interference of 10 µV at 50 Hz (or 60 Hz, depending on your geographic location). Such an interference voltage will not be a big problem in a power stage, bit it might in the preamplifier. The filament supply-wire pairs therefore usually are installed twisted around each other; the magnetic fields generated by the individual wires largely compensate each other that way, as do the induced interference voltages.

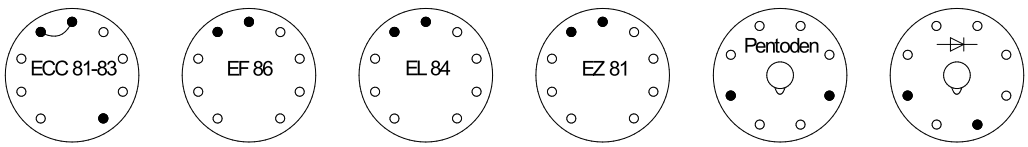


**Fig. 10.7.1:** Filament connections of some selected tube sockets (seen from below). “Pentoden” = pentodes

 

### 10.7.2 The charging circuit

In tube amplifiers, the typical supply-voltage lies in the range of 200 – 500 V DC. The mains transformer can only deliver AC and therefore a rectifier is required. Older guitar amplifiers mostly include a tube rectifier while newer ones often (but not always) sport a silicon rectifier. The main difference is that a tube rectifier necessitates a filament heating while Si-rectifiers do not. Moreover, the Si rectifier will generate a voltage drop of about 1 V in the flow-direction while this will amount to 40 V or more in a tube rectifier.

In most guitar amplifiers, both halves of the sine wave are rectified, this approach being termed a two-way or **full-wave rectifier**. The two secondary voltages generated by the transformer are in opposite phase so that each of the two rectifier-diodes conducts only during one half-wave (**Fig. 10.7.2**). However, this does not happen during the complete half-wave but only close to the maximum voltage, because the supply-voltage generated at the cathodes of the diodes is smoothened by an electrolytic filter capacitor. From an idealized point of view, the diode will only conduct if the anode/plate-potential (at the transformer) is higher than the cathode-potential (at the capacitor). With none of the diodes conducting, the capacitor-voltage will decrease exponentially: $u = \hat{u} \cdot \exp(-t/\tau)$; here, $\tau$ is the time-constant given by the capacitance and the load-resistor, e.g. $\tau = 32\ \mu F \cdot 2000\ \Omega = 64$ ms. If this time-constant is large relative to half the cycle-duration, there will be only a small voltage decrease, and the current through the diode will flow only during a short time (small **angle of current flow**). It follows according to the law of charge-conservation, that the peak current will be the higher the smaller the angle of current flow is.

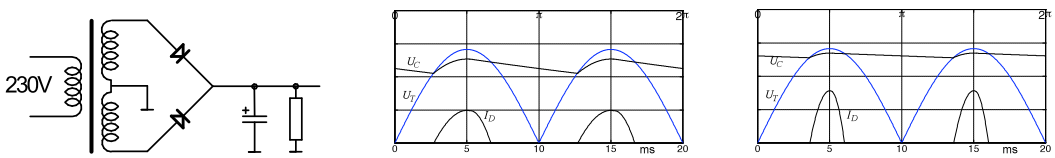


**Fig. 10.7.2:** Full-wave rectifier. Voltages and currents for two different angles of current flow.

In strongly simplified terms: if, given a load current of 200 mA, a current is flowing through the diodes only during 1/5$^{th}$ of the time, then this current needs to be five times as strong as the load current i.e. 1 A. In reality, load- and diode-currents can only be described with relatively complicated formulas, but the factor five mentioned here is a good benchmark. If a power supply is designed for 400 V / 100 mA, a <u>peak</u> current of 1 A may flow through the diodes. This peak current is specified in extended datasheets – in the abbreviated versions, however, only an allowable average current value is given. In the above example, this average is 100 mA per diode. The following **table** indicates both the peak current $\hat{\imath}$, and the average $I_{DC}$ for a number of diodes. For the tube diodes, $I_{DC}$ is the load-current (all listed rectifier tubes are *double*-diodes), while for the Si-diodes, $I_{DC}$ is the average current per diode. Also included is the **internal impedance of the transformer** $R_{Tr}$ (per secondary winding). Together with the capacitance $C_L$ and the load resistance $R_L$, this impedance determines the actual peak current $\hat{\imath}$. If $R_{Tr}$ is made too small, of if $C_L$ is too large, the rectifier tube may be overloaded under certain conditions! Normally, $R_{Tr}$ cannot easily be changed – transformers are mostly picked on the basis of their power. If the value of $R_{Tr}$ turns out to be too small, the simple solution is to connect a resistor in series! The given maximum capacitance values are taken from the datasheet of the manufacturers, and a bit of modesty is called for here: if we install – in order to further reduce the remaining ripple – a 100-µF-cap instead of the permitted 32 µF, then the tube will be operated outside of its specifications. Depending on the quality, it will hold up for some time – or not.

| Type | Filament | $U_{Tr}$ / $V_{eff}$ | $\hat{u}$ / V | $I_{DC}$ / mA | $\hat{\imath}$ / mA | $C_L$ / µF | $R_{Tr}$ / Ω |
|---|---|---|---|---|---|---|---|
| **EZ80** (= 6V4) | 6,3 / 0,6 | 2 x 350 | 1000 | 90 | 270 | 50 | 2 x 300 |
| **5Y3-GT** | 5,0 / 2,0 | 2 x 350 | 1400 | 125 | 440 | 10 | 2 x 50 |
| **EZ81** (= 6CA4) | 6,3 / 1,0 | 2 x 350 | 1000 | 150 | 450 | 50 | 2 x 240 |
| **5V4-G** | 5,0 / 2,0 | 2 x 375 | 1400 | 175 | 525 | 10 | 2 x 100 |
| **5U4-G** | 5,0 / 3,0 | 2 x 450 | 1550 | 225 | 800 | 32 | 2 x 75 |
| **5AR4** | 5,0 / 1,9 | 2 x 450 | 1700 | 225 | 825 | 40 | 2 x 140 |
| **GZ34** | 5,0 / 1,9 | 2 x 350<br>2 x 450<br>2 x 550 | 1500 | 250<br>250<br>160 | 750<br>750<br>750 | 60<br>60<br>60 | 2 x 75<br>2 x 125<br>2 x 175 |
| **5U4-GB** | 5,0 / 3,0 | 2 x 450 | 1550 | 275 | 1000 | 40 | 2 x 67 |
| **83** (Hg-vapor) | 5,0 / 3,0 | 2 x 450 | 1400 | 250 | 1000 | 40 | 2 x 50 |
| **BYX 90** | – | 2 x 2kV | 7500 | 0,55 A | 5 A | ♠ | ♠ |
| **1N 4007** | – | 2 x 300 | 1000 | 1 A | 10 A | ♠ | ♠ |
| **BY 133** | – | 2 x 390 | 1300 | 1 A | 10 A | ♠ | ♠ |
| **1N 5399** | – | 2 x 300 | 1000 | 1,5 A | 10 A | ♠ | ♠ |
| **1N 5062** | – | 2 x 240 | 800 | 2 A | 10 A | ♠ | ♠ |
| **BY 255** | – | 2 x 390 | 1300 | 3 A | 20 A | ♠ | ♠ |
| **1N 5408** | – | 2 x 300 | 1000 | 3 A | 20 A | ♠ | ♠ |

**Table:** Operational data of mains-rectifiers (from datasheets; please consider manufacturer-specific details!)
For silicon-rectifiers (♠), the internal impedance of mains transformers are normally always big enough, and the maximum load-capacitance does not represent any constraint, either, at (typically) > 200 µF.

The elaborations above have shown that in the charge circuit – between transformer, rectifier and filter capacitor – a **peak current** of 1 A can easily flow. Multiplying this value with a resistance of 1 mΩ yields a voltage drop of 1 mV. For a 0.5-mm-wire, 1 mΩ is reached already with a length of about 1 cm – this merits some consideration: if we contact the ground-conductor of the charge circuit at *two* different points that are 1 cm away from each other, a potential-difference of 1 mV is generated. For an input of high sensitivity, the full-drive input-voltage is in the same order of magnitude! Of course, the capacitor connections also have a non-negligible resistance, but here it is only the ripple that is marginally increased. If, according to the motto "ground is ground", the input-socket ground is connected to one point of the filter-cap feed, and the input of the pre-amplifier not to the same point but to another one off by 1 cm, severe **hum-interference** is bound to occur.

It is recommended for the wiring of an amplifier to draw up a plan in which all ground-wires are shown as resistors – this gives a good idea about unwanted voltage drops. By the way, similar problems may pop up in the secondary circuit of the output transformer, because here, too, the current may reach several Amperes. Therefore note: connect the output transformer directly to the output-socket; avoid channeling the loudspeaker current through the amp chassis.

 

In the following, **measurements** taken from amplifier power-supplies will be introduced – a *calculation* would be possible, as well, but requires a lot of effort because both the mains transformer and the rectifier are non-linear components. As a first example, we will look into the power supply of the TAD-Deluxe kit. It uses the **5Y3-GT** as a rectifier tube; according to the datasheet, it has to make do with a 10-µF-filter-cap. For the measurements, this filter-cap was loaded with 10, 5 and 3 kΩ – the corresponding charge-current amounts to 45, 85, and 130 mA, respectively, and the peak current through the diodes amounts to 180, 280, and 380 mA, respectively (**Fig. 10.7.3**).

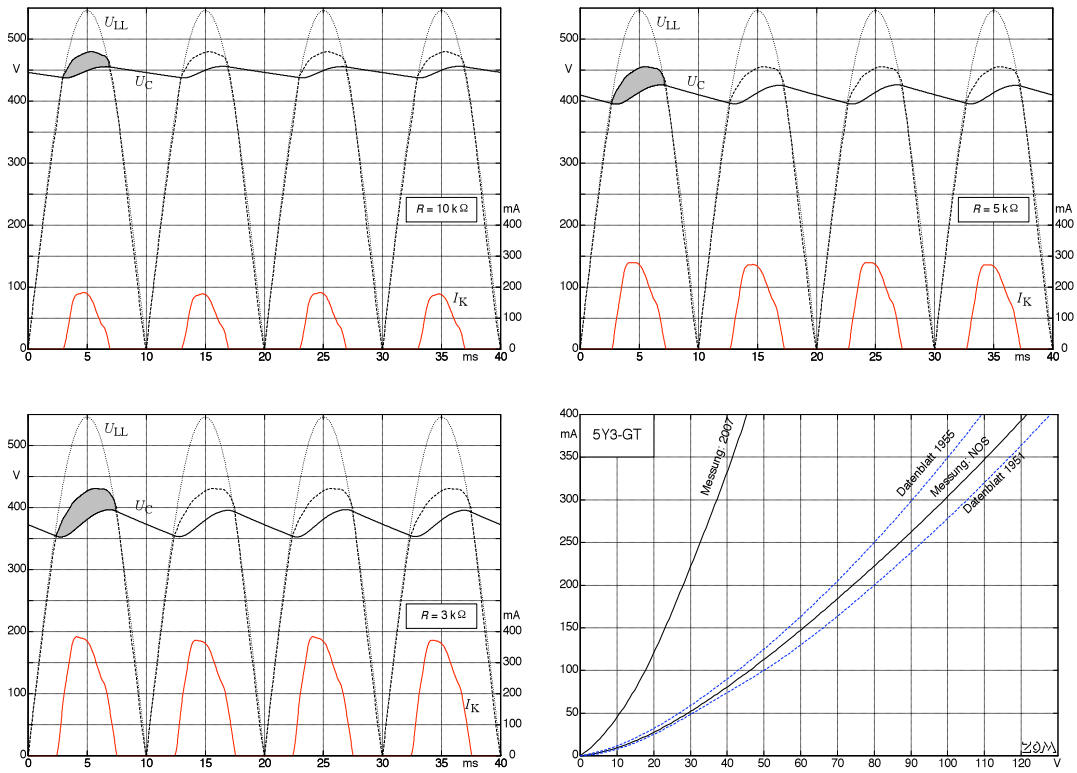


**Fig. 10.7.3:** TAD-Deluxe: voltages and currents for the full-wave tube-rectifier; $C_L$ = 10 µF.

As is easily seen, the relationship of peak-current to average current is no bigger than a factor of 2 – mainly due to the mains transformer at work here. Its secondary windings have a DC-resistance of 225 Ω, and thus the voltage breaks down strongly under load, and the angle of current-flow is relatively large. The thin line in the figure belongs to the open-loop transformer-voltage; depicted below it is the voltage under load. The voltage across the filter cap oscillates up and down in the shape of a saw-tooth wave; the forward-voltage of the tube is highlighted in grey. For the measurements, a rectifier tube of recent production was used; it shows a voltage drop in flow-direction of 30 – 40 V. In the U/I-diagram, two old datasheet-curves are entered with a dashed line, and in addition a measurement curve taken with an RCA NOS tube. **NOS = new old stock**: this designates tubes that have been remained unused on the shelf for decades, and which now are deployed for the first time. A tube with a voltage-drop of more than 100 V in the flow direction will indeed help the amplifier to a different operational behavior: the supply-voltage collapses even further than shown in Fig. 10.7.3. If this "sagging" is, in fact, desired, but no NOS-tube is available: a 200-Ω-resistor will do the same job.

The curves shown in Fig. 10.7.3 indicate that the data of a tube-type may not be simply taken from *one* datasheet. First, there are manufacturer-specific idiosyncrasies, and second, the production methods were always subject to an ongoing change. On the other hand, the almost inflationary multitude of designation letters (5Y3-G, -GT) often merely refers to differences in the glass container and not to electrical data. From this point of view it may be justified to ask horrendous prices for certain old tubes – tubes from today's production indeed do have different data. However: there are reports that it may be very easy to have any desired tube replicated even in relatively small numbers by the gentleman with the name consisting of merely two letters♣. At least as far as the cosmetics are concerned: perfect! Even the old GEC-sticker is superbly imitated. Okay … the electrical data … well, you can't have everything, can you? Back to the roots … or to revenue. Revenue, mostly, though, 'cause the NOS-tube built for 5 $ can easily be sold for 50 $ via the internet (*foun in grandads atic no garratee*). The odd tube will bring in excess of 500 $ – here the financial suffering alone will automatically take care of an "unparalleled sound experience". At least for rectifier tubes, such escapades are not required from the point-of-view of physics: any characteristic may be approximated with a few diodes and a few resistors.

Apart from manufacturer-specific and vintage-specific differences, **manufacturing scatter** within one lot also occurs, and so the luxury-tubes are individually measured i.e. **selected**. If you order selected tubes and they are delivered without a "selected" label, you can complain. You cannot complain if you receive tubes that are not selected. That is because "selected" merely indicates that the tube is labeled "selected". Whether, and how, a selection process happens – that mostly remains in the dark realm of trade secrets. Two "selected" GZ-34 acquired from a German tube distributor both were defective. How is something like that possible? A broken glass-container would be understandable – that can happen post-selection. But too low a power-capacity? That *had* to stand out during selection – because the label reads, after all: **GZ34-STR Selected**. How can anyone select without testing <u>each</u> tube? Only the third specimen of this supplier could deliver the current customary for a GZ34. This is in sharp contrast to the unselected Ultron-tubes: each of the three acquired tubes was perfect. **Fig. 10.7.4** shows measurement diagrams taken from "selected" GZ34's. RC-loading was 32 µF, the load current was 200 mA. The high-quality tube (A) has both systems operating with almost identical characteristic while the other two tubes (B/C, D/E) are expensive rejects.

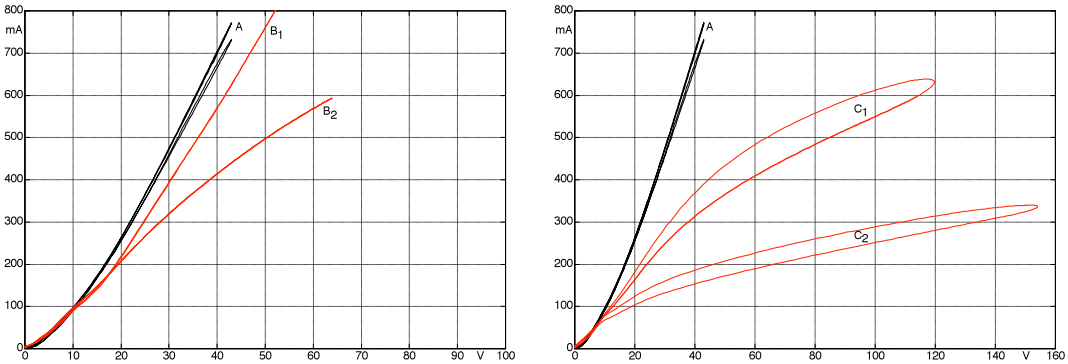


**Fig. 10.7.4:** GZ34 (full-wave rectifier). U/I-characteristic of "selected" tubes of varying quality.
A = tube o.k. $B_1$ and $B_2$ designate the two systems of a bad tube; $C_1$ and $C_2$ belong to a very bad tube the characteristic of which changes from bad to very bad within a few seconds.
[badly coated cathodes ⇒ Schade, O.: Analysis of rectifier operation, Proc. IRE, July 1943, 341-361].

♣ The RCA-tube measured in Fig. 10.7.3 was not sourced there - it could be located in the basement of the author's home.

 

### 10.7.3 The internal impedance of the power supply

Strictly speaking, the constant DC supply-voltage generated by the power supply does not remain constant at all: it varies dependent on the load, and in addition, a hum-interference is superimposed onto it. Talking about a **constant DC-voltage**, we in fact refer to the arithmetic mean-value of the supply-voltage, measured across a short period of time, e.g. 20 ms. Only when not connected to a load does the power supply generate a supply-voltage that has no superimposed ripple. This maximum voltage corresponds almost to the peak value of the secondary mains transformer voltage in idle, e.g. 500 V. As a load is connected and draws current (e.g. 200 mA), this voltage decreases to e.g. 460 V – a behavior that may be equated to an ideal voltage-source with an internal impedance: in the above example $R_i$ = (500 – 460)V / 0.2A = 200 Ω. The internal impedance depends on the transformer, the rectifier, the filter capacitor and the load-impedance, but unless the load changes dramatically, the load-dependence may be ignored, and the internal impedance may be seen as a constant characteristic of the power supply.

**Fig. 10.7.5** indicates the dependency of the supply-voltage on the load-current for different configurations. The power supply (seen as ideal) contains an ideal voltage-source and an ideal rectifier; the load-dependent voltage-drop is exclusively due to the capacitor discharge. The other two curves were measured at a power supply with a real transformer having an internal impedance of 2x40 Ω. The reason for the fact that such small resistances can already have such a considerable effect is found in the high peak currents (Chapter 10.7.2).

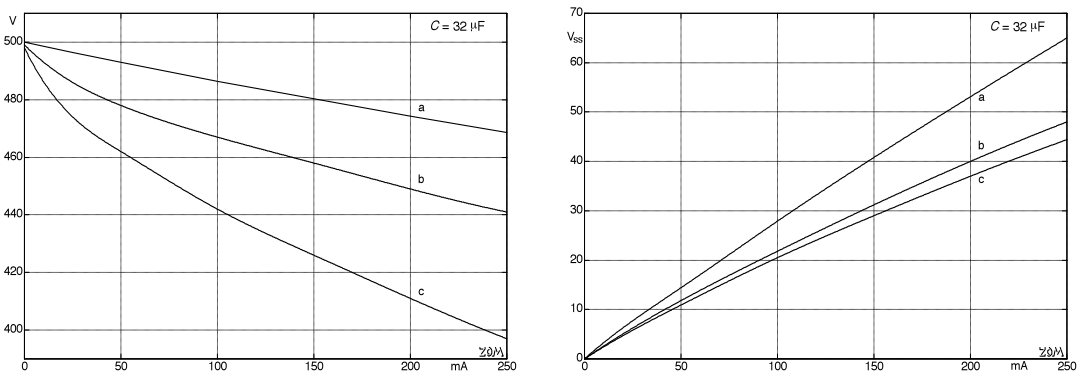


**Fig. 10.7.5:** Dependency of the supply- (left) and of the hum-interference-voltage (right) on the load current. a = ideal power supply, b = Si-rectifier (1N4007), c = tube rectifier (GZ34). Pure RC-loading.

Of course, it makes a difference whether the supply-voltage sags by 30 V or by 100 V, because the operating points of the power tubes depend on this value. Depending on the filtering, such voltage fluctuations can have an effect even up to the preamplifier tubes (Chapter 10.1). The largest sag in Fig. 10.7.5 is found in the voltage at the tube rectifier: for $I$ = 150 mA it amounts to $U$ = 75 V. With $U$ / $I$ follows the absolute internal impedance (500 Ω), while $dU/dI$ yields the differential version of it (300 Ω). Using a larger filter capacitance, both internal impedances may be reduced but this increases the peak current flowing through the diodes (compare to Fig. 10.7.2).

The hum-interference superimposed onto the supply-voltage is, according to Fig. 10.7.5, smallest for the tube rectifier because the relatively large internal impedance causes a large angle of current-flow. In push-pull power stages, the hum-currents compensate each other within the output transformer in the ideal case (Chapter 10.5.2) whereas in single-ended power stages, the hum-voltage causes audible interference.

 

### 10.7.4 Rectifier tubes

Datasheets very rarely indicate the voltage drop across a rectifier tube in the forward- (flow-) direction, although the internal impedance of the power supply very significantly depends on this. Superficial consideration of such tables easily gives rise to the impression that the main criteria are limited to the maximum allowable voltage and current. **Fig. 10.7.6** shows how big the differences can be. Surprisingly, already the datasheet-information differs: a Philips-GZ34 of 1952-vintage is something entirely different than today's Philips-GZ34, and a modern 5Y3-GT has little in common with a 5Y3-GT built 50 years ago.

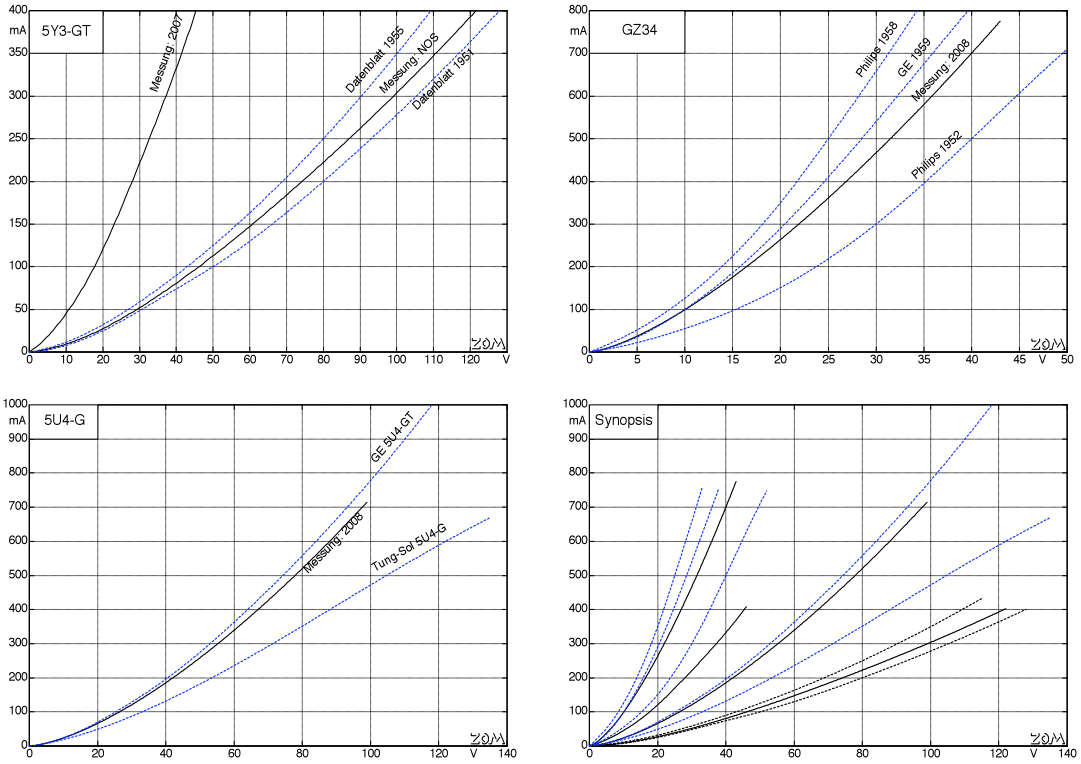


**Fig. 10.7.6:** Rectifier tubes operated in forward direction: U/I-diagrams.

Most tubes offered today have no binding **datasheets**; the reason is probably the following (as an imaginary example): expanding guitar wholesaler Pick-o-Might, Ltd.♣ decides to also carry tubes in the future. The sales assistant has projected colorful PPT diagrams including some very tasty pie charts, both the sales manager and the senior sales manager, plus in particular VP "Sales", had euphorically agreed, and the chief exec had nodded. So, tubes it is. The order is commissioned with Mr. Li♣ (or Mr. Wu♣ or Mr. Ly-ing♣); the logo (cost some serious dough to be put together by the designer) is included. 4 weeks later the first "our own – made by Pick-o-Might!"-tubes are delivered. In the meantime, the ad has been devised: "*A genuine GZ34 in its entire powerful glory*" and "*First-class, old-school-bulby GZ34: audibly sweeter sound – a reproduction of the classic Philips tube*". Datasheet? Better not, cause if Messrs. Li♣, Wu♣, or Ly-ing♣ should some day not be able to deliver anymore, the order will quickly have to be redirected to Mr. Wassili♣ (or Mr. Wischnorschow♣ or Mr Slochisow♣) – of course with the same logo. Datasheets would only tend to get in the way. Nastrowje!

♣ Any similarity to past, present of future names is purely circumstantial.

 

### 10.7.5 The filter-chain

As Fig. 10.7.5 shows, a sawtooth-shaped AC-voltage (hum interference) with a peak-to-peak voltage of easily 20 – 40 V is superimposed onto the supply-voltage. Such a high AC-component is problematic for the preamplifier because it will contaminate the signal-flow via the plate-resistor. This is the reason why the supply-voltage needs to be cleaned up using several filter-stages. Such a "filter-chain" typically consists of several consecutive low-pass filters containing, in the series branch, high-power resistors (e.g. 10 kΩ, 2 W), and in the respective parallel branch high-voltage electrolytic capacitors, e.g. 50 µF. In high-grade power supplies, the first series element is in fact not a resistor but an inductor. A filter choke (e.g. $L$ = 3 H) is used here because its AC-resistance $Z$ is much higher than its DC-resistance $R$. At 100 Hz, a 3-mH-choke has about $Z$ = 1885 Ω which is about the nineteen-fold of the copper-resistance (typically about 100 Ω). In combination with a 32-µF-filter-cap, the choke results in a 2$^{nd}$-order low-pass with a cutoff frequency of 16 Hz and an attenuation rising with a slope of 12 db/oct above that frequency.

That would be the case in an ideal world. In reality, we need to consider that filter-caps may loose part – or all – of their capacitance at higher frequencies (the may even become inductive). Therefore, it is recommended to connect high-voltage foil-capacitors (10 – 47 nF) in parallel with the filter-caps. Hold on: higher frequencies in a power supply operated at 50 Hz (or 60 Hz)? Sure: the rectifiers operate as a kind of switch, and every switching action represents a broadband event. In particular, the Si-rectifiers will interrupt the current-flow abruptly as the voltage at the filter cap drops below the voltage provided by the transformer. Integration♣ results in a sawtooth-shaped voltage that contains significant spectral lines up into the kHz-range. The reverse recovery time of the rectifier diodes may possibly cause additional interference: it takes a few µs until the charge carriers are "cleaned" out of the depletion layer, and during this minor time, needle-shaped peaks occur in the current-flow. With a correct circuit-layout, the interference-effect will, however, be rather small. If problems still ensue, it is possible to either use fast-recovery diodes, or to bridge the diodes with appropriate capacitors.

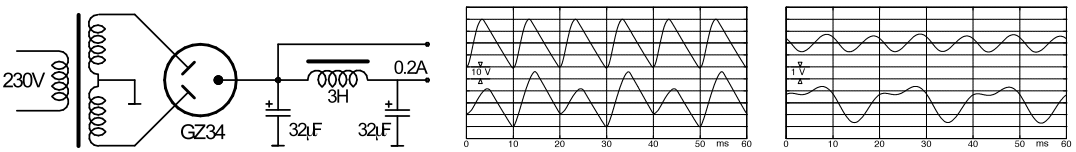


**Fig. 10.7.7:** Power supply with filter-choke. The two diagrams show the voltage curve at the filter capacitors: left at the first capacitor, right at the second capacitor. Top: with a faultless rectifier tube; bottom: with defective tube. In some countries, the mains voltage will of course be different from 230 V (e.g. 110 V).

**Fig. 10.7.7** indicates the filter-cap-voltages of a power supply operating with a GZ34. Cooperating with a 32-µF-cap, the choke (3 mH) reduces the ripple to about 0.5 $V_{eff}$, although only with a faultless rectifier tube. In the defective "selected" tube measured in comparison, the two diodes had very different characteristics, and a strong 50-Hz-component dominated the voltage. Higher-frequency signals are not apparent in this example. The faultless tube generates (on top of the DC-voltage) an almost perfect 100-Hz-tone the amplitude of which can be further reduced via the subsequent RC-filters.

♣ $I = \mathrm{d}Q / \mathrm{d}t = C \cdot \mathrm{d}U / \mathrm{d}t$.

 

### 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-transforner; 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.

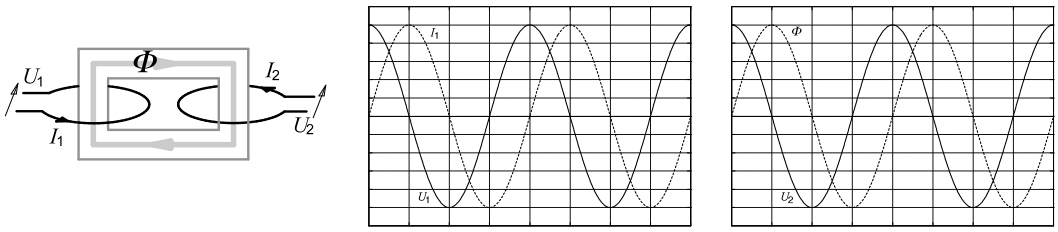


**Fig. 10.7.8:** The transformer as ideal quadripole. Voltages and currents for secondary open-loop circuit. ($I_2 = 0$).

**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 $\Phi$. 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 $\Phi_2$ generated by the secondary current is compensated by a further magnetic flux $\Phi_1$ that is in opposite phase to $\Phi_2$. $\Phi_1$ needs to be generated by an additional input current. In summary: $\Phi$ 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, 6 Ω is not an unusual value. This resistance will, however, not be the only component of the primary impedance, because: 230 V / 6 Ω = 38 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 looses 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.

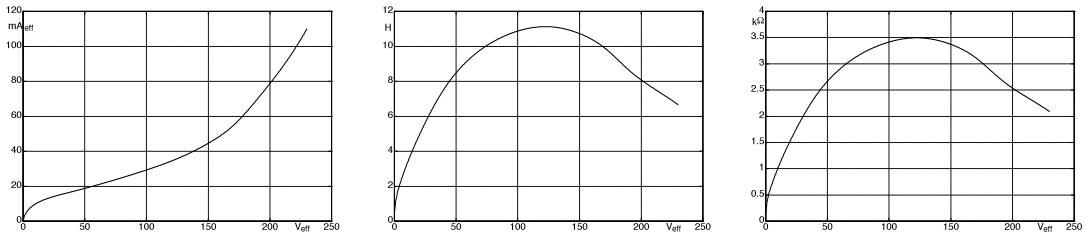


**Fig. 10.7.9:** Left: primary RMS-current vs. primary RMS-voltage for transformer w/out load; the other two diagrams show the quotient of two RMS-values: $U / 2\pi f I$ and $U / I$. (H = Henry♣).

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 (6 Ω) and inductance $L = 0.4$ H. However, already at $U = 1$ V, L rises to about 1 H, and further increases up to 11 H with increasing voltage. Already at $U = 1$ 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.

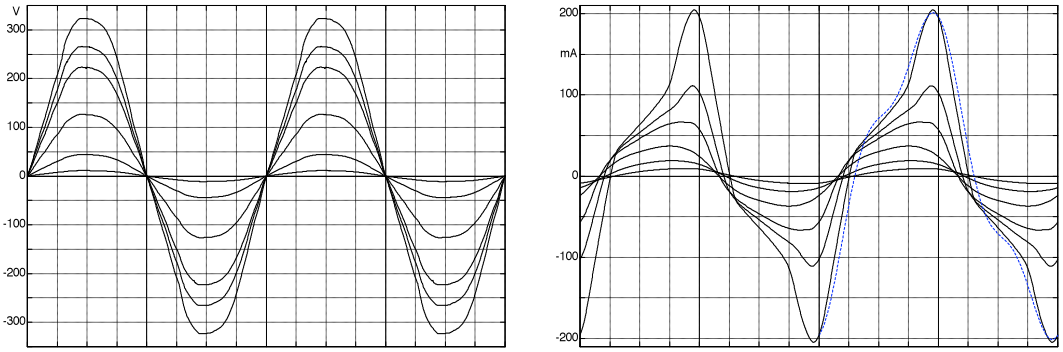


**Fig. 10.7.10:** Time-curve of primary voltage (left) and current (right) for a mains transformer without load.

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:

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

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 <u>active</u> 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-kΩ-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.

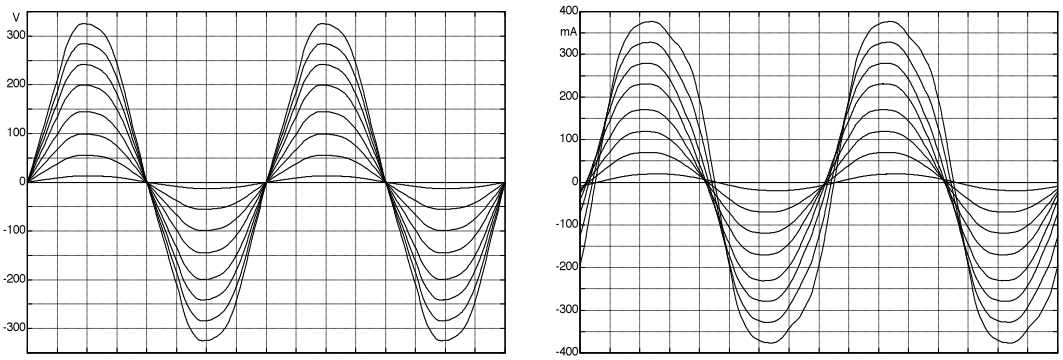


**Fig. 10.7.11:** Primary voltage (right) and current (left) over time for the mains transformer connected to a load.

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 kΩ, and 5 kΩ, 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.

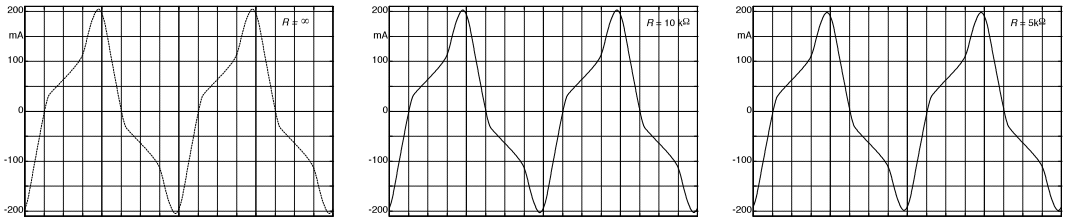


**Fig. 10.7.12:** Primary magnetization current for three different-sized loads (measurements).

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 $\Phi$.

♣ 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.

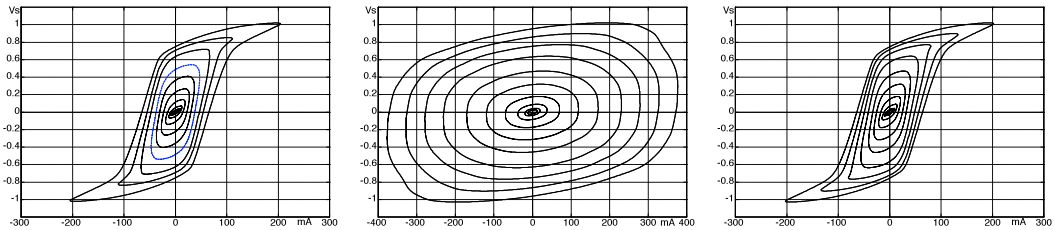


**Fig. 10.7.13:** Integrated primary voltage vs. primary current. Left: sec. open circuit; center & right: 10 kΩ load. Right: the load current (proportional to the primary voltage) was subtracted from the primary current.
The ordinate shows the interlinking flux using the unit Vs, the actual magnetic flux $\Phi$ 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 $mA_{eff}$, the RMS-value of the secondary voltage decreases from e.g. 350 $V_{eff}$ to 338 $V_{eff}$ corresponding to the **source impedance** of $Z_i$ = 40 Ω. 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 |
| *EI-92a* | 70-91 | 74 | 22.9 | 9.4 | 16.8 | 4.7 / 5.3 | 19.4 | 770 / 693 |
| *EI-92b* | 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 |
| *EI-106a* | 135-180 | 85 | 31.9 | 10.6 | 20.5 | 8.3 / 9.3 | 21.8 | 1520 / 1370 |
| *EI-106b* | 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 |
| *EI-130a* | 250-320 | 105 | 36.1 | 16.7 | 24.2 | 11.3 / 12.6 | 27 | 2570 / 2310 |
| *EI-130b* | 290-400 | 105 | 46.1 | 16.7 | 26.2 | 14.5 / 16.1 | 27 | 3280 / 2950 |
| *EI-150a* | 340-480 | 120 | 40.1 | 20.9 | 28.1 | 14.4 / 16 | 31 | 3720 / 3350 |
| *EI-150b* | 430-580 | 120 | 50.1 | 20.9 | 30.1 | 18.0 / 20 | 31 | 4650 / 4180 |
| *EI-150c* | 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.

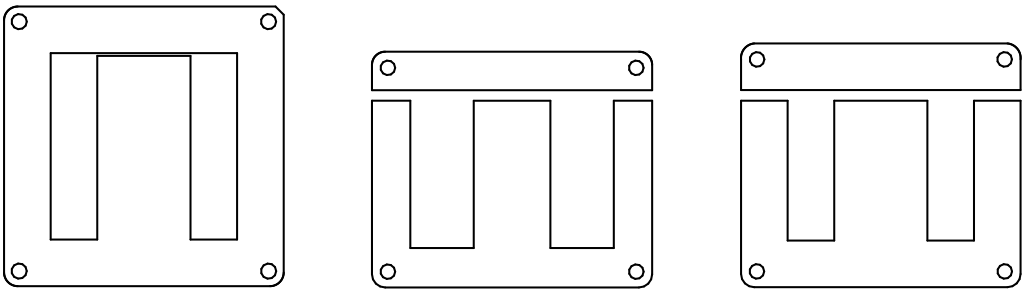

**Fig. 10.7.14:** Core sheets normalized to equal width: M-core (left), low-wastage EI-core (middle), wastage-free EI-core (right). There are different standards for the mounting holes.

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