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High temperature linear operation of paralleled power MOSFETs

Steven A. Morris
Baker Hughes/INTEQ
2001 Rankin Rd. Houston, Texas, U.S. A. 77073
steven.morris@bakerhughes.com

Abstract

Linear power supplies are often used in downhole applications to avoid generation of noise associated with switching power supplies. In high temperature linear supplies it is often necessary to use several pass transistors in parallel to reduce the power dissipated in any single pass transistor. For power MOSFETs, the threshold voltage decreases with increasing temperature. This fact, coupled with the normal variation of threshold voltage from one transistor to another, produces a current hogging phenomenon in parallel transistors at high temperature, where the transistor with lowest threshold voltage, through positive thermal feedback, carries all or most of the load current, and eventually fails. This paper presents a model of such current hogging. The model can be derived from parameters on the transistor manufacturer's data sheet. It is possible to reduce the risk of current hogging by including a source resistor in series with each transistor. Using a statistical model of threshold voltage variation among transistors, Monte Carlo simulation can be used to select a proper value of the source resistor given the acceptable risk limits of experiencing a current hogging condition. This paper presents an example design of a high temperature parallel MOSFET linear supply based on the presented theory and design techniques.

1. Introduction

In well logging applications, linear voltage regulators are sometimes used instead of more efficient switching regulators in order to avoid noise generated by switching regulators, which can interfere with many types of sensitive downhole measurements. As shown in Figure 1, linear regulators require the use of pass transistors that dissipate power as they drop the regulator's input voltage down to the regulated voltage. At high temperatures, given limited capabilities of heat sinks to dissipate heat from single transistors, the dissipated power may cause transistor junction temperatures to exceed operational limits. To alleviate this problem, several transistors can be placed in parallel operation to replace the single pass transistor. The dissipated power is shared among these transistors, and the heat generated can be carried off through heat sinks without overheating of transistor junctions.

Very often, power MOSFETs are used as pass transistors because they are voltage driven devices with simple drive requirements. It is well known that power MOSFETs have a positive temperature coefficient of on resistance, a characteristic that facilitates using MOSFETs in parallel as switches.

As pass transistors in a linear regulator, MOSFETs operate in their active region and often dissipate substantial power. Because MOSFETs have a negative temperature coefficient of threshold voltage [1], this produces positive thermal feedback among paralleled MOSFETs which can produce a "current hogging" phenomenon, where a single transistor carries all the regulator current, resulting in overheating and failure of that transistor [2].

The current hogging phenomenon is particularly problematic for high voltage, low current regulators. Such regulators are used to supply regulated DC high voltage downhole that compensates for load variations

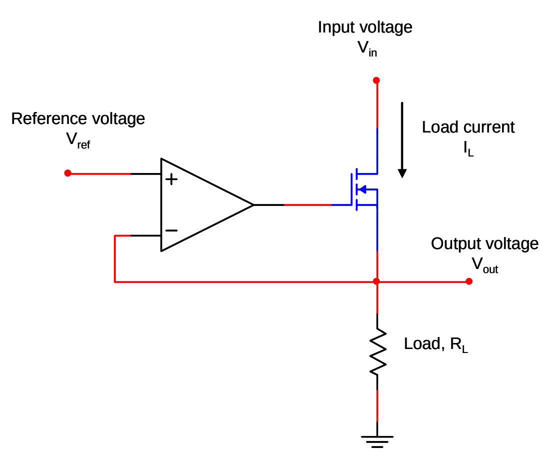

Figure 1. Typical linear regulator circuit using a MOSFET pass transistor.

and voltage drops across the wireline resistance. In this case, transistor currents are low, dissipated power is large and the gate to source voltages of the pass transistors are biased just above their threshold voltages. Due to normal manufacturing variation, the threshold voltages vary among the pass transistors, the transistor with the lowest threshold voltage will carry a disproportionately large share of current that may induce current hogging through positive thermal feedback. The “hot” transistor with the largest share of current heats up, its threshold voltage drops, causing its current to increase, starving the other transistors of current. The low current transistors consume less power, their junction temperatures drops correspondingly, so their threshold voltages increase, causing their current to decrease, further increasing current in the “hot” transistor. Eventually, the hot transistor carries all the current. Power dissipation in this transistor may overheat the transistor, causing it to fail.

This paper describes a technique to model current hogging in such situations, and discusses a method to select an appropriate source resistor value to reduce the risk that current hogging will occur.

2. A simple model of paralleled MOSFETs

For illustrative purposes, consider the IRFPG50 N-channel power MOSFET. This device is suitable for use as a pass transistor for high voltage linear regulators, and has a maximum drain-source voltage of 1000 volts, maximum drain current of 6 amps, and is rated at 190 watts of dissipation at a case temperature of 25 °C. According to the datasheet [3], the threshold voltage, V_T, ranges between 2.0 to 4.0 volts. Figure 2 shows the measured DC transfer characteristic for a sample IRFPG50 device as a function of temperature at drain currents less than 200 mA. As the temperature increases the curves shift to the left, indicating a temperature coefficient of threshold voltage of about -6 mV/°C. Large signal transconductance is fairly constant with temperature; being about 4.5 A/V^2 when current is near 200 mA. Note that for this transistor, an increase in junction temperature of about 21 °C will cause threshold voltage to decline about 125 mV.

Figure 3 shows an experimental setup for testing the parallel operation of five IRFPG50 MOSFETs in parallel. The transistors are bolted to an aluminium plate that serves as a heat sink. Four of the transistors have a single thermal ceramic spacer between case and heat sink. These spacers have a thermal resistivity of about 1 °C/W. As shown in Figure 4 the fifth transistor (the “hot” transistor) has a stack of four such ceramic spacers between case and heat sink, giving a thermal resistance of about 4 °C/W between case and heat sink. Given this difference between the hot transistor and the other transistors, and assuming that dissipated power is shared equally among them, a total power of 35 W among all transistors will cause the hot

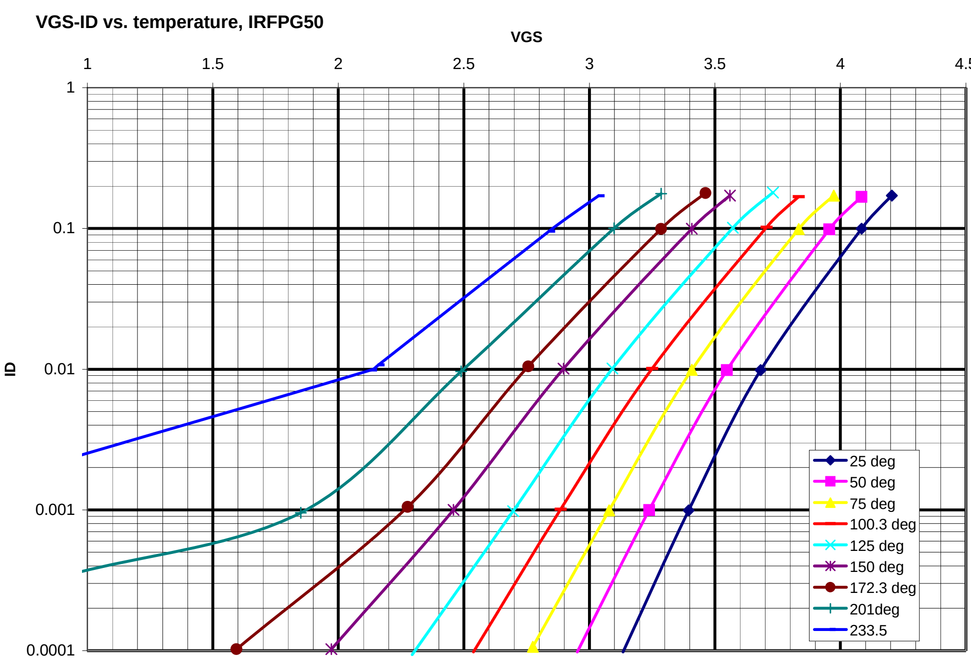

Figure 2. Transfer characteristic of a sample IRFPG50 as a function of junction temperature. Drain to source voltage is 60 volts. The temperature coefficient of threshold voltage, V_T, is about -6 mV/°C.

Figure 3. Experimental setup of 5 parallel IRFG50 MOSFETs to demonstrate current hogging phenomenon.

MOSFET to have a junction temperature of about 21 °C higher than the other transistors, resulting in its threshold voltage being 125 mV lower. Note that this circuit also includes a 1.5 Ω source resistor with each transistor.

Figure 5 shows the results of the experiment. The total current into the paralleled transistors is maintained at 200 mA, while the voltage across the transistors is varied to increase the dissipated power. The current share of the hot transistor is shown on the left while the power dissipated in the hot transistor is shown on the right. Ideally, the current share of a single transistor among 5 paralleled transistors would be 0.2. When using 1.5 Ω source resistors, the hot transistor's current share starts at about 0.26 at low power and increases as the dissipated power increases. At a DC voltage of slightly over 200 volts, where total power is 40 W, and the hot transistor's power is about 15 W, the hot transistor goes into a thermal runaway condition, hogging all the current.

The experiment was conducted a second time using 25 Ω source resistors. In this case, the hot transistor maintains a current share of about 0.2, close to ideal, across the whole range of DC voltages, including at 250 volts, when the test circuit is consuming 50 W of power. This indicates that increasing the source resistance tends to stabilize the circuit and prevent current hogging.

Figure 4. Extra ceramic insulators added to one transistor of Figure 3 to increase its junction to heat sink thermal resistivity.

To explain the effect of the source resistors, assume a worse case scenario, shown in Figure 6, where a hot transistor has threshold voltage, V_{T1} = 2.125 volt, 0.125 volt lower than the threshold voltage of the other four MOSFETs, which have V_{T2} = 2.25 volt. Because of the high transconductance of the transistors, source resistance feedback occurs, and the drain current in a single transistor can be roughly approximated as:

$$I_D = \begin{cases} 0 & V_G < V_T \\ \dfrac{V_G - V_T}{Rs} & V_G > V_T \end{cases} \quad (1)$$

where V_T is the threshold voltage for the transistor.

Using Equation (1), Figure 7 plots the total current in the paralleled transistors up to the final current of 200 mA, for two different values of Rs. In the case of Rs = 1.5 Ω, the first transistor begins conducting at V_G = 2.125 volts and increases at 666 mA/volt until V_G = 2.25 volt, when current starts increasing at 3.333 amp/volt. Beyond this point the hot MOSFET's share of the current is shown as a dashed line in the figure. Because current increases so quickly when only the hot MOSFET is conducting, its final share of the current is about 100 mA, or 50% of the total current. For the case of Rs = 25 Ω, the current increases at 40 mA/V when only the hot transistor is conducting, and increases at

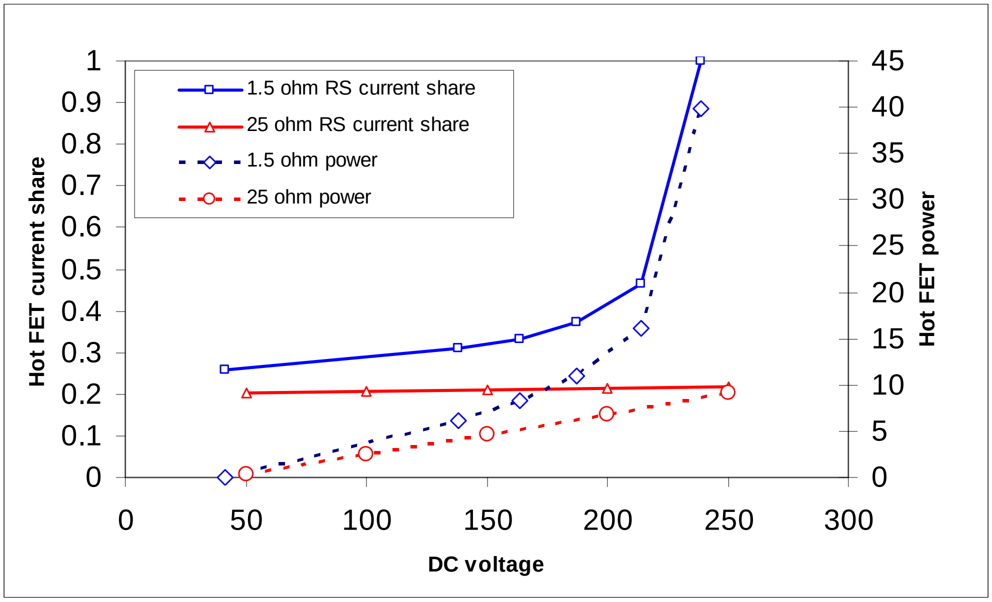

Figure 5. Current share and power consumption of 'hot' MOSFET of Figure 4.

200 mA/V when all transistors are conducting. The hot transistor current increases little in the range when only it is conducting, and the hot transistor's current share is 22% at maximum power dissipation, very close to ideal sharing of 20% for a single transistor among five parallel transistors.

3. Avoiding current hogging in paralleled MOSFETs

A straightforward way to avoid uneven current sharing in parallel MOSFETs is to use an op amp with feedback to linearize the transconductance of individual MOSFETs in the parallel circuit [4]. As shown in Figure 8, current is sensed across the MOSFET source resistor, Rs, and an error amplifier is used to fix the transistor current at V_G/Rs. This scheme effectively eliminates uneven current sharing problems, but requires an op amp circuit for each MOSFET in the parallel circuit. For a typical high voltage supply, the op amps must float at high voltage and care must be used to insure the op amps are not susceptible to transient noise spikes at both the input and output of the regulator. Because of this, and the need to qualify the op amps for high temperature downhole operation, the implementation of the

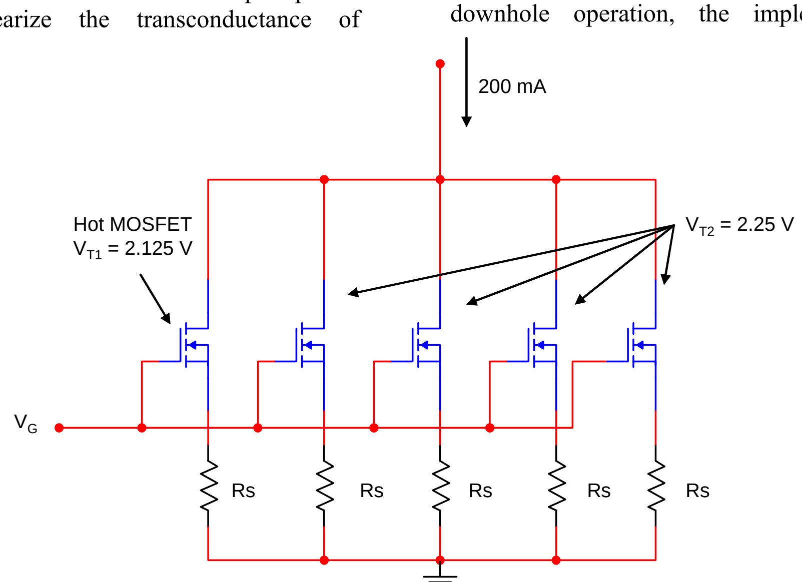

Figure 6. Model of worst case threshold voltage mismatch in 5 parallel MOSFETs. "Hot" MOSFET has V_{T1} = 2.125 volt, while remaining MOSFETs all have V_{T2} = 2.250 volt.

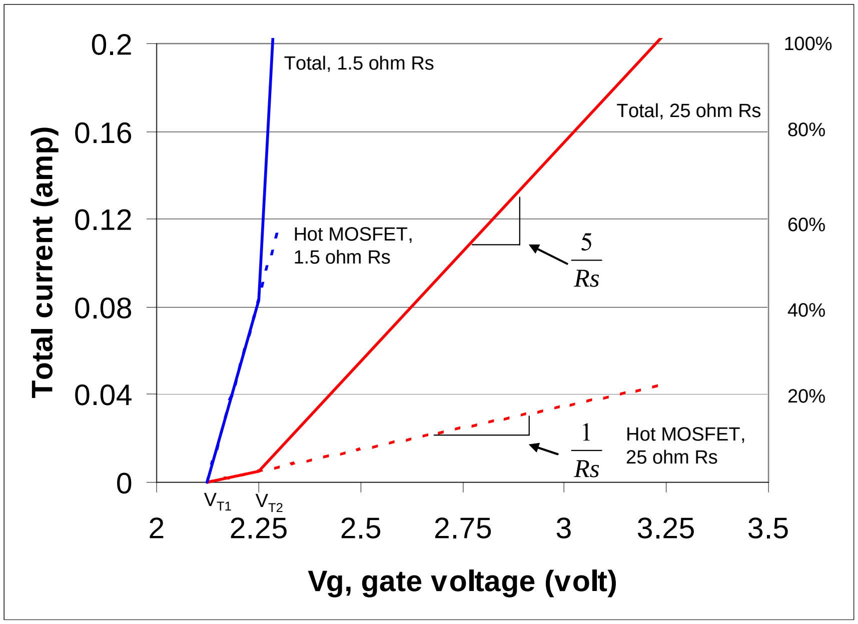

Figure 7. Diagram illustrating the effect of source resistor Rs on current hogging.

technique of Figure 8 can be fairly complex.

The technique of maintaining even current sharing by using passive source resistors is desirable because of its simplicity. The problem of selecting the value of the source resistors depends upon the expected variation in the threshold voltage of the MOSFETs. This variation is difficult to determine from the manufacturer's data sheet. Manufacturers only specify absolute maximum and minimum values of threshold voltages for their devices. Variation of threshold voltage from device to device may not be severe when the circuits are built during manufacturing, because all the devices in individual parallel circuits tend to come from the same production lot from the transistor

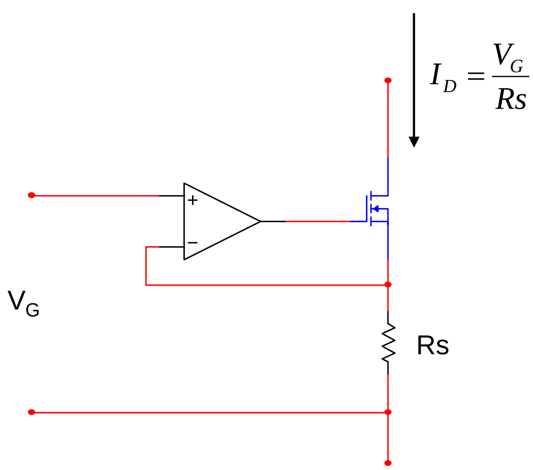

Figure 8. Use of op amp to control MOSFET current to insure equal current sharing in parallel MOSFETs. Substitute this circuit for each parallel MOSFET.

manufacturer. Later, however, if a transistor needs to be replaced in the field, the replacement transistor will be from a different production lot or device manufacturer than the remaining original transistors. If the replacement transistor has a much lower threshold voltage than the remaining original transistors, this could produce current hogging problems and lead to failure of the replacement transistor.

It is possible to use the simple model illustrated in Figure 7 to develop a design scheme for selecting the source resistor value. Given the expected load current I_L, the required gate voltage, V_G, can be found:

$$V_G = \frac{1}{n} I_L Rs + V_{T1} + (n-1)V_{T2} \quad (2)$$

and the current share of the hot transistor is:

$$\frac{I_H}{I_L} = \frac{1}{1 + \frac{(V_G - V_{T2})(n-1)}{V_G - V_{T1}}}, \quad (3)$$

where I_H is the current in the hot transistor, and n is the number of transistors in parallel. Using the datasheet maximum and minimum limits to threshold voltage as V_{T2} and V_{T1} respectively, and given a maximum acceptable current share for the hot transistor, Equations (2) and (3) can be used iteratively to find an appropriate source resistor Rs. This design scheme, is based on unexpectedly severe conditions, and can lead to excessively large values for the source resistance. For example, using maximum acceptable I_H/I_L of 30%,

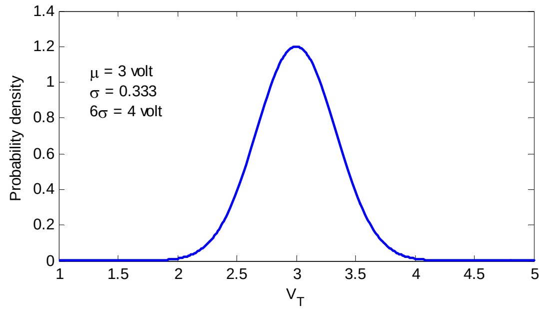

Figure 9. Probability density function of V_T of IRFPG50 assuming datasheet specified maximum and minimum V_T values represent ±3 standard deviation points on a normal distribution.

I_L = 200 mA, and threshold voltage limits V_{T1} = 2 volt, V_{T2}= 4 volts, produces, through Equations (2) and (3), a source resistance Rs = 75 Ω. Such large Rs values may be problematic, since, under heavy load conditions, the drive voltage V_G and power dissipated in the source resistors may become large.

Using the expected distribution of threshold voltages, and given the acceptable risk of exceeding some maximum shared current in the hot transistor, it is possible to select the source resistor through simulation. Given I_L, *n*, and Rs, a simulation is conducted as follows:

1. Select a set of threshold voltages for *n* transistors, using a random deviate generator drawing from the probability distribution of the threshold voltages.
2. Solve for the individual drain currents.
3. Record the current share of the transistor with the largest drain current.

If a large number of such simulations are executed, it is possible to construct a probability distribution of the current share of the hot transistor for a given value of Rs. To generate a distribution of threshold voltages, assume that datasheet minimum and maximum limits correspond to plus and minus 3 standard deviations on a normal distribution. Figure 9 shows such a threshold voltage distribution based on datasheet limits of 2 volts minimum and 4 volts maximum. For I_L = 200 mA, Rs = 40 Ω, Figure 10 shows the resulting distribution of hot transistor current share, based on 10,000 simulations. A histogram on the left represents the probability distribution of hot transistor current share, which peaks at about 25%, while the plot on the left shows the cumulative distribution. Using 1% as an acceptable risk that the hot transistor current will be greater than 30%, then the cumulative plot shows that Rs = 40 Ω is an acceptable value that puts the stated risk at about 0.8%, as shown in the plot. Thus as shown in the example, a series of simulations, based on varying values of Rs, can be used to select an appropriate value of Rs based on the acceptable risk of the current share in the hot transistor exceeding some value.

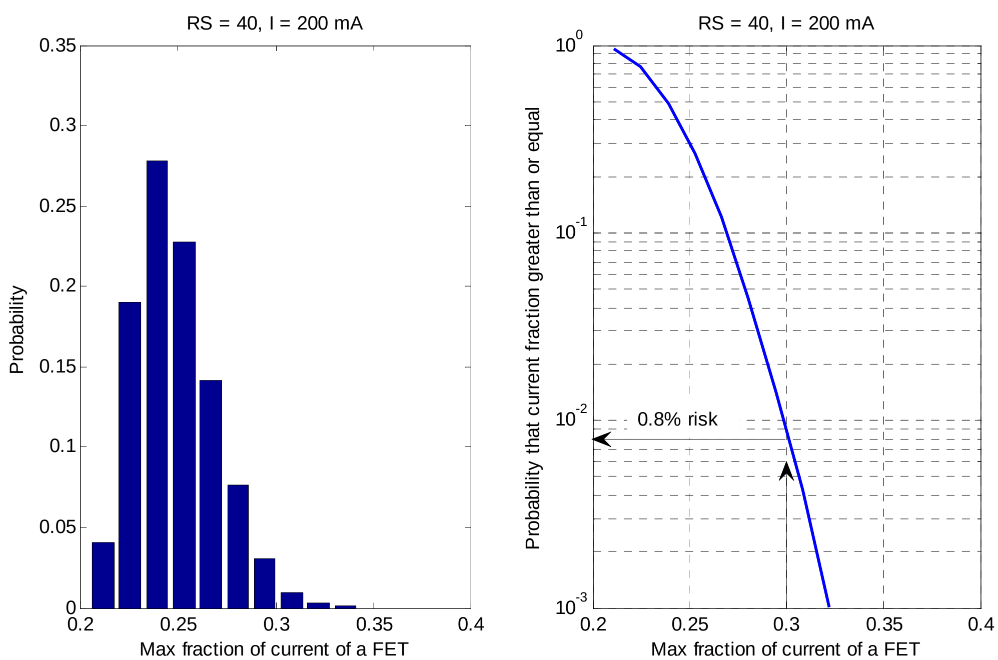

Figure 10. Probability distribution and cumulative probability distribution of maximum current share of a MOSFET, assuming 5 parallel MOSFETs, with distribution of threshold voltage V_T given in Figure 9. Total current is 200 mA and source resistor, Rs, is 40 ohms.

3. Conclusions

Using paralleled MOSFETs as pass transistors in linear regulators may lead to problems of current hogging that can lead to transistor failure. This problem stems from the variation of threshold voltage among devices, and is aggravated by the negative coefficient of temperature of the threshold voltage, which produces an unstable positive thermal feedback mechanism.

If using passive source resistors to avoid uneven current sharing, selecting source resistors values based on worst case conditions can lead to unreasonably large values of the source resistor. The probabilistic method introduced in this paper, which is based on simulation of current sharing using the expected variation of threshold voltage, gives more reasonable design values for the source resistor.

The thermal feedback mechanism discussed in this paper can be studied thru PSPICE simulation. This requires an electro-thermal PSPICE model, as proposed in [5], for the transistor being used. It is also possible to extend this design method to use the source resistor diode switching scheme of Niedra [6], to extend the use of source resistors to operate at both low current and high current situations.

4. References

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