NOvA Power Distribution Box High Voltage Current Limiter Evaluation

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1. Introduction

The NOvA power distribution box fans out 450 VDC to up to 64 front-end boards from a CAEN power supply capable of supplying 15 mA of current. As noted in Steve Chappa's 6 April 2009 report of his preliminary safety review of the power distribution box, currents as low as 5 mA present a lethal shock hazard, and even 1 mA currents can present non-lethal hazards as well. Hence a protection circuit design is needed limiting the output current to no more than about 0.5 mA with a shorted load. Because the CAEN supply can output voltage up to 500 V, the current limiter must work up to this voltage. The current limiter will be used on thousands of channels, and must have a reproducible output voltage when operating at the nominal full load condition of 10 MΩ (and a nominal load current of 50 μA). While the exact magnitude of the drop in voltage across the current limiter is not critical (although it should be minimized) there should be no more than about 100 mV of variation between channels, or within a single channel across a voltage range of 400 - 500 V. (Note that this 100 mV requirement assumes no regulation on the front end boards. The current design of the front end boards includes a shunt regulator, which if implemented makes the 100 mV requirement superfluous.)

Two designs have been proposed for the current limiting circuit: a "transistor" design and a "MOSFET" design. Each circuit was simulated using the program LTspice v4.03 (available for free download at the Linear Technology website, www.linear.com). The circuits were then assembled and tested. The main areas of interest in the simulations and tests were the circuit's current limiting ability in a short circuit condition and its voltage drop in a load condition over the nominal voltage range of 400 – 500V.

In the following tests, all resistances were measured using an Amprobe 35XP-A DMM. The same DMM was used to measure the input voltage on the circuits, while a Philips PM 2525 DMM was used to measure each circuit's voltage drop and load current. Pricing was determined by finding the lowest price available in quantities of 10,000 or more from the Newark, Digikey and Mouser Electronics websites.

2. Transistor Design

2.a. Background

The transistor limiter circuit is shown in Fig. 1. The transistors Q3 and Q4 are the output transistors through which the majority of the current flows under normal operating conditions. R1 functions as a current sensing resistor. Should the voltage across R1 become too great – a sign of increased current through the load – Q2 will switch on, removing base current in the output transistors and reducing the current flow through them.

The transistor circuit uses two inexpensive KSP44 transistors rather than a single high-voltage transistor to reduce costs. A model of the transistor design was created in LTspice and tested in the load and short conditions by setting RLOAD to 10 MΩ and 0.1 Ω, respectively. The current through the load and the voltage drop across the current limiter circuit itself were then measured in the simulation across a wide range of input voltages. In addition, a physical circuit was built and these quantities were measured experimentally.
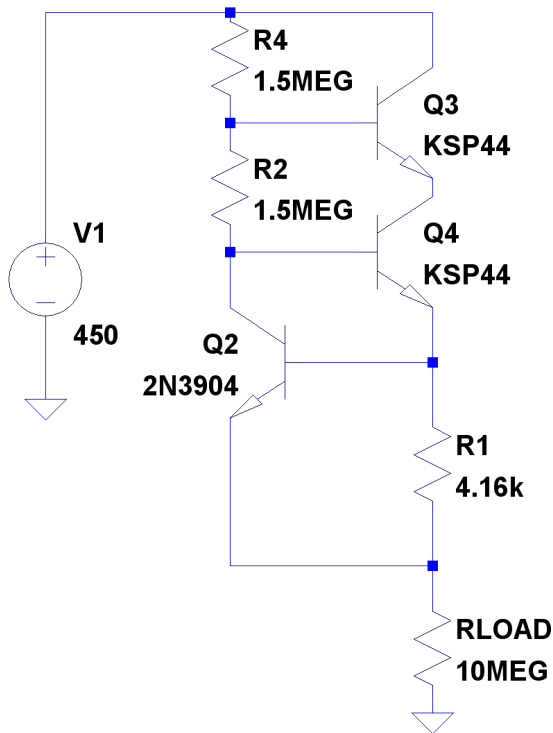
R4
1.5MEG
Q3
KSP44
R2
1.5MEG
V1
Q4
KSP44
450
Q2
2N3904
R1
4.16k
RLOAD
10MEG

Figure 1: Transistor current limiter schematic, with nominal component values.

2.b. Testing

As shown in Fig. 2, the current at short circuit condition was less than 0.5 mA over the entire voltage range, where R1 was set to 7.99 kΩ. Once the limiting kicks in after about 60 µA, the current increases at a rate of about 4×10^{-4} mA/V. In order to raise the current limit at which the limiter kicks in, we reduced R1 to 4.16 kΩ. The voltage drop across the limiter with the new value of R1 at load condition (Fig. 3) remains fairly low and flat until it begins to increase rapidly at about a kilovolt – well outside the range in which the power supply will operate. The slope of the voltage drop was 0.0053 over the entire tested range. Within the 400 – 500 V range the voltage drop varies by about a volt.
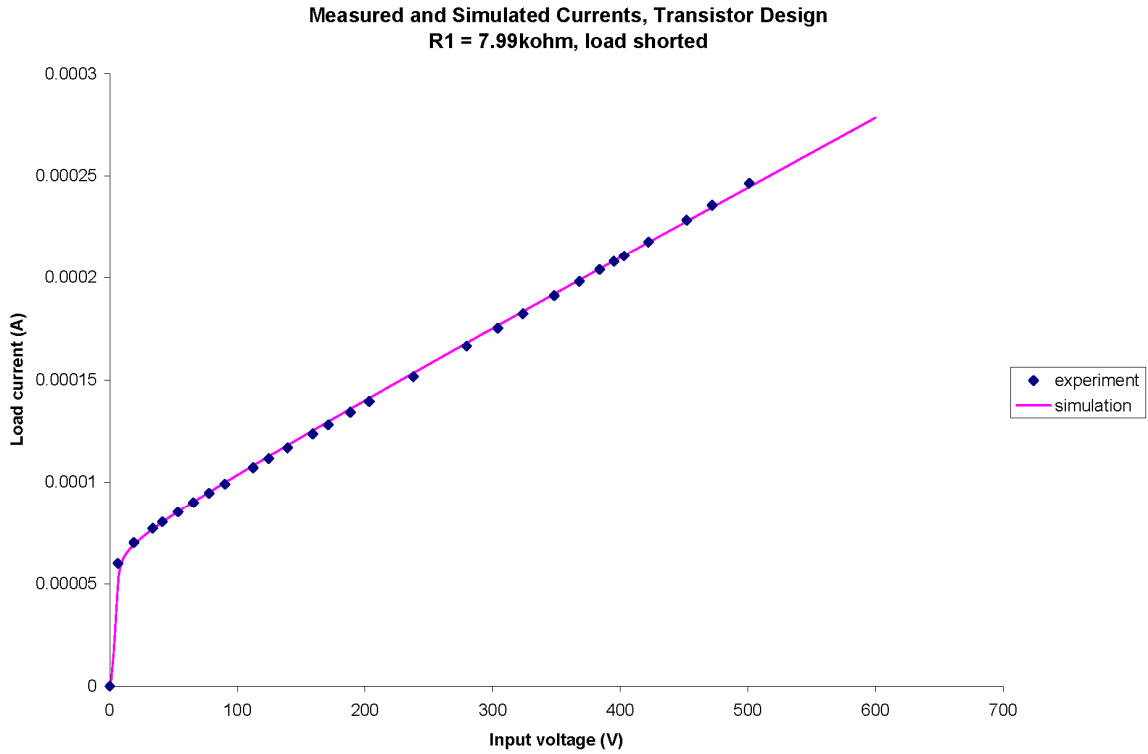
Measured and Simulated Currents, Transistor Design
R1 = 7.99kohm, load shorted

Figure 2: Load current vs. input voltage at short circuit condition with R1 = 7.99 kΩ. Current limiting behavior did not noticeably change with the change to 4.16 kΩ..
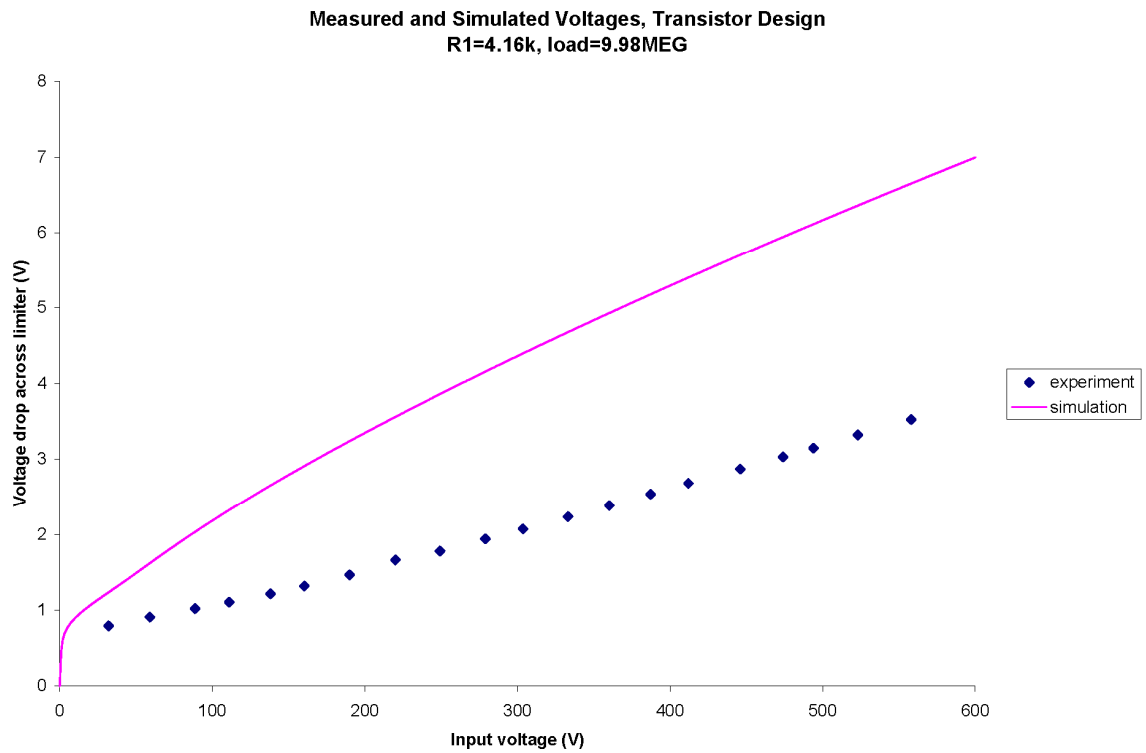
Measured and Simulated Voltages, Transistor Design
R1=4.16k, load=9.98MEG

Figure 3: Voltage drop at load condition with R1 = 4.16 kΩ.

2.c. Cost

Component	Price	#	Total
KSP44	$0.028	2	$0.056
2N3904	$0.011	1	$0.011
1.5 MΩ	$0.005	2	$0.010
4 kΩ	$0.008	1	$0.008

Table 1: Transistor circuit price

The transistor design's price per circuit is $0.09 if ordered in quantities of 10,000 or more. The use of a single high-voltage transistor would bring the total price to $0.24 per circuit.

3. MOSFET Design

3.a. Background

The MOSFET circuit design uses a low current LM385 Zener diode voltage reference to produce a uniform voltage drop across a wide range of input voltages. The circuit uses a single high-voltage MOSFET in place of the transistor design's two bipolar transistors. The LM385 features a tunable voltage reference in the range 1.24 V to 5.30 V, following the equation

$$V_{\text{out}} = 1.24(^{R2}/_{R1} + 1) \tag{1}$$

provided in the component's datasheet. The control resistors R1 and R2 were chosen to be near the maximum of that range, about 4.96 V. Although all the tests described below were done with an LM385, we prefer the LM185, which is identical except that it requires a somewhat lower minimum current (see Appendix A). The LM185 requires a minimum current of 30 μA at 4.96 V, with a worst-case minimum current of 45 μA. A search for a lower current reference diode produced no results.

The design was simulated and tested in the same way as the transistor design, with a few modifications. The adjustable LM385 voltage reference is an older device, so no SPICE models were available for it. Instead, it was modeled as a static voltage source. As the values of the control resistors R1 and R2 (100 kΩ and 300 kΩ, respectively) provide about a 4.96 V reference from the LM385, the source in the simulation was set to this value.

The simulations show that the 12 MΩ resistor R3 does not have a large impact on the two main quantities of interest – the circuit's voltage drop at load condition and the circuit's current limiting ability at short condition (Fig. 5). The voltage drop does not appear to change at all with R3, while only the slope of the limited current changes, and even then only slightly. The simulation suggests that to stay in the safe range of about 0.5 mA or less, R3 need be about 5 MΩ or higher.
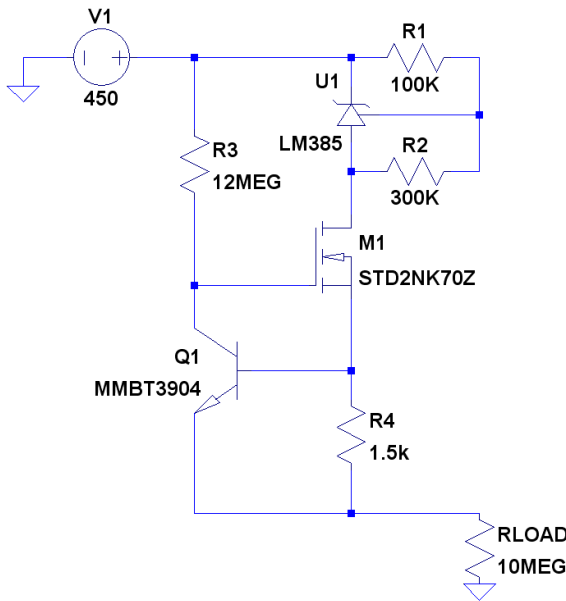
Figure 4: MOSFET current limiter schematic.

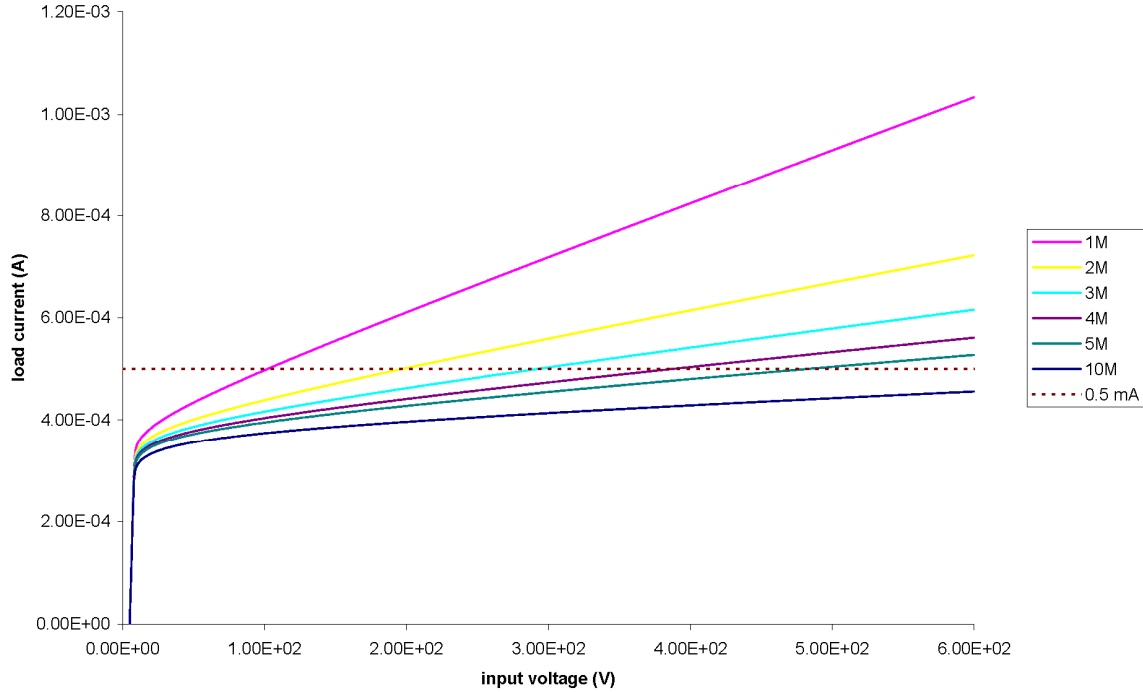**Load current vs. input voltage with varied R3**

Figure 5: Simulation of current limiting of the MOSFET circuit with different values of R3 for a short-circuit condition. The dotted line is the 0.5 mA maximum.

3.b. Testing

The circuit provided a hard cap on load current in the short condition: the current increase nearly halted at about 300 µA, with an increase of just 1.33×10^{-4} mA/V after that, as shown in Fig. 6. At load condition, the variation in the voltage drop is only about 30 mV through 400-500 V (with a calculated slope of 0.0003), as shown in Fig. 7. The only significant change in the drop over the range we tested was a ramping up to the final voltage drop of about 5V that occurred at an input voltage below 200 V.
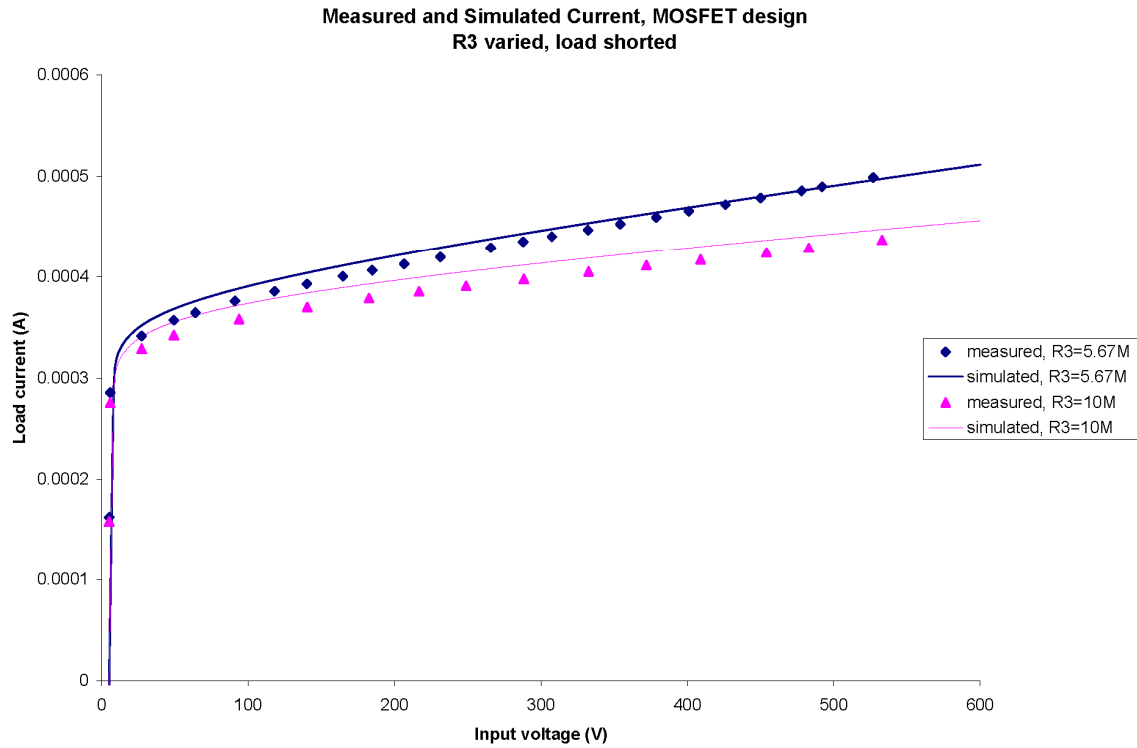
Figure 6: Current in the MOSFET limiter design with different values of R3, as a function of the input bias.
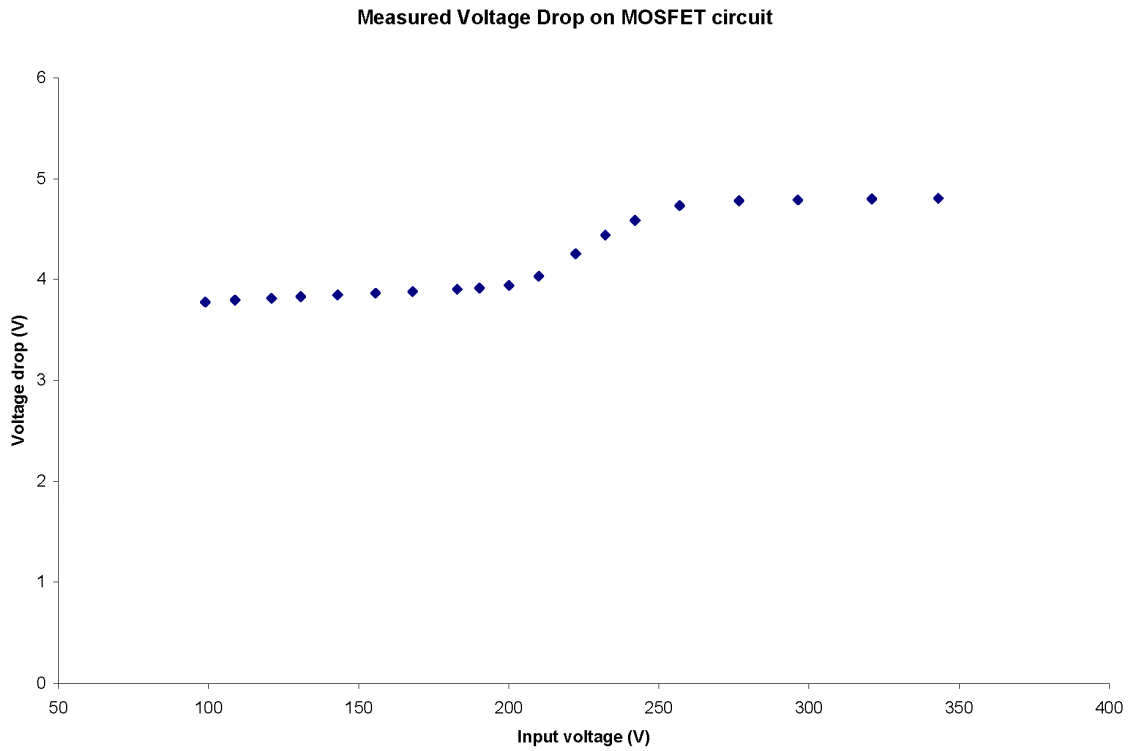

Figure 7: Voltage drop in the MOSFET limiter design at load condition as a function of the input bias.

The voltage drop measured across the MOSFET limiter circuit consists of three regions defined by their behavior as a function of the input bias. In the first region, extending up to about 200 V, the voltage drop increases slowly. The second region, the "ramp," extends from about 200-250 V and the drop rises sharply. In the third region, the plateau extending from 250 V on, the voltage drop is nearly unchanged.

To investigate this behavior voltages were measured across the LM385 and the D2NK70Z MOSFET in addition to the entire limiter circuit. These three are plotted together against the input voltage in Fig. 8. In the first region, the voltage drop across the LM385 is slowly increasing, while that across the MOSFET is decreasing at nearly the same rate. Together, these account for the slow increase in the total voltage drop. After the MOSFET is fully turned on at about 200 V, the LM385 voltage drop continues to increase, accounting for the ramping region. After about 250 V, in the plateau region, the LM385 has reached its peak voltage drop, and the circuit is stable.

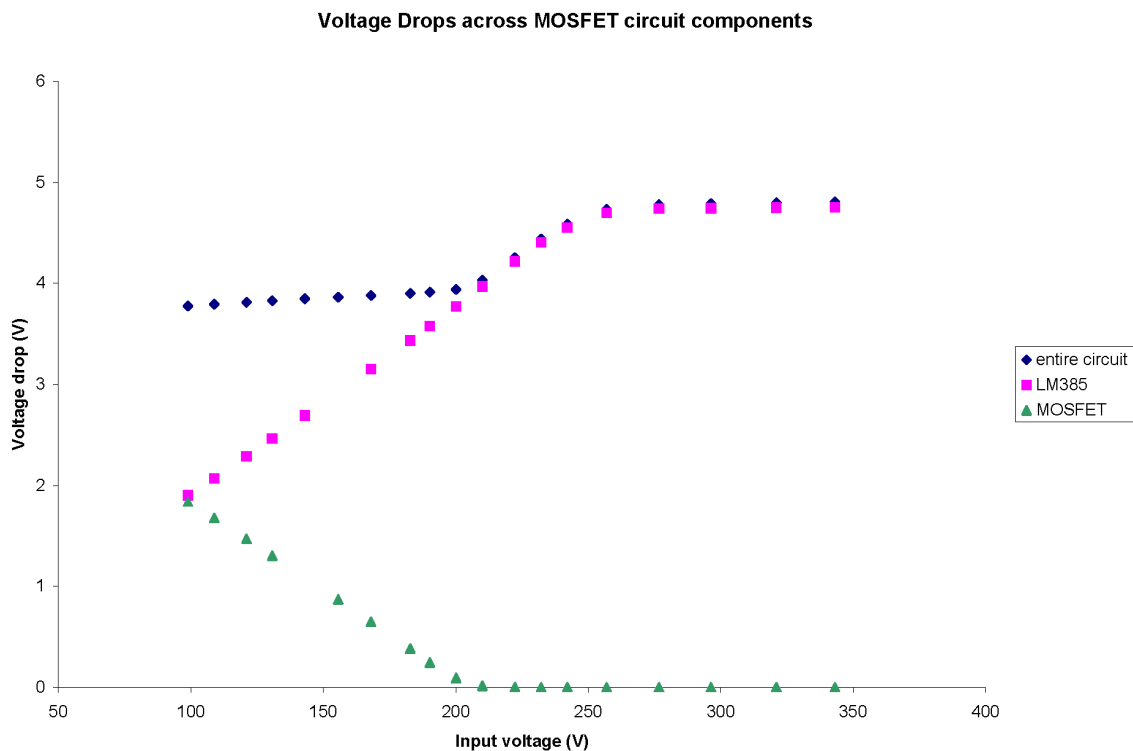**Voltage Drops across MOSFET circuit components**

Figure 8: Voltage drops across the entire limiter circuit, LM385 and MOSFET, as a function of input bias.

The reason the LM385 voltage only plateaus at 250 V and beyond is that it must be supplied a current of more than about 30 µA for reverse breakdown to occur. Past 30 µA, the LM385 voltage remains almost constant. The reference was tested up to about 0.8 mA with no change in voltage; the datasheet for the LM385 claims it will operate at up to 20 mA.

In order to verify the behavior of the LM385, the control resistors R1 and R2 were varied, confirming the validity of the LM385 equation given above (Eq. 1). Figure 9 shows the result of one such test.
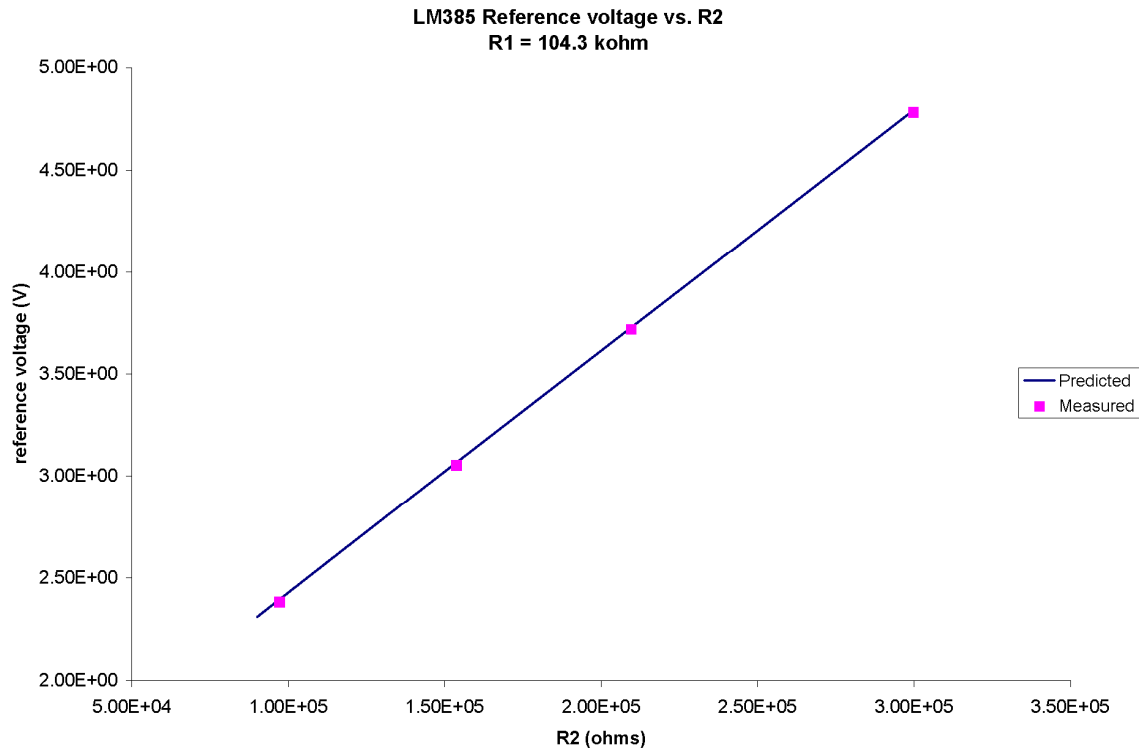

Figure 9: LM385 reference voltage vs. R2 with R1 held constant.

3.c. Required Resistor Tolerances

It is possible to calculate the required resistor tolerance needed to keep the output voltage of the LM385 within 100 mV. The variation in the voltage is given by

$$\Delta V = 1.24 \left(\frac{R_2}{R_1} \right)(x_2 - x_1)$$
$$= 3.72(x_2 - x_1)$$
(2)

where $x_1 = \Delta R_1/R_1$ and $x_2 = \Delta R_2/R_2$, and we have set $R_2/R_1 = 3$. Adding the two LM385 resistor variances in quadrature gives:

$$\Delta V = 1.24 \left(\frac{R_2}{R_1} \right) \sqrt{(x_1)^2 + (x_2)^2}$$
(3)

Assuming $x_1 = x_2 = x$ gives:

$$\Delta V = 1.24 \left(\frac{R_2}{R_1} \right) \sqrt{2}x$$
(4)

How we do the resistances need to be known? Solving for x gives:

$$x = \frac{\Delta V}{1.24\sqrt{2}\,{R_2}\big/{R_1}}, \tag{5}$$

which, with ΔV = 100 mV, R_2 = 300 kΩ and R_1 = 100 kΩ, gives x = 1.9%.

       Generally, resistors are made in large batches of a certain resistance. A representative sample of a batch is tested for resistance. The variation in the sample is used to determine what tolerance the batch will be marked with. Resistors marked as 1% tolerance, therefore, should be guaranteed not to exceed this requirement. (Note that one set of 5% resistors we used was not within specifications!)

3.d. Tests of Variation of Active Components on Performance

       To determine the impact of the variation of the active components on the output voltage a circuit was built such that the LM385, MOSFET and BJT were all easily switched out for testing. The voltage drops across the limiter circuit was measured with ten of each component. The drops due to the different LM385s all fell within about 25 mV of each other (Fig. 10), those due to the different STD2NK70Z MOSFETs were all within about 10 mV (Fig. 11), and those due to the different MMBT3904 transistors were all within about 3 mV (Fig. 12).
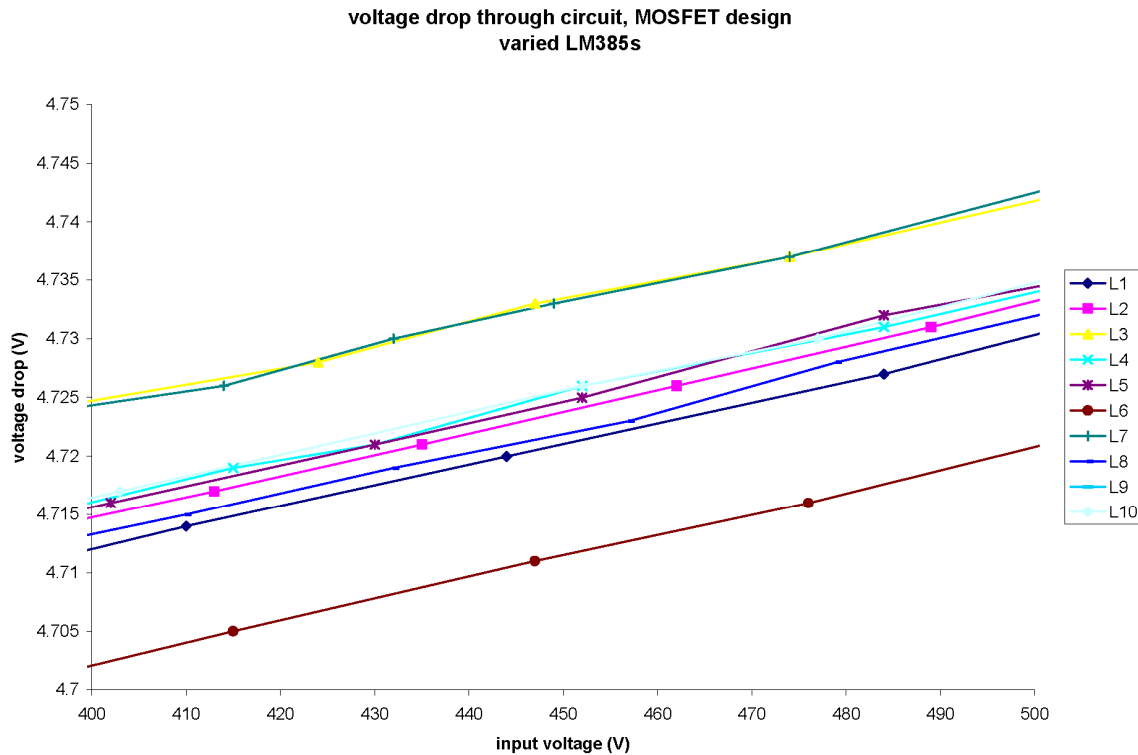

Figure 10: The voltage drops of the MOSFET limiter circuit using 10 different LM385 reference diodes.

Voltage across limiter at load condition, MOSFET design (detail)
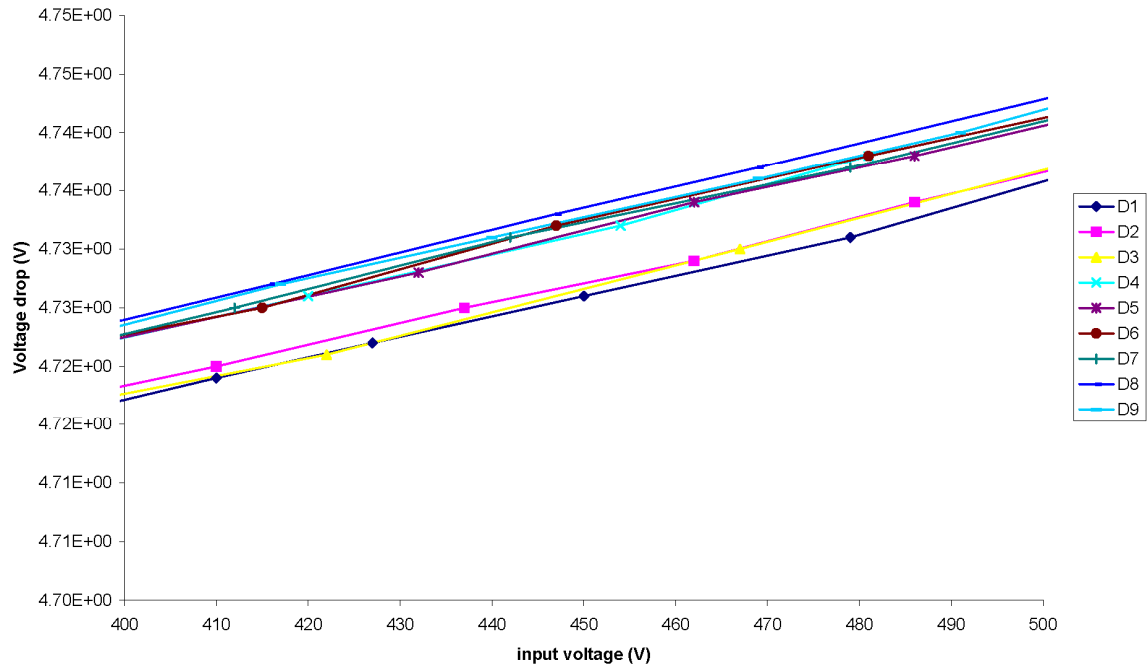**Varied D2NK70Z**

Figure 11: The voltage drops of the MOSFET limiter circuit using 10 different STD2NK70Z MOSFETs.

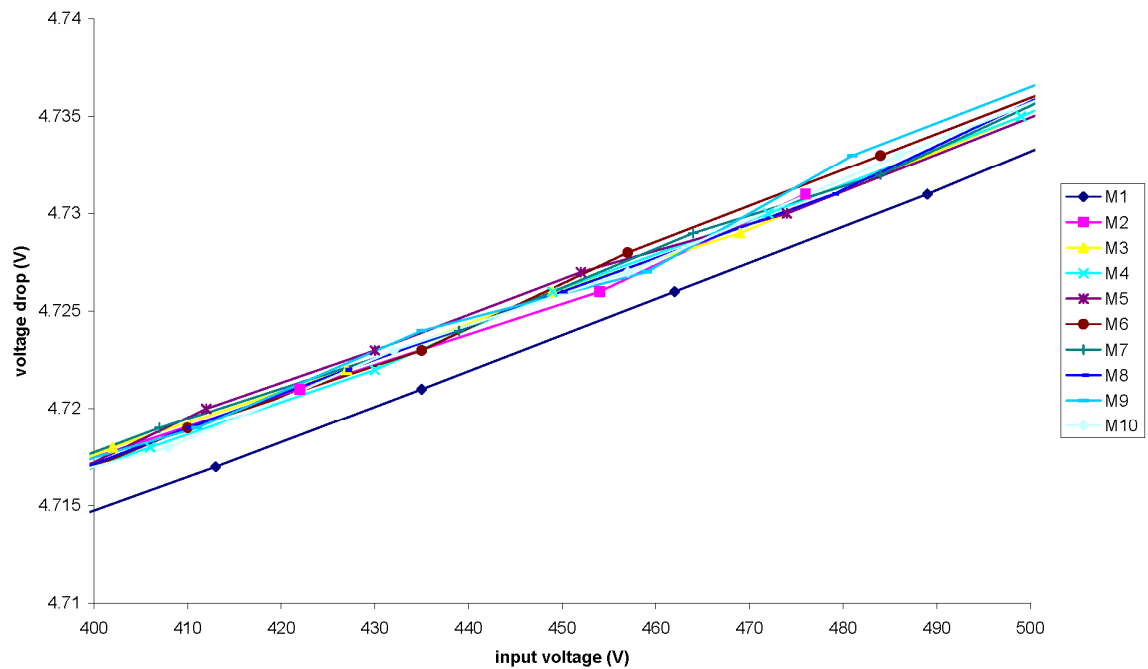**Voltage drop across MOSFET design at load**
varied MMBT3904

Figure 12: The voltage drops of the MOSFET limiter circuit using 10 different MMBT3904 transistors..

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3.c. Cost

Component	Price	#	Total
lm385	$0.30625	1	$0.306
MMBT3904	$0.01000	1	$0.010
10Mohm	$0.00500	1	$0.005
1.5kohm	$0.00512	1	$0.005
100kohm 1%	$0.00825	1	$0.008
300kohm 1%	$0.00900	1	$0.009
STD2NK70Z	$0.54000	1	$0.540

Table 2: MOSFET circuit price.

Due to the cost of the LM385 reference diode and the high-voltage transistor, the MOSFET circuit design is more expensive than the transistor design, with a per-circuit parts price of $0.88.

4. Conclusion

The transistor current limiter circuit does an excellent job of keeping short-circuit current in check. In addition, it is very low-cost, does not require any precision components and has fewer components overall. The voltage drop variation, however, is such that a downstream voltage regulator is needed.

The MOSFET current limiter circuit, while more expensive than the transistor circuit, has an extremely even and reproducible voltage drop, although somewhat larger. (Care must be taken to keep the load current above 50 μA when using the LM185.) Hence it could be used without a downstream voltage regulator. Using one circuit per board rather than per channel will ameliorate the price.

References

Chappa, Steve. "NOvA Power Distribution System Preliminary Design Review Notes and Concerns." 06 April 2009.

National Semiconductor. LM185/LM285/LM385 Adjustable Micropower Voltage References datasheet, 30 January 2008. http://www.national.com/ds/LM/LM185-ADJ.pdf (accessed 09 July 2009).

Appendix A: Component datasheets.