This article discusses protection topics related to a valve amplifier's output transformer.

Over-current and over-voltage stresses are common causes of output transformer failure, so these two topics are discussed in detail. The influences that can cause stress are described, along with common techniques for managing those stresses. Fuse and PTC selection for over-current is discussed. MOV selection for output transformer over-voltage protection is presented as a simple addition.

Techniques to test for a failed output transformer are described.

Protection of power transformers and chokes used in valve amplifier power supplies is also discussed.

Contents

The output transformer (OT) is expensive to replace, and finding an authentic replacement may be a struggle, so adding extra protection is a wise move when restoring, improving or cloning an amplifier and may also help protect the power transformer (PT) as well.

Although output transformers are a pretty tough part, there are many stories of amplifiers with a failed or replacement OT, or no OT at all.

Like all parts, adequate cooling is required for the OT. Some amplifiers have a very poor layout of transformers and valves, with parts sandwiched together in close proximity, and with marginal ability for free air movement to allow removal of heat. This situation is compounded in some old amplifiers that were intended for PA use, where output power was often only intermittently needed, or the amp was not often loaded to a maximum level. A restoration can also mean an amplifier used nowadays for guitar or bass could have a much higher continuous output loading than originally intended, and be often cranked in to over-drive.

Figure 1. Amp purchased with no OT. OT sandwiched between output valves and barriers.

Electrical protection of an OT is commonly achieved using over-current and over-voltage protection techniques.

Over-current Protection

Over-current protection of the OT primary winding as in a single ended (SE) output stage, or primary windings as in push-pull (PP) or ultra-linear (UL) output stages, is often just by a power supply fuse on the mains input. Typically, there is a direct connection of the high voltage DC power supply to the OT, either to one end of the OT primary as in a SE stage, or to the primary centre-tap (CT) as in a PP stage. As such, a fault in the output stage may cause a damaging current level to flow.

Fault causes

One example of an over-current inducing fault cause is the loss of bias voltage in a fixed bias amp which would cause maximum continuous tube current conduction in both half-windings of a PP output stage (loss of bias can be simply from a poor pot wiper or broken pcb trace).

Another example is a leaky coupling capacitor between driver and output stage, which can force an output valve grid positive in voltage, and hence also cause a loss of bias to an output stage valve. Similarly, a failing grid-leak resistor on an output valve, or an output valve going 'gassy' (whether by a leak, or by excessive outgassing under red-plate operation) can lead to the grid voltage going more positive, and hence a loss of bias voltage, with the current in that valve increasing uncontrollably.

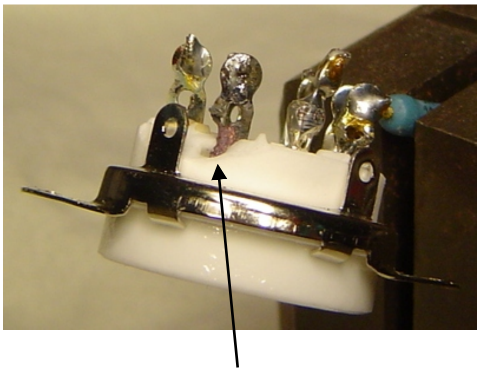
There is some evidence to show that output stage valve screens can short to cathode or other internal electrodes, as is likely when screen dissipation limits are exceeded and the screen wire sags or breaks.

Failure of heater-to-cathode insulation in a cathode biased output tube can force that tube in to full conduction if the heater is grounded (as the bias is forced to 0V). For this type of fault, both tubes in a PP stage with common cathode biasing would also fully conduct.

Another failure mode is when OT primary current shorts or arcs from an output stage anode pin 3 to the heater pin 2, and then through the heater circuit to ground (see next section for cause). In a somewhat similar manner, a valve with a broken base peg could be incorrectly inserted, which could connect an output stage anode circuit to cathode circuit through the valve heater.

Faults can even occur during servicing – note pin in photo.

A meter probe accidently shorted pin 3 of an output valve to a nearby grounded socket holder's earthing tab when the amp was on. The OT half-primary winding inductance ensured the arc continued, even when the probe was quickly removed, and the arc continued for a few seconds eating away at the pin 3 terminal and cracking the ceramic edge, until the only fuse in the amp (PT mains side) blew. The OT survived in this particular case!



Fault current level influences

A 'prospective' fault current level can be estimated or even simulated with PSUD2 using known or measured resistance values of parts in the fault current path.

A fault on the B+ supply line is likely to reach the maximum prospective current that the power supply can deliver. PSUD2 is great for indicating that fault current level, as it takes in to account primary and secondary winding resistances in the PT, and in the rectifier diode, as well as the sagged B+ voltage, and can calculate rms current level through the fault resistance path.

Fault current that passes through a heater supply can be very influenced by the type of heater supply grounding configuration used. A heater winding with CT connected to ground (or one end of heater grounded) imposes a very low resistance path. If the heater is grounded through a fixed resistor humdinger, or humdinger pot, then the series resistance to the fault would be increased, but is likely to still

be low, as both sides of a humdinger connect to ground. An elevated heater could introduce a relatively high resistance fault path from a resistive divider elevated supply, or a relatively low resistance path if using for example a common cathode voltage of an output stage. A heater supply with high resistance to ground could cause the heater supply to be elevated towards HT B+ level if a fault occurs, and lead to heater-cathode failure of all valves in the amp.

Fault current protection techniques

Depending on PT and OT, a fault current may end up damaging the PT before damaging the OT.

If at all possible, a power supply fuse on the secondary side of the PT should be included as it offers better protection than just a single fuse on the primary side of the PT for the many types of fault that can occur in an amp. A procedure for selecting an appropriate fuse is provide in the link - Valve amp fusing.

For larger amplifiers, especially those that run parallel valves in the output stage, the addition of a fuse in each valve cathode 'leg' provides much better protection as each cathode fuse rating can be made significantly lower than the secondary side PT power supply fuse rating. Even the low wattage current sense resistor used for idle current bias adjustment for each cathode can be used as a 'poor man's fuse' – the resistor needs to have a wattage rating just suited to overdrive conditions[1]. Some hi-fi amps even capacitor bypass the fuse, or sense resistor and fuse, to minimise their influence on signal performance.

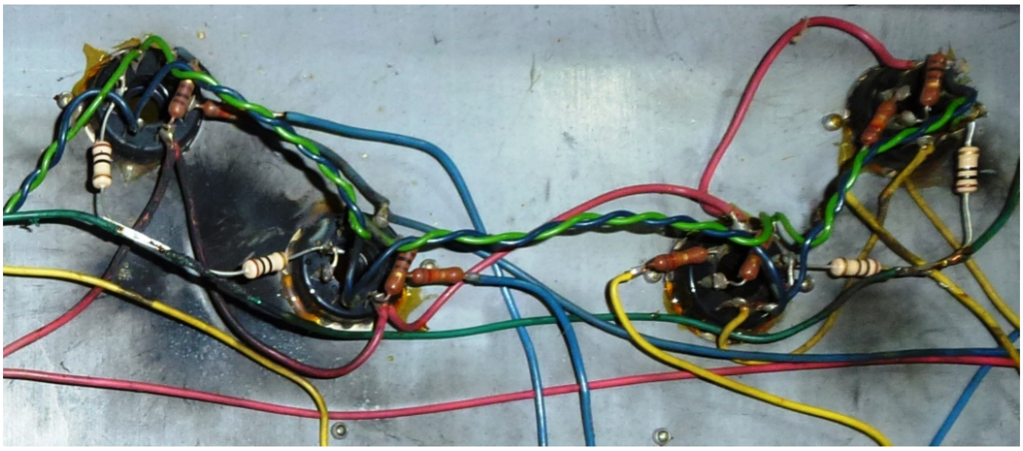


Figure 2. Poor man's fusing probably saved the OT in this repaired Fhone amp.

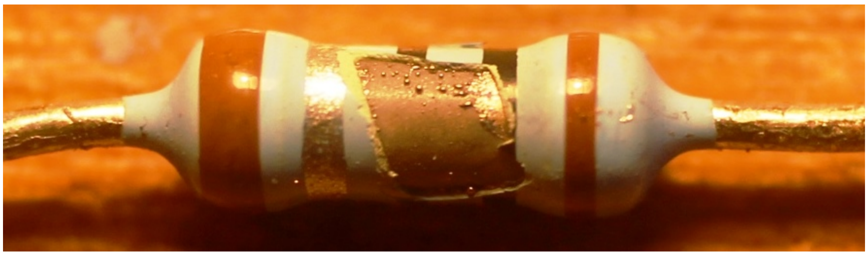


Figure 3. Philips MRS25 metal film, 1Ω, 0.6W for cathode current sensing. "Popped" by bad 6GW8.

A parallel 150V Zener diode across each cathode 'fuse' is preferable. If a cathode fuse fails, and the valve itself is still ok, then the zener diode aims to keep the cathode from rising more than the valve's cathode-to-heater voltage limit (200V for most valves, although 100V for EL34, and 150V for the KT's). Initially, high current flows in the cathode circuit and Vak will be low with the fuse still intact. If the bias supply has failed then the grid may be up to 0V and Vgk~0V. When the fuse fails, Vgk will go negative as cathode voltage increases, and Vk will increase to the Zener voltage. If the grid is stuck at 0V, then Vgk ~ -150V and in deep cutoff, so little current flows through the Zener diode, and a normal 1-5W Zener will dissipate little power.

[1] Overload testing on some 0.6W MF MRS25 1Ω and 10Ω resistors showed they could still 'function' even when subjected to 15x their dissipation rating (ie. 9W, or 3A for 1Ω, and 1A for 10Ω), with the acrid fumes being an indicator of a fault. Only some manufacturers make 1Ω MF resistors in 0.4W or 0.25W ratings

If the valve were damaged, and the fuse opened, then the Zener would likewise be damaged (but it is <<$1, so is a fair trade-off).

Fusing of the HT (high tension) DC voltage from the power supply to the OT is not recommended as high DC voltage is prone to tracking across fuse holders and normal 20mm and 3AG fuses don't have DC voltage ratings, and may well shatter. If such a fuse blew, then it may also generate a high-voltage spike in the OT, depending on the circuit. In addition, if a pentode output stage still has screen voltage applied after the plate voltage has disconnected then the valves will get damaged.

A poor-man's fuse technique can be used for the humdinger fixed resistors or trimpot. If the humdinger acts as a poor man's fuse, then the fault current is stopped, and heater-cathode voltage limit can be constrained by connecting a 150V Zener with back-to-back 1N4004 diode from a heater side to ground.

Cathode biased output stages, and screen 'stopper' resistors can play a major role in reducing fault current levels for some types of over-current fault. Adding screen stoppers in an old amplifier that had none in place is often worthwhile, and can reduce OT over-current stress in UL stages, or triode connected pentode PP stages, as well as PT stress if the screen internally shorts. Typical parts used for protection in a fixed bias PP stage are shown in Figure 4 below.

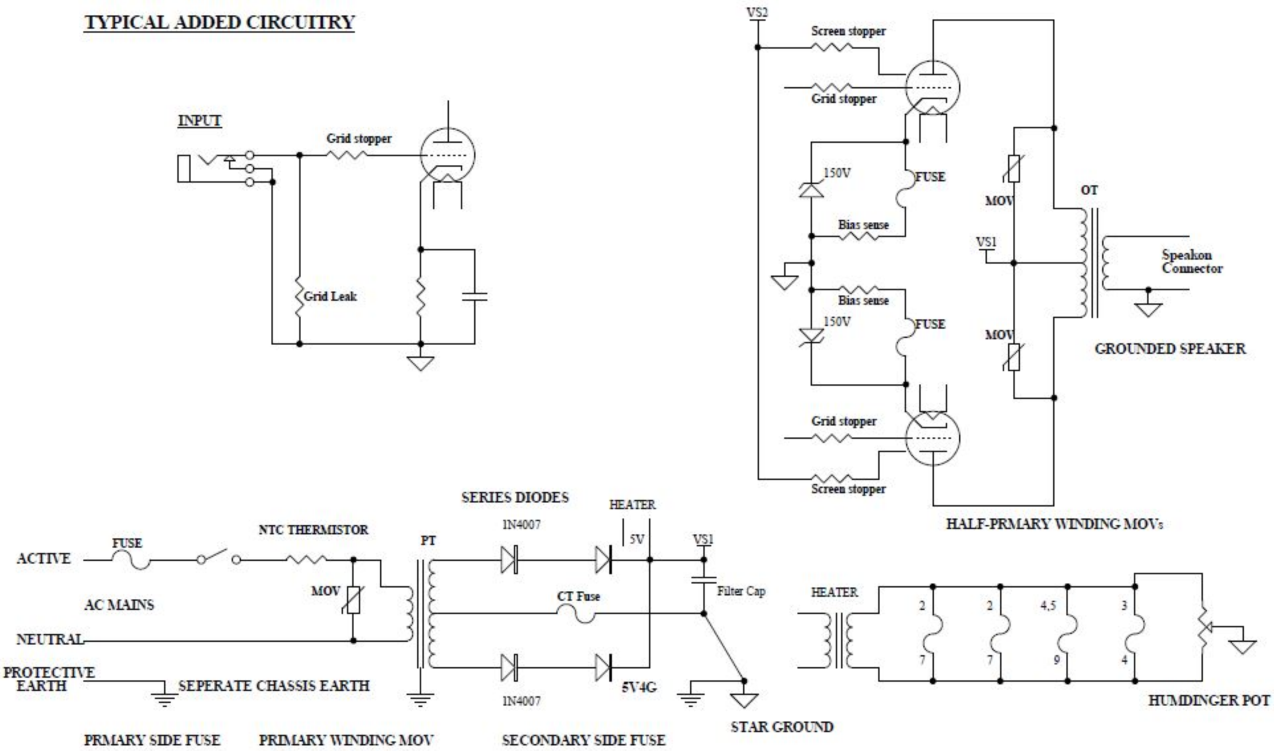


Figure 4. Typically added circuitry for protection.

Of note is GEC's technique for bias loss, where a relay contact shorts out a protective cathode bias resistor during normal operation. If bias is lost then the relay contact opens, and the output stage operates with cathode bias. A modern optomos form B device like an LCB110 device would introduce less than 10Ω when connected in DC only configuration, and needs only about 2mA of LED current.

PTC over-current protection

A positive temperature coefficient (PTC) varistor may also be a suitable over-current protection technique. A practical level of 'cold' resistance of about 1Ω, that then rapidly increases to many kΩ as the PTC reacts to an over-current, will effectively raise the cathode voltage and suppress the over-current. Somewhat like a fuse, the time taken for the part to heat up to a point (typically 70-80^{o}C) where the resistance starts to rapidly increase, depends on the ratio of over-current and the physical mass of the part. The part will then self-cool somewhat until an equilibrium is reached where the applied voltage and the available current

maintain a high enough internal temperature. Although some PTCs have voltage ratings above 100V, the readily available and cheap PTC's used in solid-state power amplifiers typically come with a voltage rating up to about 60-85V, in which case it would be appropriate to parallel the PTC with a Zener diode to both maintain the integrity of the PTC and to restrain the cathode voltage rise. A main concern with using a PTC is to isolate it from experiencing a high ambient temperature , as the current level at which the PTC changes from 'cold' to 'hot' is very dependant on ambient temperature, and the PTC may 'trip' operation at a lower level than expected.

PTC parts like Littelfuse's RXEF series, have 'HOLD' current ratings from 50mA to many A, and so something like a 0.4 to 0.5A HOLD rating should cover most valve amp applications (eg. a KT88 may peak to 0.5A for 50% duty cycle), as their nominal cold resistance is below 1Ω, and they will trip for continuous fault currents above 0.8-1A. But note that the ratings are in a 20^{o}C ambient, and would be nominally derated to 80% if local ambient reached 40^{o}C, and to 60% at 60^{o}C.

If a Zener diode was used to restrict the fault level voltage at the cathode, then the prospective fault current level with the cathode at circa 80V needs to be assessed, as the Zener could then fail open-circuit and the PTC could then fail.

Over-voltage protection

Over-voltage protection of an output transformer (OT) is a much more complex topic. OT's typically have windings in layers separated by insulation, with each turn of wire insulated from the next turn by the winding wire's enamel coating. Layer end turns and lead in/out wires have defined creepage and clearance distances to other conducting parts. Insulation between layers and creepage/clearance performance can break down if voltage levels become too high. A breakdown of insulation can subsequently cause arcing between turns, or between layers, or between layers and core, or between lead-in wires and winding layers, leading to local heating and either a local short-circuit or an open-circuit within a winding.

Stress influences

OT primary winding over-voltage conditions can arise from:

- instability oscillations.
- abrupt changes in primary or secondary winding current causing the inductive winding energy to transfer to the winding's self-capacitance and connected capacitances and raise the voltage across the winding.
- being forced by speaker emf applied to the secondary winding.

Instability oscillations are mainly due to poorly managed or inadvertent feedback of the amplified signal (either at the OT primary or secondary windings) to an earlier stage. Many guitar amps don't use feedback around the output stage, but poor wiring layout or poor placement of the OT can sometimes cause induced feedback in to sensitive high-impedance points of preamplifier stages. Gross instability could stress the OT, and is likely to be noticed as distortion or noise of some kind. As an example, AWV investigated a number of KT66 base flashover failures circa 1950, only to find that constructors had overlaid grid and anode wiring to make a "squegger" oscillator.

Abrupt changes in OT primary winding current can occur for a myriad of reasons, for example:

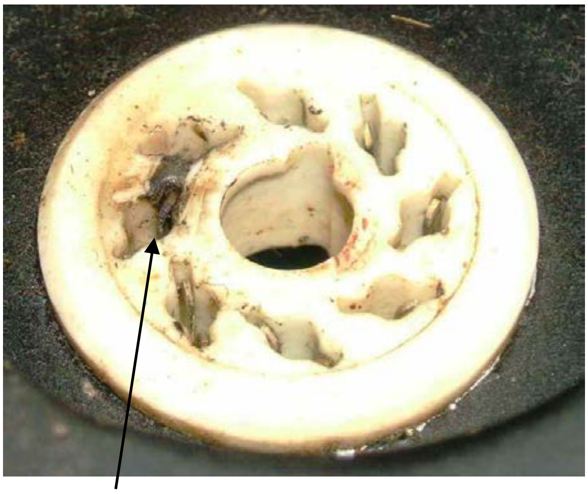
- when a conducting output valve fails open circuit.
- when an output valve(s) is forced to a short-circuit condition which then blows a fuse.
- when an arc-over occurs on a valve base (eg. between anode and heater pins), or internal to a gassy valve.
- when a speaker lead is accidently disconnected or a poor quality plug/socket gets twitched or a

speaker impedance selector is used or a selector switch contact arcs.

- when a 'speaker protector' such as a fuse blows.
- when a speaker fails and goes open-circuit when over-driven.
- when a speaker is left unconnected and the output stage is over-driven then plate current can reach high levels prior to being driven off fast.
- when cross-over distortion causes one valve in a push-pull stage to be driven in to cut-off, when the other valve is already in cut-off.

If an abrupt change of current in a transformer winding occurs, then the energy in that winding looks for other ways to continue to flow. In a transformer, energy transfers from one winding to another winding when the other winding continues to allow power to flow at the same rate (ie. the other winding is loaded), and there is good coupling between the windings (ie. leakage inductance of each winding is low). If no other windings are loaded, then the inductive energy in a winding transfers to raising the voltage across the winding's self-capacitance ($CV^2/2$) and any connected parasitic capacitance. Even when other windings are loaded, energy in the leakage inductance of the winding can cause a transient voltage.

Most of the reasons above are related to a one-off fault situation, when just a single overvoltage event occurs. In contrast, situations that relate to cross-over distortion cause repetitive over-voltage transients. Cross-over distortion drives the PP stage valves into cut-off at the same time, such that the OT primary windings are not loaded for a short period of time. In that situation, the speaker coil's emf voltage is capable of forcing primary voltage transients.



Arc-over from heater to anode [thanks Ian]

Speaker fusing is not common – with good reason!

Figure 5. Some practical examples.

For the example of an abruptly disconnected speaker lead, the inductive energy in the OT secondary winding could couple to a primary winding that has a valve conducting, and hence the energy has an escape path that would not likely cause a problem. If the primary winding valves were in cut-off (eg. due to crossover distortion) at the time of the fault then the inductive energy in the faulted winding has no other option than to couple to all OT windings and raise all available stray capacitances within the OT to a high voltage spike level. The inductive energy ($0.5 \times L \times I^2$) is transformed to a voltage rise V across stray capacitances in the OT windings ($0.5 \times C \times V^2$).

A similar example would be when a conducting valve fails abruptly. The current in the primary winding associated with the failed valve forces inductive energy to want to transfer elsewhere. If a speaker is connected then the secondary winding may provide a low-impedance path for the energy to couple to, although the speaker impedance is likely to be high for a single fast transient.

Managing over-voltage stress

Some circuit designs provide a noticeable loading on OT windings, especially in the context of suppressing high voltage spikes. A resistor-capacitor RC conjunctive filter circuit, or a capacitor, are sometimes applied across an OT primary winding (for PP stages this can be from plate-to-plate, or plate to CT, or plate to ground). These filters were often used to retain stability in amplifiers with feedback, or to shape high-frequency response, but can also provide a significant 'snubbering' effect on any voltage spike level generated across a winding.

Over-voltage protection was sometimes included in amplifiers, especially Public Address (PA) amplifiers. An example was the 'spark gap' technique, shown in Figure 6, with the gap placed from plate to plate in a PP stage - although crude in form and not very accurate under varying humidity and dust conditions, it probably worked ok and was certainly appropriate for very high powered amplifiers [An approach to audio frequency amplifier design, GEC, 1957]. It may well have saved the OT shown in this video link when a newb foolishly checked if an old amp was still working.

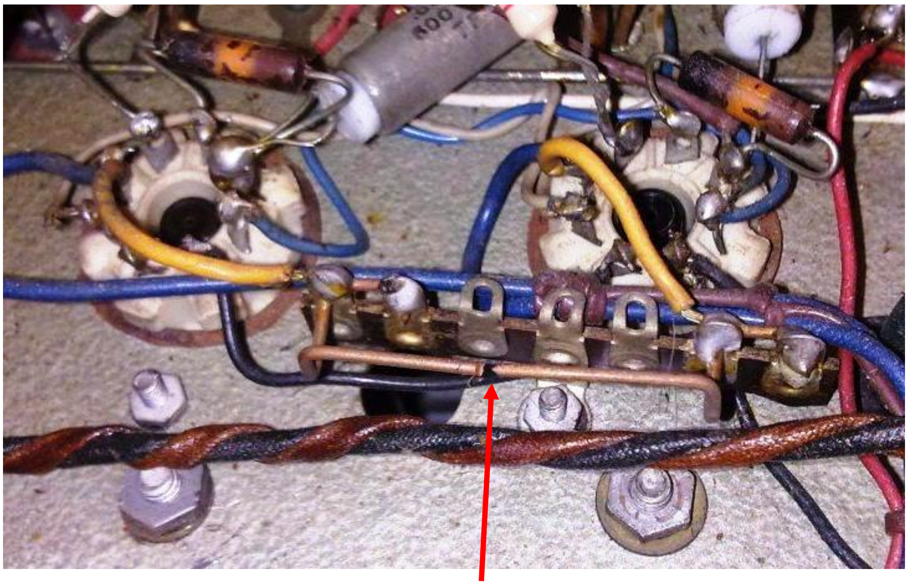


Figure 6. A crude spark gap placed from plate-to-plate.

Gas discharge tubes were widely used in telecommunications for over-voltage suppression, and have been seen in German Dynacord amps connected from plate-to-plate. The gas discharge tube has an arc voltage that varies widely with dV/dt and waveform, and once triggered will significantly clamp the voltage. Thyrectors (a type of semiconductor diode over-voltage protection device) were used in Traynor amps.

A more common technique was a 'catch diode' placed from plate to ground, also known as a suppressor, flyback or free-wheeling diode. For older amps this meant using valve diodes, such as the two 6AL3 TV damper diodes shown in Figure 7 under the chassis in the Australian Sound and Television 100W A-series PA amp. Solid-state diodes were obviously easier to implement, but often required two or three connected in series to provide a suitable PIV rating and had a reputation for failing. Modern diodes are more robust, and this technique is by far the most commonly used in guitar amplifiers, for example in Fenders, Ampeg SVT, V4, V2 & similar, MusicMan, Peavey SR2873, Bugera R2000, and Trainwrecks.

A disadvantage of the catch diode technique was that only the conducting half-primary winding section was directly protected, with the other half-winding left unprotected. The half-winding with a voltage spike going below 0V relative to OT CT (sitting at B+ voltage level) caused a large loop spike current to flow through the diode and the power supply main filter capacitor back to the CT.

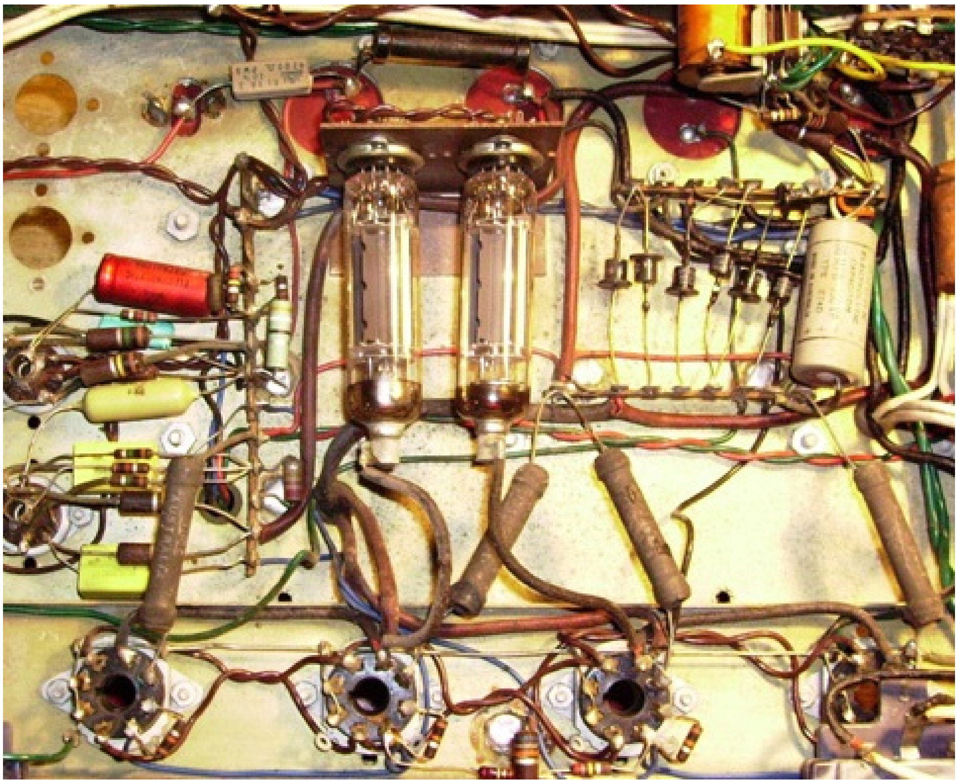


Figure 7. 6AL3 damper valves used as 'catch diodes' in a PP amp – and located underneath the chassis!

Another common technique is to place a loading resistor on the OT secondary winding. The added resistance needs to be high enough to not need a large power rating, and not divert too much power away from the speaker. This simple technique provides some suppression of any high voltage spike. Power loss is inversely proportional to resistance, so an 820Ω resistor loading a nominal 8Ω speaker impedance would dissipate about 1% of the amp's power rating (ie. a 2W resistor should be fine for most amps). If the speaker was disconnected, and a voltage spike across the loading resistor reached say 3x the peak level normally seen, then the loading resistor would transiently dissipate 10% of the amp's power rating. Apart from wasting part of the signal power, and slightly modifying the load impedance seen at the OT secondary, this technique is somewhat soft in nature in that it doesn't force a voltage limit, and choosing a resistance for the loading resistor is a subjective compromise, not an empirical science.

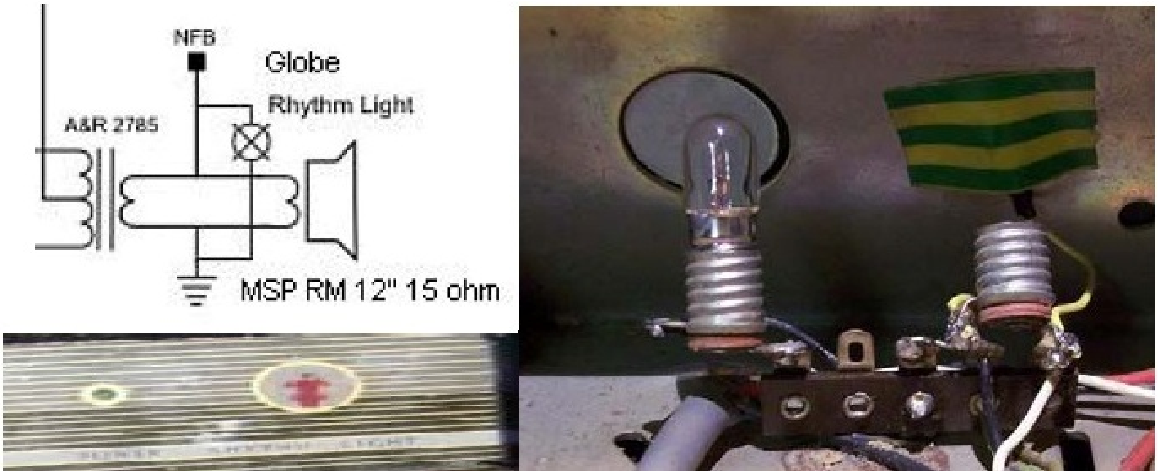


Figure 8. Goldentone made their OT secondary loading resistor into the RYTHYM LIGHT 'feature' on the front panel, which provides about 10% loading, and a touch of non-linear compression due to resistance change.

Another form of over-voltage snubbering proposed back in the 1970's for a VOX30 amplifier was a diode-resistor-capacitor circuit connected across the primary, with a series connection of neons across the

capacitor to limit its voltage rise (Everyday Electronics, June and July 1978 and Jan 1979 editions).

An uncommon control technique to constrain anode voltage excursions was a signal level limiter type circuit seen in a few PA amps (AWA PA-30BZ, Philips EV4437A). A plate voltage excursion beyond a set level triggered a neon light that was coupled to a light dependant resistor that was used to attenuate the signal level prior to the output stage.

Using and selecting MOVs

In recent times, the metal oxide varistor (MOV) has provided another convenient technique for over-voltage clamping across an OT winding. The MOV doesn't conduct current (ie. start loading) until a voltage threshold is met, and is cheap and available in a wide variety of voltage and energy ratings, so can be easily connected to an amplifier with negligible influence until voltage transients reach a high level.

The MOV voltage clamping characteristic starts very softly, and progressively presents a heavier loading if the transient energy is sufficiently large to keep pushing the voltage higher – which really suits the application. The MOV clamping voltage-current curve and tolerance is wide, especially if comparing it to a zener diode or some other kind of solid-state voltage clamp, although this is no disadvantage to transformer protection as there is normally a large voltage separation between typical winding working voltage levels and the typical voltage insulation rating provided in the transformer.

MOVs are typically used for AC mains protection, but most MOV data sheets provide DC voltage specifications (eg. the Littlefuse LA series at Littelfuse_MOV_LA-34212.pdf). An example 250VAC rated 7mm diameter disk MOV (eg. V250LA4 model) has a continuous DC voltage rating of 330V DC, and a DC voltage operating range from 354V to 473V at a current level of 1mA. Other relevant specifications for that example device are the capacitance of 90pF, the 21 joule rating for a single transient, some characteristic curves of how the clamping voltage increases with current level, and the indefinite repetitive surge current capability. What is missing is the average power dissipation, which is about 0.25W for that size disk.

The wide voltage range for 1mA DC conduction indicates the wide tolerance in voltage that the MOV starts to conduct current and hence start loading a transformer winding. For example if a V250LA4 MOV was connected across each OT primary half-winding (plate to B+ as shown in Figure 4), a plate voltage would need to swing at least 354VDC away from B+ for the MOV to start conducting 1mA (ie. the MOV would look like a 354kΩ resistor just at the peak of the waveform, but otherwise would effectively present an open-circuit to the winding). Plate voltage can't typically swing closer than 50V to ground due to valve saturation, so that particular MOV would normally look like an open-circuit for a B+ level up to about 400VDC with the output stage plate voltage swinging to sinewave clipping levels.

Some comments on MOV datasheets are worth making, as they can influence selection:

- the characteristic curves and max clamping voltage ratings are often for an applied AC voltage, so need to be interpreted with some caution, but do indicate the likely percentage increase in DC clamping voltage as MOV current increases above 1mA.
- The capacitance of MOV devices gets larger as disk diameter increases, but reduces as voltage rating increases.
- The 'indefinite repetitive surge current capability' indicates the current level for a particular pulse width that can be passed without device degradation. The repetition frequency of such a pulse needs to be such that the average power dissipation within the MOV is within rating (7mm disk has a 0.25W typical rating).

The DC voltage rating at 1mA of a MOV placed across an OT primary winding should be above the maximum B+ power supply level (at high mains voltage and lowest idle current) by at least a good margin, as the MOV should not be loading the OT for the normal situation where the plate pulls its voltage down from B+ to near 0V (and vice-versa where the other plate in a PP stage gets raised to twice the B+ level by transformer action).

Depending on what MOV voltage ratings are available, MOV's can be connected in series to double or triple the DC voltage rating so that it is high enough for the position. Eg. a 400VDC 1mA part becomes an 800VDC

1mA part when two MOV parts are connected in series. Only MOV parts of the same type/rating should be connected in series to make a higher voltage rated 'MOV'.

With respect to protecting the OT from insulation stress, a modern output transformer should be able to withstand at least 2kVDC from primary winding to core, and primary winding to secondary winding. Some manufacturers specify the test voltage they apply to confirm adequate insulation, but many don't. Although the transient withstand voltage across a winding is not typically specified, it is likely to be similar the primary to core continuous rating. Choosing a MOV, or MOVs, with a 1.5 to 2kV DC clamping voltage for about 1A seems a reasonable selection target as that should provide a MOV DC 1mA rating that is well above the B+ level, and should constrain peak voltage across insulation to within a transformers ratings.

For an amp with 500VDC B+, then two or three of the V250LA4 MOVs in series, connected across each OT half-primary winding would be appropriate. Two MOVs would start to load any transient voltage peak rising above 708V to 946V, and if the energy level in the transient was sufficient to force the winding voltage to about 1200Vpk then the MOVs shunt load the winding with 600 + 600 =1k2Ω, passing about 1A. Three MOVs in series are also likely to clamp half-winding voltage to below 2kV, so may be the preferred arrangement. If a fault transient was a single pulse of width less than about 8ms, and current up to 1A, then the MOV experiences no degradation. If a repetitive transient was experienced, then MOV max average power level would determine if MOV degradation could occur.

If a MOV was placed across an OT secondary winding, the MOV AC voltage rating needs to be compared with the maximum AC signal voltage generated by the amplifier for the speaker impedance used, as the MOV should not be conducting when max output power is being delivered to the speaker. A 50W amplifier output in to a 16Ω resistor would generate an AC voltage of 28Vrms, indicating a MOV with at least 30-35Vrms 'continuous maximum Vrms' rating should be used. A speaker's impedance varies with frequency and so a 50Vrms MOV would be a safer rating (the LA range only goes down to 130Vrms, but Varsi have a range down to 11Vrms – www.varsi.si).

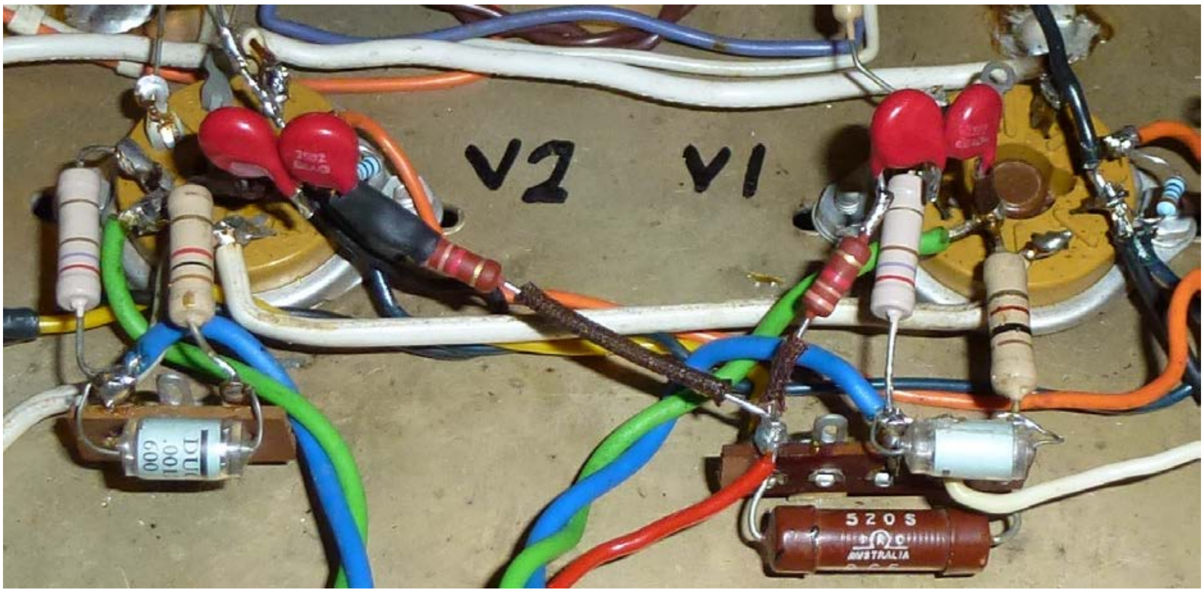


Figure 9. Ultra-linear PP stage (RTV&H 1960 100W PA amp). Original RC network from plate to screen. 1Ω cathode sense resistors added. Series MOV-R circuit added to each primary half. No screen stoppers added.

As an example of the energy level in joules that may need to be clamped during a one-time fault event, the primary inductance of hi-fi OTs can exceed 100H (P-P). The inductance value is normally based on an applied excitation sinewave voltage of about 5-10Vrms, so P-P inductance is likely to be substantially greater if a fault occurred when a high signal level excitation was present. However, if the fault scenario caused an over-current condition in the winding prior to the fault, then the winding inductance may have reduced dramatically due to core saturation.

An amplifier's operating current in an OT primary half-winding may peak at many hundreds of mA,

especially for larger power amps. A fault event such as an open-circuit between valve anode pin and socket terminal could cause such a current level step. If a MOV bypass was used for protection, then the operating current level at the time of the fault would continue to flow through the protection MOVs if no other path was available.

For a PP stage with 100H P-P inductance, and a current of 0.4A at the time of the fault, the energy in an OT primary half-winding is (100H/4) x 0.4A x 0.4A / 2 = 2 Joule. A single V250LA4 7mm diameter MOV has a 21 Joule rating, so any practical deployment of MOV's should cope well with that event.

The largest practical winding current could flow if the anode shorted to a heater winding with a grounded heater CT, in which case the current would be limited by circuit resistances including the OT half-winding resistance, and the effective PT source resistance, and any valve rectifier resistance, and any fault current fusing. That current may exist for some time until a power supply fuse blows. The winding current could be in the 1-10A range, and the inductance of a PP OT is likely to be quite low, so it is difficult to clarify if the winding energy would be substantially greater than for the previous 2 Joule scenario.

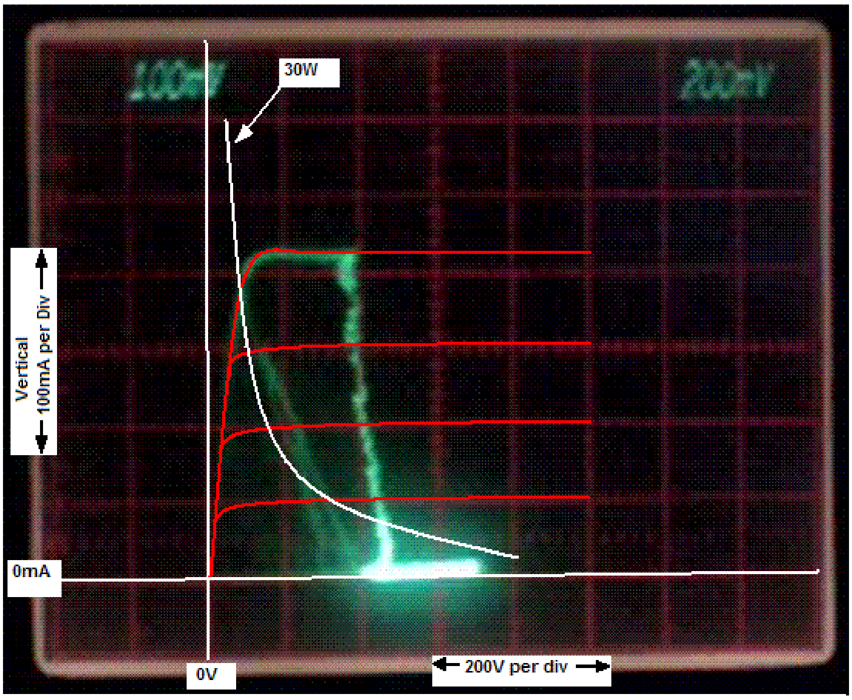
If more than one over-voltage protection technique is used, or MOVs are used on more than one winding, or MOVs are connected in series, then the energy being clamped would spread itself out to multiple protection parts, and hence each part would experience a lower level of power and energy dissipation than if only one part was trying to constrain all of a transient's energy.

The MOV capacitance could be a significant high frequency part for some hi-fi amp designs. Where this is of concern, a small diameter MOV model with multiple MOV's connected in series would minimise capacitance loading. In addition, a resistor can be placed in series with the MOV to form a conjunctive R-C filter. The series resistor could be at most a value similar to the winding impedance (eg. 25% of an OT primary impedance when used with a MOV placed from plate to CT), but is preferably a lower value so as not to cause a large increase in clamping voltage at the likely peak fault current that could flow. For example, a 5kΩ P-P OT could use a 1.2kΩ series resistor in series with a MOV across each half-winding, but this resistance value would drop 600V if transient MOV current reached 0.5A, in which case the example V250LA4 MOV clamping voltage would be 700-1,000V, so a lower series resistance of at most 470Ω would seem more appropriate. Note that for this example MOV and a 1.2kΩ series resistor, the conjunctive filter corner frequency is over one megahertz.

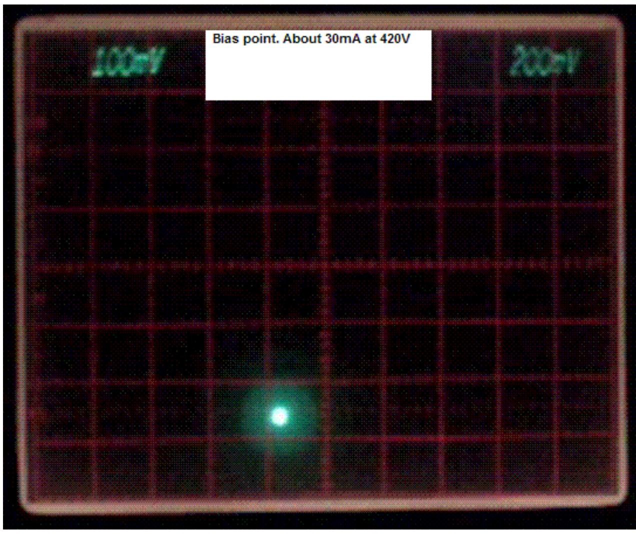
Measurements

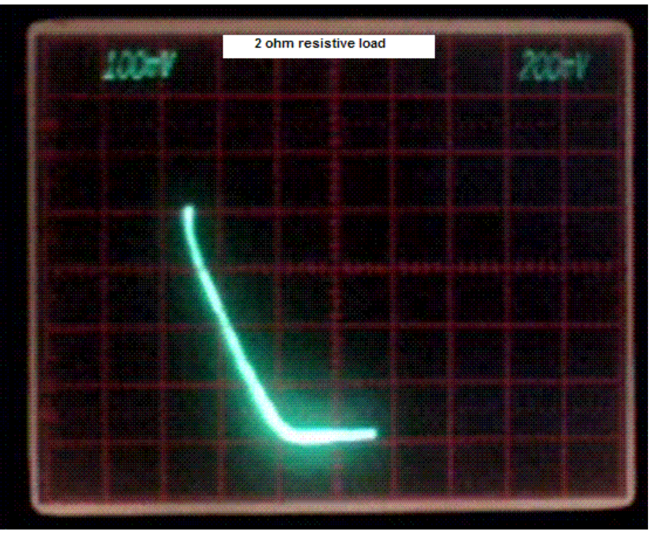
In the real world, the plate voltages in a PP stage do not lay themselves simply on a resistive loadline, but fly off to levels below 0V, and levels significantly in excess of twice B+, due to OT winding inductance, speaker load reactance and emf, and unloaded plate conditions when both valves are in cut-off.

Oscilloscope measurements shown below on a Fender 5F6A re-issue using 6L6 tubes (thanks to Loudthud on Music Electronics forum for permission to use his measurements and further discussions on them) clearly indicate the voltage levels experienced at the anode in a fixed-bias PP circuit. The first oscilloscope plot shows a trace for 6L6 plate voltage and cathode current for a sedate guitar input signal (display of the voltage trace is helped by the persistence of the oscilloscope screen). The plot shows superimposed 6L6 datasheet anode current versus grid voltage curves, along with a 30W plate dissipation curve.



For a reference, the next plot below shows the 6L6 idle operating point at about 420V and 30mA. The 5F6A amp has a choke-fed screen voltage close to the idle anode voltage. The third plot shows the load line being followed when a sinewave signal is applied to a resistive load – the operating point moves away from the idle point, to a lowest anode voltage of about 80V and highest cathode current of about 400mA when being driven in to conduction by the signal, and to a highest anode voltage of about 720V at near zero cathode current when being driven in to cut-off. In this plot the anode voltage moves symmetrically below and above the B+ level (which would sag from 420V to about 400V) and indicates no sign of voltage stress on the OT winding. The peak anode current (and hence OT primary current) would be somewhat less than the measured 400mA cathode current, as the screen current contribution is seen to increase the trace's gradient noticeably as grid conduction conditions are approached.

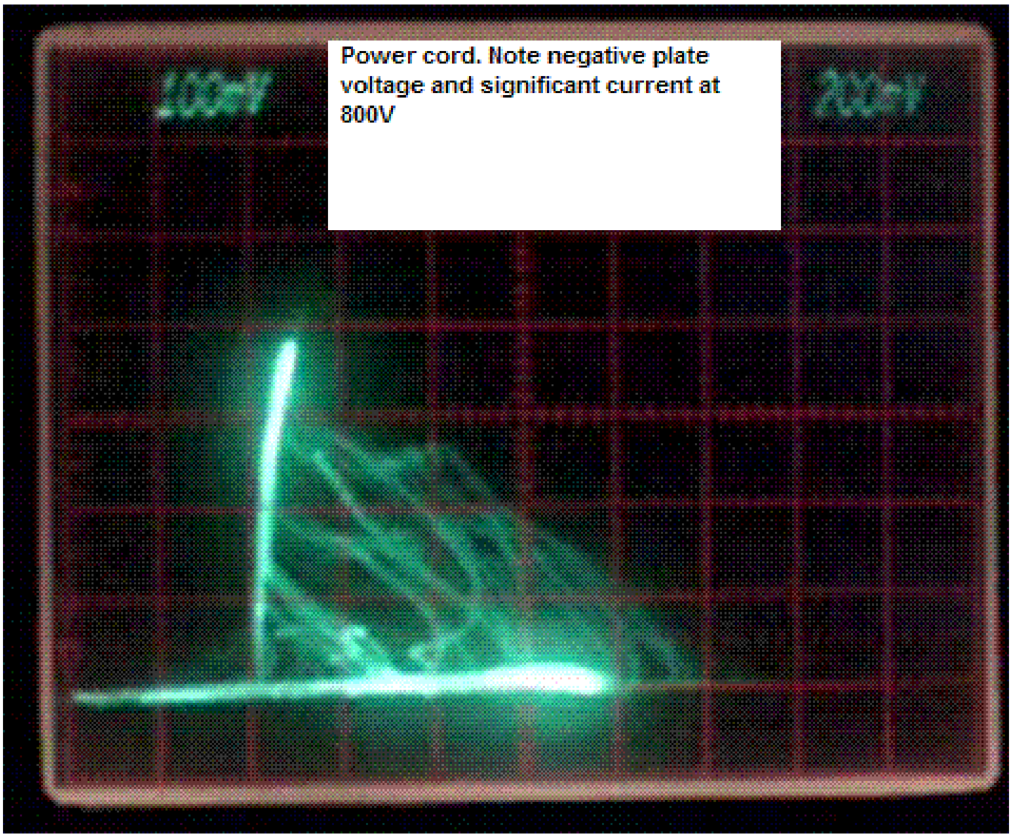




The 6L6 experiences more dramatic voltage excursions as shown below when a speaker load is used with a more aggressive guitar playing style, but still a long way from extreme over-drive conditions. The plot shows plate voltage extending down to at least -800V, and up to +1100V, which is about -1200V and +700V relative to B+ on the CT of the output transformer.

The 5F6A is likely to be experiencing blocking distortion under high signal level, which causes crossover distortion that would force both valves in to cut-off at the same time for a portion of time. The plot below indicates a square-wave type plate operation, with an unloaded horizontal plate voltage fall, followed by plate current rising along the Vg1=0V vertical curve to a high plate current period, followed by Vg1 falling

and plate current and voltage falling back to idle or cut-off conditions.



If used, RC conjunctive filters would influence the actual plate voltages experienced, and MOVs would start to influence plate voltages whenever the MOV voltage reached its clamping level.

Testing for a failed OT

The best first check to do on a suspect OT is to measure the OT's primary and secondary winding resistances using an ohmmeter (resistance range on a multimeter). The primary winding(s) resistance should easily show up on a meter as tens or hundreds of ohm, depending on the power rating of the OT, and is easily measured when the amplifier is off (pulling the output tube or tubes should disconnect all circuitry from an OT's plate terminal, but reference to a circuit schematic is worthwhile). The half-primary windings on a PP OT (CT to each plate terminal) should have similar resistance, but are unlikely to be exactly the same (especially for lower quality PA OT's). The OT secondary windings are likely to measure very low in resistance (disconnect the speaker first), and it may be difficult to determine a winding's resistance as it can measure like a short circuit. Connecting the meter probes together can give a zero or close to zero reading, and then measuring the winding resistance may show a slightly higher reading. A high or over-range resistance would likely indicate an open-circuited winding fault.

If there is no obvious winding resistance concern, then the next step is more complicated, and would involve applying say 5VAC to 12VAC (eg. from a power transformer secondary) to the primary winding (or PP half winding), and then measuring the AC voltage on the secondary windings (and on the other half-primary winding). Knowledge of the OT winding impedances can be used to determine the turns ratio's between the primary and secondary windings, and hence the turns ratio and the applied signal voltage can indicate the level of secondary voltage that should be measured. Output transformer MS Excel calculation spreadsheet

If a reasonable voltage level is not measured across a winding or windings, then there may be an internal short type fault between some turns within one of the windings (ie. an internal short circuit between two adjacent turns within a winding will exhibit a normal winding resistance, but would cause the transformer to lose its voltage transfer ratios between windings on the same core).

Another worthwhile test to perform is to measure the insulation resistance between primary windings and the core, and between the primary windings and the secondary (speaker) windings. This test is done with a megohm meter at a hazardous voltage so is a safety risk. A typical megohm test voltage is 1kVDC, which almost any OT can sustain between primary windings and core or secondaries, and the measured resistance should typically be well above 20 MΩ. Breakdown of insulation in the transformer can occur as primary winding voltages reach transiently high levels.

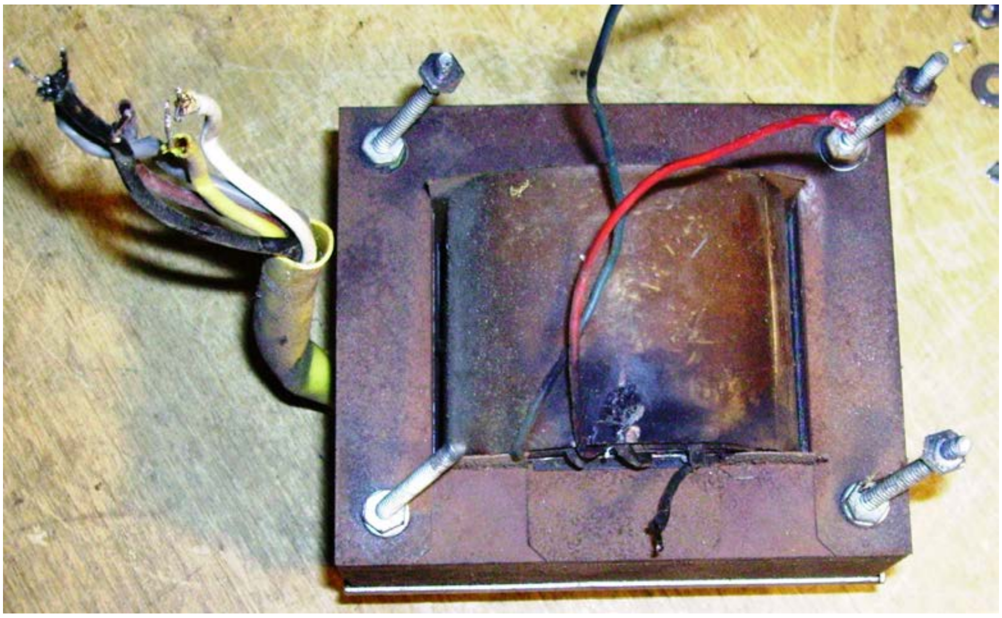


Figure 10. A dropped amplifier caused this OT to bend its mounting bolts and short a primary plate wire to chassis – no internal wiring damage, so it's back in the amp and working now.

A more pernicious fault to identify is if some internal arcing between turns or winding layers occurs only during operation at the on-set of high signal level conditions, where the speaker output level may quickly fall away. This type of fault usually continues to degrade internal insulation, and so the symptoms get worse. Testing for this type of fault may be difficult, and require continued operation in the amplifier, but with protections in place if a hard fault occurs.

Note that symptoms of no 'speaker output' may not be due to the OT even though everything else appears initially to be ok, as highlighted by the discussion in gretschpages.com/forum/ by mrock. And some OT faults may appear to be unfixable, but end up being quite easy to fix as the fault is not internal to windings.

If an OT has failed, then other related parts need to be checked for stress or failure – especially output stage valves, and screen stopper resistors.

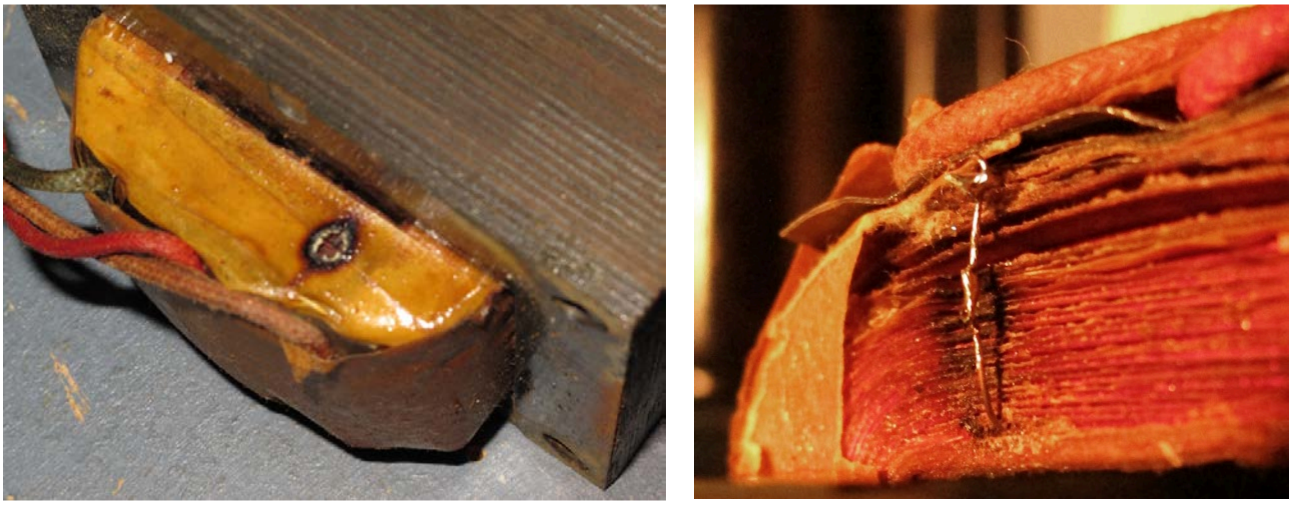


Figure 11. Repairable fault in output transformer.

Figure 11 shows a repairable fault in an OT. Arcing from half-primary winding layer edge turns to the other half-winding plate link wire had caused an obvious area of over-heating damage that resulted in an open-circuit. The OT was repaired by replacing the link wire, and carefully insulating it (not shown). [Hoffman Amplifiers Forum but thread now lost]

Power transformer and choke protection

Similarly to an output transformer, the power transformer (PT) in a valve amplifier, and the choke in a choke input filter, can also be subject to over-voltage and over-current stresses. Over-voltage transients can stress insulation within the PT and choke windings as well as parts connected to the windings, such as the primary side AC switch, any secondary side fuses, standby switches and diodes. Parts in the power supply and amplifier output stage can fail and cause over-current stress within the PT and choke.

Over-voltage protection

When the amplifier power switch is turned off, the PT winding currents are stopped abruptly, which could exacerbate arcing on the mains switch's contact, leading to increased pitting of the switch contact. This is not such an issue if the PT winding currents are low – such as when the amp is in standby or idling, and if the switch off occurs at the time in the mains cycle where current is not passing through a rectifier diode. A MOV with a suitable voltage rating on the primary side winding, and even MOV's on secondary side windings could be used to reduce over-voltage transients generated on those windings.

Some amps use a standby switch that opens the PT secondary CT connection to 0V, which could interrupt a large current level through one of the secondary HT windings, especially if the standby switch is toggled a few times and the main filter caps are being charged up under full idle load conditions. The leakage inductance in that winding can stress the standby switch, as well as the diodes, and a MOV across each secondary HT winding could be appropriate.

Often a power supply choke has a sizeable filter capacitor on each end of the choke, as in a CLC type filter, where the capacitors dampen any possibility of a transient voltage across the choke due to a fault that abruptly stops choke current. However, if just a choke input filter is used after the rectifier diodes, then a fault (or even during regular operation) could generate a high voltage at the diode-choke node as there is little stray node capacitance to dampen the voltage at that end of the choke. GEC recommended an RC snubber across the choke [An approach to audio frequency amplifier design, GEC, 1957]. Some designs add a small capacitance to ground at that node for noise filtering, where for a 10H choke dumping 0.2J (from 200mA current step) into a 100nF capacitor, the voltage on that cap could change by 2kV as $½LI^2$ transfers to $½CV^2$. Some designs add an RC zobel network across the choke to improve the filtering response of the choke (resonant frequency of parallel choke L and zobel C set at ripple frequency so that impedance of "choke" to ripple is higher), and that 'ripple trap' network can certainly alleviate transient voltages. If a MOV (or zobel network) is added in parallel to the choke then its DC voltage rating needs to accommodate the turn-on condition where one end of the choke is at $+VAC_{pk}$ and the other end is still at 0V, and similarly where one end of the choke is at $–VAC_{pk}$, and other end is at peak B+ (ie. $+VAC_{pk}$), which is more onerous. So a DC voltage rating of at least 2 VAC_{pk} is needed for parts across the choke. Parts from the diode-choke node to ground need a DC voltage rating of at least VAC_{pk}. Those situations are likely to require a series connection of MOVs, and any capacitor is likely to be a physically large metalized plastic type. The resistor in the zobel network is mainly to dampen the resonant Q of the LC, along with choke ESR. Any capacitor used in these locations should be carefully rated for continuous VAC operation, and preferably have an X type rating for failure protection.

Covering a MOV or in-rush limiting thermistor placed on a mains primary side, with a sleeve of heatshrink tubing is a good idea so as to constrain the part if it becomes damaged.

Over-current due to failed valve diodes

Adding a silicon diode (one or more 1N4007 in series depending on the HT level – see 'Power supply issues for tube amps') in series with each anode of a diode valve (as shown in Figure 4) can avoid shorting out the power transformer HT secondary winding if the valve diode starts to conduct continuously, or arcs between anode and cathode (eg. gassy tube). When using protection solid-state diodes, a valve diode fault could go unnoticed, unless it is observed as an increase in hum, or as a B+ level when B+ AC and DC voltage is next checked, in which case it should be fixed as soon as possible. Using an insulation resistance tester at 1kVdc is also a practical maintenance action to check for valve diode performance.

Rectifier valves with a 6.3V heater (eg. 6V4/EZ80, 6X4, 6X5, 6CA4/EZ81) are typically powered from a secondary winding with CT connected to ground, and as the valve ages the cathode-to-filament interface can become a low resistance or short, which then loads or short-circuits the high voltage secondary winding. This type of fault can be alleviated by disconnecting the heater winding CT, and using a fixed or tuned heater humdinger (as used for hum reduction) connection to ground which should then fail open, or alternatively fusing the high-voltage CT.

Over-current due to failed parts

Parts within a valve amplifier age, and can fail causing a high current to be drawn from the PT. Any series resistance in the circuit loop between the PT, the failed part, and ground, in which the fault current flows will suppress the prospective fault current level (ie. the maximum level that the fault current could reach).

A failed part like the first main filter capacitor may only have the PT winding resistance and diode resistance to constrain the fault current. A failed part like an output stage valve will typically have a higher fault circuit resistance (due to output transformer primary winding resistance and maybe a valve cathode resistor) and hence the prospective fault current level will be lower. Any fuse used to interrupt such a fault current has to be able to pass the normal operating current of the circuit, but also open in an acceptably short time should a fault occur, so that the PT winding is not damaged. See Valve Amp Fusing.