CURRENT LIMITING

APPLICATION NOTE 9

POWER OPERATIONAL AMPLIFIER

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INTRODUCTION

Power op amp circuits without suitable current limiting can be compared to putting a gun in the hands of a child – you may get away with it but disaster is waiting to strike. While elaborate circuits have been used, most power op amps use a simple and cost effective circuit which still requires engineering homework to be safe. The objective is delivering desired power to the load without violating the SOA.

BASIC CURRENT LIMITING

Current limiting circuits in power op amps are local to only the output stage so they can very quickly (sub microsecond) reduce output current to a predetermined level. There are at least four reasons to incorporate such a limit:

1. The output transistors of the amplifiers are almost always capable of delivering more current than the ABSOLUTE MAXIMUM RATING of the amplifier. Exceeding this limit can destroy metal, usually a wire bond to the supply or the output pin fuses. A common mistake is to rely on the power supply current limit for this protection. Do NOT fall into this trap. Filter capacitors (both inside the supply and local to the op amp) often store plenty of energy to vaporize a wire bond.
2. Loads with variable impedance may need protection against possible fault conditions. A mechanical jam on a motor drive is a good example.
3. Current limit can prevent overloading power supplies. This may be critical if other circuits share the same supply.
4. Observing the Safe Operating Area (SOA) of the power amplifier keeps junction temperatures to a reasonable level. Output current is one term of the power equation.

A fixed current limit is usually adequate for the first three reasons. A simple and cost effective approach to current limiting is shown in Figure 1. Current through the output transistor Q1 is converted to a voltage by the sense resistor Rcl. When this voltage exceeds the Vbe of the current limit transistor Q2, drive current from the preceding stage is diverted to the output to shut down Q1. In addition to being an amplifier, Q2 serves as an imperfect voltage reference for the current limit set point. At room temperature the typical value is around 0.65V. Rb along with the capacitance of Q2 slow the circuit just enough to prevent oscillation. In equation form:

$$Icl = 0.65/Rcl \tag{1}$$

or

$$Rcl = 0.65/Icl \tag{2}$$

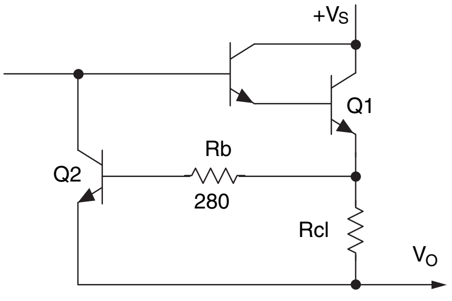

FIGURE 1. CLASSIC CURRENT LIMIT CIRCUIT

where Icl is the current limit in amperes and Rcl is the current limit resistor in ohms.

The fourth reason is more complex. Figures 2 and 3 illustrate the challenge of meeting SOA limitations with fixed current limit. First, note that the X axis labeling of the PA10 SOA graph is NOT output voltage but the stress voltage across the conducting transistor. Assume DC signals and a case temperature of 25°C for the following. The resistive load implies stress voltage is limited to single supply voltage and that maximum heat in the output transistor occurs at an output of 50% of supply. At 25V the SOA graph tells us maximum current is 2.7A. This implies a minimum load of about 9.3 ohms will limit current to safe levels at any output voltage. Maximum current will be 4.75A (44V/9.3 ohms) and maximum output power will be 209W. Note: The voltage swing specification of the PA10A is Vs-6V at 5A. However, if the application must survive a shorted component or cable on the output, the stress voltage jumps to 50 and maximum safe current is only 1.05A. Once this current limit is set output power is limited to 46W peak into 44 ohms. For energy storing loads, assume an initial voltage of nearly -50V and a positive going signal. Initial supply to output stress is nearly 100V and maximum safe current is less than .3A.

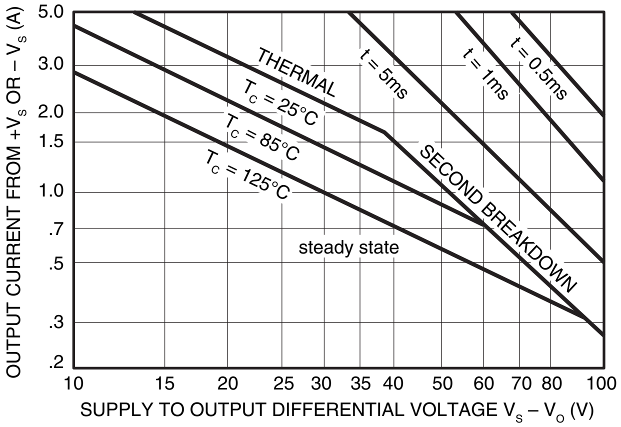

FIGURE 2. SOA GRAPH OF PA10

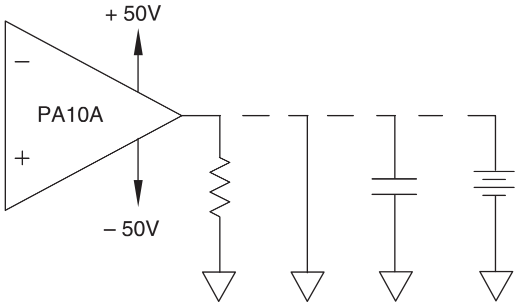

FIGURE 3. DIFFICULT LOADS OR POSSIBLE FAULT CONDITIONS

CURRENT LIMIT IS A MOVING TARGET

The largest variable of the current limit circuit is the temperature coefficient of the imperfect reference voltage, the Vbe of Q2. It decreases approximately 2.2mV for each degree C increase in case temperature. Thus the 0.65 term ranges from 0.826 at -55°C to 0.43 at 125°C. From an steady state power dissipation point of view, this slope is in the right direction but it is still possible to get in trouble. Comparing this slope to our initial reasons to limit current:

1. The reason does not vary with temperature.
2. The reason is load dependent.
3. The reason is supply dependent.
4. The reason does not vary with temperature.

It is best to plot the limit on the SOA graph and compare to other requirements of the system. To this end, visit the Apex web site at www.apexmicrotech.com or contact Apex applications engineering for software to automate the task.

Looking again at Figure 1, we can find several reasons actual current limit varies from the equations presented. When in the limiting mode, Q2 is shunting drive stage current away from Q1 directly to the output. This means actual current limit can not be less than drive stage capability. Some data sheets give a minimum practical current limit. Operation in this region is unusual because drive stage current is so much less than output capability that being in this region implies amplifier capability is likely an overkill for the application.

Now consider that when Q2 is conducting there will be base current flowing through Rb which effectively increases the reference voltage. On some amplifiers this effect is large enough that the specific data sheet will give a unique value greater than 0.65 to use in the equations.

Although it is not immediately obvious looking at figure 1, resistance of internal wire bonds, solder joints, wiring traces and the leads of Rcl all add to the rated value of Rcl unless pins are provided to implement four wire current sensing. In high current applications, measurements of prototype circuits may be the best way to finalize the design.

We now have a very wide range of "safe" currents depending on loads or fault conditions which must be tolerated. We have also seen that while simple and cost effective, these limiting circuits are not reference standards; think in the area of +/-20%. The sad part is that the fixed current limit set to protect for worst case fault condition also limits current for the non-fault condition. It is also interesting to note that we assumed an unrealistic heatsink and safe currents are still only a fraction of the absolute maximum for the amplifier. This shows the importance of both heatsinking and current limiting. An ideal solution for SOA protection might be the addition of a stress voltage sensor and multiplier for each output transistor such that limiting could be based on watts. If all this circuitry is fast enough, SOA concerns would be no more. This approach is quite rare because the cost measured in components, design time and space is almost always more than that of using a larger amplifier. Clearly, an affordable improvement in current limit technique is called for.

FOLDOVER CURRENT LIMIT BASICS

Apex models PA04, PA05, PA10 and PA12 can take advantage of foldover current limiting. Adding only one resistor to the classic current limiting circuit (Figure 4) provides dynamic response to output voltage swing. Realizing that Rcl is typically three orders of magnitude below Rb, it is reasonable to ignore Rcl and say Rb and Rfo form a voltage divider between ground and the output voltage. With Rfo typically being a couple orders of magnitude larger than Rb, the divider adds a very small portion of the output voltage in series with the base of Q2. With a 0V output, current limit will be the same as the classic circuit. However, as the output goes positive, the addition of the divider voltage effectively increases the reference voltage (Vbe of Q2) allowing more current to flow. For negative output voltages (Q1 is still conducting), the very small fraction of the negative output added reduces current flow. Another way to view this would be state we have added a term to the current limit equation based on output voltage but modifying current limit in an inversely proportional manner to voltage stress on the conducting transistor. While this is still a long way from the ideal of a multiplier calculating watts, and it does nothing in the case of variable supplies, it does add a desirable slope to the current limit function. In equation form:

$$I_{CL} = \frac{0.65 + V_O \bullet \left(\frac{Rb}{R_{FO} + R_B} \right)}{R_{CL}} \qquad (3)$$

$$R_{CL} = \frac{0.65 + V_O \bullet \left(\frac{Rb}{R_{FO} + R_B} \right)}{I_{CL}} \qquad (4)$$

where Vo is output voltage in volts and resistors are from Figure 4 and in ohms.

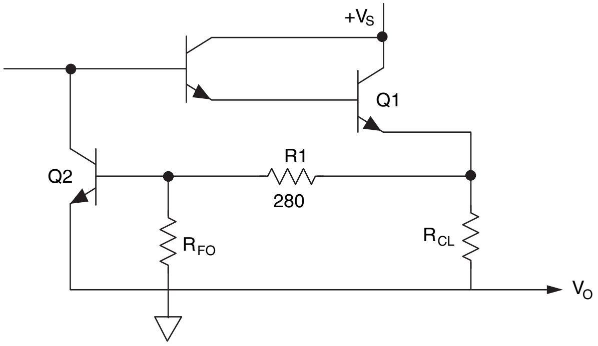

FIGURE 4. BASIC FOLDOVER CURRENT LIMIT CIRCUIT

Looking again at the case of the resistive load driver which must tolerate a short on the output, let us further assume the objective is to drive 22 ohms to 88W peak (44Wrms, 44V pk and 2A pk). Start with an Rb of 280 ohms and Rfo of 20Kohms and use Equation 4 to calculate Rcl = 0.629 ohms for peak current at peak voltage. Use a 0.62 ohm resistor. Equation 1 now shows us current during the short fault condition is limited to 1.05A. Plotting the current limit on the SOA graph as shown in Figure 5 reveals that this current limit is safe for any output voltage from zero to supply. Using foldover instead of fixed current limit has nearly doubled the power delivery capability.

In the case of the energy storing load, Equation 3 shows us this foldover circuit current limit crosses zero and turns negative within the swing capability of the amplifier at all temperatures above 25°C. This can cause amplifier latch-up and MUST be avoided. A lower supply voltage or a larger foldover resistor will solve this problem.

Even though we know the current limit is safe for a short to ground and for the full 100V stress level, Figure 5 shows that at 25°C and colder allowable current crosses above the SOA line in between these points. Increasing Rcl will lower current limit at all output voltages and solve this problem.

TWO TYPES OF FOLDOVER

The PA10 and PA12 have an internal Rb of 280 ohms and internal Rfo of 20K for both the positive and negative current limit transistors. The two 20K resistors tie together at pin 7 where the user may ground the pin for maximum foldover slope or

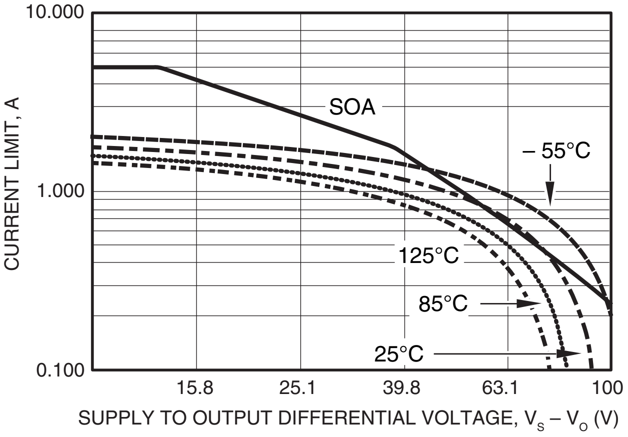

FIGURE 5. FOLDOVER ILIMIT VS. VOUT

add an additional resistor in series from pin 7 to ground for less foldover action. Since both 280 ohm resistors tie essentially to Vo and the two series networks of 0.28K + 20K are essentially in parallel, the equations specific to the PA10 and PA12 are more complex than the previous example:

$$I_{CL} = \frac{0.65 + V_O \bullet \left(\frac{10.14}{10.14 + R_{FO}}\right) \bullet \left(\frac{.28}{20.28}\right)}{R_{CL}} \qquad (5)$$

$$R_{CL} = \frac{0.65 + V_O \bullet \left(\frac{10.14}{10.14 + R_{FO}}\right) \bullet \left(\frac{.28}{20.28}\right)}{I_{CL}} \qquad (6)$$

where Icl is in amperes, Vo is in volts Rcl is in ohms and Rfo is the PA10 or PA12 external foldover resistor and is in Kohms.

Foldover connections for the PA04 or PA05 are shown in Figure 6. Use 270 ohms for Rb and use equations 3 and 4. Beware that even momentary shorts directly at pin 10 can destroy the amplifier now that pin 10 is isolated from the output by the 270 ohms.

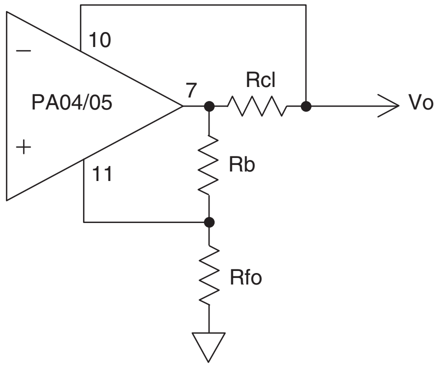

FIGURE 6. FOLDOVER CIRCUIT FOR PA04 OR PA05

CONCLUSION

Current limit is to the power op amp as survival instinct is to an animal; a REALLY good thing to have. While basic current limiting is simple, adding temperature variations and circuit options such as foldover make the job of checking all the points of possible danger quite a chore. First comes the math, then data plotting on the SOA graph with those log scales we all love so well. This drudgery has become history with the spreadsheet automation. Get your copy from the Apex web site at www.apexmicrotech.com or call Apex applications.