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Chapter 7

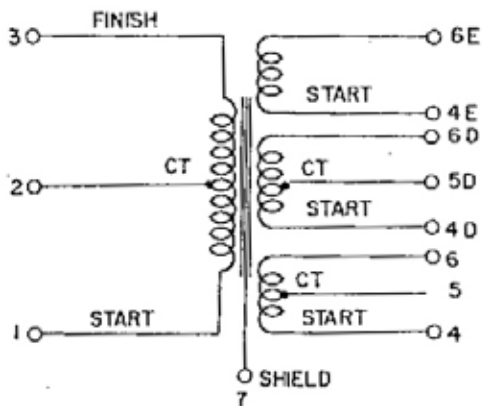
Speakers are Important In or Out of the Circuit

**by
Hartley Peavey**

SPEAKERS ARE IMPORTANT IN OR OUT OF THE CIRCUIT.

Most guitar players have heard that operating a tube type guitar amp without a speaker plugged in can cause problems. Few understand WHY; thus, this brief discussion.

In years past, most guitar amplifiers utilized vacuum tubes. Vacuum tubes (valves) are inherently high voltage, low current devices. This simply means that tubes typically operate at relatively high voltage at moderate to low current, which in turn, implies that they are (in essence) "high impedance" devices. By necessity, audio amplifiers (including guitar amps) deliver their output power to loudspeakers which are inherently low voltage, high current devices. One of the challenges for audio amp designers has always been the problem of matching high voltage, low current (high impedance) tubes to low voltage, low impedance, high current loudspeakers. The almost universal "solution" to this "matching" problem has been (and still is) to utilize what is often called an "output transformer." An output transformer IS a "matching transformer," which has the unique capability to match two dissimilar devices (i.e. vacuum tubes and loudspeakers).



Impedance-matching transformer with multiple secondaries.

The advent of solid state guitar amplifiers back in the 1960's confused the issue somewhat, especially since most solid state guitar amps DO NOT have output transformers. There's a simple (but little understood) reason for this. Both power transistors and loudspeakers are inherently low voltage, high current devices. Speakers, by their very nature, have voice coils with impedances generally between 4 and 16 ohms. Output tubes optimally expect to see matching impedances measured in the thousands of ohms, so it's easy to understand that tubes and loudspeakers represent

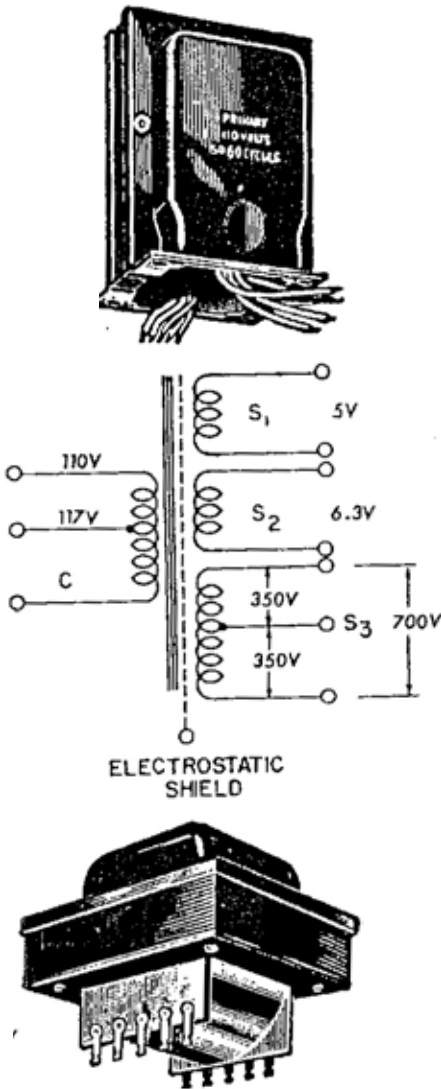
a serious "mismatch." Where power is concerned, proper "matching" of "load impedances" is necessary. Solid state power amps utilize power transistors which are high current, low voltage devices that can easily DIRECTLY drive loudspeakers, which as we now know, are also high current, low voltage devices. The simple fact is output transformers are not necessary (in most cases) with solid state amplifiers.

Matching a loudspeaker to a vacuum tube amplifier generally requires the use of an output ("matching") transformer to optimize loading on the tubes, while at the same time, achieving optimal current and voltage drive to the loudspeaker. In a very few examples, tube amps have been designed that can drive speakers directly, but these designs have not been commercially viable because of their high cost and complexity. Therefore, 99.9% of all tube amps use an output (matching) transformer to properly match characteristics of the tubes to the loudspeaker.

Transformers are relatively efficient devices. The science of transformer design and manufacturing has had well over 100 years to evolve and develop. Today's transformers are among the most efficient electrical devices available. Even though transformer design and manufacture has reached a high level of development, transformers do exhibit inherent characteristics that every musician should understand. In order to appreciate the process that enables a transformer to work, we'll have to discuss some basics.

Devices that we call transformers are able to take one form of energy and convert it into another; i.e. they "transform" one type of electrical energy into another...That's WHY they are called "transformers." A power transformer converts the AC (alternating current) from the mains socket into the appropriate current and voltage required by the amplifier. In a tube amp, this generally means a so-called "step up" power transformer that converts the mains/line voltage to a higher value to enable proper operation of the tubes. Remember, tubes are high voltage devices (typically 250 volts to 500 volts) therefore the tube amp's power transformer has to convert the mains/line voltage into a HIGHER value. Conversely, most output transformers convert a high voltage signal into a low voltage signal (albeit at a significantly higher current) in order to properly drive loudspeakers. Power and output transformers exhibit certain vital characteristics that have come to be appreciated by guitar and bass players.

A typical power transformer.

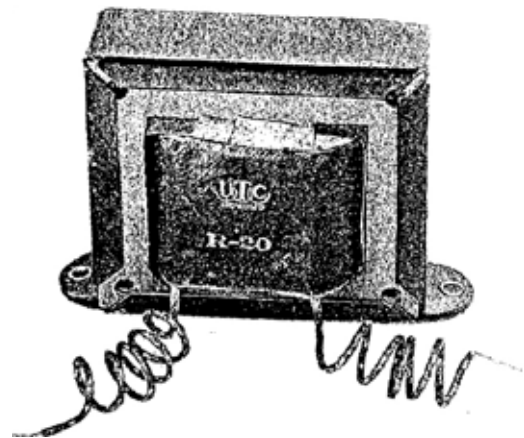


Back in the 1940's and 50's, guitar amp designers never ever thought that their "creations" would ever be played "wide open." As a result, they typically designed both power and output transformers to be as economical as possible (while still performing the task intended by the designers). Economics dictated that both the power and output transformers be as small as reasonably possible so as to minimize the amount of steel and copper used. They were NOT designing for "continuous maximum output," so they accepted that their power transformers (and the associated rectifiers and filter capacitors) would suffer some amount of voltage drop (sag) under maximum output conditions. Today, many musicians actually seek amps whose power supply is poorly regulated (meaning that the voltage drops or "sags" under full load conditions). Many players believe that this is a form of "compression" that they feel is desirable. In truth, this kind of voltage "sag" was not the result of "intelligent design," but was an attempt to economize on the power transformer and

the associated components in the power supply.

Much the same situation exists with output transformers. Amp designers in the 50's and 60's never envisioned that their amps would be used "wide open," and the same thought processes re: economics were used in regard to output transformers. The low E on a guitar is approximately 80Hz, so that was generally the lowest frequency of interest in many (guitar) amp output transformer designs. Because maximum output conditions were expected, only momentarily, by most guitar amp designers, their output transformers were designed with minimal amounts of steel and copper which produced some interesting and still rarely understood results regarding MI amplification.

Before going further, a short discussion on the way transformers work would probably be helpful. Transformers used in guitar amplifiers are typically divided into two basic categories, i.e. either "power transformers" or "output transformers." There is a third type of "transformer like" device utilized in many audio amplifiers called a "filter choke." However, this device is an inductor that physically appears similar to a transformer but is actually an inductor that converts electricity into "stored" magnetic energy in its core to help "smooth" the "pulsating direct current" delivered from the rectifiers and filter capacitors. Although a "filter choke" looks similar to a transformer, it has only one winding, as opposed to the two or more windings present in power and output transformers.



Choke

A transformer works by utilizing current flow through its primary winding to magnetize a steel "core." These cores are almost always composed of thin strips of special steel whose characteristics are optimized for use in this application. As current flows through the primary coil, a magnetic field is created around the core

(which itself absorbs the electrical energy as magnetic energy). This magnetized core alternates up and down in intensity in direct proportion to the amplitude and frequency of the voltage and current in the primary. The changing magnetic field (flux) in the core creates (by induction) voltage and current in the secondary. The voltage and current created in the secondary is **DIRECTLY PROPORTIONAL** to the voltage current in the primary in a specific “ratio” which is determined by the number of turns of wire in the primary and the number of turns of wire in the secondary.

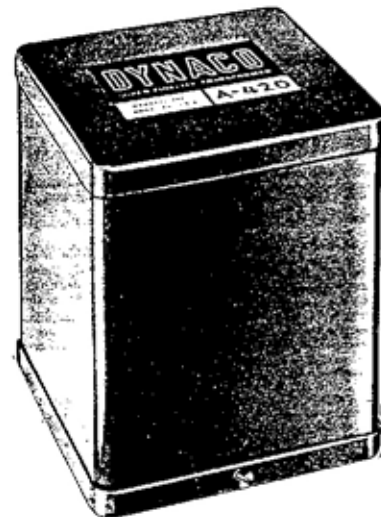
Simply put, an output transformer operates by utilizing electrical energy supplied by an amp’s output tubes, to magnetize the core at the “rate” of the input. As the core’s magnetic strength varies up and down, it transfers energy to the secondary by “induction” in the necessary ratio. Ideally, the output transformer primary coil is optimized to “match” the tubes being used, and the secondary (which has **NO** “direct connection” to the primary) is “matched” to the speaker used. As referenced above, there is **NO** “direct connection” between the primary and secondary, except by the “magnetic action” of the transformer’s core. Simply put, a transformer operates by converting electrical energy into magnetic energy and then back into electrical energy.

Generally speaking, one of the greatest limitations of transformers is the ability of the core to create enough magnetic energy to produce the desired effect in the secondary. This is true of both power transformers and output transformers. A minimally designed power transformer exhibits a pronounced voltage drop (sag) when called on for maximum output because the primary is unable to sufficiently magnetize the core with enough energy to transfer to the secondary. Typically, this occurs because the core was “minimized” by design.

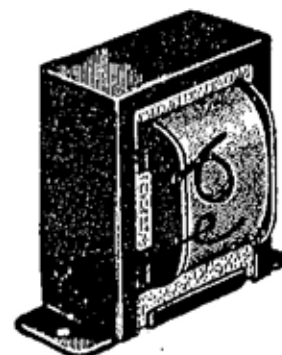
Magnetic cores in transformers have a “threshold,” beyond which, further magnetization is impossible. This is generally referred to as “core saturation.” Magnetic saturation is determined by a number of factors, including size, design, type of materials, etc, etc. Once the magnetic core of a transformer is “saturated,” no more energy transfer is possible...even if you could connect the entire output of Hoover Dam to it! Simply put, when a transformer core “saturates,” that’s it!

Tube Hi-fi audio amplifier designers are certainly familiar with the realities of transformer design. Since hi-

fi amplifiers usually try to operate over extremely wide frequency ranges (usually from lower than 20Hz to well above 20kHz) Hi-fi designers have to design tube amps with power and output transformers significantly larger than the equivalent guitar amp. The open low E on a six-string guitar is approximately 80Hz. Most guitar speakers rarely have significant response above about 8kHz, so that is the approximate bandwidth that most guitar amp output transformers are designed to handle. Because 20Hz is four times lower than 80Hz, tube hi-fi output transformers tend to be significantly larger than guitar amp transformers of equivalent power, i.e. a 100 watt hi-fi amp output transformer would be typically several times larger (and more expensive) than a 100 watt guitar amp transformer. Given this, it should be apparent that a guitar amp’s output transformer has less “iron” in the core than a hi-fi amp, and as a result will “saturate” much quicker than the hi-fi amp’s transformer. “Technically speaking,” operating a transformer close to its “saturation point” is a questionable practice. The truth is, much of a tube guitar amp’s sound has a great deal to do with the characteristics of the guitar amp’s output transformer!



Hi-Fi Output Transformer



Guitar Amp Output Transformer

Because modern output transformers are usually well designed, most people don't realize that they have such a profound effect on the frequency response of amplifiers. A little known aspect of output transformers is that their frequency response tends to drop off rapidly at both the high and the low frequency EXTREMES as the signal level approaches "saturation" of the core. This is a "dynamic process" which means that it is CONSTANTLY CHANGING with the frequency and amplitude of the driving signal supplied by the valves. In normal operation, frequency response is usually reasonably flat, but as the signal approaches saturation (maximum output) the extreme ends of the transformer's bandpass tend to drop considerably, but in a "dynamic fashion" (meaning that the transformer's "bandpass characteristics" are CONSTANTLY CHANGING!).

Actually, the above referenced "dynamic frequency response" changes of the output transformer are vital and incredibly helpful characteristics. Most people believe (wrongly) that tubes/valves "clip" with rounded edges on clipped output waveforms. This is NOT true! Tubes clip just as "squarely" as transistors, albeit usually asymmetrically (with one side clipping before the other). What causes the "rounded edges" is the action of the output transformer as it approaches saturation. Happily, this rapidly changing frequency response of the output transformer has the overall effect of "rounding off" square waves generated by the tubes, while at the same time, it LIMITS the lower end frequency response coupled to the speaker. This happy and "accidental" tonal enhancement is caused by the output transformers unique "dynamic" tone shaping capability. A tube guitar amplifier's performance and operation is greatly enhanced by these characteristics, which only occur at (or near) maximum output. As the signal approaches the point of saturation of the output transformer, these desirable effects are created that play such a vital role in creating the "sound" of a tube amp.

The fact that solid state amps almost never use output transformers allows clipping to blast DIRECTLY into the loudspeaker. This can often result in the characteristic "rasp" of overdriven solid state amplifiers, unless special precautions and designs are utilized, such as with Peavey's patented TransTube® technology (which emulates the output transformers unique bandpass capability as well as other characteristics of overdriven vacuum tubes, such as asymmetrical clipping, bias shift, etc, etc.). Overall, much of the "sound" of a tube amp is attributable to the unique output characteristics of its output transformer.

There have been many attempts over the years, by many companies, to design "proper" transformers for guitar amps. This usually means larger, more expensive transformers that are (from a technical standpoint) "better;" i.e, better steel, more laminations, larger size, etc, etc. Almost every one of these attempts to fit "proper transformers" to guitar amplifiers has failed because adding a "proper" (i.e. a hi-fi) transformer often destroys "the sound." While it might be argued that many bass players prefer a hi-fi type of sound (even in valve amps) guitar players certainly don't. This is easily proven by plugging your guitar into a hi-fi amp (which almost always sounds bad and doesn't have the "dynamics" and "feel" of a guitar amp). Unfortunately, guitar amps are one of the few areas of audio where bigger is NOT necessarily "better." If you don't believe this, I invite you to plug your guitar into a tube hi-fi amp and draw your own conclusions.

The above discussion relates to saturation (or near saturation) and its effect on the output characteristics of a tube output transformer. Power transformers encounter many of the same limitations re: the ability of the magnetic core to transfer energy from the primary to the secondary. As the core approaches saturation, the transformer's ability to transfer additional energy becomes marginal. Thus, the output voltage tends to "sag," which is a characteristic that lots of guitar players find desirable, seeing this as a sort of "compression." This is another area where "bigger is NOT better." Larger and more robust power transformers result in what is TECHNICALLY a "better" unit, having better regulation, less sag/compression effect, and therefore, is not necessarily a "better" guitar amp "soundwise" (as far as most guitar players are concerned).

Tube/valve amps sound like they do for a number of reasons, which include asymmetrical clipping, which is mostly because tubes use a "single ended power supply," i.e. a high voltage (B+) and ground. Most high gain amps have the ability to drive the tube's grids positive with respect to the cathode, which causes "grid current" to flow, which in turn creates an effect called "bias shift." As the output transformer nears its maximum design limits, the frequency response at the extremes vary "dynamically" with significant "rolloffs" at both the low end and high end. Lastly, some amount of "sag" in the power supply creates a kind of "compression effect" familiar to guitarists. These effects work together in a rather fortunate "choreography" to produce what we today recognize as a "good" guitar sound.

Since solid state amplifiers generally have no output transformers, they usually do not clip asymmetrically, have no grids, and therefore no grid current and the resulting “bias shift.” It’s certainly not any “news” that a solid state amp’s distortion characteristics are usually much different from the distortion of a tube amp. Only by a thorough understanding of what goes on inside a tube amp, was Peavey able to emulate all these phenomena with our patented TransTube® technology. One might wonder why Peavey still makes tube amps if we have achieved such a close replica. That answer is simple! Many of our customers WANT tube amps! If that is what our customer wants, then that’s what we’ll build as long as decent tubes are available. Unfortunately, that will probably not always be the case.

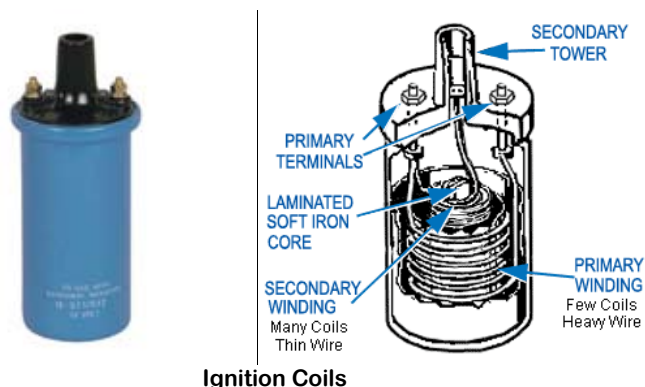
The above is a rambling discussion about transformers (both power an output) and their effect on the sound of a tube guitar amp. I felt it was important to understand what transformers do (and generally how they do it) before getting to the final point of this discussion. As mentioned above, a transformer works by converting one form of electrical energy into another. In the case of a tube amp, to achieve the matching, we “trade” high voltage in the primary, for high current in the secondary to properly drive the speaker. This is a “two step” process where electrical energy from the tubes magnetize the core of the transformer at the audio rate. Then, the varying magnetic field in the core induces voltage (and current) into the secondary suitable to drive the speaker. The important point here is the energy is put into the transformer through the primary, which converts that energy into magnetic energy (i.e. it magnetizes the core) and then that energy is reconverted into electrical energy in the secondary windings, which drives the loudspeaker.

If (for whatever reason) the SECONDARY of the transformer has no “load,” the magnetic energy created by the primary (and “stored” in the core) has NO place to GO! As the alternating signal in the primary goes down, the magnetic field built up in the core “collapses,” thus inducing an extremely high voltage “spike” back into the transformer’s primary windings. Because this energy is substantial, and because the primary coils have many turns of wire, an extremely high voltage “transient” (often 3000 volts or more) can be developed. The primary of the output transformer is directly connected to the tubes and tube sockets of the amp, and neither the tubes nor the sockets (and associated wiring) are designed for that kind of voltage. These electrical “spikes” can (and often do) cause “arcing” inside the transformer and/or the tube elements, especially between the terminals on

the tube sockets and the associated wiring.

Remember that we learned in high school physics about the “law of conservation of energy.” This taught us that energy can’t simply “disappear,” it has to “go somewhere.” When a tube output transformer doesn’t have a place for the energy to go (i.e. a speaker or its equivalent) the energy developed in the magnetic core “flashes back” into the amplifier, often destroying the output transformer, the tubes, the tube sockets, and/or the associated wiring.

This is WHY you should NOT operate a tube amp without a “load!”



Ignition Coils

Ignition coils for gasoline engines work essentially the same way. There’s a “secondary” coil of wire with many “turns” of wire wrapped around a steel core. In operation, a connection is made to a power source (battery) then current flows through the primary coil and magnetizes the iron core. The contacts (points) then open and the magnetic field is allowed to “collapse,” which results in a huge “pulse of energy” being inducted into the secondary coil (which is what produces the electrical “pulse” that is fed to the spark plug). This is also a two step process where basically the primary coil is energized, producing a magnetic field, then “de-energized.” As the magnetic field “collapses” the magnetic energy stored in the core induces a high voltage into the secondary coil which is then fed to the spark plug, thus firing the air/fuel mixture.

An “UNLOADED” tube output transformer produces high voltage “spikes” in EXACTLY the same manner as an “ignition coil” does. The difference being that a tube amp output transformer is NOT designed to operate that way, but an ignition coil IS! Operating a tube amp with its transformer unloaded can easily damage or destroy a perfectly good tube amplifier by the “flyback” action described above. Hopefully, the above will provide a little background as to exactly WHY it’s important NOT to operate an amplifier WITHOUT a proper “load” for the output transformer’s secondary output terminals.

Peavey (recognizing that accidental operation of its tube amps without a proper load is a possibility) has endeavored to try to protect the output tubes, sockets, wiring, and the output transformer against damaging voltage spikes as described above. Although there is no 100% "fool proof" method to protect an amplifier against the spikes generated by an unloaded output transformer, the most effective protection is by use of so-called "flyback diodes." "Flyback" is an old term applied to high voltage systems in tube type TV sets, but it has come to be applied to any high voltage transient (spike) in electronics. Silicon diodes have certain characteristics that engineers find very useful. At a certain voltages, silicon diodes encounter a "threshold" and conduct energy in the reverse direction to their normal operation. This "avalanche effect" occurs at very high voltages and thus inclusion of these into the output circuit allows some measure of protection for the tubes, output transformers, sockets, and wiring. If voltages occur above their "avalanche" level, the diodes conduct in the "reverse direction," thus the destructive voltage transient generated by the unloaded output transformer is shorted to ground. Although this method has proven very effective, it should be noted that super high voltage transients can cause arcing either inside the output transformer, the output tubes themselves, and especially between the terminals of the tube sockets. Cheaper plastic or phenolic output tube sockets are especially prone to this and can be easily identified because they are usually BLACK or BROWN. If a voltage transient "arcs" between the two socket terminals, it usually leaves a "carbonized path" between the terminals that REMAIN CONDUCTIVE which can (and often does) render the amp unserviceable. This is WHY Peavey now utilizes white GLAZED CERAMIC sockets for our output tubes, since these white ceramic sockets are MUCH more resistant to arcing between terminals and the "carbonized path" problem is totally eliminated.

Hopefully, the above will give players a better idea why tube amps should never be played or operated without a speaker load, or a proper termination by a load resistance of some kind.



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