Performance Testing

PAS

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The PAS Power Supply

Part 1

This final installment of the PAS analysis series will examine the power supply. I had originally intended to cover this in a single comprehensive article however, due to various time constraints, it has become greatly delayed. So, to get things moving, I have chosen to break it down into two parts and release them as they are completed.

Part 1 will focus on the power transformer since it has often been criticised as being a weak point in the power supply. How this was determined is unclear since no objective evidence is ever presented. Nevertheless, it is regularly cited as fact on various online forums along with recommendations on how to reduce the load on the, allegedly, overburdened transformer. We will endeavour to determine if the criticisms are valid beginning with some basic background information on how power transformers are rated.

Power Transformer Ratings in General

Power transformers are rated to supply a certain current at a certain voltage. In doing so, heat is generated due to resistive losses in the windings and eddy currents and hysteresis in the core. Ultimately, it is the amount of heat the insulation materials can safely tolerate that limits the rating of any particular transformer.

Insulating materials are grouped in classes according to their maximum working temperature. The chart in Fig. 1 displays some common insulation classes and ratings.The ratings are based on an ambient operating temperature of 40°C. The temperature rise margin is the amount the *average* temperature is allowed to rise above ambient. An additional 10°C hot spot margin is added since winding temperature is not uniform, being hottest near the center. The maximum allowable temperature is the sum of the ambient temperature, the temperature rise margin and the hotspot margin. Thus, for a Class A/105 rated transformer: 40°C ambient + 55°C temp rise margin + 10°C hotspot margin = 105°C max. In practice, the temperature rise margin may be higher or lower depending upon the actual ambient temperature, but the sum of the ambient, average temperature rise and hot spot margin should never exceed the insulation class rating. Or, stated another way, the maximum *average* winding temperature (not rise) is the class rated temperature minus the 10°C hot spot margin. For Class A/105: 105°C - 10°C = 95°C.

Letter Class	Insulation Class	Ambient Temp	Temp Rise Margin	Hotspot Margin	Max Temp
A	105		55 °C		105 °C
B	130		80 °C		130 °C
F	155	40 °C	105 °C	10 °C	155 °C
H	180		130 °C		180 °C
R	220		170 °C		220 °C

Fig. 1 Common Insulation Classes

Note: this is not a comprehensive listing

Note that a power transformer operating at its rated capacity, in a 40°C ambient environment, will approach, but not exceed, its insulation rating while still providing normal life expectancy. However, when exceeded, the insulation begins to break down and life span will typically be halved for every 10°C rise beyond the rating. Awell designed transformer, operating within the limits of its insulation class, can provide decades of reliable service.

Dynaco PA-211 Power Transformer (aka PN 464007)

The PA-211 was commonly employed throughout the long production cycle of Dynaco's PAS 2, 3 and 3X series of stereo preamplifiers. Less common was the PA-522 which had two primary windings allowing it to be wired for either 120VAC or 240VAC operation. Only the more common PA-211 will be examined in this article.

Three windings are employed consisting of a single primary and two secondary windings to accommodate filament and HV supply needs. Oddly, the primary winding is not fused.The HV winding is center tapped and, along with a 12X4 recitifer, is configured in the typical CT full wave rectifier fashion followed by RC filtering. The filament winding powers the 12X4 filament and power indicator lamp directly, as well as a voltage doubling rectifier which provides DC power for the 12AX7 amplifier tubes.The general configuration is shown in Fig. 2. Note that the specifics of the HV rectifier, voltage doubler, and associated loads, will not be discussed in this article, only their loading *effects* on the transformer. Thus, they are shown only in block diagram form.

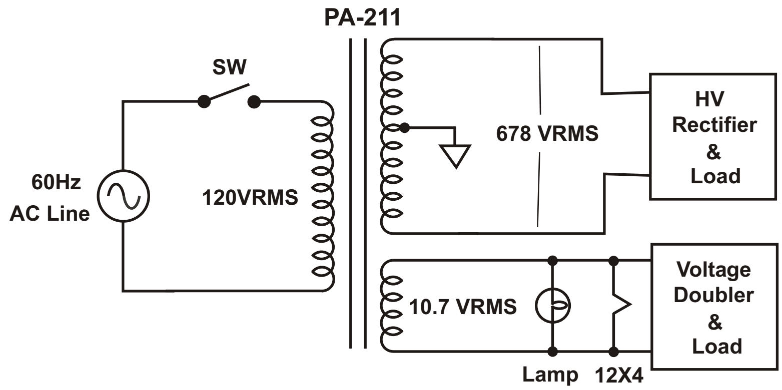


Fig. 2 PA-211 Winding Configuration

Note: loaded voltages shown for 120VRMS line voltage

It is common knowledge that, in the PAS series, the tube filaments are operated at a somewhat lower voltage than their specified ratings. One can speculate on whether the reason was reduced noise and/or increased lifespan, but we may never know for sure. Some, however, have taken this as a sign that the transformer is being overloaded, but that alone is not a valid assumption. Being a professionally designed product, proven reliable over a period of decades, it is likely the PAS was operating as Dynaco intended. Realistically, if we wish to assess how stressed it really is, we will need to determine how closely the PA-211 approaches its insulation temperature rating during normal operation. Without markings, or published ratings, some assumptions will have to be made as to the insulation class it employed. Considering it is vintage, was only powering a preamplifier, did not run particularly warm, and was employed in a consumer device, it would be reasonable to assume that it was likely rated no higher than Class A/105°C. Thus, we will consider that to be the rating for the following temperature related testing. That being the case, the average winding temperature should not exceed 95°C allowing for an additional 10°C hotspot margin.

PAS Test Subject

The same PAS 2 that was used for the phono and line stage analysis continues to be the test subject. It has been fully tested and confirmed to be in proper working order. Differences within the PAS series were primarily cosmetic and the same active circuitry, power supply and enclosure were used throughout. Thus, the PAS 2 should be properly representative.

For the purpose of transformer testing, the selenium rectifier for the filament supply was replaced with 1N4007 diodes. This was done because most PAS units still in service will have had the modification performed to avoid possible failure of the old selenium rectifier stack. This modification, along with the 120VRMS line voltage that will be used for testing, will also slightly increase current draw and transformer temperature, but is more representative of the conditions under which most will operate today.

Ambient Operating Temperature Test Setup

The ambient operating temperature is the temperature of the interior of the chassis, with all covers installed, after the amplifier has been operating long enough for it to have stabilized. To make this determination a thermocouple was suspended mid way between the phono and line stage circuit boards, away from the tubes. For interest, and to help confirm when the transformer temperature had stabilized, an additional thermocouple was attached to the top of the transformer. It had no purpose in determining the actual winding temperature.

Average Winding Temperature Test Setup

As winding temperature increases, so does its resistance. The change in resistance from cold to hot states, along with the temperature coefficient of copper, allows the average winding temperature to be calculated using the formula shown in Fig. 3. Since the heat from each winding must travel through each layer to be dissipated outside the coil, the inner most winding, the primary, will be the hottest and this is the winding that will be measured. It is also the most convenient to measure since, with the power cord disconnected from the AC source, there is nothing else connected to the winding. To facilitate quick and convenient measurement, as well as bypass the resistance of the

$$T = \frac{R - R_0}{\alpha R_0} + T_0$$

Where:

T = hot winding average temperature
T_0 = initial winding temperature
R = hot winding resistance
R_0 = initial winding resistance
α = temp. Coefficient of copper (0.00393/°C)

Fig. 3 Calculate Average Winding Temperature

power cord, two short wires were connected to the primary winding and brought out of the chassis through the rear panel cooling slots. The Fluke multimeter used to measure the winding resistance had the ability to correct for test lead resistance.

Test Procedure

With the thermocouple and primary winding test leads routed through the rear panel cooling slots, the top cover was installed and the PAS 2 was positioned on the test bench. Before applying power the cold state internal ambient (room) temperature and primary winding resistance were measured as being:

Cold state internal ambient temp: 21.5°C
Cold state primary winding resistance: 39.85 Ω

120VRMS power was then applied, via variac, and the internal ambient and transformer case temperatures were monitored. After 3 hours of operation the temperatures appeared to have stabilized but an additional hour of operation was allowed for a total of 4 hours stabilization time. At this time the internal temperatures were measured as being:

Hot state internal ambient temp: 38.2°C
Hot state transformer case temp: 55.9°C

The power was then disconnected and the resistance of the primary winding was measured as being:

Hot state primary winding resistance: 47.65 Ω

Calculate Average Winding Temperature

Using the measured results, the *average* temperature of the primary winding was calculated:

$$T = \frac{R - R_0}{\alpha R_0} + T_0$$

T_0 = initial winding temperature = 21.5°C
R = hot winding resistance = 47.65 Ω
R_0 = initial winding resistance = 39.85 Ω
α = temp. Coefficient of copper (0.00393)

$$T = \frac{47.65 - 39.85}{0.00393 \times 39.85} + 21.5 = \boxed{71.30\,^{0}C}$$

Average winding temp

Calculate Hot Spot Temperature

Knowing the average winding temperature, the hot spot temperature becomes:

71.30°C (average winding temp.) + 10°C (hotspot margin) = 81.30°C

Calculate Safety Margin

Knowing the hot spot temperature, the safety margin before exceeding the insulation limit becomes:

105°C (max allowable temp) - 81.30°C (hotspot temp) = 23.70°C

Summary of Temperature Test Results

From the measured results it was determined that, under normal operating conditions:

- The internal ambient temperature of the PAS preamplifier rises 16.7°C above room temperature

- The transformer case rises 34.4°C above room temperature and 17.7°C above internal ambient temperature

- The average primary winding temperature rises 49.8°C above room and 33.1°C above internal ambient temperature

- The primary hot spot temperature was 81.30°C while the maximum allowable was 105°C for a safety margin of 23.7°C

Conclusion

The test results do not indicate any particular cause for concern. Even assuming a minimal Class Arating, the PA-211 is operating with a comfortable temperature margin under normal operating conditions with adequate ventilation.

Power Dissipation

While testing has shown that the transformer is operating with a reasonable temperature margin, it would be interesting to know how much power is it actually dissipating. We'll go through the process of determining the amount of power being dissipated within the iron core (core loss) as well as that being consumed by the resistance of the windings (copper loss).

Core Loss

An estimation of the core loss can be made by employing the "open circuit" test procedure. With the secondary windings open, the output power is zero, and the only power consumed is that used to support flux in the core plus primary winding copper loss. Since the no-load current is so low, copper loss is minimal so the power dissipated is, essentially, the core loss. Unfortunately, the power cannot be determined by the simple product of input voltage and current. Because the load is reactive, voltage and current are not in phase, and neither is the current sinusoidal. V x I would only determine the "apparent" power being consumed. The "true" power must be determined by integrating the voltage and current over a period of time. Barring expensive instrumentation that can "do the math", a watt meter capable of displaying the true power can be used and this was the method employed. The test is setup shown in Fig. 4. For this test, the rectifier tube was removed and one lead of the filament winding disconnected resulting in the secondary windings being open circuit. A *consumer grade power meter was employed to measure the true power. While the power meter could also measure voltage and current, True RMS multimeters were also included to aid in verifying its accuracy.

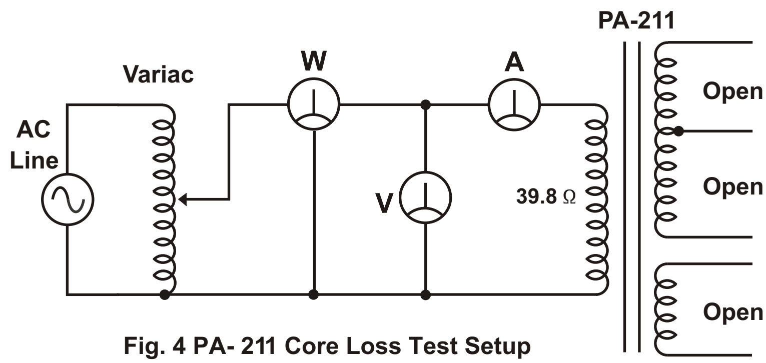


Fig. 4 PA- 211 Core Loss Test Setup

The variac was adjusted to provide 120VRMS to the primary winding as indicated on the voltmeter, resulting in 31.4mA being indicated on the ammeter. The watt meter display correlated well indicating 119.9V and 0.03A respectively. That being the case, I felt confident that the indicated power level of 1.1W was a reasonably accurate representation of the true power.

With a measured resistance of 39.8 Ω and current being 31.4mA, the primary winding copper loss becomes:

$$31.4\text{mA}^2 \times 39.8\,\Omega = 0.039\text{W}$$

Thus, the power being dissipated in the core becomes:

$$1.1\text{W (measured)} - 0.039\text{W (copper loss)} = 1.06\text{W}$$

***Note:**

Consumer grade power meters are typically intended to monitor household appliances and accuracy may suffer when attempting measure low power levels. I used such a device because I did not have access to a laboratory grade instrument, but only after verifying the accuracy at the power levels of interest. The particular meter used in this case was the Kill-A-Watt® P4400, one of the most popular devices of its kind. To make a determination of the accuracy in the range of about 1-2W, various purely resistive loads were connected. The indicated power levels were within 2% (typically about 1.7%) of the calculated values, while the rated accuracy of the device is 0.2%. The reduced accuracy was expected, but still good enough go provide a reasonable determination of the core loss. It should be noted that the low power accuracy exhibited by such devices can be quite variable from unit to unit and must be determined on an individual basis.

Copper Loss

The "short circuit" test may be employed to determine power dissipation due to copper loss. The test setup is similar to that shown in Fig. 4 except that the secondary windings are now short circuited. The variac is adjusted such that the primary current is equal to the normal load current. Since the voltage will be very small compared to the normal operating voltage, core loss will be negligible and the power indicated by the wattmeter will be related primarily to the copper losses of the windings. However, for a couple of reasons, that method will not be employed in this case. First, the Kill-A-Watt® power meter, as with most others of its kind, will not function below about 80VRMS, and thus is not suitable to perform this test. But also, the short circuit test can be less accurate when multiple secondary windings are involved. Instead, the true RMS current in each winding was measured and then the power dissipation calculated based on the winding resistance. Fig. 5 displays the setup with winding resistance and currents measured at full operating temperature.

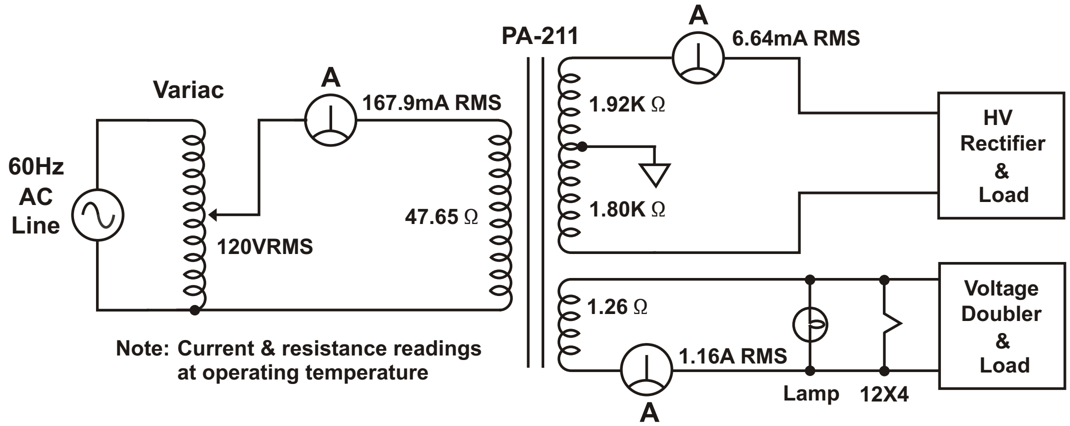


Fig. 5 PA-211 Winding Resistance & Current

Using the measured resistance and current, the copper loss in each winding was calculated:

Primary: $167.9\text{mA}^2 \times 47.65\,\Omega = 1.34\text{W}$

Filament: $1.16\text{A}^2 \times 1.26\,\Omega = 1.69\text{W}$

*High Voltage: $(6.64\text{mA}^2 \times 1.92\text{K}\,\Omega) \times 2 = 0.169\text{W}$

The total copper loss thus becomes: $1.34 + 1.69 + 0.169 = 3.19\text{W}$

*** Note:**

The 6.64mA HV current shown represents ½ of the CT winding which conducts on alternate half cycles. Thus the power is multiplied by 2 to include the other ½ of the winding. The resistance for each ½ winding is slightly different, but close enough that we'll call the power dissipation equal in each.

Total Power Dissipation

Combining the core and copper losses, the total dissipation at 120VRMS line voltage is:

1.06W core + 3.19W copper = 4.25W

Efficiency

The efficiency of the transformer can be determined by following formula:

$$\%\ \text{Efficiency} = 1 - \frac{\text{core + copper losses}}{\text{input power}} \times 100$$

To perform the calculation, we still need to know the true input power and this was also determined with the Kill-A-Watt® power meter. The indicated power, at 120VRMS, was 18.6W thus the efficiency becomes:

$$1 - \frac{4.25\text{W}}{18.6\text{W}} \times 100 = 77.2\%$$

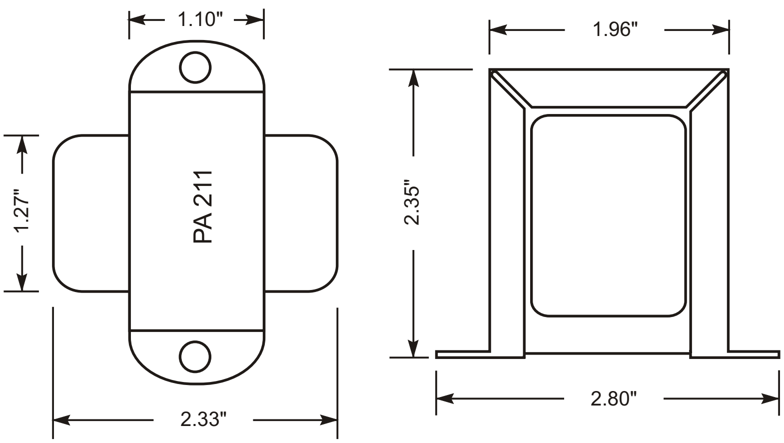
Although, seemingly, less than spectacular, this is within the expected range for small transformers like the PA-211. While the efficiency of large power transformers may even exceed 99%, those used to power smaller consumer electronics are often less than 85% efficient due to the increased winding resistance. The amount of iron and copper employed is often reduced to the minimum required to reduce cost.

PA-211 Construction

I would like to say that no transformers were harmed in the making of this article, but that would not be true. A PA-211 was, in fact, sacrificed and dissected to reveal how it was constructed.

Dimensions and Weight

The physical dimensions and weight of the PA-211 transformer are shown in Fig. 6.

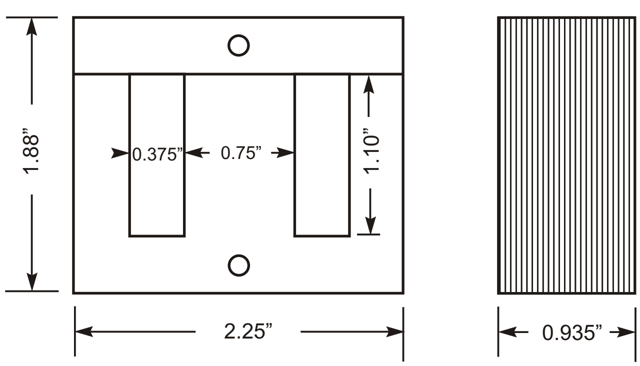


Weight: 1.2 lbs / 545grams

Fig. 6 PA-211 Dimensions & Weight

Core

Having removed the bells, and the crimped mounting frame that retains them, shell-type construction with a common EI lamination stack was revealed. To facilitate more accurate core measurements, as well as dissection of the windings, the laminations were separated and removed one by one until the bobbin, complete with winding layers, was free. A very time consuming process. The particulars of the core construction are illustrated in Fig 7.



Weight: 1.03lbs / 478grams

Number of laminations: 37

Lamination thickness: 0.025”

Material: *M19

Fig. 7 PA-211 Core

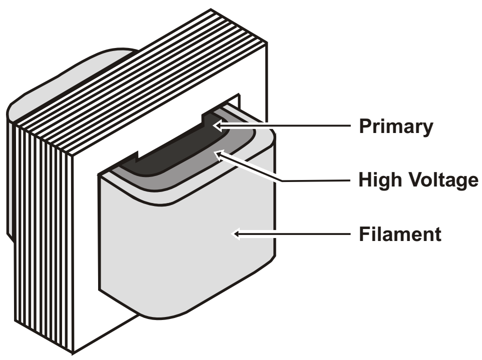
***Note:**

The core material was determined based on core loss, weight and estimated flux density. M19 non-oriented steel seemed to be the best fit, however this is an estimation only and not absolutely guaranteed to be correct.

Windings

The winding layers are concentric, the primary being closest to the core and wound on an impregnated cardboard bobbin, followed by the HV winding, and then the outermost filament winding. The primary and filament layers are insulated by wrappings of impregnated paper, while the HV windings employed a plastic-like film (mylar?). The primary and filament layers were carefully unwound and counted. It was not practical to count the large number of HV turns, so this was calculated knowing the primary count and secondary voltage. There was no indication of charring or melting on any of the insulation materials, or any other indications of overheating. In fact, internally, the transformer looked like it could have been made yesterday!

The diameter of the wire used for each winding was measured using a digital caliper. Perhaps not the best tool for the job, but what I had at hand. The wire used for the HV winding in particular is very thin and was difficult to measure with consistent results. Nevertheless, the readings were recorded as indicated in Fig. 8.



Primary: **39.8 Ω**
0.008"/ 0.21mm dia.
897 turns (counted)

High Voltage: **1.52K / 1.45K from ct. (2.97K total)**
0.002" / 0.05mm dia.
5428 turns (calculated)

Filament: **1.06 Ω**
0.019" / 0.48mm dia.
94 turns (counted)

Fig.87 PA-211 Windings

Quick Summary of Test Results

Hot Spot Temperature: 81.3°C @120VRMS and 21.5°C room ambient

Insulation Safety Margin : 23.7°C (assuming a minimal Class A rating)

Good margins. PA-211 not overly stressed.

Core Loss: 1.06W

Copper Loss: 3.19W

Efficiency: 77.2%

Windings: Primary: 897T / 0.008" dia / 39.80Ω cold / 47.65Ω hot
HV: 5428T CT / 0.002" dia / 2.97KΩ cold / 3.72KΩ hot
Filament: 94T / 0.019" dia / 1.06Ω cold / 1.26Ω hot

Comments

Is the PA-211 being overly stressed?

The main requirements for the PA-211 were to provide the voltage and current needs of the *intended PAS circuitry* while maintaining an adequate temperature rise margin to ensure a reasonable lifespan. Thermal testing has confirmed that the temperature requirement was met while decades of reliable service stand as a testimony to long term reliability. The PA-211 is not being overly stressed in its intended application.

Of course, cost was also a consideration. Given the price point for the PAS, it should not be a surprise that the transformer would employ the minimum amount of iron and copper needed to meet the operational requirements. This is reflected in the size, efficiency and certainly the cost of the PA-211. Yet, it was still up to the task it was expected to perform. So very Dynaco!

Replace the power lamp with an LED?

A common recommendation, propagated on online forums, is to replace the power lamp with an LED to reduce the load on the transformer. Keep in mind that the lamp was part of the intended load, is operating at well under its rated voltage, and only draws about 90mA. And the transformer is already operating with a good temperature rise margin. Removing the lamp will only lower the core temperature by about 1.3°C (yes, I tested this). So, by all means install an LED if you like the look, but realize that in doing so you are not bringing the transformer back from some thermal brink. It won't care much either way.

A Word on Modifications

Over the years, various modifications and after-market "upgrade" boards have been promoted, some of which require considerably more current than the PA-211 was ever intended to supply. It is possible, if not likely, that these are the conditions which precipitated negative comments as to its suitability. If so, the criticism is unjustified. No manufacturer can be expected to anticipate the requirements of unintended circuit alterations. When considering modifications, or alleged upgrades, it would be wise to determine if the voltage and current requirements are similar to the original PAS circuitry before implementing them.

Part 2 of the PAS power supply analysis will cover the HV rectifier and voltage doubler circuitry in detail.

Acknowledgements

Rodger Rosenbaum: for consultation and reference materials

Dave Gillespie: for critical review