

1.0 INTRODUCTION

With the massive amounts of literature on the subject of power dissipation, one may question why any more time should be devoted to such a basic subject. Assume for a moment you have your favorite text book(s) in front of you. Your mission is to look up formulas to find heat both in the load and the driving amplifier. The chances are high that you will find yourself in several chapters before you find Ohm's Law (OK, forget that one), impedance, phase shift and power factor for reactive load elements and finally power dissipation in the amplifier. By now you probably have 10 to 20 formulas with at least three devoted to the amplifier.

Of the three amplifier related equations (typically DC, current-to-voltage phase angles less than 40°, and phase angles greater than 40°), only one may be required. Even the power amplifier data sheet is likely to present two separate thermal ratings for below or above 60Hz. With the proper equations selected and worked out in the right order, you have a wattage rating to apply to the next group of equations needed to select a heatsink. The sad part is that hours have passed.

By the way, did your research turn up a procedure for plotting load lines? This is especially important for bipolar transistor output amplifiers having second breakdown limitations which can be destructive even though a properly selected heatsink keeps the amplifier cool. On top of all this, text covering amplifier power dissipation presents classic circuits where one amplifier using dual symmetric supplies drives a load with respect to ground. This still leaves you on your own when it comes to bridge circuits, single supplies, highly reactive loads at very low frequencies or parallel amplifiers. Calculating power dissipation is anything but a basic subject.

If intuition or experience tells you it would be a major benefit to have one piece of software that remembers all the equations, can select the right ones and can apply them in the right order, then Apex's Power Design is a tool you need. It is a Spice alternative dedicated to the analysis of power dissipation and local loop stability of the most common power amplifier circuits. While written with hybrid power operational amplifiers in mind, it can be used with just about any power amplifier from multiple KW discrete monsters down to the monolithic world.

2.0 FASTER WAY TO MORE ACCURATE ANSWERS

The traditional power dissipation equations for amplifiers do not appear in any cell of Power Design. Calculations start by finding peak and RMS values of current, voltage and power (both apparent and true) in the load. For frequencies less than 60Hz, stress levels are picked off the load line plot. This procedure catches some stress levels that can slip by the traditional equations. The DC equation yields peak power levels, but assumes

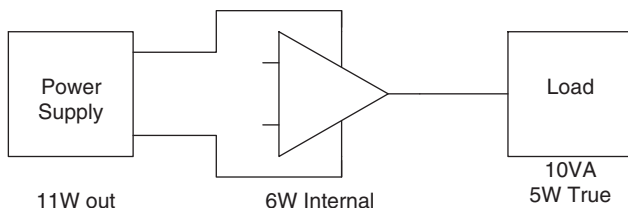


FIGURE 1. A SIMPLE VIEW OF WORK AND HEAT

zero current-to-voltage phase shift. Both AC equations account for increased heating in the amplifier due to the phase shift, but yield only RMS power levels. Consider a 5Hz, 60° load where the frequency is too low to use RMS power, but the peak power is substantially more than identical currents and voltages in a purely resistive application.

Power Design next calculates power delivered to the amplifier from the power supplies. For frequencies at or above 60Hz, true power in the load is subtracted from delivered power to yield internal power dissipation. The key element here is knowing what signal amplitude corresponds to worst case power dissipation. A polynomial approximating worst case signal amplitude is used to eliminate the step function found when switching between the pair of traditional equations at the 40° mark.

3.0 THE CLASSIC AMPLIFIER

Figure 2 illustrates the most common power amplifier configuration and the one that relates directly to the traditional power dissipation equations. It is also the starting point for Power Design which will compute power levels for DC and sine wave signals.

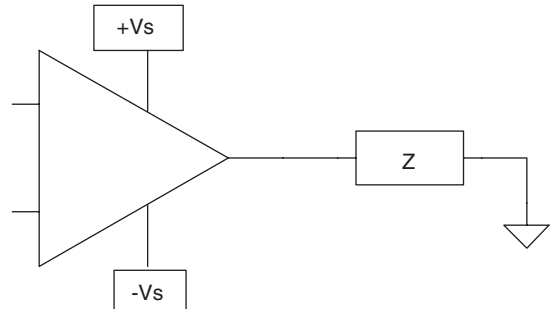


FIGURE 2. THE CLASSIC DUAL SYMMETRIC SUPPLY OP AMP DRIVING A GROUNDLED LOAD

All data entry cells in Power Design are yellow on the monitor (shaded in black and white as in Figure 3 shown on next page). The data shown here will be used in the following example. In the top left, a pull-down entry of amplifier model reads an internal database containing enough specifications to flag operation outside the amplifier's capability and to calculate a heatsink rating. The data base contains all amplifiers manufactured by Apex and comments in the cells with red triangles tell users how to enter other data. This feature makes Power Design valuable to a very wide spectrum of engineers designing one ton rack mount systems down to monolithic users. Model data has no effect on calculation of load parameters. Going down, enter the supply voltage that will be assumed to be the magnitude of both positive and negative supplies. The next two cells specify minimum and maximum frequencies for the output signal. .001KHz will work fine for most DC applications. Next is magnitude of the output signal followed by a pull down entry labeled "Sig as ?". This is where those magnitude units are defined as volts, amps or watts with choices of peak, peak-to-peak or RMS. Yes, it's that easy to find what is needed to drive a 3.2 ohm speaker to 150W!

If your load can be modeled by one of the four simple dia-

Selecting an Apex Heatsink		See ACCESSORIES INFORMATION data sheet for specifications								
Thermal Resistance	Package	Velocity Calculator:					Units of Measure:			
1.96 °C/W	TO-3	15 CFM	2 Inch Width			English				
	Update heatsink List	4 Inch Dia	3 Inch Length							
READ ME		171.8873 Ft/min	360 Ft/min							
		0.873198 M/sec	1.8288 M/sec							
Notes:										
Beware: Flow rates change as you enter Thermal Resistance, but may be wrong until the Command Button is used!										
Model	Fluid	Thermal resistance, free air, °C/W	Your rating requires FPM or GPM flow	Package(s) accepted	Style	Length, inches or cm	Width, inches or cm	Height, inches or cm	Weight, ounces or grams	Singles Price USD Domestic
HS02	Air	4.5	298.0982	TO-3	Cup	1.81	1.81	1.5	1.89	\$16.85
HS03	Air	1.7	0	TO-3		3	4.75	1.25	5.6	\$38.45
HS04	Air	0.95	0	TO-3		3	4.75	3	12	\$74.85
HS05	Air	0.85	0	TO-3		5.5	4.75	2.63	18.3	\$58.60
HS11	Air	0.68	0	TO-3,MO127		6	8	2	44.8	\$214.80
HS11	H2O	0.68	0	TO-3,MO127		6	8	2	44.8	\$214.80
HS13	Air	1.48	0	TO-3		5.5	4.81	1.312	13.9	\$53.95
HS14	Air	2	100	TO-3		3	4.81	1.312	7.6	\$33.95

FIGURE 5. HEATSINK SELECTION AND AIR VELOCITY CALCULATIONS

Build yourself a Complex Load Read Me

C1 = 2200 uF	C4 = 10 uF	C7 = 1E+15 uF	C10 = 4.7 uF	C13 = 1E+15 uF	C16 = 1E+15 uF
R1 = 0.2 ohms	R4 = 4.5 ohms	R7 = 4 ohms	R10 = 5 ohms	R13 = 0 ohms	R16 = 12 ohms
L1 = 0.0001 mH	L4 = 0.3 mH	L7 = 0.001 mH	L10 = 0.001 mH	L13 = 0 mH	L16 = 0 mH
C2 = 0 uF	C5 = 0 uF	C8 = 1E+15 uF	C11 = 0 uF	C14 = 1E+15 uF	C17 = 0 uF
R2 = 0 ohms	R5 = 1E+15 ohms	R8 = 0 ohms	R11 = 1E+15 ohms	R14 = 0 ohms	R17 = 1E+15 ohms
L2 = 0 mH	L5 = 1E+15 mH	L8 = 0 mH	L11 = 1E+15 mH	L14 = 0 mH	L17 = 1E+15 mH
C3 = 0 uF	C6 = 0 uF	C9 = 1E+15 uF	C12 = 0 uF	C15 = 1E+15 uF	C18 = 0 uF
R3 = 0 ohms	R6 = 1E+15 ohms	R9 = 0 ohms	R12 = 1E+15 ohms	R15 = 0 ohms	R18 = 1E+15 ohms
L3 = 0 mH	L6 = 1E+15 mH	L9 = 0 mH	L12 = 1E+15 mH	L15 = 0 mH	L18 = 1E+15 mH

38 Data Input 44 Print Load 36 View Results Frequency Sweep

Notes: _____

Zero the Load 65 View Last Frequency Sweep

FIGURE 6. THE COMPLEX LOAD

grams keep going down, entering component values. Each load is computed independently so the previous entries other than the 15 ohms and 0.3mH of our current R-L load make no difference. If you have both an L and a C in your load and the resonant frequency is shown as lying between your min/max range, check the READ ME to see if you have a peak or a dip as far as internal power is concerned. If your load is more complicated, you will use the "Define" command button. More on this later. Just below the data entry cells, note the number of watts labeled "Piq". This is the standby power of the amplifier you entered as the Model when running on dual supplies of the value you specified. For hybrid op amps this will be the total quiescent current of the amplifier. For discrete designs, quiescent current would normally be set to the quiescent current of only the output transistors because the driver stages are not normally on the same heatsink as the output transistors.

Referring again to Figure 3, to the right of the signal magnitude entry cell is the pull-down bridge question cell. Make sure this cell contains "No". Below this is the cell specifying the number of amplifiers connected parallel. Make sure this cell

contains "1". Below this, we need to specify "Bipolar" output current. From here, go up to enter the maximum ambient temperature your application will encounter. This is the starting point for the heatsink. To the right, enter the maximum junction temperature you wish to allow for the power transistors. 150° is acceptable for many commercial applications but in one respect transistors are just like cars: the hotter you run them, the shorter the life. Using lower temperatures should be considered when down time would be very costly. The last entry cell on this screen is that of maximum case temperature. In addition to life concerns, case temperature affects DC accuracy of the power op amp (check voltage offset and bias current drift) and often has significant effect on current limit values. In this example, a tight DC error budget mandates a maximum case temperature of 70°C.

To see power calculations use the "Results" button under the appropriate load diagram. The entire power data output is shown in Figure 4. Load lines based on voltage output from 90° to 270°. With purely resistive loads this produces one-quarter cycle of current output. With purely reactive loads one-half cycle of current is displayed. In this case the amplifier seems to be loafing at high frequency and is comfortably within SOA at low frequency.

The left side of both curves seems to indicate current drops to zero abruptly. This is not the electrical case, but is a function of Excel plotting routines. Note that at low frequency the load is mainly resistive (only ~7°) and the curve shows maximum current at minimum voltage stress across the conducting transistor (at the peak of the output voltage wave form). It drops to zero current (right end of the curve) at a stress voltage of just a little more than supply voltage or just a little after zero crossing of the output voltage. At high frequency, the load is mainly inductive (~85°) and peak current appears at a stress voltage approaching the supply voltage (near zero crossing of the output voltage). Current does not drop to zero until stress voltage is considerably more than supply voltage or until well after zero crossing of the output voltage. This explains why current drops better than 12:1 from low to high frequency but RMS internal dissipation drops only about 6:1 and peak drops less than 5:1.

This SOA graph is dynamic in that the constant power portion of the curve is drawn to meet the maximum case and junction temperatures you specified earlier. Data sheet graphs usually show one curve for a case temperature of 25°C plus others for elevated temperatures. All these curves assume maximum

junction temperature as published in the product data sheet (up to 200°C on some bipolar transistors) but this is not in the best interest of long-term reliability. Power Design draws only one constant power line according to the case and junction temperatures you specify. If you assign an actual heatsink more generous than the minimum for the application, the constant power curve will be artificially low until you use the “Set Tcase max according to last used Actual HS on...” button.

For details on the load, refer to upper left block of numbers. Just about all the electrical information you could want is detailed. Mixed in here is a line showing power delivered to the amplifier by the power supply (except for quiescent current). “Percent Efficiency =” is based on watts drawn from the supply (including quiescent) and VA delivered to the load. It does not include power factor of the load. “Vpk Capability” is supply voltage minus an estimate of the saturation voltage of the power amplifier at the peak load current.

Turn your attention to the upper right hand corner where the first line of numbers indicate the peak output voltage producing the maximum internal power dissipation. Below this are results of power calculations at these worst case signal levels. The bottom two are the most important: true watts in the load and power delivered to the amplifier. At low frequency signals, peak internal power dissipation is at about 22.3Vpk, less than the maximum signal amplitude specified earlier. The Power Design assumes real signal amplitude does vary and the amplifier must be able to survive the lower signal level.

The 32.86W is then used on the left (long arrow) as well as the 16.31 true watts that is subtracted from input power to yield “Dissipation RMS” of 16.55W. “Dissipation Peak” is higher than the RMS value but is ignored because minimum frequency is well above 60Hz in this case. “Total in the heatsink” at low frequency is the addition of the 16.55W RMS and 5.25W calculated for quiescent earlier.

The same calculations are repeated for maximum frequency. In this case the very high phase angle demands the amplifier swing all the way to the supply rail (35V) to experience worst case internal heating. As our maximum signal amplitude is less, the input power (short arrow) and true load power are used from the user specified signal amplitude. Again, RMS and quiescent powers are added to find the heatsink total at maximum frequency (peak values are ignored). The last line picks the higher power level of the two frequencies and displays the DC thermal resistance if the frequency is below 60Hz or the AC thermal resistance.

To the right with bold face heading we find the minimum heatsink rating for this application. Your job is to find or design a heatsink and enter its actual thermal rating. Entering the 1.7°C/W rating causes display of case and junction temperatures for the amplifier. A little below this area are the actual calculations which include thermal interface resistance between the amplifier and the heatsink. Separate calculations are made to insure both case and junction limitations are met. In this example, case temperature is the limiting factor. If the heatsink had been sized according to junction temperature only, the case would have been running about 97°, outside the guaranteed performance range for drift with the commercial part.

In this general area you may also find up to three warning flags. The most common warning is for excessive temperatures. The other two warnings will pop up if your application is demanding more voltage or current output than the amplifier is specified to deliver. The voltage calculation takes into consideration the supply voltage and the output saturation characteristics of the amplifier.

If you’re asking what’s so magic about 1.7°C/W, refer to Figure 5 where an Apex heatsink can be selected. To use

this sheet, simply enter the desired heatsink rating and package type, then click on the command button. Even though our example used the HS03 without a fan, note that an HS02 inside a 2”x3” duct fed with a 15CFM fan would be more than adequate to produce the required thermal rating.

4.0 USING THE COMPLEX LOAD

Using the load shown in Figure 6 requires complex numbers which most Excel users do not automatically activate. You will probably need to use Tools, Add-Ins and Analysis ToolPak. Unless you have known good data already entered, use the “Zero the Load” button to place extremely high impedance components in all the vertical strings with a ground connection and extremely low impedance components in the horizontal strings.

Refer to the sample load diagram in Figure 7 to illustrate data entry. Let’s start on the left at the amplifier connection. Use any one of the three strings for the capacitor. Note that we are also entering values for ESR and ESL for the capacitor. These may be found on the data sheet or measured with an impedance analyzer. R1 is used to model ESR of the 2200uF capacitor and L1 to model ESL. It is important to open the other two unused strings in parallel with our component model. The easiest way to achieve this is entering zero capacitance in each string. Our second group of components could again use any of the three strings with a ground termination. The resistor is actually a coil and parasitic inductance is also entered. Proceed through groups of components until finished.

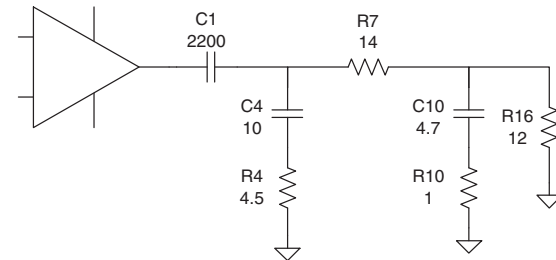


FIGURE 7. A SAMPLE COMPLEX LOAD (PARASITICS NOT SHOWN)

After entering your load data, the “View Results” button will show performance at the minimum and maximum frequencies. To see what’s happening in between, press the “Frequency Sweep” button. Figure 8 illustrates typical results of a sweep. This specific load shows the need to analyze carefully in the low KHz area.

Setting the min/max frequencies to 2/4KHz and re-running the sweep as shown in Figure 9 will allow a more precise determination of the peak values for current output and internal power dissipation. Notice that peaks and dips do NOT coincide exactly. In this case set Fmin to 2.54KHz and Fmax to 2.84KHz and click “View Results” to see maximums in numerical form and select the heatsink rating.

5.0 NORMAL BRIDGE CIRCUITS ARE EASY

The master/slave approach shown in Figure 10 is an easy way to implement a bridge circuit. The master maybe be configured any way desired. The job of the slave is to invert the master’s output such that the load is driven equally but opposite at its two terminals. The schematic suggests calculating internal power dissipation might be tricky, but not so when using Power Design. Enter signal amplitude applied to the total load, enter the total load components, enter “Yes” for the bridge question and all the modeling is taken care of automatically. Load impedance shown will be the total value, currents are for load and each amplifier. Voltages, wattages and heatsink ratings are for a single amplifier and are flagged as such.

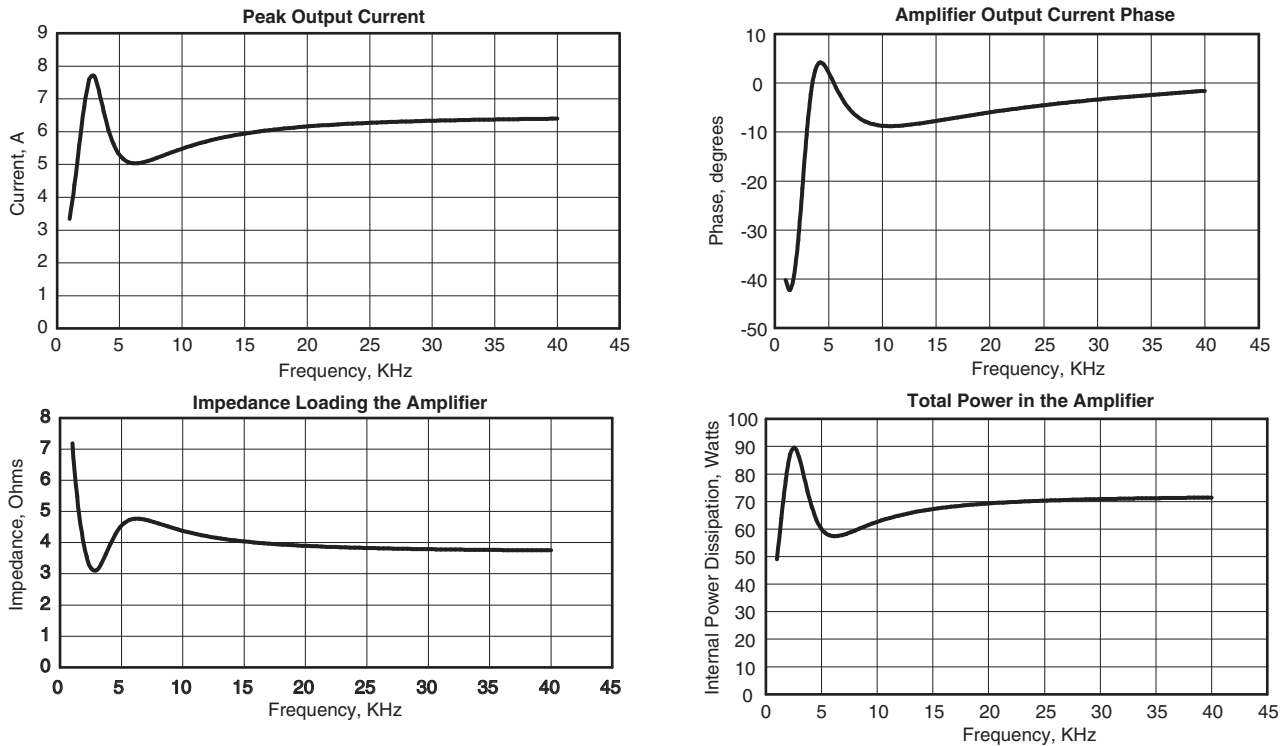


FIGURE 8. GRAPHS RESULTING FROM A FREQUENCY SWEEP

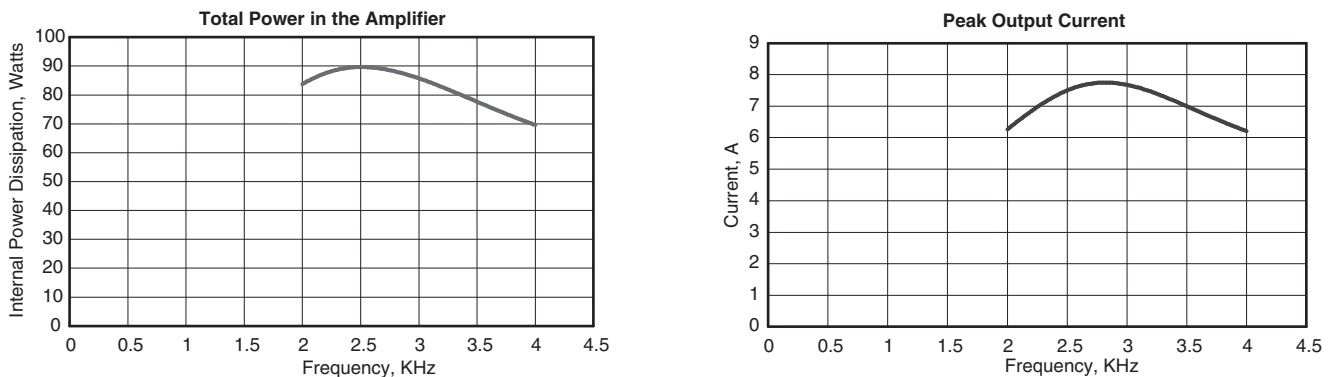


FIGURE 9. ZEROING IN ON THE PEAK VALUES OF A COMPLEX LOAD

6.0 SINGLE OR NON-SYMMETRIC SUPPLY BRIDGES REQUIRE A TRICK

The circuit shown in Figure 11 is often used to achieve bi-directional drive on a single supply or to double voltage swing capability when a single higher voltage amplifier is not cost effective or does not exist. To easily accommodate ground referenced small signal driver circuits, a small negative supply is often used to overcome common mode voltage restrictions.

Note that zero drive to the load requires both amplifier outputs to be equal to that of the voltage divider (two equal resistors). This forces the center of the load to be constant and at 50% of a true single supply or centered between the two supply voltages. If one algebraically subtracted the correct voltage from both the positive and negative supply pins of the amplifiers and the lower divider termination, you would end up with operation identical to the symmetric supply bridge of Figure 10.

For Power Design to analyze this circuit, enter a supply voltage equal to half the single supply or half the sum of the absolute values of both supplies. For 110V single supply, enter 55V. If an opposite polarity supply of 10V is added, enter 60V.

7.0 BIAS LEVELS ON AC ONLY LOADS

There are two bias voltages to determine with AC only loads; one affects internal power dissipation, the other does not. Refer to Figure 12, noting that neither bias level affects output current. The DC blocking property of the load capacitance means current demand is a function of only the load impedance and the applied AC signal. DC bias levels can be ignored, even if they result from the load being terminated at one of the amplifier power supplies or a separate supply. While constant load bias has no affect on internal power dissipation, output bias directly affects voltage across the conducting transistor and therefore power levels. Power Design always assumes output bias is zero meaning equal power dissipation in both transistors.

Given a requirement to drive a capacitive load at 7.07VAC riding on 100VDC, the least expensive op amp solution would be a 100V reference supply and a low voltage op amp. The catch is that this reference supply must sink and source current. If using an output filter capacitor 10 to 100 times the value of the Cload is acceptable, this type solution is likely to be lower cost overall. Remember that if these two capacitance values are constant, the resulting drive voltage errors due to the non-

zero impedance of the reference supply can be compensated by increasing the drive signal.

Refer to TABLE 1 for a way to approximate power levels given the following assumption: +120V and -10V will be used to accommodate voltage saturation on the high side and

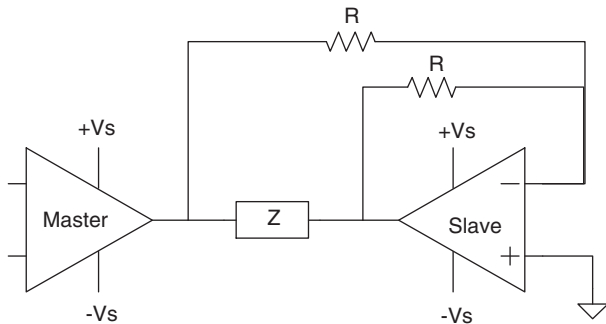


FIGURE 10. THE MOST COMMON METHOD USED TO IMPLEMENT A BRIDGE CIRCUIT

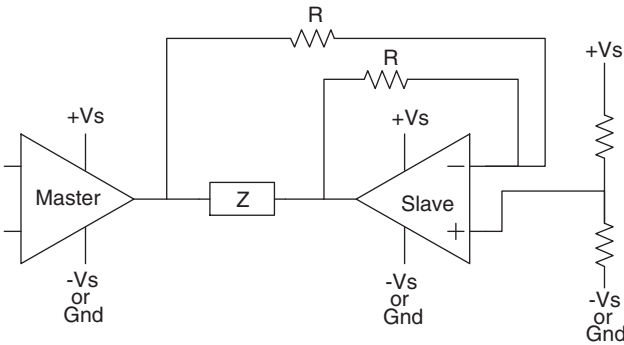


FIGURE 11. THE CLASSIC NON-SYMMETRIC BRIDGE CIRCUIT

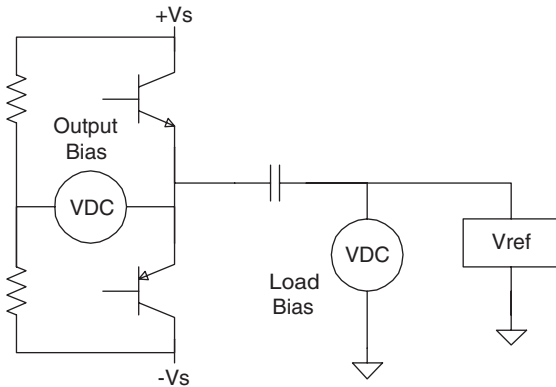


FIGURE 12. BIAS LEVELS FOR AC ONLY LOADS

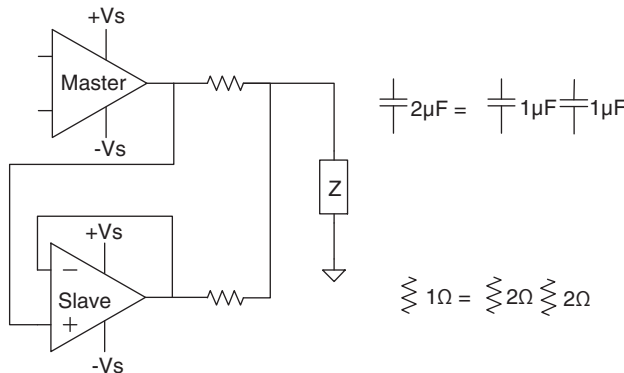


FIGURE 13. A COMMON PARALLEL CIRCUIT AND CIRCUIT ALGEBRA TO MODEL A SINGLE AMPLIFIER'S LOAD CURRENT

common mode voltage on the low side. Calculate voltage stresses on each transistor from mid point of the sine wave to each supply. In this case, 20V to the positive supply and 110V to the negative supply. Run two calculations using each of these values. Select an arbitrarily large initial heatsink value. The numbers in TABLE 1 are a result of a PA88 driving 15 ohms and 0.04uF at 40kHz with $T_a=25^\circ$, $T_c \text{ max}=70$ and the actual heatsink 1.7°C/W . Subtract case temperatures from junction temperatures to find temperature rise. The 110V data tells us the hardest working transistor is 35.5° above case temperature. The 20V data tells us the other transistor is only 6.2° above case temperature. Now set supply voltage to 65V (the average of 110 and 20) to find a minimum heatsink rating of 10.3°C/W is required. Enter an actual heatsink rating, such as 4.5°C/W corresponding to an Apex HS02 with no fan. To find a case temperature of 44.8°C add to this the previously calculated temperature rises. To find the output transistors junction temperatures of 80.3° and 51°C . Iterate the last step if this is too hot.

Vs	Tj	Tc	Delta	Heatsink
110	73.2	38.2	35.5	6.1
20	33.5	27.3	6.2	

TABLE 1. MULTIPLE PASS METHOD OF DETERMINING TEMPERATURE WITH DC BIAS ON A CLOAD

8.0 TECHNIQUES FOR PARALLEL OPERATION

Calculation methods for parallel operation of power amplifiers is simple; however, getting two or more power amplifiers to cooperate rather than kill each other is often quite another matter. Power Design assumes all the precautions of Apex Applications Note 26 PARALLEL CONNECTION or some other authoritative reference have been followed. Potentially destructive currents between amplifiers are NOT modeled. Causes of these currents include voltage offset, common mode errors and violations, phase shift, and current limit sequence errors. If you have overcome all these, refer to Figure 13 for the most common approach to parallel operation along with a way to think about an equivalent load for the single amplifier.

To use Power Design for parallel operation, enter the number of amplifiers in parallel in the yellow cell below the bridge question. Total values are then calculated for the load results area and scaled by the number of amplifiers for the SOA graph and amplifier internal power dissipation results. The heatsink rating will then need to be applied to each amplifier.

9.0 UNIPOLAR OUTPUT CURRENT

Programmable Power Supplies (PPS), Thermo-Electric Coolers (TEC) and heaters are often configured for current of only one polarity. This means only one output transistor is doing the work and therefore the DC thermal resistance specification of the amplifier must be used even if the signal frequency is quite high. Most op amp data sheets footnote the AC rating as applying if current alternates between the two output transistors are at a rate greater than 60Hz. The mechanism yielding an improved AC rating is simply a larger square area of the package materials used to conduct heat when two transistors are active.

All the previous examples assumed output current was bipolar. In cell D13 (under the parallel question), you can enter "Unipolar" to force all heatsink calculations to be based on DC thermal resistance and change the quiescent power calculation to reflect the supply voltage you entered as being a true single supply, plus change the supply problem flag.

A word of caution is in order here. Many loads will demand bipolar current even though the voltage is uni-polar. The easiest to visualize is the capacitive load: current flow is determined only

