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# High Power, High Voltage FETs in Linear Applications: A User's Perspective

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*Abstract*— The specifications of the current crop of high-power, high-voltage field-effect transistors (FETs) can lure a designer into employing them in high-voltage DC equipment. Devices with extremely low on-resistance and very high power ratings are available from several manufacturers. However, our experience shows that high-voltage, linear operation of these devices at near-continuous duty can present difficult reliability challenges at stress levels well-below their published specifications. This paper chronicles the design evolution of a 600 volt, 8 ampere shunt regulator for use with megawatt-class radio transmitters, and presents a final design that has met its reliability criteria.

## I. Introduction

High power Class B or C RF amplifiers exhibit self-rectification in the grid circuit of the RF drive signal applied to the grid or cathode [1]. To prevent an upward-shift of the bias voltage under RF drive, a return circuit is normally provided in the grid bias supply. This can be provided by resistive pre-loading, a zener diode, or in large amplifiers, a shunt regulator. The shunt regulator technique is especially useful in multi-megawatt transmitters where the power and heat load of a resistive pre-load is significant.

## II. Grid Regulator Circuits

High voltage, high-power field-effect transistors (FETs) have been used in grid regulator service for the past several decades. Early FETs had relatively low voltage and current capability, requiring a dozen or more devices in series-parallel configurations for a complete 600-volt, 8-ampere shunt regulator.

More recently, very high power FETs with very low on-resistance became available from a number of manufacturers. Manufacturers appeared to vie with each other in the trade literature for the highest current and lowest on-resistance devices. We chose a 600W, 900V device [2] that seemed to allow a much simpler circuit configuration than previous circuits. We initially settled on a design using two parallel sets of three series 50-ohm, 1000-watt load resistors and two ballasted FETs. A simplified version of the configuration is shown in Fig. 1.

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The gates of the FETs are tied to a reference voltage of -600V through a damping resistor to prevent oscillations. The sources of the FETs are tied to the reference voltage through a

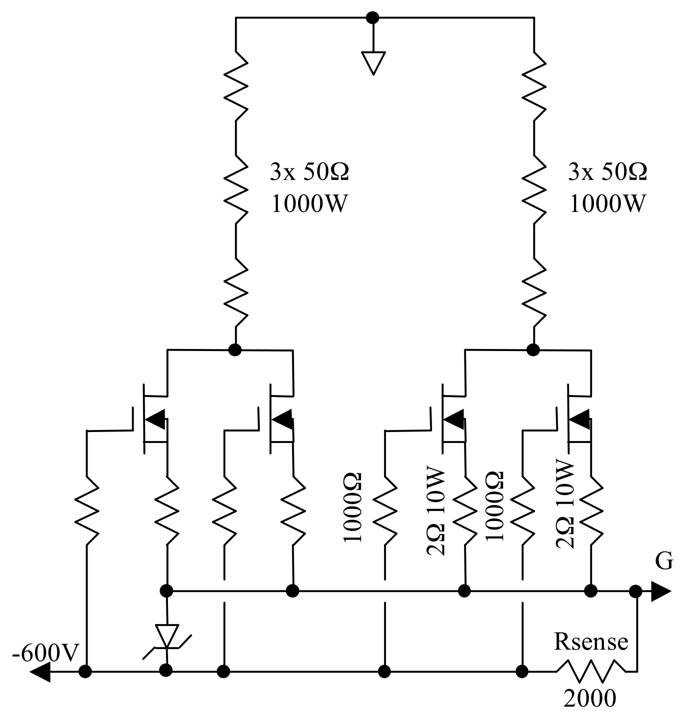


Figure 1. Simplified 600V, 8-ampere grid regulator, version 1. Gate clamps and bypass capacitors omitted for clarity

sense resistor. When the associated RF power amplifier is under sufficient RF drive and producing grid current, the point marked "G1" will be driven more negative than -600V. This causes a voltage drop across the sense resistor. The FET is driven into conduction when this voltage exceeds the FET's threshold voltage which is typically four volts. The conduction path through the FET and load resistors removes all excess current through the sense resistor, resulting in nearly no change in the G1 voltage. This is classic shunt-regulator action. The circuit was fabricated with two matched FETs per string to ensure reliability. The circuit was tested at low voltage and installed into the transmitter.

The circuit of Fig.1 proved unreliable under operation in the transmitter. We experienced repeated FET failures with just a fraction of an ampere transmitter grid current.

We theorized a number of scenarios for the failures:

- Overvoltage of the drain-gate junction caused by RF drive on or off transients
- Questions about the actual dissipation capability of the FETs
- Oscillation of one or more FETs causing a DC run-away
- Poor thermal contact with the heatsink leading to thermal run-away
- Stray RF pickup from the transmitter leading to FET destruction
- Unbalance of the FET pairs despite having been matched in threshold voltage and separately ballasted

Successive circuit additions were made to remedy each of the above scenarios. More parallel FETs were added, their baseplates lapped flat, ballast resistors increased, RF bypass capacitors added everywhere, transient suppressors and clamp circuits added, all with little or no improvement. It is interesting to note that failures were occurring at power dissipations less than one-fourth of the manufacturer's rated device dissipation capability.

An Internet search on high-voltage FET failures revealed several papers documenting thermal effects in certain types of large-area FETs that can result in failures well below their published specifications [3,4]. Although no one paper described our problem, we concluded that we likely did have a thermal stability issue specific to large-area, high-gain, low-resistance, high-voltage FETs in linear service.

An informal experiment with a heat gun and a power supply revealed nearly 0.5V change in gate threshold voltage for about 70-100 °C increase in case temperature. If applied as gate bias, the FET would be driven from cutoff to several amperes due to the very high Gm of the device (10-20 mhos is typical). This would not be a problem if the temperature of the silicon is assumed uniform because all areas of the device silicon would have equal gate threshold voltage and equal Gm, resulting in even conduction current density.

Many questions arise if the above statement is assumed false:

- What happens when the temperature of the silicon is not uniform?
- Can non-uniform temperature lead to the formation of hot areas (hotspots)?
- Are those hot areas stable or unstable under our operating conditions?
- Can those hot areas thermally "run away", leading to dopant re-diffusion or silicon destruction?

We theorized that a destructive thermal hotspot can be sustained in an FET device under a combination of conditions:

1. That the device is operated at high voltage such that significant power dissipation occurs at low currents.
2. That the silicon dimensions of the device are much larger than the thickness of its heat spreader such that significant temperature differences can occur across the silicon surface.
3. The temperature drift of the threshold voltage combined with very high gain can cause large drain currents to flow under fixed bias.
4. That this can occur in small spots if the resulting heat is not removed into the surrounding silicon and heat-spreader well enough.
5. That the increased dissipation in the spot is not sufficiently limited by the increase in bulk silicon resistance from increased temperature of the spot.
6. That the device does not have internal resistive source-ballasting to equalize parallel cells or silicon areas.
7. That the device heat spreader may be unevenly cooled by the external heatsink because of the classic "3-points-of-contact" nature of surfaces.
8. That the heat sink thermal contact at those three points is good enough to allow sufficiently uneven temperature to occur, even with thermal compound.
9. That "ordinary" thermal compound may not be good enough for the job.

Today's emphasis on high efficiency and reduced energy consumption has pushed FET designs towards ever lower on-resistance, higher voltage, higher current, larger gain and faster switching speeds. FETs of this type are widely used in switching power supplies, switching power amplifiers and switching inverters, for example. An examination of high-power FET data sheets from a number of manufacturers revealed an interesting lack of DC specifications on their safe-operating-area curves for many parts [2], or lack of SOA curves entirely [5]. Often there are no specifications for pulses longer than 100mS, yet they claim high power dissipation capability. It is unclear how the device can be usefully employed in this manner. This may be a clue to differentiating FET types for suitability in linear service.

We concluded that many devices of the switching type are not suitable for high-voltage linear service because they may become thermally unstable at low current and high voltage. They may indeed be stable at higher currents if the device dissipation capability can handle the heat. This led us to devise a test set to determine the suitability and limits of a particular FET for our purposes.

## III. FET Test Set and Test Results

A test set similar to Figure 1 was made up of a 0-600V/2A unregulated power supply, an adjustable-output pulse generator for gate drive, a 5-ohm source ballast resistor and a collection of power-resistors for the drain circuit. Device current was monitored with an oscilloscope using a small sampling resistor in the source return. Drain voltage was monitored with a high-voltage oscilloscope probe.

Samples of two different types were tested to destruction to determine their capability:

- ST40NK90Z, 600W 40A 900V, ISOTOP package
- IXFH12N100, 300W, 12A, 1000V, TO-247 package

Tests showed that a particular FET can withstand considerably higher power dissipation if operated at lower voltage, higher current than at higher voltage, lower current. Although the mechanism may differ, this behaves much like the secondary-breakdown effect in ordinary bi-junction power transistors. The IXFH12N100 part showed a non-destructive latch-up phenomenon at 70 watts average 200mS into a 500V/0.2A pulse. When operated at 125V, the device withstood 100 watts average nearly 700mS into a 125V/1A pulse. The device had been operating at 950mS on, 250mS off pulses for several minutes before the latch-up for the lower-voltage condition versus just a few pulses at the high-voltage condition.

The ST40NK90Z part failed after a few manually-triggered pulses at 125V/1A for 0.3 seconds. Note that this part is rated at 600W, yet withstood only a few 300mS 125W pulses at low duty-factor. This is less than one-half the capability of the smaller part. The damage was found to be similar to the damaged parts removed from the in-service grid regulator. The gate showed several hundred ohms to the source, and the drain showed very low breakdown voltage.

We concluded that it was better to use multiple smaller parts with individual ballasting resistors, and operate them in lower-voltage series/parallel groups rather than all in parallel at higher voltage.

## IV. Final Circuit Configuration, Tests

The final configuration of the grid regulator consists of two parallel strings, each string is capable of up to 4 ampere sink capability at 600V. Each string is composed of three sets of 50-ohm, 1000W thick-film resistors and three ballasted IFXH12N100 FETs in parallel for each load resistor. All of the components are mounted on a 12” x 6” water-cooled heat sink. A simplified final schematic of one-half of the completed regulator is shown in Fig. 2. A second section is connected in parallel at the “-600V” and “G1” points without a separate sense resistor. FET gate clamps and bypass capacitors have been omitted for clarity. Two of these units have been in service for several years with no failures.

## V. High-Performance Heatsink/Compound Tests

A later design for a 10kW water-cooled load resistor for a high-voltage power supply led to a test of thermal compounds and high-performance heat sinks. The goal was to confirm the choice of water-cooled heatsink and determine the proper application technique of thermal compound. One 800-watt thick-film resistor [6] was mounted on a 12”x 6” 4-pass water-cooled copper-aluminum heatsink [7]. Tests were started using “standard” zinc-oxide-loaded silicone heatsink compound [8].

A sample water-cooled heat sink was grooved to allow two thermocouples to be installed under the high-power resistor. One thermocouple contacted the heatsink slightly under the surface and insulated from the resistor above it; and the other thermocouple contacted the baseplate of the resistor and was insulated from the heatsink below. Using a differential thermocouple meter we could measure the temperature difference across the thermal compound joint with moderate influence from the heatsink aluminum. The test set is shown in Fig. 3. We found that the amount of thermal compound applied was critical to achieving the lowest thermal resistance. Too little or especially too much compound caused the temperature of the resistor baseplate to soar as we approached 600 watts dissipation. The correct amount can be visually evaluated as a “heavy haze” applied to both mating surfaces. A “light haze” is too little and opaque white is excessive. Our simple test set was incapable of confirming the 0.05 °C/watt/mil rating claimed by its manufacturer.

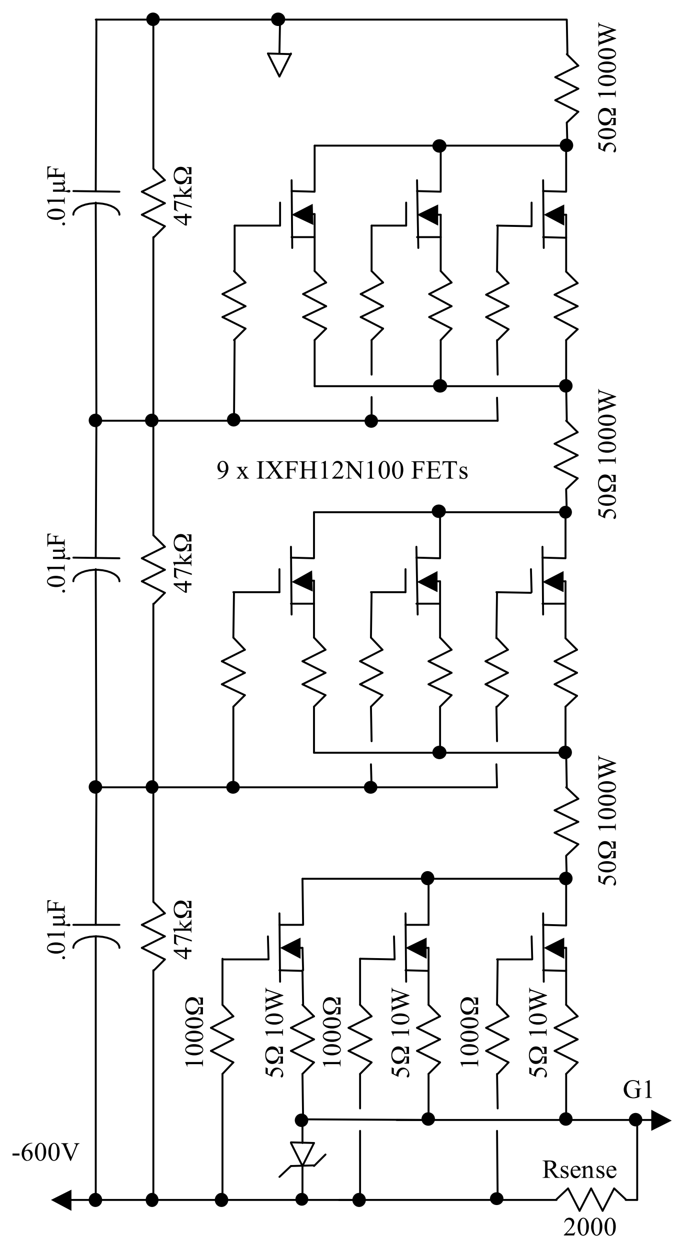

Figure 2. 600V, 4-amp grid regulator section, version 5. One of two parallels shown.

As a side experiment to improve our results we tested an advanced silver-loaded aluminum-oxide thermal compound designed for the computer enthusiast "overclocker" market [9]. This material is a dark grey color and required considerable rubbing to get adherence to surfaces. Although again our test set was inadequate to confirm the manufacturer's claim of 0.0045 °C/watt/mil, the results were considerably less sensitive to application technique than standard heatsink compound. We deliberately applied too little and too much, with little effect on the temperature rise of the resistor baseplate.


Figure 3. Heat sink / thermal compound application tests

## VI. Conclusions

- The old adage, "FETs can be readily paralleled because they are self-balancing" may not be valid in linear high-voltage, low-current applications.
- Many recent very high power FETs are optimized for switching service and are unsuitable for high-power linear service. A clue is the lack of DC specifications on their safe-operating-area curves.
- Newer may not be better than older. Older designs of power FETs may be more suitable for high-voltage linear service than newer ones because technological advances had not yet "improved" the older types.
- Bigger may not be better. Multiple smaller devices are still more reliable than fewer larger devices, despite advances in technology. Adding ballast resistors did not help the larger parts.
- Despite the small sample size of our destructive FET tests, the design philosophy we concluded has been demonstrated to be correct. The grid regulator has been in service for several years with no failures.
- High-performance silver-based thermal compounds originally developed for the computer-enthusiast market have broad applicability in power electronics. Their installation technique is much less critical than the older, widely-used zinc-oxide-loaded silicone types.

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