AC Transformers

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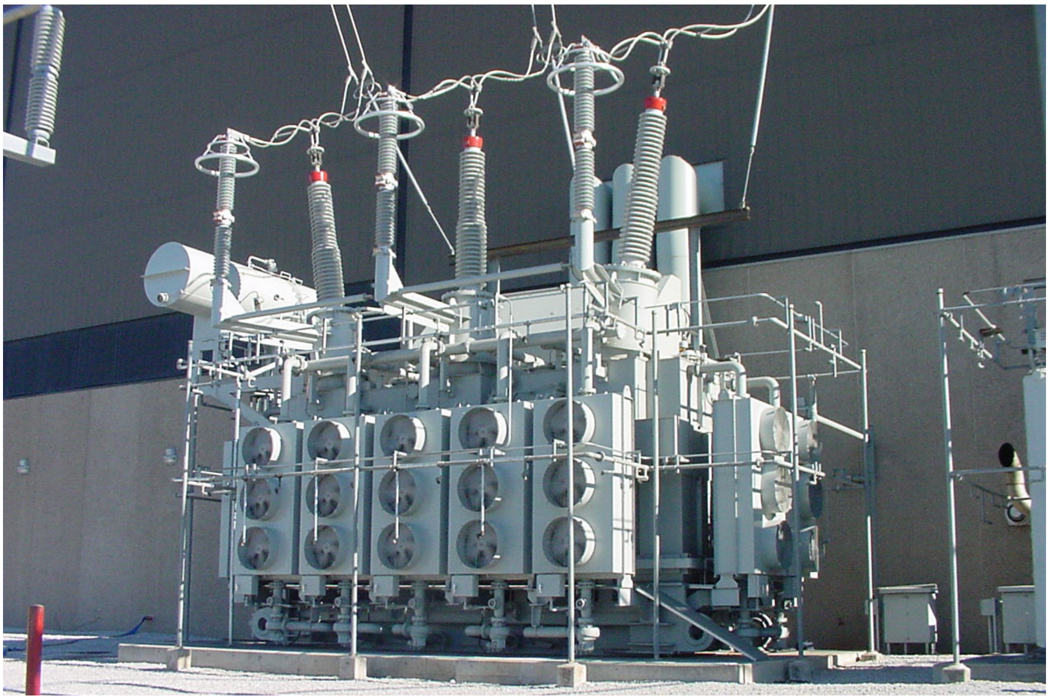
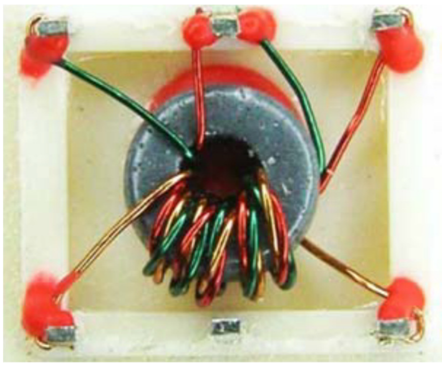


A 345 kV 360 MVA transformer used for high voltage power distribution (photo courtesy Mitsubishi Electric).

A small 230V-12V 1A plug-pack power transformer.



A miniature radio frequency transformer used for RF impedance matching (Courtesy Mini-circuits).

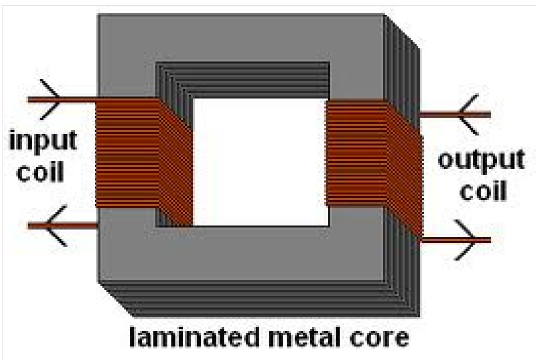
Transformers come in all shapes, sizes and applications. They range from huge oil cooled hundreds-of-megawatt 50 Hz power distribution transformers, to miniature transformers you can hardly see used in radio frequency applications well over 1GHz.

They are most often used to transform AC voltages, but in doing so they also transform impedance. They also provide voltage isolation, where a sensitive circuit needs to be isolated from external high voltages. You will also learn later how 'balun transformers' connect an 'unbalanced' radio transmitter (with an output connection to earth/ground) to a 'balanced' antenna (one without a ground/earth connection).

Transformer Construction and Mutual Inductance

Most transformers have an input coil, called a **primary winding**, and one or more output coils called **secondary windings**. A varying AC current through the primary winding creates a changing magnetic flux in the transformer's core, which flows around through the core, and induces an AC voltage in the secondary winding.

This effect is called **mutual inductance**: the induction of a voltage in one coil (secondary) in response to a change in current in the other coil (primary).



In mains power transformers, and other low frequency transformers, the primary and secondary windings are wound around a large **ferromagnetic** core such as iron. In higher frequency transformers a non-conductive **iron powder** or **ferrite powder** core is used. Radio frequency transformers may be ferrite or **air cored**.

Regardless of their size, construction or frequency of operation, all transformers have the same basic electromagnetic property – they step-up or step-down an AC voltage in direct proportion to the turns-ratio of two magnetically coupled inductors, and in doing so also transform the current flow and the impedance of a circuit.

Let's assume an 'ideal' transformer, that is, one without loss, where the power going into the transformer primary exactly equals the power taken out from its secondary.

Voltage Transformation

In an **ideal transformer**, the output voltage from a secondary winding (V_S) equals the voltage applied to the primary winding (V_P) multiplied by the turns-ratio.

The relationship between primary and secondary voltages is described by the following formula:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Where:
V_S is secondary voltage
V_P is primary voltage
N_S is number of secondary turns
N_P is number of primary turns

Or putting it another way, **V Secondary = V Primary x Turns Ratio**

Current Transformation

In an ideal (lossless) transformer the power into the primary winding must exactly equal the power taken out from the secondary windings.

From Ohms law we know that, for a constant power, if the voltage is changed the current must also change. We can now include a current factor into the transformer equation.

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} = \frac{I_S}{I_P}$$

Where:
I_P is the primary current
I_S is the secondary current

In other words, if the secondary voltage is increased by the transformer, the secondary current must decrease to maintain the same total power, and vice-versa.

Impedance Transformation

Ohms law also tells us that, if the ratio of voltage to current is changed, the AC impedance will also change. In an ideal transformer, the impedance into the primary and out of the secondary is transformed by the *square* of the turn's ratio.

$$N^2 = \frac{Z_P}{Z_S}$$

Where:
n is the turns ratio
Z_P is the primary impedance
Z_S is the secondary impedance

Say a transformer has a primary winding of 100 turns, and a secondary winding of 200 turns. The turn's ratio is 2, so the impedance ratio between primary and secondary would be 2 squared, or 4. If an impedance of 50 Ohms was attached across the primary winding, it would appear as 200 Ohms across the secondary winding, and vice-versa. The voltage in the secondary would be doubled and the current for the same total power would be halved.

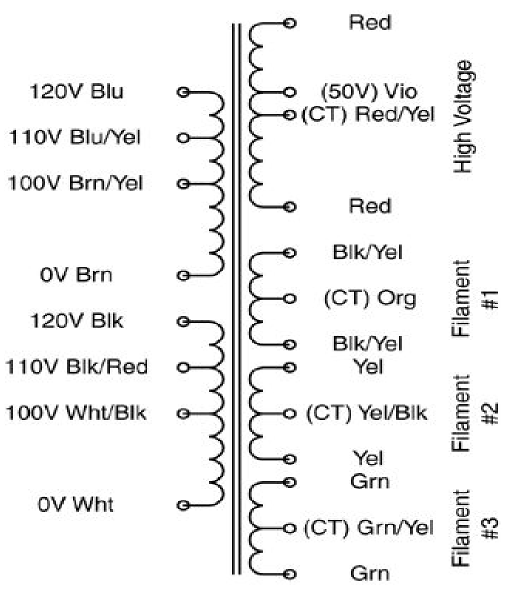
This impedance transformation characteristic of transformers, or the concept of looking into a device in one direction and seeing one thing, and looking into it another way and seeing a different thing, is very useful in many electronic applications, especially in audio frequency and radio frequency circuits.

For Instance, in a valve audio amplifier a low impedance 8 Ohm loudspeaker may need to be connected to the much higher anode impedance of the output valve, often about 5000 Ohms. This is done with a large iron-cored transformer that is designed to operate across the full range of audio frequencies, with a turn's ratio of 25.

Transformers with Multiple Windings

Transformers may have multiple primary and secondary windings. For instance, multiple primary windings on power transformers may be arranged to allow the transformer to be used with various international AC mains voltages, (such as 110V, 120V, 220V, 230V, 240V etc).

Multiple secondary windings at different voltage and current ratings may be provided for circuits that require a several different supply voltages.



This "universal mains voltage" transformer has multiple primaries and multiple secondaries for different purposes. Courtesy Hammond Manufacturing.

Generally, just like with batteries, secondary windings with equal current capacity can be connected in series to increase the total voltage, and secondary windings of equal voltage can be connected in parallel to increase the total current capacity. When series or parallel connecting windings of a transformer it's very important to follow the manufacturer's datasheet to ensure the phase of each winding is not reversed.

If the phase is reversed, the voltage from each series connected winding will cancel out the other and the result will be zero output voltage. In a parallel connection the windings will short each other out and maximum current will flow, quickly destroying the transformer, or worse…. *"poof".*

Auto Transformers

It is possible to obtain a lower output voltage by using a tapping point on a single winding.

Autotransformers are often used during testing of electrical and electronic equipment to reduce or adjust the mains voltage. Some auto-transformers are built with a sliding tapping point so the voltage can be constantly adjusted from zero to full voltage.

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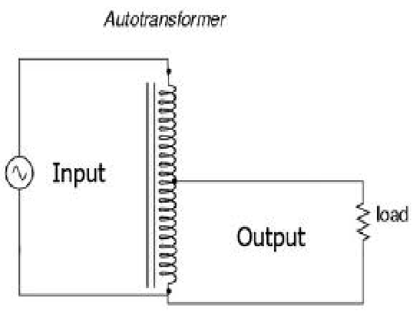


The transformer turns ratio is the ratio of the total number of turns, to the number of turns from the tapping point down to the common connection.

Important: Autotransformers have a critical disadvantage. They do not provide any electrical safety isolation between the input and output connections. This may not be a problem when there is sufficient electrical isolation built into the equipment being tested, but it could be a serious risk when testing older equipment.

Autotransformers have a limited range of uses and should never be used in place of an electrically isolated mains transformer.

Toroidal Transformers

A mains toroidal transformer

A collection of high frequency toroidal transformers

Toroidal transformers are wound around a continuous ring-shaped core which, depending on the operating frequency, may be made from steel, powdered iron, or ferrite.

The continuous ring eliminates air gaps and discontinuities which are inherent in the construction of common E-I laminated transformer cores, and more tightly contains the magnetic flux.

The result is a more efficient transformer which is lighter, less susceptible to external magnetic fields, and less likely to cause magnetically coupled interference to nearby sensitive electronic circuitry. Toroidal transformers are often used in audio amplifiers, high frequency radio frequency circuits, and sensitive electronic equipment, when their increased cost can be justified.

Transformer Losses

Copper Loss - Because a transformer is wound with copper wire, resistance loss occurs due to the currents in the primary and secondary windings. The resistance loss heats up the transformer windings, which in turn will increase their resistance further.

Eddy Current Loss - As stated previously, the changing magnetic flux in the transformer core induces a changing current in the secondary winding. However, as the core is also electrically conductive some unwanted currents are also induced in the core itself. These currents are called eddy currents because they are similar to swirling currents in water, or eddy's.

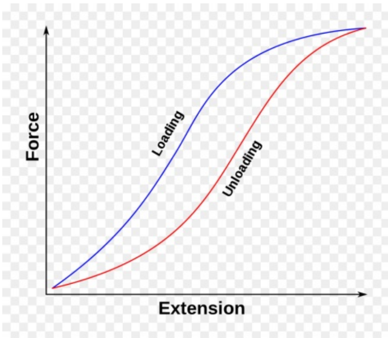
The strength of the eddy currents is proportional to the strength of the magnetic flux, and its rate of change (the frequency). Like all electrical currents, eddy currents generate heat as they pass through the resistive core, and the whole transformer heats up.

To reduce eddy currents, transformer cores are constructed in a way that minimises the area of core conductivity. In a power transformer this is done by using thin sheets of metal laminations which are sandwiched together and electrically insulated from each other, most usually forming the shapes E and I (called EI cores). Ferrite cores are solid cores made from a heat-treated ferromagnetic powder material, which has low conductivity and therefore low eddy currents.

Naturally, because air-core transformers do not have a conductive core they do not produce eddy currents. Air-core transformers are the most efficient, but because there is no ferromagnetic core material (with permeability) to magnify the impedance of the windings, a 50Hz air-cored mains transformer would be larger than a house.

Sometimes eddy currents can be useful, such as in induction heating, inductive motors, regenerative breaking for trains and electric cars, and non-destructive testing of engineering materials looking for micro-cracks, but in a power transformer they just waste energy.

Hysteresis loss - Hysteresis is a phenomenon in which the value of a physical property lags behind changes in the effect causing it. The drawing below shows a material being physically loaded and unloaded by a force. The difference in extension under the same force during the loading and unloading phase is the hysteresis.



When an AC voltage is applied to the primary of a transformer the core goes through a magnetisation and de-magnetisation process. The magnetic domains (tiny molecular magnets) present in the core material change their orientation after every half cycle and consume a small amount of power. Hysteresis occurs because the magnetic induction lags behind the magnetising force, and hysteresis loss appears as heat in the transformer core.

External Induction (Leakage Current) Loss - In a transformer some magnetic flux leaks out of the core and is lost. This is called leakage inductance and is another form of loss in a transformer. At low frequencies the leakage inductance is very small and can usually be ignored, but its effect increases with frequency and it does become important in audio and radio frequency transformers.

Audio Transformers

There are few transformer applications more demanding than audio. An audio transformer is required to operate precisely over a very wide range of frequencies with little distortion or loss, but inevitably there are performance trade-offs and compromises associated with material limitations, and naturally cost.

Small Audio Transformers

In the case of small audio transformers, such as moving-coil phono cartridge step-up transformers, (which operate at minute signals less than 1mV) the major design concern is anything that will change the accuracy and the nature of the sound. Overall transformer efficiency is not as important as distortion, frequency response, phase response over the range of audio frequencies, response to transients, and linearity. Linearity is the consistency in performance over the full range of expected input voltages.

These transformers often use exotic core materials and oxygen-free copper or silver windings, and enclose the transformer in a mu-metal shield in order to reduce pick-up of stray electric and magnetic fields (such as mains hum and radio frequency interference).

It's also important the winding turns-ratio matches the impedance transformation required for the particular application.

The RedRoo PR5 phono stage uses Lundahl phono step-up transformers that have an enviable reputation for accuracy and can impedance-match a large variety of phono cartridges.

Audio Output Transformers

Another demanding audio application for transformers is in the output stage of tube amplifiers. The output transformer is usually the most expensive single component in a tube audio amplifier, and there are inevitably cost/performance trade-offs.

The transformer needs to impedance match the high impedance at the anode of the output tubes to the low impedance at the loudspeaker. It needs to do this efficiently so there is little power loss over a very large frequency range. The phase response is important to avoid oscillations when negative feedback is applied (see the primer on negative feedback), and it needs to provide very large voltage isolation between the primary and secondary windings for safety and to protect the loudspeaker from damage.

Core saturation in Audio Transformers

The energy **that is** stored in a transformer is proportional to the number of turns in the primary and the current flowing through it. The maximum amount of energy **that can** be stored in a transformer core depends on the size of the core, and the magnetic properties of the core material.

If the energy put into the primary exceeds the capability of the core to store it, the transformer core will magnetically 'saturate'. When this happens, the output will not accurately follow the input, and the sound produced will be heavily distorted.

As the core saturation point is approached the transformer will start to become increasingly non-linear and distortion will increase. For this reason, quality Hi-Fi transformers do not operate anywhere near their point of magnetic saturation, and often a very long way below it where the magnetic response of the transformer is linear.

Also, for good low-frequency performance, the transformer's primary winding needs to have a great deal of inductance, say 10-50 Henrys. This means a large number of primary turns, but, as core magnetisation is proportional to the number of turns and the current through them, good low-frequency performance means an increased possibility of core saturation unless the core size is proportionally increased.

Single-ended transformers used in Class-A amplifiers are particularly susceptible to core saturation. In a single-ended amplifier, the bias current continuously flows through the transformer in one direction, so the transformer is already biased highly in one direction towards the point of core saturation. To increase the core's DC handling capacity a small air gap (or other nonmagnetic material) is placed in the laminated metal core, but this also has the effect of lowering the primary inductance.

Transformers intended for Class-A operation are larger, heavier, and more expensive than those intended for push-pull Class AB operation. They also have a maximum DC current rating that should not be exceeded. Push-pull transformers intended for Class-AB or Class-B operation do not have this problem as the DC bias current flows through the transformer in anti-phase, so the total magnetic field is cancelled.

Eddy Current Loss in Audio Transformers

Transformers with core materials (most transformers other than air-cored radio-frequency transformers) have some loss due to ‘eddy currents’ – electrical currents that flow in the magnetic core in a circulator motion like an ‘eddy’ in water. In an audio output transformer, it's important to minimise these losses because that also will affect the audio performance.

In order to minimise eddy current loss, the steel core of a transformer is usually made from thin laminations - sheets of metal pressed together but electrically (not magnetically) isolated from each other. A quality audio output transformer will use very thin laminations in its core, usually less than 0.35mm thick or even less.

Leakage Inductance in Audio Transformers

Another audio transformer trade-off occurs with leakage inductance. In any transformer, some magnetic flux leaks out of the core and is lost. At low frequencies, the leakage inductance is very small and can usually be ignored, but its effect increases with frequency. Quality audio transformers use a special (and expensive) ‘layered’ winding technique to increase the inductive coupling between the primary and secondary windings, and minimise ‘leakage inductance’. Generally, large transformers have greater leakage inductance than smaller ones, so it’s best not to oversize too much.

So, there is another trade-off between high-frequency performance, transformer size, power capacity, and cost.

Resonances in Audio Transformers

Transformers also have resonances at very high frequencies which cause large phase changes in the output voltage. If these phase changes are large enough to cause the negative feedback in amplifiers to turn positive, they will cause oscillations in the amplifier. Resonances in transformers are reduced by using the (expensive) layered winding technique, so there is another trade-off between unwanted resonances and cost.

So, there are many trade-offs in an audio transformer design between the size of the transformer, its low-frequency performance, its power handling ability, its maximum DC unbalanced current, its distortion, its insertion losses, and its cost. It's not surprising that the output transformers are usually the most expensive components in a tube amplifier, and output transformer manufacture is often thought of as a 'black art' rather than a science.

Guitar amplifiers

Guitar amplifier tube output transformers are manufactured to quite a different set of performance characteristics.

As mentioned previously, transformer core saturation is very bad for Hi-Fi amplifiers and Hi-Fi amplifiers have large and expensive output transformers in order to avoid core saturation, increase frequency response, and phase response, and minimise other losses. However, in Guitar amplifiers, core saturation and frequency response are not nearly as important and core saturation may even be a desired characteristic.

Early electric guitarists used the (poor quality) public address tube amplifiers of the time, which typically had small low-cost output transformers that would easily saturate at high volume. This caused a distorting/compression effect in the sound which became a sound 'genre' in itself. Modern guitar amplifiers still typically use smaller and lower-cost output transformers to preserve this effect, but mainly to minimise production cost.

The Red Roo 'Rooser' guitar amplifier uses a large (and comparatively expensive) output transformer which delivers sound with a large dynamic range (without core saturation). Any level of distortion 'crunch' and compression can be wound in at any volume level by adjusting the gain and volume controls. Together with presence and depth controls, this allows the ultimate level of control over the sound. A further ‘compression’ option allows the user to switch-in output stage compression at high volumes, which is similar to transformer core saturation.