Vectawave
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Application Note

High Power Solid State Amplifiers under Mismatch Conditions

Introduction

Most radio frequency and microwave high power solid state amplifiers are designed to operate into a matched load. This frequently takes a value of 50 ohms, although it may be 75 ohms, a waveguide output, or otherwise. Although the load may well be other than a matched load, it is desirable that its impedance should differ by as little as possible. By this means, a system designer does not need to consider the electrical length of an intermediate transmission cable, as this will not alter the impedance presented to the amplifier.
In reality, it is frequently not possible to present a matched load to an amplifier, particularly where wide frequency ranges are concerned, so a degree of mismatch is encountered. In severe cases, the amplifier may be presented with a complete reflection. In addition, the amplifier is required to perform predictably under fault conditions, where the load may be disconnected or short-circuited. The purpose of this application note is to explain the implications of operating an amplifier into an output mismatch.

Mismatch Effects on Output Power

An ideal source can be represented as a current generator in parallel with an impedance matched to the load impedance, usually a pure resistance. The situation is as shown in *Figure 1*. The current generator output is shared between the internal source impedance and the output load. With the source and load impedances both assumed to be purely resistive, the power delivered to the load is given by:

$$P_o = \left(\frac{Z_0}{Z_0 + Z_L}\right)^2 Z_L I^2$$

Differentiating *Eqn.1* with respect to ZL and setting to zero reveals the maximum power transfer to occur when the source and load impedances are equal, and *Eqn.1* becomes:

$$P_{\max} = \frac{Z_0}{4} I^2$$

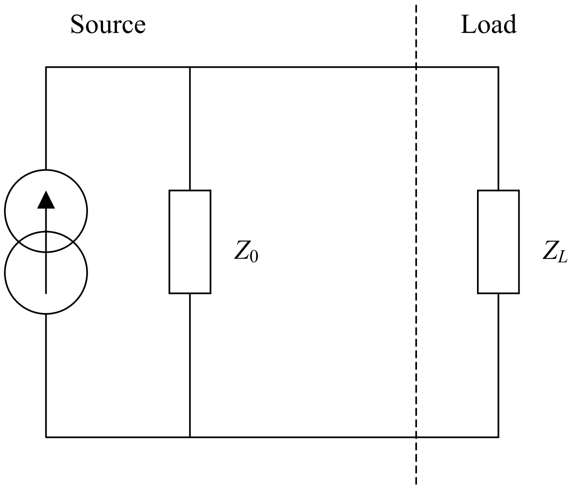

Figure 1 Output Model of Generator

Taking the ratio of *Eqns.1 and 2* gives the fraction of power transfer compared with the maximum, and can be expressed as:

$$\frac{P_o}{P_{\max}} = \frac{4\rho}{[1+\rho]^2}$$

where

$$\rho = \frac{Z_L}{Z_0}, Z_L > Z_0$$

$$= \frac{Z_0}{Z_L}, Z_L < Z_0$$

The quantity ρ can be shown to be equal to the VSWR of the load.

In a solid state power amplifier, the source impedance is frequently determined by a single transistor, the value of which is complicated by the presence of reactive components such as output capacitance and bond-wire inductance. At any particular frequency, it will be possible to devise a matching network to compensate for these components so that maximum power transfer is maintained. The situation is further complicated in the case of high power amplifiers, in that there is a limit to the amplitude of the voltage, imposed by the supply voltage. In this case, maximum power transfer occurs where the output impedance takes a value in the region of the supply voltage divided by the average DC current (The load line). This impedance is typically much lower than the impedance of the transistor stripped of its reactive elements. In addition, the output capacitance will also place a restriction on the maximum value of the resistive part presented to the current generator. In summary then, the output impedance of a high power amplifier will be different from a matched source.
A better model for a transistor output is a simple current generator. In this case, rather than the complicated expression given in *Eqn.1*, the output power is proportional to load impedance, where load impedance is smaller than the load line impedance. Where load impedance is greater than the load line impedance, the maximum voltage determines the output power. In either case, the ratio of power delivered to maximum power is given by $1/\rho$. This result is not altered by the presence of passive combiners, even though these components can be configured to improve small signal output match. The ratio of delivered to maximum power against VSWR for the case of a matched source and infinite impedance source is shown in Figure 2.

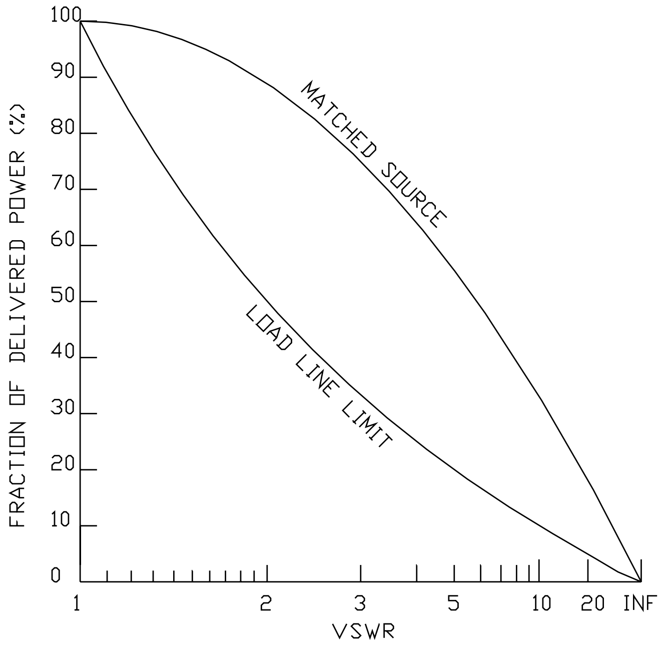

Figure 2 Delivered Power Against VSWR

In reality, there are further complications to this simplistic approach. For a start, the amplifier designer will always introduce margin into the output power capability. Furthermore, the output of a transistor consists of lossy elements, and so does any output matching network and transmission network.
With sufficient margin, it is possible that the capability of an amplifier into a mismatch is just as great as a theoretical source of the specified output power, at least for moderate VSWR.
As a result, the pessimistic prediction of the lower line in *Figure 2* may not be experienced in practice.

It is possible to remove the problem of mismatch in the design of an amplifier by incorporating an isolator into the output. The capability of such an amplifier will be greatly enhanced under mismatch conditions. This technique is only available to relatively narrow band amplifiers of up to extended octaves. In addition, physical size constraints make this technique only suitable for amplifiers operating at UHF and above.

Mismatch Effects on Stability

In a typical well designed amplifier, a mismatch to either the input or the output ports will not result in instability. Most high power amplifiers are multi-stage designs, where each stage adds a degree of isolation. Changing the match to either port produces no discernable change to the impedance of the other. This happy state of affairs can be frustrated if the isolation is compromised by careless connections to the amplifier, so that power is coupled from the output to the input by external means. Although in general a high power amplifier will be unconditionally stable, there are instances where this may not be the case. All solid state amplifiers incorporate devices that are only conditionally stable over much of their useful frequency range, even when properly installed. Their stability depends on a suitable combination of input and output matching networks. In most high power amplifiers, either the input or the output is not externally available to the user. However, where the amplifier is only a single stage, such as a power booster amplifier, both input and output may be available to the user. In this case, it is possible that a poor combination of source and load conditions could lead to instability. Particular care should therefore be paid to the termination of low gain high power amplifier modules.

Mismatch Effects on Reliability

When operated into a mismatch under large signal conditions, the output transistors of a high power amplifier experience increased stress. The phase of the reflection has a bearing on this stress. If the mismatch reflects a high impedance to the transistors, there will be additional voltage present. If the mismatch reflects a low impedance, then there is the potential for increased current and hence dissipation.

An excessive RF voltage can cause a transistor to break down. This failure mode is not usually a problem where wide band amplifiers are concerned; where low Q bias and matching circuits do not exhibit resonant qualities. Care should be taken with narrow band amplifiers, where resonant circuits can multiply the RF voltage to dangerous levels under poor load conditions.

The principle mechanism for failure in all amplifiers, but particularly wide band amplifiers is excess temperature through increased current into a low impedance mismatch. Amplifier manufacturers have to employ measures to prevent this in order to guarantee reliability under mismatch conditions. One technique is to operate the output transistors at a reduced supply voltage, so that resistances in the device, matching network and transmission system are sufficient to maintain RF current at a safe level under mismatch conditions. This technique gives a dramatic reduction in maximum output power, and so is only a partial solution. Another technique is to monitor the reflected power via an output coupler, and either reduce the input drive to the amplifier or switch it off completely if the reflected power exceeds a safe limit. This technique is suitable for amplifiers operating into a fixed load, where deviation is certainly a fault condition. It is not suitable for amplifiers required to operate into a variety of loads with varying characteristics. Many amplifiers employ some kind of current limit or regulation circuitry for the output transistors to prevent them conducting excess current.

It is a popular belief amongst amplifier users that Class A is inherently more reliable than say Class AB. Although this is often the case, it is not necessarily true. In Class A, the transistors dissipate most power when the amplifier is idle. This dissipation requires an extensive thermal design, with high capacity cooling. Under mismatch conditions, the amplifier is better equipped to deal with the thermal implications than a high efficiency design. Where the output transistor technology is bipolar, there is an added advantage to Class A bias. In Class A bias, a current regulator circuit is used to maintain the quiescent current. Under mismatch conditions the current does not change, so dissipation is no different to when the amplifier is idle.

In Class AB bias however, a low quiescent current is adjusted for using a low impedance base drive circuit. In order to compensate for temperature, the base drive voltage level is modified using a PN junction in close thermal contact with the main transistor. It is possible under mismatch conditions for the thermal path to be insufficient, and thermal runaway to be experienced.

Thermal runaway is not a factor in MOSFET amplifiers, and these typically exhibit high reliability under mismatch conditions. Reliability is not compromised for Class AB operation, provided that the cooling system is adequate and some method of current limit is employed.

In higher power amplifiers employing combiners, this component is often under great stress and then becomes a principal factor in amplifier reliability.

For any high power amplifier, benign operating conditions will lead to improved reliability. Although a mismatch condition may not result in an immediate failure, it is possible that prolonged subjection of this condition to the amplifier will result in a reduced mean time before failure (MTBF).

Safety Issues Relating to Poor Terminations

An amplifier with an output power of a few watts is potentially hazardous, being capable of delivering RF burns. The hazards increase in proportion to the output power. It is essential therefore to operate a high power amplifier into the correct load using transmission cable in good condition and of an adequate power rating. If the load is a radiating element, then sufficient clearance or operation inside a screened room is required. Amplifier mismatch tolerance is not a substitute for due diligence. The following guidelines should be adhered to in the use of high power amplifiers.

1. Always terminate whilst in use. The output connector and cable attached to an amplifier will be adequate for the available output power only in the matched condition. An amplifier rated at several hundred watts may have sufficient RFpotential to sustain (but not strike) an arc at the end of an open circuit. Where polyethylene insulated cable is used, the material will burn, creating a fire hazard, and aiding the supply of plasma to sustain the arc. The inner conductor of an open circuit constitutes a burn hazard at quite modest power levels.

2. Use cable of adequate power rating. Note should be taken not just of the output power of the amplifier, but also the frequency. Excessive power in a cable will cause degradation and eventually failure. Although improved power handling is possible using high temperature cables, the high temperature on the outer surface of the cable may present a hazard to personnel. In addition, high centre conductor temperatures may induce excess stress at connector interfaces, particularly where connection is made to a load that conducts some of the dissipated heat along its centre conductor. For this reason, the use of suitably rated low temperature cable is recommended, or high temperature cables derated to the power handling of low temperature cables of similar dimensions.

3. Use cable in good condition. The outer screen of a damaged cable (through misuse or wear and tear) can become broken. In this circumstance, the cable can actually become a radiator, and exhibit large RF voltages on its outer surface. Particular attention should be paid to the connector regions where greatest stress is placed on the outer screen through twisting and bending.

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