Developments in high bandwidth power amplifier technology for compact cost effective calibrator applications.

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Abstract:

The workload of a modern calibration laboratory has placed ever greater demands on the Calibration Source, both in terms of functionality and the combination of voltage, current and frequency required to calibrate today's diverse range of instruments.

This need for high voltage and high current at high frequency into demanding loads such as clamp meters and current coils, combined with a desire to produce ever more economic and compact calibrators, has resulted in a number of significant developments in the transition from the vacuum tube designs common in the past to today's solid state designs employing the latest semiconductor and transformer technologies.

This paper explores the development of technologies enabling the design of high bandwidth power amplifiers compact enough to be integrated within the calibrator in a single enclosure, eliminating the need for a separate Boost Amplifier, and their impact on calibration applications.

Introduction:

During the 1970s a number of alternating voltage calibrators were successfully developed and deployed, but where a high voltage output was required a separate power or boost amplifier was always involved. These designs were based on vacuum tubes, often utilizing tubes designed as UHF radio transmitters because of their availability in suitable power ratings and their physical suitability for mechanical mounting. Reliability was poor and many manufacturers products earned a well deserved reputation for fragility - and with one exception those manufacturers either collapsed or chose to leave the calibration business. The most successful AC voltage calibrator/amplifier partnership continued into the 1980s and was the competitive target for a new generation of AC voltage calibrator released in 1984 - the Datron 4200.

This new design employed fully solid state technology with an integrated power amplifier capable of delivering 1000V at frequencies up to 30kHz extending to 100kHz at 750V. The size of this unit was identical to its closest competitor which could only provide 200V - the additional vacuum tube boost amplifier required to obtain 1000V capability occupied almost twice the volume of its partner. Analysis of workloads revealed that high voltage capability at high frequency was an essential requirement for complete calibration of the precision DMMs appearing on the market at that time - one in particular which required 700V at 100kHz. And this even in the days before ISO9000 was driving the need for complete calibrations!. However, output current requirements were within the capabilities of semiconductors - vacuum tube designs were overkill for the actual workload in this respect.

The technology which enabled such a compact power amplifier design was the power MOSFET transistor. The following sections of this paper discuss the design requirements and their implementations in more detail. Initially, for the voltage amplifier used in the Datron 4700 series multifunction calibrators launched in 1986 (developed from the original AC voltage calibrator design) and employed with further development in the Wavetek 4800 series introduced in 1991. The paper continues by exploring the current source amplifier used within the recently introduced 9100 universal calibrator capable of delivering 20Amps at 10kHz from an enclosure smaller than the original AC voltage only design whilst coping with the demanding load that an external current coil can present.

Design and Development of the Solid State Voltage Power amplifier:

The design requirements for the multifunction calibrator (4800 series) were to provide a power amplifier capable of sourcing the output voltages for the DC and AC 100V and 1000V ranges. This required a high bandwidth design capable of providing up to 200V RMS at 100kHz reducing to 20V at 1MHz directly from the same amplifier that could also operate as a low noise DC source for the DCV ranges and drive a step up transformer to provide the 1000V range at frequencies up to 30kHz, extending at reducing voltage to 100kHz at 750V. (In the 1000V DC range the power amp/transformer provide a signal which is rectified and filtered to generate the DC output). Additional constraints were weight, size and load into which these levels must be driven. The most stringent requirement is the 1000V capability requiring delivery internally of 180V RMS at 1A into the 6:1 step up transformer primary to satisfy the required, mainly capacitive, load current. (At high frequency the dominant load is the capacitance of cables connecting the calibrator to its workload and internal signal path capacitance.

The design chosen utilizes complementary MOSFETs, chosen over bipolar devices for their reliability, lower distortion and more forgiving thermal characteristics - unlike bipolars which exhibit thermal runaway to destruction, MOSFET characteristics reduce drain current for a given gate voltage as junction temperature rises. Low distortion is important to ensure output sinewave purity and eliminate errors in any mean sensing DMMs which appear in the calibration workload. (The true RMS value of the calibrator output is controlled by internal sense and leveling circuits, but mean sensing instruments are calibrated in terms of a pure sinewave and relatively modest amounts of distortion introduce significant errors due to the response of the mean sensing circuitry to harmonics.) The amplifier output stage topology is shown in Figure 1. Supplies of plus and minus 400V are required to allow sufficient output voltage swing, which demands use of devices with 500V ratings series connected with voltage sharing provided by the resistors marked Rx. Devices are paralleled to increase the current capability. Those familiar with high performance audio design will recognize elements of this topology. The voltage capability of P-channel MOSFETs is much more restricted than N-channel devices due to semiconductor physics - the lower charge carrier mobilities of P-type material impacts device geometry and has limited currently available devices to 500V. The N channel devices employed are actually rated at 800V and are chosen not for voltage rating but to match the capacitance of the P-channel devices and provide a truly complementary design. The high input capacitance of MOSFETs, typically 1nanofarad per device, poses a difficult load for the driver stages and imposes a limit on the achievable slew rate which is more restrictive than attaining the bandwidth target - if the amplifier or any of its parts slew rate limit distortion will be introduced into the output waveform which the local negative feedback around the amplifier will not be able to reduce - in effect the amplifier fails to keep up with itself. Other novel features include a distortion canceling circuit which cancels distortion introduced in a pre-driver cascode stage resulting from the drain-gate capacitance of another MOSFET which varies non linearly with voltage. The achieved Volt-Hertz profile is presented in Figure 2.

Design and Development of the Current Power amplifier:

Design objectives for the 9100 universal calibrator were to produce a precision high current source capable of delivering up to 20A at DC with compliance voltages up to 4V, and up to 20A AC from 10Hz to 10kHz (30kHz at lower currents) into a 700µH load with compliance voltages up to 2.5V RMS. (Inductive load capability is limited at higher frequencies by the compliance voltage developed across the load). High output impedance is critical in producing a constant current source to avoid compliance errors. The workload requiring this capability are the common current clamp meters or clamp accessories which typically measure currents up to 1000A. To achieve these high currents a pair of ten and fifty turn current coil accessories were designed to accompany the calibrator. Magnetic shielding within the coil minimizes the influence of stray fields and allows a physically small low inductance design. However, the coil inductance is significantly modified (increased) by applying the clamp, with the hall effect clamps presenting the most difficult loads. Producing a compact calibrator design was the other objective of enabling a small and easily transported single enclosure unit to supply the wide functionality needed to address the diverse workload now common in calibration labs - from handheld DMMs through analog meters and frequency counters to oscilloscopes.

The topology chosen was a ground sensed voltage to current converter employing bipolar transistors in the power output stages, shown in block form in Figure 3. In this case bipolar transistors were chosen over MOSFET devices due to their better cost/performance ratio in this application. Bipolars have a lower thermal resistance than MOSFETs for a given current requiring fewer devices for a given power dissipation capability, and they have lower capacitance - bipolars do not suffer the high gate input capacitance of MOSFETs and have lower output capacitance which simplify driver circuits and improve output impedance of the current source.

The output stage is constructed from complementary current mirror stages with low current drive from a preceding error amplifier stage. Figure 4 shows a simplified current mirror stage - more devices are actually used to achieve high current output. A novel bias technique referred to as 'Class Aa' is used to provide Class AB type operation except that the output devices never enter Class B operation - a small bias current ensures devices do not fully switch off. This enables relatively slow bipolar devices to be used in a high bandwidth amplifier with low distortion, whilst maintaining low power dissipation (important in a small enclosure) and requiring low power supply overheads.

Power supply design is also simplified since these current mirror stages are effectively self regulating avoiding the need for regulation of the high current supplies. Stage gain and linearity, and hence distortion performance and output impedance, is improved by utilizing active current mirrors composed of several devices (to obtain the required current capability) and an operational amplifier. The bandwidth of these stages is much wider than the overall amplifier, however the gain bandwidth product for the overall amplifier is still large and its performance is desensitized from the individual device characteristics contributing to distortion and output impedance performance over the required wide frequency range.

Systems Integration - delivering circuit performance in the final product design:

Physical layout and mechanical design is critical to enable the performance inherent in the power amplifier design to be delivered to the output terminals. In the universal calibrator employing the current amplifier described above the high current power supply and output current signal routing involves novel design features. For example, to avoid voltage drops in printed circuit tracks and associated local temperature rises due to the power dissipated in the track resistance. Special pcb design and manufacture techniques are employed to avoid the use of busbars or loom wiring. In AC applications the magnetic fields surrounding high current carrying conductors can cause serious problems by inducing unwanted voltages and currents in other parts of the circuitry. This is eliminated by careful layout design minimizing loop areas, which also reduces stray inductance, another significant factor.

Systems design and operation also contribute. The output turn on and turn off sequences within the firmware for the universal calibrator employing the current amplifier described above are designed to enhance the load tolerance of the product. In the quiescent state a zero input signal is applied to the voltage to current converter input in parallel with an input clamp 'short circuiting' the input. An internal short is connected across the current source output and the output terminals are isolated. The turn on sequence in response to front panel or GPIB operation starts from this quiescent state by connecting the output terminals, followed by removal of the internal short. The input clamp is removed and the input signal is then ramped up (around 70msec) at a rate slow enough to avoid any voltage transients on an potentially inductive load, but fast enough to present the output quickly.

Turn off is the reverse. This approach avoids nuisance tripping of overload detectors or potential damage to either the internal circuitry or the load. The output is monitored by voltage detectors which can trigger the controlled shut down and initiate a user warning if an unsuitable load is connected which cause a high compliance voltage or disturbance on the output signal.

Conclusions:

Even in today's calibration equipment marketplace, an integrated 1000V wide bandwidth capability is unique - both in precision multifunction calibrators and in the universal/multiproduct calibrator areas.

Achieving a robust wide bandwidth high current capability within a small single enclosure together with wide functionality is also unique. Recent analysis of field failure data for the calibrators employing the described design confirm that reliability has not been compromised - an MTBF (mean time between failures) figure in excess of nine years was reported.

Utilizing the techniques described above has enabled these compact designs to be developed and provide reliable cost and space efficient solutions to calibration equipment users, whilst offering improved load driving capability and wider Volt-Hertz and
Amp-Hertz profiles than alternative two unit solutions.

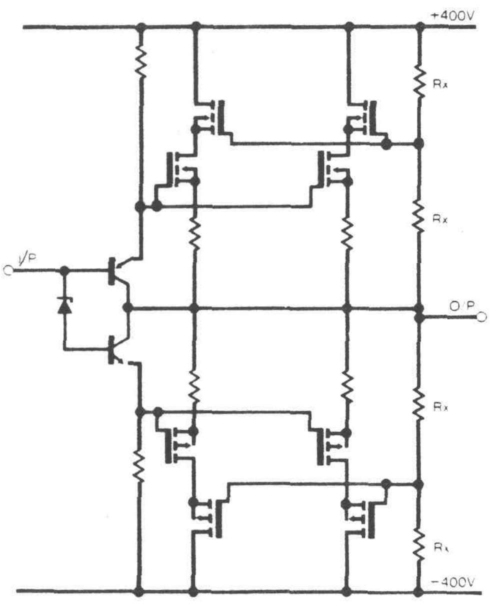

Figure 1.
4808 Voltage Power Amplifier Output Stage.

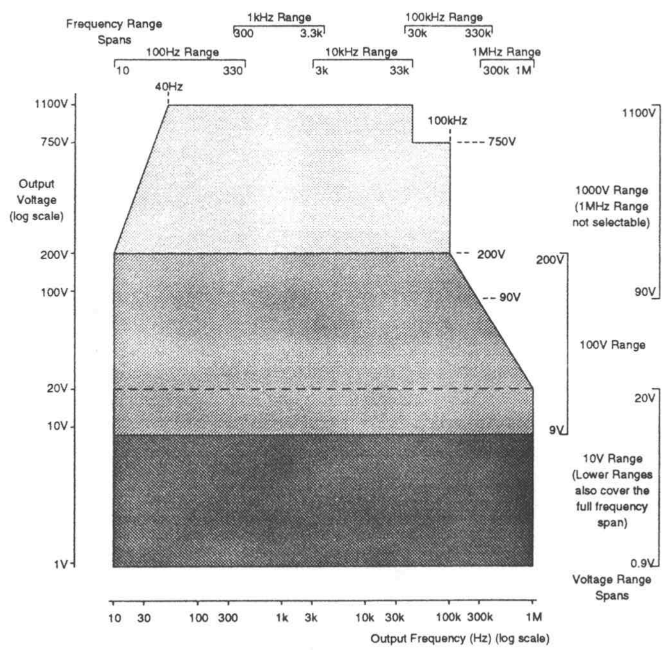

Figure 2.
4808 Volt-Hertz Profile.

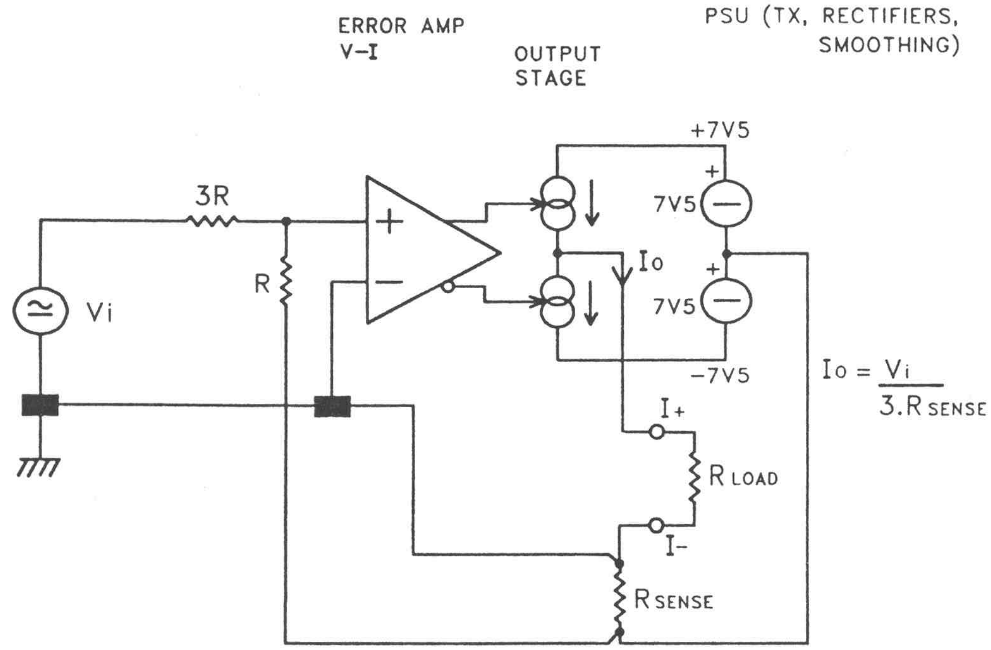

Figure 3.
9100 AC/DC Current Source Topology.

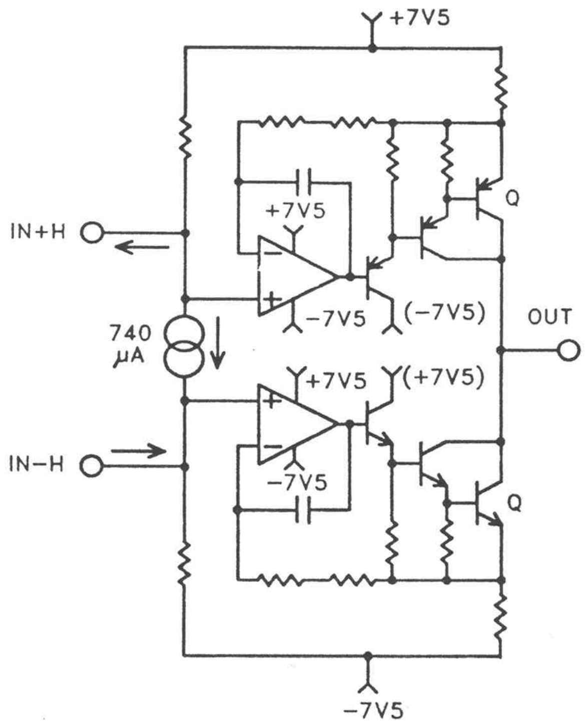

Figure 4.
9100 High Current Output Stage.
In practice devices marked Q are multiple transistors connected in parallel with emitter degeneration resistors.