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What Makes a Good Solid-State Amplifier for the Contester? — Part 1

A solid-state HF amplifier differs fundamentally in its design concept from a tube amplifier. Vacuum tubes operate at high anode (plate) voltages and moderate anode currents; typically, a tube power amplifier (PA) stage requires an RF anode load resistance of approximately 2,000 Ω for optimum efficiency. Modern tube amplifiers are single ended, with one or more tubes. Multiple devices are connected in parallel; a tuned output tank circuit, such as a pi (or pi-L) network, is used to transform the load resistance to the nominal 50 Ω load. A working Q of 12 ensures adequate harmonic suppression.

The RF input circuit of a vacuum-tube amplifier may be either broadband or broadly tuned. Grounded-grid configurations with broadly tuned input networks and resistively swamped grounded-cathode topologies are most often encountered in modern amateur tube amplifier designs.

The topology of a solid-state PA stage is quite different. The relatively low voltages and high currents required by the RF power transistors (typically 50 V at 40 A for a 1-kW amplifier) dictate a low collector (or drain) load resistance, of the order of 3 Ω for a 250-W PA module. The difficulty of matching the low impedances involved here to a 50-Ω resistive load over a wide frequency range has dictated a broadband, base-driven (or gate-driven) architecture, using ferrite-cored input and output matching transformers. A working Q of unity or less is not uncommon; these matching networks thus offer *no* harmonic suppression.

The output-transformer secondary expects to "see" a 50-Ω resistive load. The input-transformer primary presents a 50-Ω resistive load to the source over its entire frequency range; thus, tuned input networks are not required. The exciter always sees 50 Ω resistive. It is therefore unnecessary to engage the transceiver's auto-tuner when driving a solid-state amplifier.

The RF matching transformers used in solid-state PA stages are wound on rectangular "binocular" two-hole ferrite cores. Bifilar or trifilar windings made with miniature coaxial cable are used. These are designed in such a way that the series reactance and resistance of the windings is very small compared to the already very low RF load resistance, or input resistance, of the power devices. Ferrite cores must always be sufficiently large to avoid saturation at full RF drive or output. Such saturation is a major cause of intermodulation distortion. The transformer cores are thermally coupled to a heat-dissipation device and/or mounted in the cooling-air stream, to remove heat caused by iron loss[1].

The PA stage is always push-pull. This minimizes even-harmonic generation. A matched pair of RF power devices is always used. Typically, a PA module (one pair of devices) is designed for 250 W RF output, two modules are combined for 500 W, and four for 1 kW. Each module, in fact, is a larger version of the PA stage found in popular 100 W-class HF transceivers (see Figure 1).

In a 500 W-class amplifier, a three-port hybrid-transformer power splitter divides the drive power equally between two 250-W modules. A three-port hybrid power combiner adds the two module outputs to produce 500 W. A 1 kW-class amplifier is made up of four 250-W PA modules; the splitter and combiner are five-port circuits. The transformer construction in the splitter and combiner is as described.

Why three and five ports? The splitter has one input and two or four outputs. Conversely, the combiner has two or four inputs and one output.

The combiner output is fed to a bank of band-switched low-pass filters (LPF). These filters are designed to suppress harmonics and spurious emissions to levels required by radio regulations (typically –46 dBc or lower). The output of the filter bank is routed via the output T/R relay to a reflectometer, and thence via the internal auto-tuner (if installed) to the antenna connector.

The splitter and combiner ports must be correctly terminated in 50 Ω resistive. A mismatch can cause saturation of the transformer cores, leading to intermodulation distortion (IMD) degradation, and can also produce excessive dissipation in the hybrid balancing resistors.

The input connector is wired via the input T/R relay to the input port of the splitter. Some inexpensive amplifier designs consist of one PA module with four MOSFETs in push-pull parallel. There are some concerns when connecting these

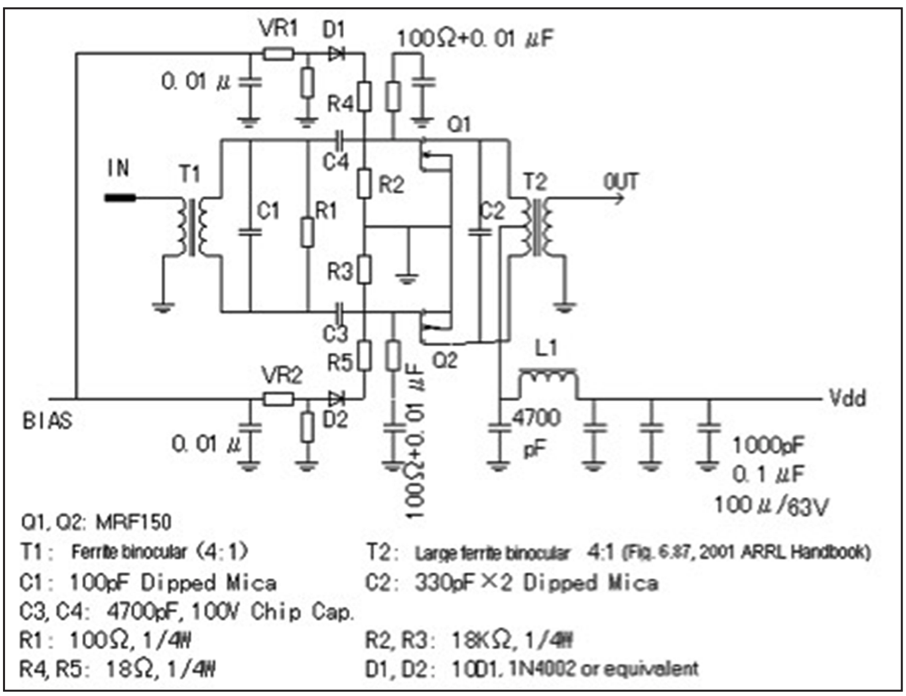

Figure 1 — A typical 250-W MOSFET power amplifier module.

devices in parallel, as their VHF power gain can be sufficiently high to send the parallel-connected pair into a self-destructive parasitic-oscillation mode. Paralleled MRF150s can break into oscillation at ≈ 450 MHz, unless isolating resistors (typically 2.7 Ω) are connected in series with the gates. These resistors reduce stage power gain by a few dB[2].

For this reason, two to four push-pull modules (two devices per module) with a hybrid splitter and combiner (or one push-pull pair of high-power devices) are the preferred topology.

Recent advances in LDMOS (laterally diffused metal oxide semiconductor) power devices have made possible the design of 1 to 1.5 kW-class amplifiers using a single (dual) power device operating at V_{DD} = 50 to 65 V without the need for a splitter or combiner. The elimination of these networks, along with their insertion loss, improves the efficiency, power gain and linearity of the amplifier.

So there we have it — the basic, broadband, no-tune (or self-tuning) solid-state HF amplifier.

Building Blocks of a Typical Solid-State Amplifier

Adequate Cooling and Duty Cycle: The efficiency of a solid-state Class AB amplifier typically runs around 45 to 50%. Thus, the PA stage should incorporate a heatsink or heat-dissipation system capable of dissipating at least half the dc input power, while maintaining a safe transistor case temperature.

Typically, the PA cooling system should be designed to keep the device case temperature in the range of 70 to 80° C (158 to 176° F) at 25° C (77° F) ambient, for a 30-minute SSB voice transmission or a 5- to 10-minute "key-down" CW transmission at rated output. These are minimal duty-cycle values for an amplifier operating in average amateur service. Longer key-down intervals, necessitating larger heat-dissipating surfaces and greater air circulation, are required for contest operation or at high ambient temperatures. Some amplifier manufacturers specify the power-output rating as ICAS (Intermittent Commercial and Amateur Service).

The physical configuration of the amplifier's cooling system can be a large, finned planar heatsink, with fans blowing air across it, a cylindrical heatsink structure through which a fan moves a large volume of air, a circulating-water cooling system, or a thermodynamic heat exchanger. The last is an innovative approach, in which the power devices are mounted on hollow blocks through which a refrigerant circulates. The evaporation of the refrigerant cools the devices, and the vapor is recondensed by blowing cooling air through a finned condenser. This transfers the heat generated in the devices to the ambient air.

These forced-air cooling methods necessitate the use of one or more fans. One fan generally suffices at the 500-W power level; a 1-kW amplifier requires two or three fans. These are usually dc-powered "muffin" fans. Excessive fan noise can be an issue with some amplifier designs. The prospective buyer should test the various amplifiers in a quiet environment, if possible, to judge whether the fan noise would be disturbing in the ham shack. Various fan-control schemes are in use; fans may run continuously, or only when the amplifier is keyed. In some designs, fans run at half speed in standby, and at full speed in transmit. Yet another option is to speed up the fans when the power device case temperature reaches 50° C (122° F) — see Figure 2.

Thermal Packaging: In addition to adequate air-mover (fan) capacity, air intakes and outlets of sufficient area to ensure proper airflow must be engineered into the mechanical packaging of the amplifier. Any dust filters should be easily accessible for cleaning; an airflow detector (such as a vane switch) is an excellent refinement to the amplifier's protection system.

A solid-state amplifier must be fitted with over-temperature protection, which will reduce RF drive and/or initiate shutdown if the transistor case temperature exceeds the safe operating limit. This will be discussed in greater detail later.

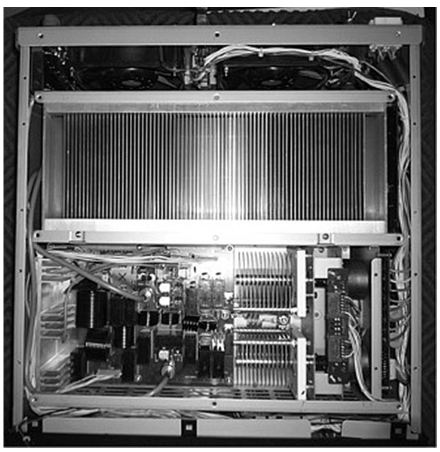

Figure 2 — Yaesu Quadra interior, showing the power amplifier heatsink, fans, and auto-tuner.

Electronic Packaging: All printed-circuit boards used in a solid-state amplifier must be top-quality FR4/G10 fiberglass, with solder-plated tracks of sufficient width and thickness to carry the very high RF and dc currents encountered in the PA stage. PA board stock should be at least 3 millimeters thick. Low-inductance layouts should be used in all cases other than for onboard inductors. Push-pull circuits should exhibit a reasonably symmetrical layout. RF-component lead lengths should be as short as practicable.

Shielding: Each amplifier subsystem (PA stage, LPF module, auto-tuner, controller, power supply unit) should be totally enclosed in its own shielded compartment within the amplifier chassis. Power and control leads should enter these shielded enclosures via feed-through capacitors; RF interconnecting cables should have their braiding grounded at shield entry points. Lead dress should be observed.

These shielding measures will maintain RF integrity, minimize internal RF feedback, and ensure regulatory EMC (electromagnetic compatibility) compliance.

Linearity: Several factors determine the linearity of an HF "linear" amplifier. These include changes in device power gain (ratio of output to drive power) over the range from zero to full output, the collector/emitter (bipolar junction transistor — BJT) or drain/source (MOSFET) peak RF voltage excursion, the regulation (stiffness) of the collector (+V_{CC}) or drain (+V_{DD}) supply voltage, the standing (idle) current and the onset of saturation in the RF transformers.

The limiting factor is the constancy of power gain over the entire power-output excursion. To visualize this, one can inspect the curve of output vs drive power in the transistor data sheet. Generally, MOSFETs will exhibit superior linearity as compared to bipolar junction transistors (BJTs). MOSFETs such as the Motorola MRF150 began to displace BJTs (e.g., MRF448, 2SC2652) in the late 1990s. Newer MOSFET devices include the ST Microelectronic SD2931, SD2933, and SD2943[2].

LDMOS power devices such as the NXP MRF1K50H (50 V) and MRFX1K80H (60 V) have enabled several amplifier manufacturers to offer single-device HF amplifiers with up to 1.8 kW output (see Figure 3).

The higher the voltage excursion, the

Figure 3 — Typical RF power devices (L-R) MRF150 (150 W MOSFET), MRF448 (200 W BJT), MRF1K50H (1.5 kW LDMOS).

longer the linear portion of the output/drive power curve. For this reason, amplifiers powered from 40 V dc or higher exhibit considerably better linearity, and thus lower IMD, than 13.8-V units. Typical third-order IMD (IMD3) values relative to PEP are –32 to –35 dB for 50 V and –24 dB for 13.8 V. Additionally, the much higher current requirements of a 13.8-V design (typically 100 A peak for 500 W PEP) render power supply design much more difficult.

Extending this principle further, a tube amplifier, with its peak plate-voltage excursion of thousands vs tens of volts, is somewhat more linear than any solid-state design (typically, $IMD_3 < -40$ dB relative to PEP).

The collector-to-collector (or drain-to-drain) load impedance must be maintained as close to resistive as possible. This, in turn, requires optimizing the wideband output transformer(s), combiner (if used), and low-pass filter passband VSWRs to as low values as possible. The load presented to the low-pass filter output must also be as close as possible to 50 Ω resistive. Improper termination of the low-pass filter will degrade the filter's amplitude/frequency and phase/frequency response and will generate excessive RF voltages and/or currents, which can cause serious damage[3]. The exciter's IMD products also can degrade the overall system IMD performance.

Efficiency: There is always a trade-off between amplifier efficiency (the ratio of RF output power to dc input power) and linearity. Solid-state amplifiers are generally operated Class AB (180° < conduction angle < 360°). This is a compromise between Class A (360°, most linear, least efficient) and Class B (180°, most efficient, least linear owing to crossover distortion). The devices are biased on to a standing current sufficient to minimize crossover distortion. It is possible to adjust the bias for minimum IMD_3 by performing a two-tone test at full rated PEP, and observing IMD3 on a spectrum analyzer during the adjustment procedure.

As mentioned, the efficiency of most solid-state HF amplifiers is approximately 45 to 50% at rated PEP. This compares favorably with many tube amplifiers, when one factors in the filament and screen power requirements of the latter.

Adequate Power Output: Solid-state amateur HF linear amplifiers generally fall into two power classes: 500 W PEP and 1 to 1.5 kW PEP. All of the current high-end offerings are in the latter class.

The power output is limited by the maximum ratings of commonly available RF power transistors, and by the linear operating region of these devices. The most cost-effective designs employ a single LDMOS device. The earlier topology with multiple devices rated at 150 W to 250 W output each is still current. As discussed, devices are arranged in groups of two or four push-pull pairs, each module being capable of 250-W output.

In the 1980s, popular 500 W-class amplifiers used two pairs of BJT RF power transistors. The operating instructions recommended operation at 500 W CW or PEP SSB output. Even though the 200 W-per-device maximum rating offered some headroom, users were advised against exceeding 500 W, as severe IMD degradation would result. In current 1 kW-class MOSFET amplifiers — eight MOSFETs each rated at 150-W output — are arranged in four pairs. Headroom is somewhat less than for 200 W BJTs, although IMD does not degrade quite as rapidly for $P_o > 1$ kW. Typically, these amplifiers are comfortable at 1.0 to 1.1 kW PEP. MOSFETs and LDMOS devices have a higher cut-off frequency than BJTs, allowing full-power operation on 6 meters.

Power Gain: This is the ratio of RF output to RF drive power. The system power gain of a given amplifier is the power gain of the PA devices minus the insertion loss of the input splitter, output combiner and output filters. The auto-tuner insertion loss must also be factored in, as applicable.

The power gain of any RF transistor decreases as frequency increases. This can be seen from the curve of power gain vs frequency in the transistor data sheet. Typical values for system power gain at 14 MHz are 10 dB for BJTs, 12 dB for MOSFETs, and 15 dB for LDMOS. (System power gain = device power gain – insertion loss of matching network, input pad, and harmonic filter.) This equates to drive power levels of 100 W (BJT), 65 W (MOSFET), and 32 W (LDMOS) for 1-kW output. MOSFET power gain will typically increase by about 2 dB at 3.5 MHz, and decrease by 2 dB at 28 MHz (4 dB at 50 MHz). The frequency-dependent power gain roll-off of MOSFETs is somewhat less severe than that of BJTs.

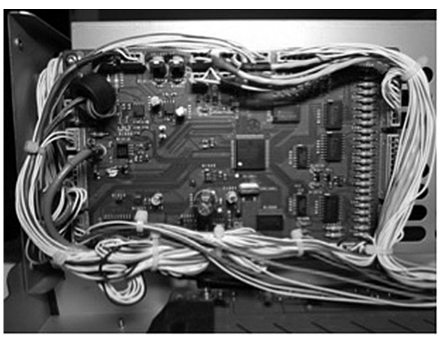

Figure 4 — Yaesu Quadra controller module.

The "good news" for radio amateurs considering a solid-state amplifier is that a 100 W-class solid-state transceiver will drive it to full rated output.

Reduced-Power Operation: Some solid-state amplifiers feature a "low power" setting that reduces the drain (or collector) supply voltage to lower the maximum output by 3 dB. This is preferable to merely reducing the drive power by the same amount.

The problem is that the limiting condition for reduced-power operation is the onset of crossover distortion, which will degrade system linearity. Crossover distortion is significant at low drive levels. In Class AB operation, the bias is set to provide the best compromise between standing current and small-signal linearity; some crossover distortion is inevitable at settings that hold standing current (and its resulting dissipation) down to acceptable levels. It is thus best always to drive the amplifier to a point near the top of its linear operating region, where E_{DD} (P-P) is just less than $2 \times V_{DD}$. This increases the margin on the device transfer characteristic between the peak voltage corresponding to PEP and the point where crossover distortion becomes significant. Lowering V_{DD} will achieve this objective, while lowering the power output by the desired amount.

QSK Capability: Some earlier solid-state HF amplifier designs used open-frame input and output T/R relays. These relays operated somewhat too slowly to follow full-break-in keying much in excess of 10 to 15 WPM.

Current designs utilize miniature sealed high-speed relays rated for a life of many millions of operations. Carrier-on timing in the exciter prevents "hot-switching" by delaying the application of drive until the relays have switched. This will prolong relay life. In addition, some designs provide a transmit-inhibit line to a compatible exciter. This line enables the RF drive only when all relays in the amplifier's signal path have settled after keying.

Some amplifiers also offer a feature that "exercises" all relays in the amplifier, low-pass filters, and auto-tuner by operating and releasing them periodically when the amplifier is idle, but powered-up. A few amplifier designs feature PIN diode T/R switching. PIN diodes are much faster than relays, but a load mismatch can destroy them instantly.

Monitoring and Protection Features: The PA stage is fitted with sensors that measure a variety of operating parameters, and forward their readings to the system controller (microprocessor or logic board). These parameters include dc supply voltage and dc PA input current (total and per-module), RF drive power, RF power-device case temperature, per-module output power, and total forward and reflected power (at the combiner output, the LPF output and the auto-tuner output). The controller also drives metering functions (see Figure 4). At a minimum, these should include the dc supply voltage, dc PA input current, RF power output, load SWR, and ALC (automatic level control). In a well-designed amplifier, reflectometers located between the PA combiner output and the LPF input, the LPF output and the auto-tuner input, and also at the auto-tuner output send forward- and reflected-power signals to the controller.

These signals control auto-tuner settings; they also drive power-output and SWR metering and monitoring functions, and the ALC line. If the wrong LPF has been selected for the operating band, the reflectometer at the combiner output will detect high reflected power and signal the controller to shut down the amplifier. Likewise, if the load SWR exceeds the matching range of the auto-tuner (typically 3:1), the reflectometer at the auto-tuner output reports high reflected power and signals the controller to lock the amplifier out. This feature protects the amplifier and auto-tuner against possible damage due to antenna-system failure.

At a minimum, the protection subsystem should detect overcurrent, overvoltage, over-temperature; overdrive, insufficient power gain, power gain imbalance between PA modules (where applicable), incorrect band selection (exciter and amplifier not set to the same band), excess forward power, excess reflected power, and auto-tuner out of range (load VSWR > 3:1).

There are two stages of protective action — automatic drive fold-back via the ALC line, followed by amplifier shutdown or lockout. For example, drive fold-back may commence for SWR > 1.5:1, with 3 dB reduction in output at SWR > 2:1 and lockout at SWR > 3:1. In some designs, the controller signals the power supply unit (PSU) to drop the collector/drain supply voltage to the "Low Power" value, thereby reducing output by 3 dB for VSWR > 2:1. This has the added benefit of reducing the impact of any increase in IMD due to the mismatch at the amplifier output[3]. Note that the drive fold-back prior to lockout or shutdown also protects the amplifier's transmit/receive relays against hot-switching during a forced transition from transmit to receive/standby state.

Other Protective Features: Some amplifiers incorporate a simple "brute-force" drive-limiting circuit in the RF input signal path. This serves to absorb initial RF power overshoots or spikes generated by certain older exciters. Other designs provide a high-speed, high-current SPDT relay in the RF input signal path as an additional protective measure. Under lockout conditions, the controller will operate this relay to remove the drive signal from the splitter input and divert it to a 50-Ω termination. (In amplifiers that do not reduce the drive via the ALC line at the onset of anomalous operation, this relay will be hot-switched, shortening its life. In some cases, the relay may not open sufficiently fast to prevent damage to the power devices.)

A power attenuator in the primary circuit of the input transformer or splitter stabilizes the input load impedance and sets the PA stage power gain as required by radio regulations. In some amplifier designs, an additional attenuator is switched in to reduce unwanted RF output during the ATU tuning cycle.

Automatic band selection is a feature of almost all solid-state amplifiers. This may be implemented in several ways. The exciter can supply coded band information to the amplifier via a proprietary protocol, or the amplifier's controller can count the excitation frequency and thus determine the correct band. The band-data input is one of the amplifier's external interfaces.

Once the controller has determined the operating band, it selects the correct LPF for that band. In an amplifier with an internal auto-tuner, the controller also presets the tuner to the setting last stored for that band. (If the controller is aware of the drive frequency, it sets the tuner to the previously stored tuning point closest to that frequency.)

In general, care should be taken to avoid transmitting during a band change or auto-tuning cycle, to allow the amplifier to drop back to the standby state once the cycle is complete.

In Part 2, we'll discuss ALC, low-pass filtering, auto-tuners, external interfaces, and power supplies for amplifiers.

NOTES

[1] *The ARRL Handbook for Radio Amateurs* (2001), Fig. 6.87.

[2] Motorola Engineering Bulletin EB-104.

[3] *HF Radio Systems & Circuits*, Sabin & Schoenike, eds. Chapter 12, Noble, 1998.