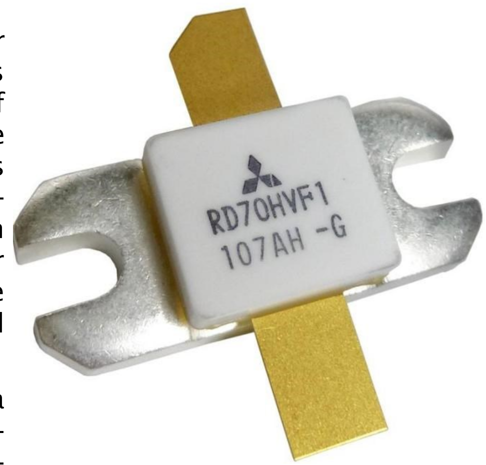
Brass Tacks

An in-depth look at a radio-related topic

How to protect your finals

Every once in awhile, I hear about somebody who has *blown his finals*. If you're not familiar with that term, it might sound at first like he's failed a couple of his college end-of-term exams. What he's actually referring to is something that happened inside his radio. It means that, somehow, his transceiver's output circuitry has been damaged to the point of rendering the transmitter section inoperable. Not good.

Every transceiver contains an *output circuit* with a power amplifier and a set of filters, the last stage in a signal's journey, before being sent out to an antenna. The heart of the power amplifier is one or more transistors we call the *final amplifier transistors*, or simply ***finals***, whose job is to raise (amplify) the signal level to that of the transmitter's current power level setting. (We also refer to vacuum tube finals this way, but this article addresses transistor finals, which are more susceptible to the type of damage described here.) If a rig's finals become damaged beyond use, we say that its *finals are blown*.



50-watt final transistor for an Icom IC-V8000

It's been passed around the ham radio community quite a lot, that your finals can get blown by connecting your radio to an antenna with a high SWR. While I can't completely disagree with that assessment, let me say that, by the end of this article, you'll understand just what it is that blows a rig's finals, and how, or even whether, SWR can play into that unfortunate event.

Background

Even though the transmitter section of your rig tends to be a lot simpler in design than your receiver, it's still complex enough to warrant some simplified discussion. Many of today's ham radio final amplifiers are made with FETs (field-effect transistors, or more specifically, MOSFETs, metal/oxide/semiconductor FETs), which are designed to carry a heavy current. If a large-enough voltage appears across the FET for long enough, it goes into avalanche breakdown, triggering the parasitic BJT to latch, destroying the poor, little FET.

But where does that high voltage come from? Many hams (wrongly) believe that the high voltage presented by the *reflected wave* from the mis-matched antenna can present that high voltage, because it adds to the initial voltage. However, the resulting higher voltage is not large enough to cause damage to the FET. One of the many conditions that can damage a FET is an ***excessively low impedance*** on the amplifier's output, resulting in a high current draw, which can melt the wire and die.

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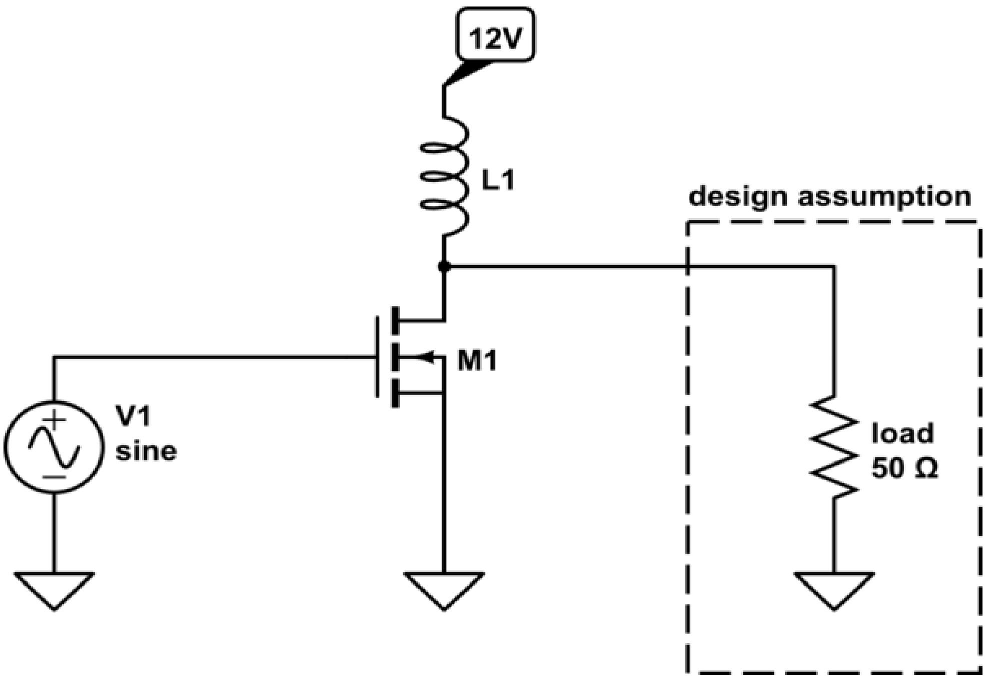
Let's take a different look at this destructive phenomenon, from an ***excessively high impedance*** point-of-view. Below is a simplified schematic diagram of a final amplifier circuit. V1 represents the transmitter section of your rig, all lumped together in a single sine wave generator. M1 is the MOSFET of the final amplifier, L1 is the pullup inductor (instead of a resistor, to reduce resistive losses), and the load is whatever you've connected to your rig output, including your coax, tuner, meter, and antenna. The output of this amplifier was designed on the assumption that the load presents a 50-ohm impedance.



Because V1 presents a sine wave to the gate of M1, M1 goes from an "off" state when the sine wave is at zero volts, to an "on" state any other time in the cycle, meaning M1 is almost always on. During the relatively long, nearly-half cycle that M1 is on, the current in L1 has time to rise to its maximum, say, 1 A, and stores that energy in its magnetic field. When M1 returns to being off at the end of that half-cycle, the voltage across the load will rise to (1 A) x (50 ohms) = 50 V. Therefore, at design time, M1 is specified as V_{ds} > 50 V, assuming our arbitrary value of 1 A through L1 is correct.

The open-circuit (no load) case

Now, if we remove the load, such that its impedance appears open, or infinite, no current can flow through the load, so the voltage between the source and drain of M1 will rise even higher, to maintain the current flowing through L1. In fact, the voltage across M1 will rise rapidly until M1 goes into avalanche breakdown, which voltage level ***is*** high enough to destroy M1. This is similar to the effect your friend experiences when you place a battery across the primary terminals of a transformer while your (now former) friend holds the secondary terminals.

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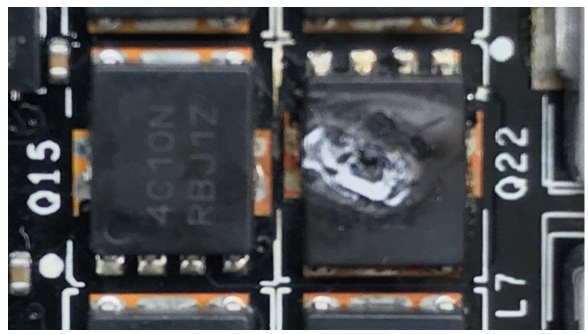
The no-load case might seem to contradict the low-impedance case, yet it's just as real, and no less destructive. Remember that this occurs during the short time when the MOSFET gate is turned off, and no current can flow through the device, causing the voltage to rise until the final breaks down.

Still, because of this case, it's best to ensure that you do not attempt to transmit from your rig without an antenna. Fortunately, however, the duration of the cycle when the gate is disabled is very short, so while damage due to a disconnected antenna system is possible, that likelihood remains small.

Effects of high SWR

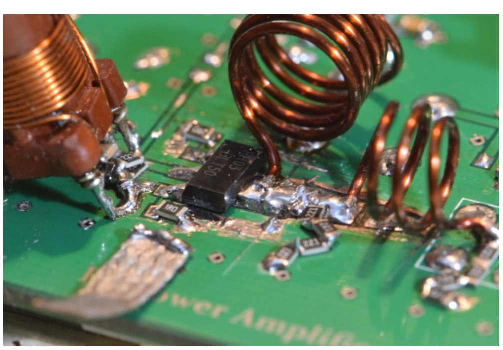


Because many believe that high SWR can destroy their finals, let's examine that theory. You and I probably agree that an SWR of 10:1 for an antenna is pretty high, and many will tell you that such an antenna will likely spell the end of your radio. Because we're considering the total effects of all the components after the signal leaves the rig, let's call them collectively the ***antenna system***.

All else being equal (fair to say in amateur radio transmission line applications), your antenna system's SWR can be calculated by the simple ratio between its impedance and the transmission line (feed line) characteristic impedance. And for the sake of amateur radio, let's assume that characteristic impedance is always 50 ohms. (You might be tempted to re-do some of the calculations using a characteristic impedance of 75 ohms, as is common with television coaxial cable, only to find the results change very little.)

This way, an antenna system of 100 ohms will result in an SWR of 100 ÷ 50 = 2:1, and a 250-ohm system will result in an SWR of 250 ÷ 50 = 5:1, and so forth. Moreover, due to the absolute value nature of the calculation, a 10-ohm system will result in an SWR of 50 ÷ 10 = 5:1.

As you can see, to result in an SWR of 10:1, your antenna system can have an impedance of **500 ohms** (500 ÷ 50 = 10:1) or **5 ohms** (50 ÷ 5 = 10:1). Let's see what happens when we apply these two cases to our final amplifier diagram, using your antenna system for the load. (Your antenna system can have a myriad of complex impedances between 5 and 500 ohms that will result in an SWR of 10:1, but I'm going to keep things simple here.)



With an antenna system impedance of 500 ohms, which is at your final output, the load will not draw much current from M1, and damage is unlikely. But with an antenna system impedance of 5 ohms, the load will draw a heavy amount of current from M1, resulting in a large voltage across its drain and source, which can cause M1 to burn up, due to the excessive junction heat generated by the high power (current x voltage) there. As you can see in these two photos on this page, burned finals can be invisible, very visible, or downright spectacular.

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So, can high SWR burn up your finals? Very possibly, if the antenna system impedance is low, but not likely if it's high, unless it's a near-open circuit, and there's nowhere for the pullup current to go. That means an SWR number alone (read on your SWR meter) can't tell you whether your antenna system can damage your rig. To determine whether a high SWR presents the potential for damage, you need to use an ***antenna analyzer*** to display the antenna system (not the antenna alone) impedance.

Fold-back

To help protect your investment from such a destructive force, I've mentioned two things you can do, which are to never transmit without an antenna attached, and to try and keep your antenna system SWR low. But we're human, and we make mistakes, so today's transceiver designers have included a self-protection mechanism called the ***fold-back circuit***. However, the circuit comes with a side-effect that seems to take a few hams by surprise.

The fold-back circuit monitors the transmission line reflections at the final amplifier output, and reduces the maximum output power according to the strength of the reflected signal. The fold-back circuit in most HF and mobile transceivers are designed to reduce the final amplifier maximum output power *incrementally*, rather than either on or off. Because the reflected signal is related to standing waves, the fold-back circuit might start to throttle the output power when the antenna system SWR reaches a particular threshold.

For example, say you've set your HF rig to transmit at 100 watts. But let's also say that your antenna system presents a 90-ohm impedance, making an SWR of 90 ÷ 50 = 1.8:1. When you transmit, your rig will likely transmit at a full 100 watts.

But let's say something occurred, that pushed your system impedance to 101 ohms, making an SWR of 101 ÷ 50 = 2.02:1. At that point, you might not realize that your output power has been reduced to, say, 70 watts (making these numbers up), due to the detected reflection. Then, say your impedance jumped to 145 ohms, for an SWR of 145 ÷ 50 = 2.9:1. Now your output power has been limited to, say, 15 watts. Finally, your poor antenna system jumps to 155 ohms, and your output power has been reduced to its bare minimum of 5 watts! The only indications of these might be that your power meter is barely moving, and nobody can hear you. Each HF rig is designed differently, but what I've described here is generally how fold-back works, to protect your finals from damage, not from reflected energy, but from a possible antenna system mis-match, *detected by monitoring the reflected energy*.

Summary

It's very possible to destroy the final output power transistors of your transceiver, or finals, but not always in the ways many hams believe. Transmitting without an antenna connected can damage them, but a high SWR with an excessively low impedance, rather than a high SWR with a high impedance, can also burn out your finals. You can check for which type of high SWR is exhibited on your antenna system by using an antenna analyzer. Contrary to popular mythology, the reflected power from a mis-matched antenna will not damage your radio. Finally, most of today's transceiver finals are outfitted with a fold-back circuit, to protect against possible damage by reducing output power in the case of an antenna system mis-match.

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