This article collates design information relating to fuse selection for protection of the high-voltage secondary side winding of the power transformer in valve or ss amps, but is generally applicable to most single phase rectifier configurations.

IEC 60127-2 (sheets 2 & 3) and UL 248-14 compliant miniature fuses are considered, due to standards maturity and commercial availability of fuses. Fuse ratings for those two standards are not interchangeable, and many fuses do not identify compliance with a standard.

Duncan Munro's PSUD2 simulation program is used to determine rms current levels in different power supply configurations, and at selected times after amplifier turn-on.

Fuse selection based on comparing PSUD2 results with fuse minimum open time ratings is described. Protection performance is discussed based on fuse maximum open time ratings. For applications with a very high initial pulse current, the I^2t value rating is discussed.

Selection of an AC mains side fuse is considered, as well as using an NTC thermistor, heater supply fusing, and output stage cathode circuit fusing. Safety of panel mount fuse holders is discussed.

Contents

Preamble

Vintage valve amps often had no fuse protection of the power transformer secondary-side high tension (HT) winding or B+ dc supply. Some well-respected modern references recommend not fusing amp circuitry. However, I highly recommend adding secondary side fusing during restoration to lessen the chance of damaging costly and rare parts such as the power transformer, output transformer, and output stage valves.

Standardised fuse parts are commonly available in miniature formats typically used in valve amps, such as M205 and 3AG, where fuse current rating is almost invariably below 10A, and fuse voltage rating is almost invariably 250VAC (even when used for 115VAC mains, or valve amplifier B+ protection). Although fuses can be purchased with voltage ratings up to 500VAC as well as with DC voltage ratings, there is generally no need for such ratings in a common well designed amplifier.

Fuse performance is better defined nowadays due to standards compliance and regulatory requirements around the world. As such, a modern design approach can be applied to fuse selection, with the aim of minimising damage within a valve or solid-state amplifier, should a fault occur.

A valve amp B+ supply can use a variety of rectifier and filter configurations, which can markedly change the selection of fuse type and rating. The Duncan Tool's PSUD2 power supply simulation program is free and commonly used to identify power supply voltage and current levels and waveforms, especially during the turn on period of an amplifier, for both valve or solid-state diode power supplies in valve or solid-state amps.

Miniature fuse types

There are many fuse types and standards, but the type most likely to be used in valve amps is generically referred to as a miniature cartridge fuse, with the most common formats being M205 (5x20mm) and 3AG (¼ x 1¼") in a glass tube style, with a 250VAC rating. The important compliance ratings are IEC 60127-2, along with UL 248-14, which have been applicable for more than 20 years now.

A miniature cartridge fuse is usually mounted in a fuse holder or with fuse clips, although fuses can be purchased with axial leads (pigtails) which can be very practical when trying to retrofit a fuse into an amplifier.

Within IEC 60127-2 there are six sub-categories (sheets), but only the low breaking capacity types #2 and #3 are of general use for valve amps, where the letter F and T on the end cap identify the quick acting (F) and time-delay (T) types. High breaking capacity fuses may be appropriate for larger solid-state amplifier, especially where short circuit current can exceed 35A.

In IEC 60127-2, min and max limits on operating time are defined at certain current rating multipliers (of the fuse current rating), where the fuse rating in amperes is also the max allowable operating current through the fuse in the equipment. So as identified in Table 1 for either the F or T type fuses, they must not break when carrying 1.5x their current rating for at least 1 hour, and the T fuse must break within 2 minutes when carrying 2.1x the current rating. The main difference between F & T is the operating time performance for larger over-current events. Note that the operating time limits shown in Table 1 are different for 63mA-100mA, and 8A-10A fuse ranges.

IEC60127 Rating multiplier	**1.5x**	**2.1x**	**2.75x**	**4x**	**10x**
Sheet 2 Quick-acting F	1hr -	- 30min	50ms – 2s	10ms - 300ms	- 20ms
Sheet 3 Time-Lag T	1hr -	- 120s	0.6s – 10s	150ms – 3s	20ms – 300ms

Table 1. IEC 60127-2 compliant fuse mandated performance levels (125mA-6.3A range).

Unfortunately, other fuse standards have less definition in their operating times when compared to the IEC standard. The UL 248-14 standard is common due to USA usage, but the circuit operating current must be no more than 75% of the fuse current rating, and operating time performance is only mandated at three current rating multiplier values as shown in Table 2.

The nominal breaking performance at higher multipliers than 2x must be interpreted from fuse manufacturer datasheets. Fuse characteristics can vary widely between models and manufacturers, so caution is needed when trying to generalise comparisons.

UL248-14 Rating multiplier	**1x**	**1.35x**	**2x**
Fast acting (F)	4hr -	- 1hr	– 5s
Time delay (Slo-Blo)	4hr -	- 1hr	5s – 120s

Table 2. UL 248-14 compliant fuse mandated performance levels.

The current time characteristics shown in Figure 1 are for IEC type fuses of F and T types. An IEC compliant fuse will blow if current reaches I/Irat for at least the min specified curve time, and no longer than the max specified curve time.

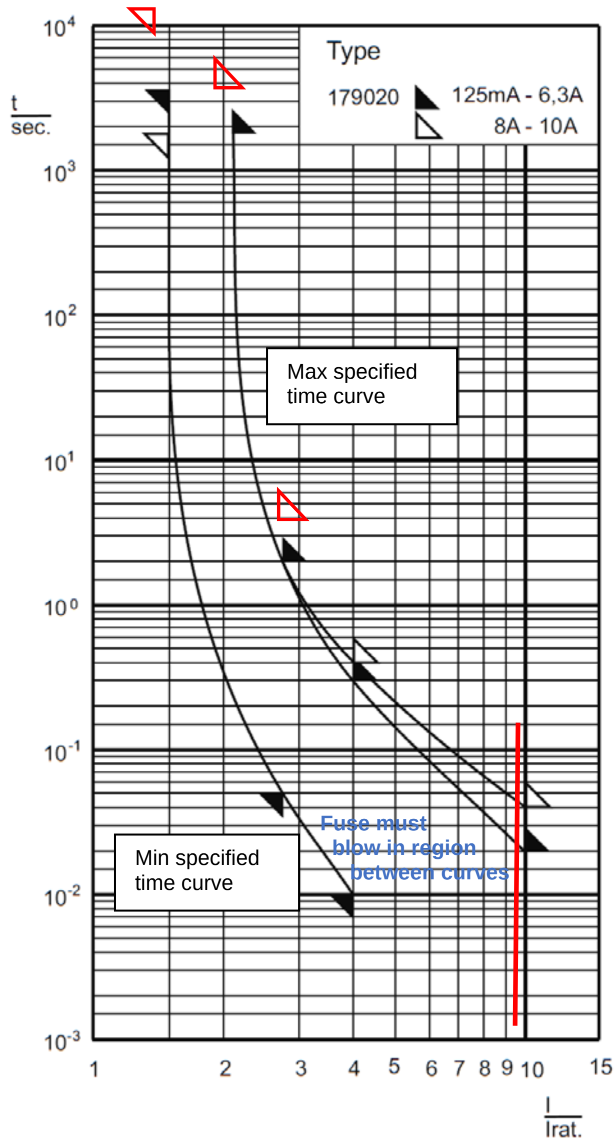
Manufacturer specified performance levels may differ from those in Table 1 for fuse current ratings below about 100mA, and higher than about 8A, so some care is required to check the manufacturer datasheet.

An example UL type fuse performance has been overlaid using the red triangles, but normalised so that a comparison can be made with the same Irat for the max operating current rated for the fuse (so the UL fuse current rating is multiplied by 0.75).

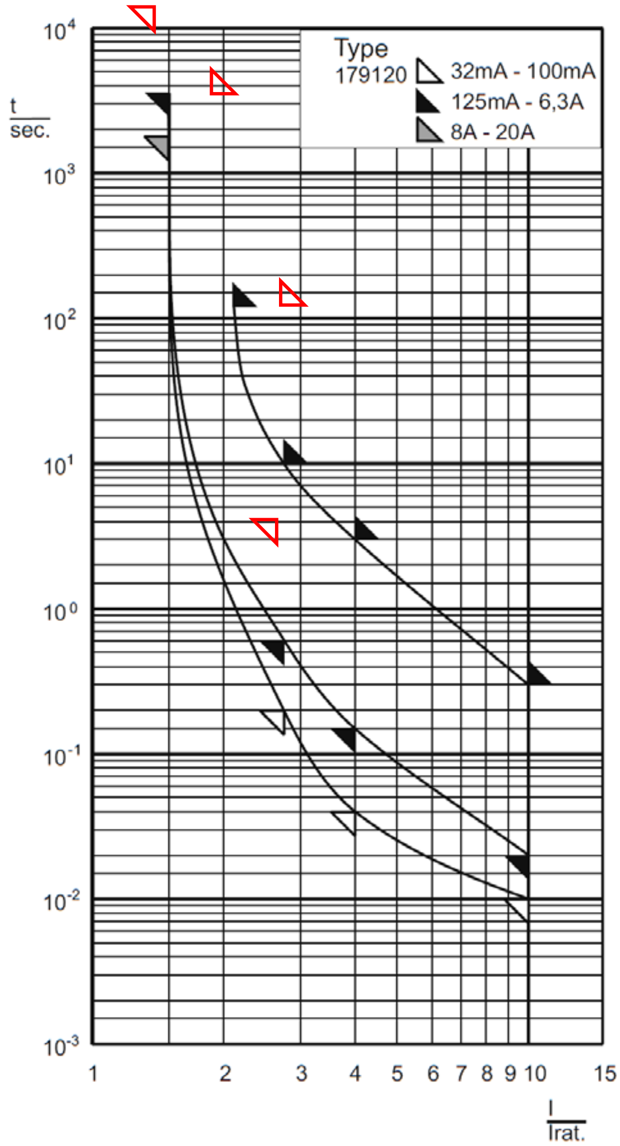
Although 250VAC is a ubiquitous voltage rating for this type of miniature cartridge fuse, it is considered acceptable [1] to use them for higher working voltage levels in excess of 500VAC within circuits having limited prospective current levels, where prospective current does not exceed about 10x the fuse current rating. This allows a 250VAC rated fuse to be used in common valve amplifier B+ power supply circuits where transformer secondary voltages typically exceed 250VAC, especially in the CT link where working voltage is 0Vac.

A fuse located on the secondary side of a power transformer is exposed to a peak prospective current determined by the effective source resistance of the fault current path. If the fuse was protecting a bolted short-circuit across a secondary winding, then the effective source resistance can be estimated from the secondary winding DC resistance, and the voltage-ratio reflected primary winding DC resistance (see PSUD2 circuit model help for the power transformer). In this situation, the prospective current could well peak to 10x the fuse current rating, but is unlikely to be substantially more than 10x for a valve amp.

If the fuse was protecting against an output stage tube that was biased fully on (eg. due to a failed coupling capacitor), then the effective source resistance also includes series resistance contributions from the rectifier diode, the output transformer primary winding, any cathode circuit resistor, and the output stage valve V-I plate curve for a grid-cathode voltage of 0V nominal.



IEC60127-2 Quick-acting (F) fuse current-time characteristic for Siba 179020, with indicative UL248-14 fast-acting definitions in red for 0.75xI.



IEC60127-2 Time-delay (T) fuse current-time characteristic for Siba 179120, with indicative UL248-14 time delay definitions in red for 0.75xI.

Figure 1. Indicative fuse current – time curves at min/max specifications.

[1] Referenced by Littlefuse in their 2014 design guide, but removed from 2022 design guide [6].

Full-wave rectifier circuits

The most common rectifier circuit in vintage valve amps is a full-wave with valve diode in each HT leg of a HT-CT-HT secondary winding, and the CT taken to the negative terminal of the first filter capacitor.

If the filter was a capacitor input filter, then the diode cathodes connect to the positive terminal of the first filter capacitor, as shown in Figure 2. If the filter was a choke input filter, then the diode cathodes connect to the choke, with the other end of the choke connected to the positive terminal of the first filter capacitor.

The simplest form of protection is with a fuse in series with the CT connection to capacitor negative terminal. For a capacitor input filter, the fuse experiences DC current pulses as shown in the simulated plot in Figure 2, and the periods at zero current allow the fuse arc to extinguish. Once the fuse is an open circuit, then both diodes stop conducting and the B+ circuitry is de-energised.

However, for a choke input filter, the normal CT fuse current is a continuous DC. If a fault causes high fuse current levels, then the fuse current will remain DC and not extinguish as easily, although the fuse current tends towards half-sine DC current waveforms depending on choke saturation.

A 250VAC fuse voltage rating is acceptable for secondary voltage up to circa 500VAC where the fault current is limited by sufficient path resistance, such as by choke DCR, or output transformer primary winding DCR.

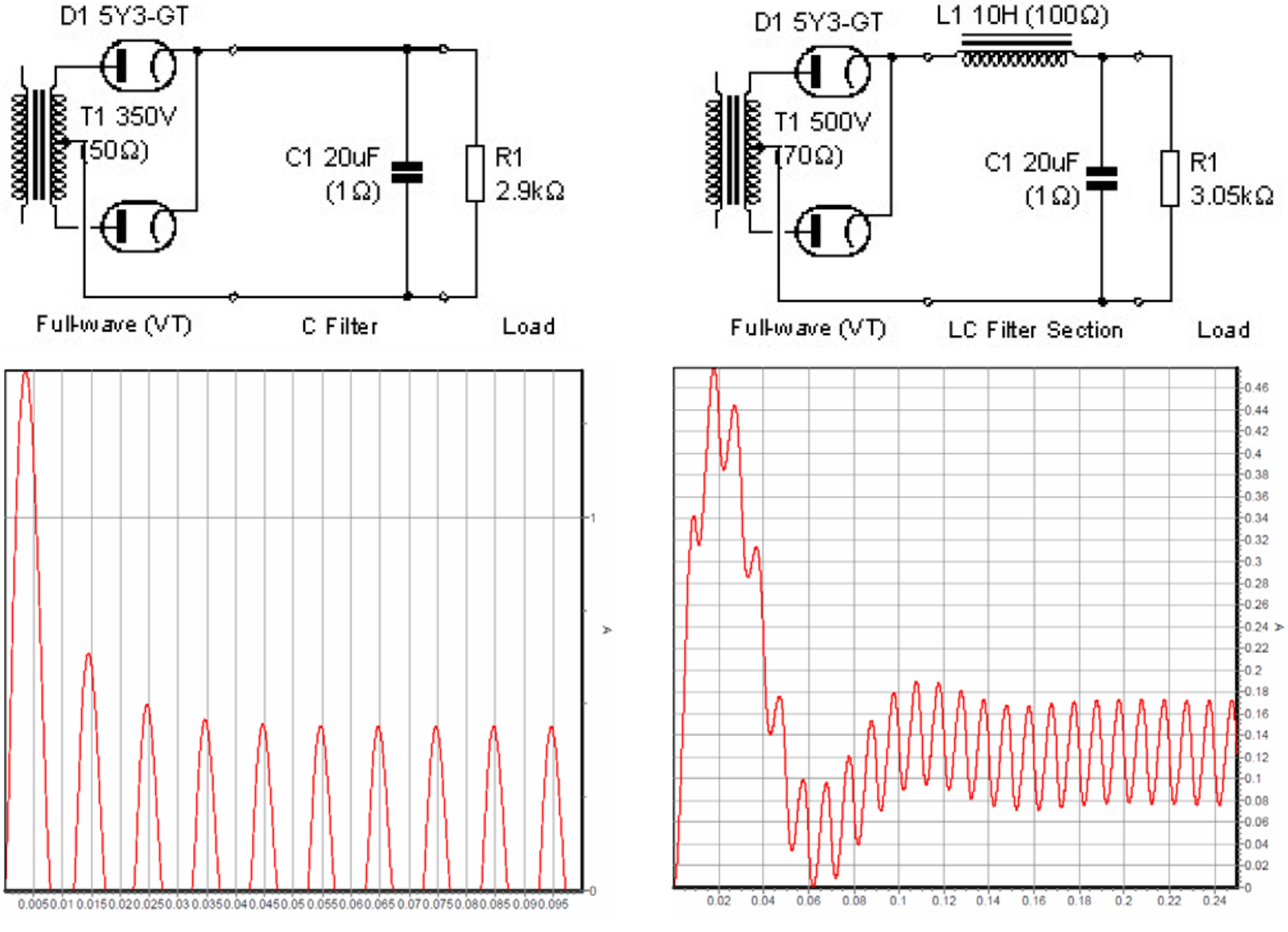


Figure 2. Full-wave rectifier CT fuse current waveform: (a) capacitor input; (b) choke input filter.

Note that if a diode fails short, then the CT fuse does not protect the power transformer secondary winding from high current peaks, and the mains side fuse would need to provide protection. A common form of additional protection for valve diodes is to add an ss diode in series with each valve anode connection, which stops any faulty reverse current flow through the valve diode from anode to cathode, or anode to anode. For secondary voltage above circa 300VAC, two 1kV PIV diodes (ie. 1N4007) should be used (see [7]). Similarly, an original ss diode is best replaced by 2 or more new ss diodes in series to improve reliability, as long as diode heat dissipation is not diminished, and the diodes are the same make and from the same batch.

Note that the fuse could similarly be placed between diode cathodes and the first filter cap positive terminal.

A fuse can be placed in series with each HT leg. Each fuse experiences DC current pulses, with the current waveform normally at a zero level for half the mains period. If a fault causes high fuse current levels, then the zero current periods allow the fuse arc to extinguish even easier than with AC current operation. If only one fuse opens then that leg diode stops conducting, however the B+ circuitry remains energised from the other diode providing half-wave rectifier currents into a filter capacitor exposed to noticeably higher ripple current.

Faults can occur in a wide variety of ways and fuse current levels can vary widely due to influences such as choke or capacitor energy, the resistance and impedance in series with the faulty part, and the character of the failing part (eg. from a bolted short circuit, to an output stage valve becoming increasingly gassy).

Note that valve diodes with an indirectly heated cathode have an insulated heater where the heater supply is common to other valves in the equipment (eg. a 6X5) is worth mentioning. A breakdown of heater-to-cathode insulation in the valve diode shorts the B+ to the heater supply (which is often solidly connected to 0V through a heater CT, or through humdinger resistors). A CT fuse could stop that fault current.

Note that some amplifiers derive a bias supply from one of the HT legs, passing through a series capacitor or resistor and diode and then filter circuit. If a CT fuse is used for protection and opens, then charging pulses can circulate through the bias and B+ supplies leading to damage of bias electrolytic capacitors from reverse bias. In that situation fusing each HT leg is an option, or locating a fuse between the common cathodes of the diodes and the first filter capacitor (although the fuse holder then has to insulate against B+ dc).

Note that some amplifiers have independent power supplies for the output stage B+ and the output stage screen circuitry. In that situation the B+ supply typically shouldn’t be fused as the screen supply would still be available and that would likely damage the tubes – one option is to use a single fuse that is common to both the B+ and screen feeds (eg. in common link to 0V) so that both feeds disconnect if the fuse opens.

Bridge and doubler rectifier circuits

A power transformer secondary HT winding only needs a fuse in one leg of a bridge or doubler rectifier circuit, as shown in Figure 3. The fuse experiences AC current pulses where the zero-crossings will assist extinguishing the arc.

In a bridge rectifier circuit, the two diodes connecting to the positive DC can be a typical dual valve diode, but the other two diodes would be separate valves and need independent heaters (although nowadays ss diodes are often used to achieve a ‘hybrid’ bridge rectifier). Valve diodes are not commonly used with a doubler rectifier circuit as each diode needs an independent heater winding (caution as there is a PSUD2 bug).

Philips PA amplifiers commonly used a ss bridge rectifier on a 0-120-240V secondary winding to obtain 340VDC for plate supply, and used the 120V tap to directly supply 170VDC for screens. To ensure the plate supply is always available if there is a screen supply, a fuse would be placed in the bridge neg link to 0V and in the 120V screen supply link. To reduce voltage stress, place the fuse in the 0V, or capacitor mid-point link.

Bias power supplies

Fusing a transformer secondary winding for a valve amplifier bias supply, as used for a fixed bias output stage, is not recommended as an accidental loss of bias voltage can damage many parts. The preference is to protect the bias winding by careful layout and insulation of parts to avoid short circuits. If possible, connect a resistor directly to one winding leg and insulate that joint. That resistor would form the first RC filter in the bias supply, and should limit any short-circuit current to within the continuous rating of the bias winding (not a problem when the bias winding is just a tapping off the main HT winding). If needed, a half-wave rectifier can be changed to a full-wave rectifier to generate a higher raw voltage and hence allow a higher valued protection resistor to be used.

Simulation with PSUD2

PSUD2 can assess fuse current levels for the two important situations during normal operation:

- continuous operating current level,
- at power turn-on (especially when the valve diode cathode is hot).

Even though valve stages do not normally load the power supply at amplifier turn on, as the heaters are cold, it is not uncommon to turn off the amplifier for a few seconds and then turn it on again, such that valve heaters and cathodes are hot and the power supply caps have been discharged. This can cause a hot turn-on event similar to using ss diodes, and with at least full load applied. In some valve amplifier circuits, the output stage bias may also discharge rapidly, and so a hot-turn-on event could load the power supply with an even higher initial loading (ie. all output stage valves fully conducting).

To allow a reasonable estimate of fuse current waveforms, the power supply and load circuit part values need to be correctly included in PSUD2, especially the effective series resistance of the power transformer and the unloaded secondary winding voltage (which may be typically 7-10% higher than the rated winding voltage).

Continuous operation

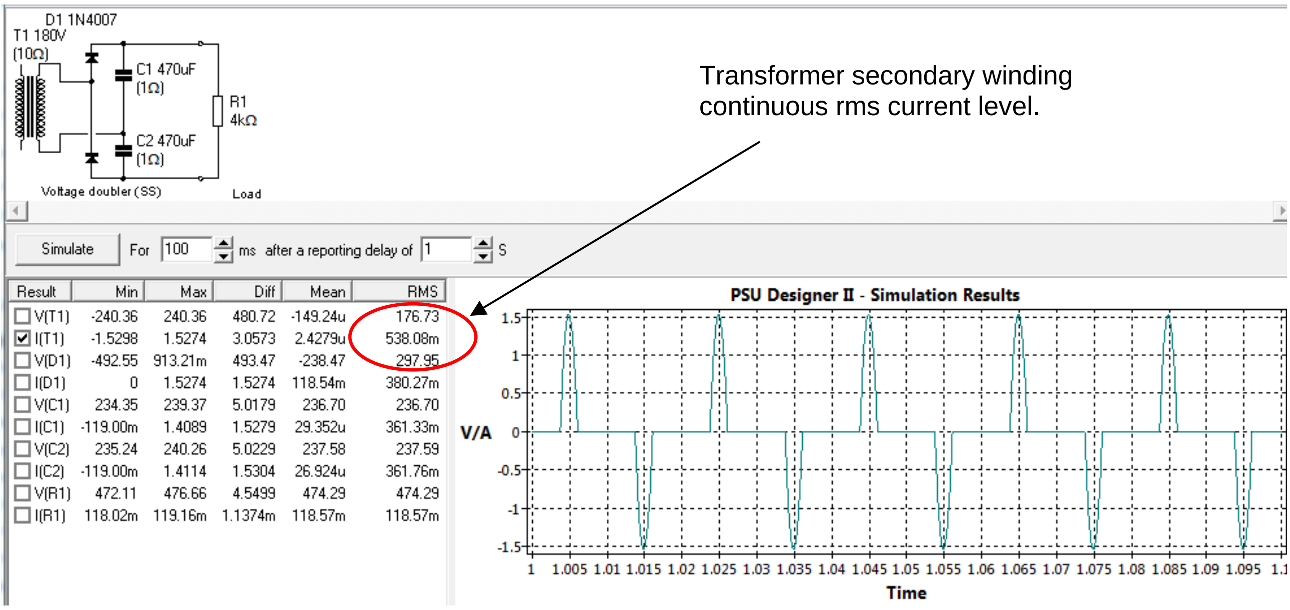


Figure 3. PSUD2 screen showing doubler power supply and simulated operating levels.

PSUD2 can identify the rms current through the fused secondary winding or CT connection when the amplifier's maximum loading is being applied to the B+ power supply. The power supply circuit is configured in PSUD2, and either a constant current sink or a resistive load is chosen to model the actual amplifier circuit loading. Depending on the operating class of the output stage, the amplifier loading can increase significantly above the idle power consumption when the output stage is overloaded/cranked.

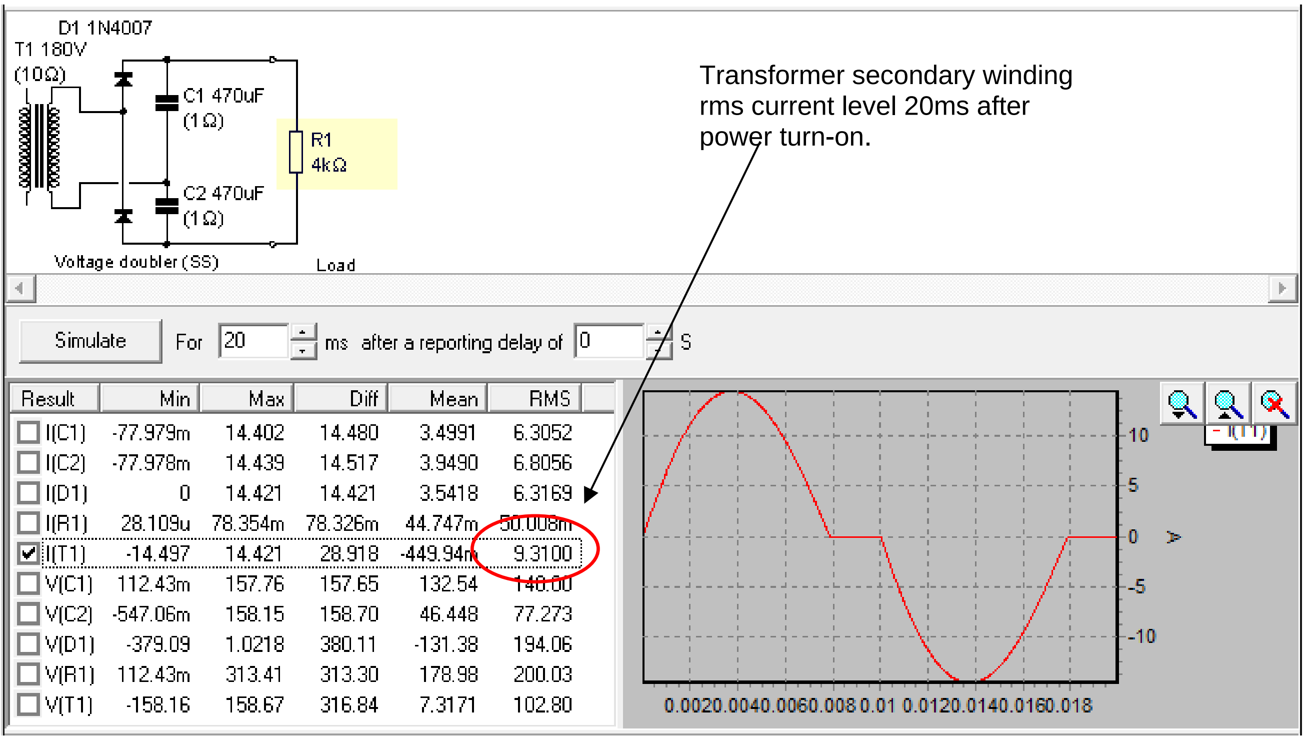


Figure 4. PSUD2 simulation screen example for VASE 100W KT88 PP fixed bias amp.

For example, a simple doubler circuit with ss diodes is simulated by PSUD2 in Figure 3. 'Simulate' is set for 100ms after a reporting delay of 1 sec, with the slow start option off, to identify the steady-state operating current levels (after any power turn-on disturbance has settled). Assuming the max DC loading is 119mA (through R1), a fuse in series with the secondary winding needs to have a rating of at least 538mA (ie. 600mA or higher for an IEC 60127-2 fuse), otherwise it may blow during normal operation.

Power turn-on

For the same example, PSUD2 can assess the rms current through the fused winding as a power turn-on event progresses towards a steady-state condition. To allow easy assessment for IEC F and T type fuses, the simulation times (after 0 sec reporting delay) should align with the minimum operating times given in Table 1, ie. 10ms, 20ms, 50ms, 150ms and 600ms. In Figure 4, PSUD2 has 'Simulate' set for 20ms after a reporting delay of 0 sec, with the slow start option off, to identify the rms current level for the first mains cycle pulses after turn-on.

The simulated rms currents can be divided by a target fuse current rating to give multiplier values that are then compared to the datasheet minimum I-t limit curve (or reference points) for the simulated periods to see if they are less. If a multiplier value lies above the min limit multiplier, then choose the next higher fuse rating as the target, otherwise the fuse may blow during a normal power turn-on event.

The above simulation examples are for a VASE 100W PA amp with 180V winding (10Ω effective resistance) and an ss doubler circuit with 470uF doubler capacitors and a 4kΩ cranked load.

Table 3 compares the IEC61027-2 F and T type fuses that would be acceptable. The PSUD2 results are in the top two rows, showing the simulation period and the rms current calculated for that period (as per Figure 4). Each table's third row is the multiplier value that is calculated by dividing the PSUD2 simulated rms level by the target fuse rating (eg. 8.8Arms/2.5A = 3.5 multiplier value) – and the last row is the minimum limit multiplier specified for the fuse not to blow.

A 2.5A rated quick-acting F fuse to IEC 60127-2, is seen to have a simulated multiplier level that is acceptably below the minimum fuse multiplier ratings for 10ms and 50ms.

A 1A rated time-lag T fuse to IEC 60127-2, is seen to have multiplier levels below the minimum standards rating for 20ms and 600ms, although for 150ms the multiplier is marginally above the rated min value.

The better choice of fuse for this particular application is the time-lag T, as its continuous 1A rating is substantially less than the 2.5A F fuse that would be otherwise needed, and so would provide much better protection for typical amplifier related faults.

Simulate period in PSUD2	**10ms**	**20ms**	**50ms**	**150ms**	**600ms**	**continuous**
Simulated RMS current	8.8A		6.7A			0.54A
Multiplier (for 2.5A fuse rating)	3.5		2.7			0.21
IEC 60127-2 **F** min limit multiplier	4		2.75			1

Simulate period in PSUD2	**10ms**	**20ms**	**50ms**	**150ms**	**600ms**	**continuous**
Simulated RMS current		9.3A		4.1A	2.0A	0.54A
Multiplier (for 1A fuse rating)		9.3		4.1	2.0	0.53
IEC 60127-2 **T** min limit multiplier		10		4.0	2.75	1

Table 3. Comparison of simulated current levels versus minimum fuse specification levels.

CT leg fuse in full-wave rectifier with capacitor input filter

Fuse current in the CT leg of a full-wave rectifier is assessed in PSUD2 by changing the first filter capacitor stage to an RC stage. The value of R is set to a low value (eg. 0.1Ω) and acts as a current sense component to allow PSUD2 plot and calculate current through that sense resistor (as it is the same current as passed through the CT leg).

The example in Figure 5 is for a more complex CLC filter, with a low load current such that the fuse selection process needs to check fuse values below 125mA. Note the resonant start-up current through the fuse due to the extra LC filter network.

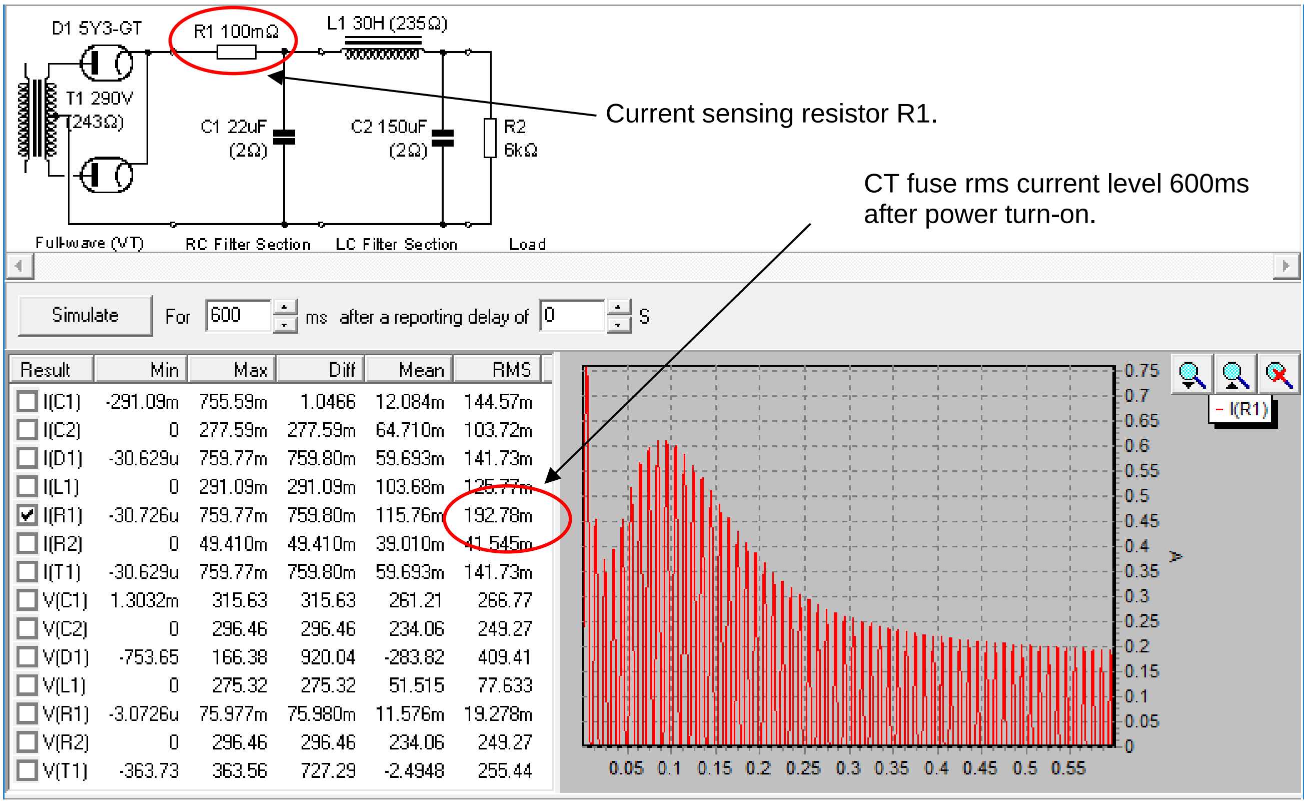


Figure 5. PSUD2 simulation screen example for CT fuse in 5W 6V6 SE amp.

The CT fuse assessment looks at results for an IEC 100mA fuse and a 125mA fuse. The 125mA F fuse results in Table 4 indicate a marginal condition for the 10ms duration. The 125mA T fuse results in Table 5 indicate an acceptable use, whereas the 100mA T fuse is not acceptable for the 200ms duration – noting that the 100mA fuse uses different durations for its multipliers. The IEC 125mA T fuse is considered the most appropriate fuse choice for that particular amplifier circuit.

Simulate period in PSUD2	**10ms**	**50ms**	**continuous**
Simulated RMS current	0.47A	0.312A	0.085A
Multiplier (based on 0.125A fuse rating)	3.8	2.5	0.68
IEC60127-2 Quick-acting F min limit multiplier	4	2.75	1

Table 4. 125mA F fuse assessment for Figure 5 circuit.

Simulate period in PSUD2	**10ms**	**40ms**	**200ms**	**continuous**
Simulated RMS current	0.48A	0.33A	0.31A	0.085A
Multiplier (based on 0.1A fuse rating)	4.8	3.3	3.1	0.85
IEC60127-2 Time-lag T min limit multiplier	10	4	2.75	1

Simulate period in PSUD2	**20ms**	**150ms**	**600ms**	**continuous**
Simulated RMS current	0.39A	0.33A	0.2A	0.085A
Multiplier (based on 0.125A fuse rating)	3.2	2.6	1.6	0.68
IEC60127-2 Time-lag T min limit multiplier	10	4	2.75	1

Table 5. 100mA and 125mA T fuse assessments for Figure 5 circuit.

Verifying PSUD2 results

Simulation inaccuracies

PSUD2 simulates circuit operation using idealised components and conditions. Actual circuit operation includes non-ideal behaviour which can cause noticeable differences between simulation and actual results.

Non-ideal behaviour can occur with:

- Choke parts.

  Simulation of a choke-input filter power supply is prone to noticeable error whenever the choke is not at or near the choke's rated AC voltage and DC current specification levels, as the choke inductance may be significantly different. Caution is required for situations such as at power turn-on, and when a step load can cause a large resonant swing in current, and when assessing fault current level conditions. Numerical accuracy differences can occur for choke-input filters when choke current reaches zero (ie. choke inductance below critical value for regulated operation).

- Transformer and choke dc resistance.

  Winding resistance is typically measured at ambient room temperature, however during operation the internal winding temperature may well be tens of °C higher than ambient. Copper winding resistance increases about +4% for each 10°C rise, so could well increase by circa +30%.

- Mains voltage waveform.

  A flat-topped mains primary voltage sine waveform is quite common, and can reduce the power supply DC voltage from what is expected using simulation. In addition, leakage inductance of the secondary winding can significantly modify the voltage waveform presented to rectifiers.

- Other parts.

  Parts such as fuses and NTC resistors that are placed in the primary or secondary side circuits have resistance values that may need to be included in the effective series resistance of the simulated transformer winding. For example, a primary side NTC can be modelled by its cold or hot resistance, depending on whether the simulation's initial condition aims to replicate a cold start or a hot start event.

- Loading current.

  A valve amp with no input signal presents a near constant 'idle' current load to the power supply, where the current is likely to include a constant DC level, plus some AC ripple current. A valve amp operating class AB at max output would include a constant DC level (significantly higher than the idle current level), plus a mix of AC ripple and signal current.

  A PSUD2 current tap does not model the ripple or signal current behaviour, only the constant DC level. A PSUD2 resistor load will better model the ripple current behaviour, but the resistor load can only be positioned at the end of the circuit (PSUD3 should allow a resistor load to be positioned anywhere within the circuit).

- Electrolytic capacitor reforming.

  Electrolytic capacitors that have been inactive for months and years reform their oxide layer during the initial application of voltage at turn-on. This effect of reforming is exacerbated by any initial over-voltage (surge) due to the power supply being unloaded for a few seconds. During a turn-on event, capacitors draw current to charge the simulated value of capacitance, but in addition may also draw a substantial additional current for reforming that is not modelled (this may be one reason why a fuse could blow on initial power up of an amp that has not been used for years/decades).

- Fault current.

  A failed part in an amp may rely on the fuse to operate for protection. PSUD2 can simulate the step from normal to fault, but only by using a stepped current tap. Alternatively, PSUD2 can be used to separately simulate the normal circuit conditions, and then the faulted circuit resistances to determine the sagged voltages and fault current expected. PSUD3 is likely to introduce a stepped resistance part that can be placed at various points in a circuit, to allow better assessment.

  Different fault scenarios need careful consideration of the different part resistances in the fault path. For example, an output stage pentode with input grid stuck near 0V (ie. leaky coupling capacitor or failed bias voltage) would likely experience sagged plate and screen voltages, whose operating levels will be determined by the power supply, the output transformer primary winding resistance, and the pentode characteristic curves. Setting the part values may take an iterative approach to generate acceptable operating points (ie. all part currents and voltages are close to reality).

For the VASE 100W amp power supply simulated earlier, with a KT88 PP output stage, if output bias was lost then both KT88's would conduct, and each anode fault path would present about 600Ω as the power supply is very stiff and the anode operating point would be past the datasheet I-V knee in the constant current region. The secondary side winding current would be about 4Arms, and a 1A T IEC fuse would blow in the range 150ms to 3 sec. The output transformer primary winding would need to conduct about 0.7A per side until the winding fuse blows.

For the 5W amp power supply simulated earlier, with a 6V6 triode-mode SE cathode biased output stage, if the 6V6 went gassy or lost its grid bias then the 6V6 fault current path would present about 3kΩ, comprising the output transformer primary 640Ω resistance, the 6V6, and cathode bias 300Ω resistor, with a 6V6 V-I plate operating point on the triode curve at about 180V and 85mA cathode current. The CT current would be about 135mArms, and a 0.125A T IEC fuse would be unlikely to blow. The output transformer primary winding would likely then operate close to its thermal limit.

Varying a part parameter, and noting sim result differences is an important way to appreciate how influential a non-linear part can be. Also, caution is needed with using public domain diode models, as some publicly uploaded models have incorrect parameter values. PSUD2 has a bug for valve diode voltage doublers.

Measurements

Secondary side CT fuse current can be measured directly by replacing the fuse with a sense resistor (eg. 1Ω), as the probe is referenced to signal ground (ie. amplifier chassis protective earth). Caution is needed with the rms voltage reading from a meter (even a true rms meter), as meter accuracy may degrade if the charging pulse crest factor is greater than 3 (and it typically is >> 3). Crest factor is the ratio of min or max peak current to rms current, and PSUD2 provides those values. An oscilloscope can be used to measure peak sense resistor voltage, so turn-on current pulse levels can be captured and compared to PSUD2 results.

An isolation current transducer, such as a LEM LA 25-NP, can be very useful for mains side as well as secondary HT side current measurement (rms and peak) when used with an oscilloscope.

To determine a resistive load value, the B+ voltage is easily measured, although the load current can be difficult to directly measure. It may be possible to insert a sense resistor (eg. 1Ω) between the first filter negative terminal, and the rest of the amp circuitry, and measure load current from the sense resistor voltage. Idle and cranked load current can be estimated from the sum of output stage cathode currents (derived from their sense or bias resistors) and adding a bit for preamp stage current consumption.

Selection of a fuse current rating

Not all fuse datasheets provide sufficient I-t detail to be able to confidently choose a fuse, and it is difficult to rationalise how best to choose fuses from old stock that have no markings other than the current rating.

Mains AC voltage could vary by more than 10% from the nominal value present during testing, due to local mains supply issues such as from PV grid-connect inverters. This effect can be simulated by increasing the power transformer voltage level by say 10%.

A specific fuse manufacturer and model may not be obtainable during the life of the amp. If a fuse rating is added to a schematic, then best to also add in the IEC 60127-2 or UL 248-14 along with the F or T type.

Most general 5x20mm and 3AG fuses and fuse holders are just 250VAC rated, however even the smaller 5x20 format is available in up to 500VAC rating if needed for high powered amps, and axial leaded fuses may avoid having to locate and fit a suitable fuse holder on a chassis.

Some electronic part outlets provide a range of fuses with the same current, voltage, and dimensional format. Some fuse datasheets specify compliance to IEC 60127-2 or UL 248-14 standards, whereas some datasheets just imply compliance by identifying a variety of agency approvals, and providing a table of electrical characteristics that are the same as required by a standard.

I recommend only buying fuses from reputable sources, and only buy fuses with an IEC 60127-2 or UL284-14 compliance, and keep those fuses with their original packaging/purchase details so you can identify the manufacturer/model in years to come (as the fuse end caps don't contain much information).

Selection based on I^2t value

A fuse datasheet will typically provide an I^2t value in A^2s, for each fuse rating, which relates to the level of current needed to melt the fuse in a very short time frame (typ t<10ms) where heat built up in the fuse has not had time to thermally transfer away.

For an application with a high initial surge current pulse, such as a mains side fuse passing transformer in-rush current as well as secondary side surge current levels, then the peak current level Ip passing through the fuse can be estimated. Assuming a half-sine waveform of one mains half-cycle with a peak current of Ip, then the fuse needs to pass an estimated level of $I^2t = Ip^2/(4.f)$.

Some fuse manufacturers have determined a nominal number of initial surge pulses that a fuse can sustain, as a ratio of the surge pulse I^2t level to the fuse's rated melting I^2t value. In practice the estimated $Ip^2/(4.f)$ value needs to be below about 30% of the fuse melting I^2t rating to allow an adequate lifetime from surge pulse events. Figure 6 indicates the number of such pulses that can be sustained by a fuse. See later example for Mains side fusing.

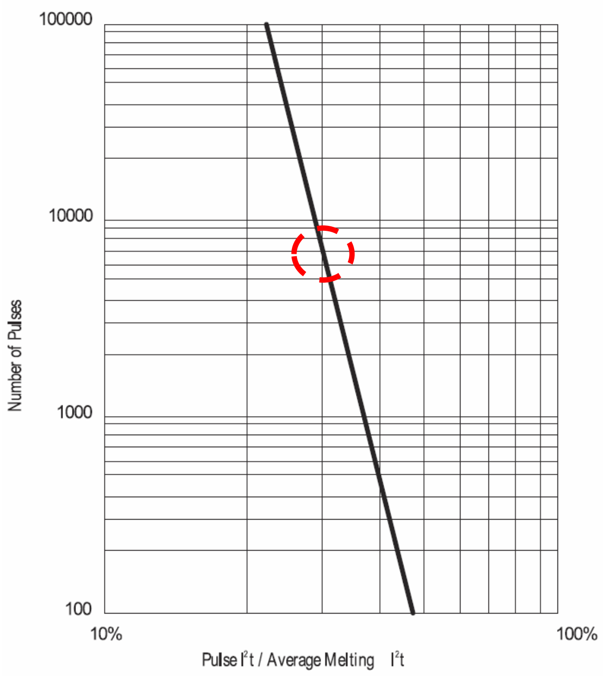


Figure 6. Pulse I^2t capability [6].

Fuse protection performance

Although a fuse may be chosen to survive continuous operation, and power turn-on events, based on its min specified I-t performance curve, the ability to protect equipment from damage is more conservatively assessed by the fuse's max specified I-t performance curve, as shown in Figure 1.

A fault situation may pass a damaging current level through the power transformer and other parts, with the fuse's worst-case opening time hopefully providing acceptable protection from collateral damage.

Max specified fuse blow time	**20ms**	**300ms**	**2 s**	**3 s**	**10 s**	**120 s**
IEC 60127-2 **F** max limit multiplier	10	4	2.75	~2.5	~2.3	~2.1
Fault RMS current needed to blow fuse (for 2.5A **F** fuse rating)	25A	10A	6.9A	~6.2A	~5.8A	~5.3A
Fault current level ratio to fuse operating current (0.54Arms)	46x	19x	13x	12x	11x	10x

Max specified fuse blow time	**20ms**	**300ms**	**2 s**	**3 s**	**10 s**	**120 s**
IEC 60127-2 **T** max limit multiplier	>>10	10	~4.6	4	2.75	2.1
Fault RMS current needed to blow fuse (for 1A **T** fuse rating)	>>25A	10A	~4.6A	4A	2.75A	2.1A
Fault current level ratio to fuse operating current (0.54Arms)	>>46x	19x	9x	7x	5x	4x

Table 6. Max fault I-t levels to blow fuse in VASE 100W example circuit.

For the same VASE amp example circuit used in the simulation section, if a fault within the amplifier caused the fuse current to rise then the max fault I-t shown in Table 6 may be needed before the fuse opens. The multiplier values in Table 6 are extracted from Table 1 and Figure 1. The same F 2.5A, and T 1A fuses are assumed, from which the fault current levels are calculated for each of the time durations. Then as an indicator of how large that fault current is, the last row in each table shows the ratio of the worst-case fault current needed to blow the fuse, for each of the time durations. Note that although the F 2.5A fuse shows the same max fault current needed to blow the fuse in 300ms to the T 1A fuse, the T 1A fuse provides a much better performance at more moderate fault current levels (ie. fault levels less than 19x the highest expected operating current) as would be typical for many amp type faults. Even with a T 1A fuse, a significantly large fault current may need to flow for quite some time before the fuse blows – although actual times should be less as the results in Table 6 are considered worst-case.

Given the wide tolerance of fuse operation, it is important to make every effort to avoid the need for a fuse by fitting any other practical form of protection that could minimise the chance of faults occurring.

As well as the power transformer's effective winding resistance, a fault current path may include substantial resistance from commonly used parts such as a valve diode, choke, output transformer primary winding, and output stage valve, which would restrict the current level passing through any fuse protection. If the max fault current level achievable (the prospective current) ends up being too low, then a fuse may not be capable of always blowing. Some examples of valve amp fault situations are described below, and how the likely level of fault current to flow through a fuse can be assessed by PSUD2 by estimating a load resistance that is equivalent to the fault circuit path total resistance :

- Output stage anode to heater short

  This fault could be due to pin 2 to 3 flashover on a valve socket.

  The fault current path is through the resistance of the output transformer primary winding (half-winding for PP), and then to ground through the heater circuit:

  - a heater CT connected to ground introduces negligible added resistance;
  - a heater connected to ground via a humdinger has the two humdinger arms in parallel (eg. perhaps 25-50Ω of added series resistance);
  - a heater connected to an elevated supply can have a high resistance to ground if a resistive divider is used, or could be via the output stage cathode resistor if that DC voltage level is used.

  The prospective fault current level depends on power transformer effective resistance, the type of diode used, the OT primary winding resistance, and any series part used like a choke or humdinger.

- Output stage loss of bias

  This fault could occur to one or all output stage valves depending on the origin of the fault. The bias supply itself could fail (eg. a bias adjustment pot wiper becomes open), or a valve could become gassy, or a coupling cap could become leaky.

  The fault current path is through the resistance of the output transformer primary winding, and through the saturation resistance of the valve. Parallel fault current paths may exist through both output transformer primary half-windings, and parallel output stage valves.

  - As an example, a worst-case EL34 saturation resistance would be estimated from the plate data curve for Vg=0 in the region from 0V up to the knee of the pentode curve (eg. ~20V/150mA = 130Ω initially for high screen voltage). If the power supply is stiff enough, the pentode would operate above the knee in the 'constant current' region, and so its effective resistance will increase and will depend on the screen voltage which would likely sag during a fault event (eg. ~250V/280mA = 900Ω for 250V screen voltage).
  - The likely fault currents in the VASE 100W amp example were identified in the earlier section on verifying PSUD2 results, where each KT88 would operate well above the anode characteristic V-I knee as the power supply is very stiff.
  - The likely fault current in the 5W amp example was identified in the earlier section on verifying PSUD2 results, where the 6V6 would operate near its max rated anode+screen dissipation limit operation point, but the secondary side CT fuse would likely not blow due to the substantial series resistance in that fault current path.

- Diode failure

  A short-circuited diode (anode to cathode) is not a common fault. A valve diode requires bridging of internal structures, or more commonly arcing to occur between anode to cathode or anode to anode, and an ss diode is likely to end up an open-circuit due to fault thermal stress.

If one diode in a valve shorts or arcs, then the valve diode on-resistance and saturation characteristic of the working diode (assuming the faulty diode has a continuous anode-cathode conduction path) would load the secondary winding directly for alternate mains half cycles. The rms fault current would approach 50% of the diode saturation current level.

A short-circuited diode (cathode to heater) is only a concern for an indirectly heated cathode, where the heater is also used by other valves. In that case, diode on-resistance and saturation characteristic would load the secondary winding directly for every mains half cycle.

A diode like the 6V4 has a short duration peak current rating of 900mA, and a continuous rating of 90mA. The 900mA level would be similar to the saturation level forced by a fault. The rms fault current would approach the saturation current level.

- Distribution faults

  The relatively high resistance of dropper resistors used in power supply distribution would mean a fault on a distribution supply would not cause the power transformer secondary side fuse to open. The likely outcome is that the dropper resistor(s) would overheat and fail open-circuit.

Using an NTC thermistor to reduce peak current

An NTC thermistor can be included in the power transformer primary circuit, or a secondary side circuit, so as to reduce the peak current level during power turn-on. The NTC can be simulated by increasing the primary or secondary resistance in the transformer by the cold resistance of the NTC device. Simulation based on the cold thermistor resistance is only valid for a short period of time after turn-on, as the resistance will change rapidly. In addition, an NTC can take many seconds/minutes to cool after power is turned off, so caution is required in assessing a suitable fuse rating. Similarly, the hot NTC resistance should be included in simulations if it is significant compared to other resistance parameters.

The following discussion assumes the thermistor is placed on the HT secondary winding (eg. between diode cathodes and filter capacitor; or in series with CT fuse), as that simplifies the assessment (the thermistor only experiences the HT current, whereas a thermistor on the AC primary experiences other current related influences – see next section). For PSUD2, the thermistor cold resistance can be added to the transformer resistance, or the capacitor input filter changed to an RC filter stage where the R is the added thermistor.

A thermistor datasheet indicates a maximum filter capacitance (C) level when the capacitance is directly after a mains side rectifier with a mains voltage (VAC), which identifies a level of energy throughput = $½C(\sqrt{2}.VAC)^2$ at turn-on that would not damage the thermistor. A valve amp places the filter capacitance on the secondary side of a transformer, and so the $½CV^2$ throughput relates to the amplifier secondary side AC voltage and filter capacitance. An amplifier with a higher secondary AC voltage, or more filter capacitance, requires the thermistor to throughput more energy, and so a physically larger thermistor may be needed.

A thermistor datasheet indicates the maximum continuous current rating, which needs to be adjusted for ambient temperature range. A valve amp can be a hot environment without air flow under the chassis, and easily place a thermistor in a ~60ºC ambient, where the thermistor current rating would be derated by about 10%. The application must also maintain a continuous current through the NTC of at least 30% of max rating, in order for the NTC to retain its low hot-resistance level.

The cold resistance rating is typically for 25ºC, and has a wide tolerance (eg. ±25%).

A thermistor time-constant rating indicates how long it takes for the thermistor resistance to increase itself back to a higher value after power is turned off. A valve amp could be turned off and then on again after just a few seconds by accident. The main filter capacitor can easily discharge to almost zero volts in that time, which may cause the fuse to see a higher than normal current at turn-on, as the thermistor resistance has not had sufficient time to recover to a higher level.

For the example simulation circuit used previously, the transformer 10Ω effective resistance was increased to 50Ω to represent the inclusion of a CL-80 NTC thermistor [2]. The $½CV^2$ energy throughput is 0.5 x 940u x $(\sqrt{2}.180)^2$ = 30J, and the thermistor has a 72J capability. That thermistor has a relatively long time-constant of 100 seconds and handles at least 2A continuous.

Table 7 indicates that the fuse rating could be almost halved when that NTC thermistor is used.

If a fault occurs in the amp, the thermistor has only a minor influence on the prospective fault current level as long as the fault current does not damage the NTC. However, the lower fuse rating (allowed by using an NTC) has a major effect on the worst-case clearing time. For example, a 1A IEC 60127-2 T fuse would clear within 10 secs for a 2.7A fault current, compared to only 1.5 sec max needed for a 0.5A fuse.

NTC temperature	Cold				Hot
Simulate period in PSUD2	**20ms**	**40ms**	**100ms**	**500ms**	**continuous**
Simulated RMS current	3.1A	2.7A	2.1A	1.0A	0.54A
Multiplier (based on **1A** fuse rating)	3.1	2.7	2.1	1	0.21
IEC 60127-2 **F** min limit multiplier	3.4	3	2.5	2.1	1
Multiplier (based on **0.5A** fuse rating)	6.2	5.4	4.2	2.0	1
IEC 60127-2 **F** min limit multiplier	10	~7	~4.6	~2.9	1

Table 7. Simulation results with added cold NTC resistance.

Mains side fusing and NTC thermistor

Mains side continuous current

The AC mains side fuse should have a continuous rating that is consistent with the nominal max current drawn by the primary winding. A simple cheap mains AC power monitor can be used to measure the mains AC operating current of an amplifier, although there is likely to be some measurement error from cheaper type meters as the current waveform may have quite a high crest factor due to a rectified power supply.

The fuse current rating should have margin above any measured current level to cover expected variations in:

- mains voltage
  - higher voltage will increase transformer magnetising current.
  - higher secondary voltages may increase power consumption of some circuits, especially the output stage and heater current.
- output stage bias setting and operational use under overload conditions
  - valve output stage bias may be manually set to a higher level in the future.
  - output stage operation in class AB1 can increase power consumption above idle level.
- part variations
  - valve heater current can vary.

The fuse current rating will typically include some additional margin due to the available steps in fuse current ratings (eg. 200mA, 250mA, 315mA, 400mA), and the need to stay within the time-delay T fuse multiplier constraints (see next section).

And note that the continuous current rating of a UL fuse must be derated by another 20% as described at the start of the article, whereas an IEC fuse can be operated at its rated current if needed.

The transformer VA rating indicates the maximum rated continuous output current for a given output voltage across a resistive load. With maximum rated VA being transferred, losses within the transformer mean that mains current will be a bit higher than the current calculated from VA rating and mains voltage.

In an amplifier, the poor utilisation of the secondary due to the rectified current pulse waveform means that transformer VA rating is at least 23% more than the required output DC power. When power losses from the transformer and rectifier diodes are included with the poor utilisation factor, the mains current is likely to be at least 50% more than the output DC power divided by mains voltage.

Mains side in-rush characteristic

A time-delay T fuse for the AC mains side of a transformer input power supply is typically required due to:

- power transformer in-rush current;
- the high and long peak current-time response of cold valve heaters;
- the charging characteristic of the B+ supply capacitors if ss diode rectification is used.

As an approximate design process, the initial peak current seen by a primary side fuse from each in-rush contributor can be estimated. For example, for the VASE 100W amplifier simulated earlier:

- transformer in-rush current can be estimated at 10x the rated VA current. Eg. a 160VA 230V transformer has an inrush estimate of 10 x 160VA / 230V = 7 Apk. A toroidal transformer is likely to exhibit a higher in-rush current compared to the common E-I core transformer.
- heater in-rush can be estimated at 5x the reflected heater current. Eg. a 6.3V 5Arms heater requirement is reflected to a 230VAC primary as (6.3V / 230V) *5A *√2 *5 = 1 Apk.
- DC B+ supply in-rush current was simulated by the circuit in Figure 4 at 14.5Apk on a 180V secondary. The 14.5 Apk is reflected to a 230VAC primary as (180V / 230V) *14.5 = 11 Apk.

The sum of those peak currents through the primary side fuse is then about 7+1+11 = 19Apk. The B+ fuse for 11Apk was determined previously to need an IEC T 1A fuse, so 19Apk is likely to need 19/11 = 1.7A, so an IEC T 1.6A primary fuse would be a reasonable estimate. For a Schurter IEC60127 T 1.6A 5x20 fuse the I^2t = 10.5A^2s. The expected in-rush I^2t experienced by the fuse is 19^2/(4x50Hz) = 1.7A^2s, which is about 16% of the fuse I^2t rating. Even if transformer in-rush caused double the estimated peak current level, the initial I^2t would be about 30% of the fuse I^2t rating, which is still acceptable.

NTC thermistor design

In order to select a suitable primary side NTC thermistor, this general technique used for in-rush can be used to estimate the effective in-rush energy throughput of each of the current in-rush contributors. For example, for the VASE 100W amplifier simulated earlier:

- DC B+ supply charging energy was estimated at 30J. Eg. 0.5 x 940u x $(\sqrt{2}.180)^2$ = 30J.
- transformer in-rush can be estimated by Ipk comparison. Eg. 30J x 7/11 = 20J.
- heater in-rush can be estimated by Ipk comparison. Eg. 30J x 1/11 = 2J.

The sum of in-rush energy contributions at the power transformer primary is then about 30+20+2 = 52J, which can be used to identify a suitably rated NTC thermistor.

Also note that the continuous NTC current should not be less than about 30% of the max NTC current rating, and that should be confirmed by measurement of primary winding current during idle operation.

Heater supply fusing

A valve heater causes a high initial current to flow, with a peak of about 4-10 times the rated heater current [8], depending on the power transformer heater winding capability and the cold resistance of the heater. The response in Figure 7 [1] is for tubes used in main-frame computers circa 1957.

Within a valve, it's almost impossible for a short circuit heater fault to occur, so the risk of shorting a heater supply, and hence damaging the power transformer is essentially related to the risk of faults external to the valves.

Vintage equipment often connected one end of the heater supply to chassis, making it relatively easy to short-circuit the heater supply from a single fault (ie. loose wire or bent terminal). A grounded heater CT was and is very common, so fusing of both heater supply 'legs' would be needed to insure against accidental grounding of a heater wire and hence shorting across half the PT's heater winding.

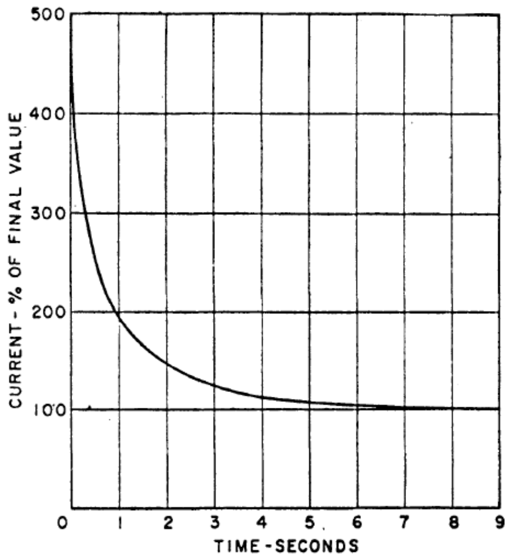


Figure 7. Heater current response.

Using a heater supply humdinger (either with fixed resistors or with a pot), or DC elevating the heater from a resistive divider, provides fault tolerance from shorting a heater wire to chassis. For a simple humdinger to ground, accidental shorting of one side of the heater to chassis only causes twice the voltage across the other humdinger resistor, so only that resistor is stressed.

The likely fault scenario in an amplifier would be heater distribution wiring where adjacent socket pins 4 and 5 shorted (eg. on an EF86 or 12V powered 12A*7). Octal sockets with the heater on pins 2 and 7, or noval sockets with heater between pins 4-5 and 9, are less prone to heater short circuits when care is taken.

Other heater related failures do not benefit from fusing. A filament open-circuit has no impact on the heater supply and is not common [1]. A heater to cathode short circuit either has no impact, or causes a local low level of over-current (eg. in cathode biased stage), or in the special case of an indirectly heated power supply diode should cause a HT fuse to break.

A time-delay T type IEC 60127-3 fuse with a rating one step above the nominal heater current rating should cope with power on current surge, even when mains voltage is high, and then should cope with continuous heater current (appreciating that heater current will have some tolerance). For example, a 2A heater supply with 2A loading of heaters, and a 2.5A IEC T fuse, would need heater current to reduce below 10A after 150ms, or 5.5A after 0.6 sec for the fuse not to possibly blow.

A UL284 slo-blow fuse of the same rating may also be acceptable as 2A is 80% of the fuse rating.

Automotive blade fuses are another option, due to the low heater voltage. For SAE J2077 or ISO 8820-3 compliant fuses (ie. from the main fuse manufacturers), time-current specifications are shown in Table 8, although many datasheets will show some variation for particular fuse models. These performance ranges indicate the likelihood that even a fuse with a rating 2-3x the heater supply rating could fail from in-rush, and so would not be recommended in comparison to a miniature cartridge T type fuse.

Rating multiplier	**1.1x**	**1.35x**	**1.6x**	**2x**	**3.5x**	**6x**
Mini blade	100 hr -	750ms - 10min	250ms – 50s	150ms - 5s	40ms – 500ms	20ms – 100ms

Table 8. SAE J2077 compliant fuse performance levels.

Another option is a suitable PTC power thermistor, especially where a high mains voltage or other influence operates the heater at more than +10% of voltage rating – the PTC would likely drop about 0.6V during normal operation, and transition to a high resistance for any continuous over-current fault, and hence act as a resettable fuse. PTC device performance is influenced by ambient temperature, and may take some seconds to increase its dynamic resistance during a fault, and does not completely disconnect current flow.

DC supply fusing

DC supply fusing is preferably avoided in valve amps as suitable high voltage DC rated fuses are not common and have a limited range of current ratings. A fuse in the B+ feed to an output transformer primary winding should at least use a flyback diode to avoid overvoltage damage to the primary (from v = L.di/dt). A fuse opening the anode supply, but not the screen supply as well, can damage output stage valve screens.

Cathode circuit fusing

Push pull output stage amplifiers split the B+ supply current in to two paths through the output transformer primary winding. In a quad of output valves, the B+ supply current is finally split in to four cathode current paths. Separate fusing of each valve's cathode should assist discrimination in isolating a faulty valve circuit, rather than hoping and waiting for the power transformer secondary side fuse to open, and hence risking damage to both the power and output transformers. See output transformer protection article.

Valves in a quad or sextet configuration may not share rms current equally during normal operation, so adding some margin (eg. +20%) to a cathode fuse rating is appropriate. For a quad, the cathode fuse current rating would then be at least 1.2x25% = 30% of a B+ CT fuse rating.

A quick acting F fuse would be most appropriate in a cathode circuit, as the fuse is not subject to turn-on stress in this location. If the prospective fault current through the cathode/fuse was 2.5x the fuse rating, then a quick-acting F fuse should operate in under 10 secs, and likely in about 1 sec. In contrast, a PT secondary CT fuse would likely not blow.

A parallel high voltage Zener diode across a cathode fuse can be used to limit cathode voltage rise if the fuse opens due to say a loss of bias. The aim is to keep the cathode-to-heater voltage within about 150V to avoid damage to the valve. If a 150V 5W Zener diode (eg. 1N5383B) clamped the cathode to +150V, and the grid was faulting to 0V, then the valve would be in deep cut-off, and the Zener diode would dissipate little power.

Panel mount fuse-holder safety

The safety of many vintage, and some modern panel-mount fuse holders is a concern to be assessed.

A main risk relates to a fuse being inspected or swapped over whilst the equipment is energised, as touching the fuse to extract it or insert it into the holder may allow contact with energised internal circuitry.

Figure 8. Vintage and modern panel mount fuse holder assemblies.

By far the most common panel mount fuse-holders have a removeable cap (screwed in place, or pushed and rotated), and the cap grips one end of a 3AG or 5x20mm fuse. The main housing of the holder has two internal metallic parts to make an electrical connection to the fuse.

With the cap removed, modern fuse-holders do not allow a finger to contact the internal connections (IP20 rating, although some are IP40 rated for enhanced protection). Although rare, some vintage fuse-holders allow a finger to touch the metallic screw in thread of the fuse holder (which connected to the side of the holder barrel terminal) and are therefore a hazard.

The concern for even modern fuse-holders is when a fuse is manually inserted into the holder using fingers (rather than when the fuse is gripped by the cap). Many holders allow the far end of the fuse to touch a terminal whilst fingers are still on the other end of the fuse.

Some modern fuse holders such as the combination panel-mount assembly in Figure 9 do not allow the fuse to be accessed until the AC mains plug is removed.

Even when the AC mains connection is turned off or disconnected, some panel-mounted fuses may be used for internal DC disconnection, and so may remain energised for some time. Also, some AC mains circuits have noise suppression or power factor correction capacitors installed, and they may still hold some voltage.

Figure 9. Combination IEC socket, fuse, switch and indicator

Another risk relates to secondary-side HT windings with voltage above 250Vac, where the fuse holder is likely only rated for 250Vac. With a fuse in the CT link, the fuse is nominally working at 0Vac. In contrast, a fuse in each arm of say a 500-0-500V full-wave winding will work at 500Vac – in which case suitably insulated pig-tail axial fuses may alleviate risk.

References

[1] "Thermistors for the gradual application of heater voltage to thermonic tubes", J Gano & G. Sandy, March 1958.

[2] NTC thermistors type CL.

[3] Schurter fuse range

[4] Littelfuse fuse range

[5] Duncan Tool's PSUD2 power supply simulation program

[6] Littlefuse Application Guide

[7] Power supply issues for valve amps

[8] Filament data - author unknown.