Commercializing Class D Amplifier Technologies

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ABSTRACT

The popularity of commercial audio systems having large numbers of channels has resulted in a growing demand for smaller, lighter, and less expensive multichannel power amplifier products. This paper describes how careful integration of power factor corrected switchmode power supplies, class D power amplifiers, and digital signal processors yields high power density and especially reliable and electromagnetically quiet products at a reasonable cost.

1. INTRODUCTION

Schools, airports, hotels, nightclubs, theme parks, and houses of worship are among the many types of venues employing increasingly complex audio systems. Such systems are characterized by the large number of independent audio channels required to deliver separate music and voice signals in various regions. At the same time, the popularity of multichannel sound is growing. These trends reinforce a growing demand for smaller, lighter, and less expensive multichannel power amplifier products. Earlier generations of products used switchmode power supply technology to reduce size, weight and heat dissipation, while continuing to employ Class AB and other analog power amplifier topologies. This paper describes how switchmode power supply and class D power amplifier technologies can be integrated to produce a high density, light weight, reliable, and electromagnetically quiet product.

2. PRODUCT REQUIREMENTS

Mains Power and Power Quality. Satisfying the special power requirements of audio power amplifiers often adds significant costs to their installation. Our design goal was to relieve the customer of the burden of providing for high power-on surge currents, high crest factor and high harmonic content mains currents and the associated degradation of audio quality.

Good line regulation, load regulation and brownout tolerance allow the amplifier to operate reliably, at rated power, from 85 to 260 volts ac, 50 or 60 Hz.

Inputs. Most of our customers require professional audio level analog inputs (+4 to +22 dBu) and simple field wiring. This product uses 'Euro' terminal strip connectors for all field connections.

Output Loads. Component power amplifiers must be able to cope with a great variety of load characteristics, including large departures from nominal impedance, and short and open circuit conditions. A viable product must tolerate the greatest variety of load characteristics and survive fault conditions, preferably without damaging loudspeakers and without offending listeners.

Output Power. For commercial applications, audio amplifier specifications assume that average power is less than peak power by something like 12 dB, allowing less conservative power supply and thermal designs. For good dynamics, the power supply must be able to deliver full rated power for prolonged bursts. However, the average power over several minutes is always substantially less than full power. The higher the power output, the greater the range of applications available to the amplifier. However, large numbers of multichannel applications are satisfied by an honest 100 watts per channel.

Reliability and Redundancy. Our professional customers expect their electronic equipment to operate for many years, regardless of their conditions of use. In addition, multichannel amplifiers are often used for safety-related applications such as emergency paging. Therefore, very high reliability and backup channel redundancy are essential.

Enclosure. For historical and practical reasons, most commercial audio products are designed for 19 inch rack mounting. Many potential customers cite 'rack space usage reduction' as a valuable attribute. To accommodate large fans, heatsinks, and transformers, prior generation power amplifiers require two or more rack spaces, substantial depth behind the rack front, and rear support bracketry. Our goal was the single rack space '1U', supported only from the front. This limits the overall height to about 44 mm (1.75 in), and our depth and weight goals were 25 cm (9.8 in) and 4 kg (9 lb.), respectively.

Certifications. These products are sold throughout the world, so designs must be compliant with a great variety of safety and quality standards. Our design practices require passage of a complete regime of testing by accredited labs prior to release. Because of the small enclosure size and the use of switchmode circuitry, radiated and conducted EMI standards presented the greatest certification challenges.

Cost. To remain competitive, we had to maintain costs at levels near those of older products, even with the advantages of the new technologies. Net savings to the customer come in the form of reductions in shipping weight, rack space, cooling requirements, ac mains burden (the number of circuits required), and setup burden, i.e., the cost of making the product work in a system. Additional savings are available from reduced power consumption and improved reliability.

3. POWER SUPPLY TECHNOLOGIES

Power Factor Correction. Size, weight, thermal and efficiency considerations dictate the use of switchmode ac to dc conversion circuitry. Although Power Factor Correction is not mandatory for professional audio products, we elected to incorporate PFC to obtain the following benefits:

- Simplified ac mains universal input (no switch required)
- Improved utilization of mains circuits
- Reduced distortion and noise on ac mains
- Simplified design and reduced size of dc-dc converter
- Much less storage capacitance for reduced power-on surge

Dc to dc Converter. The PFC stage is a conventional average-current-feedback boost converter. This stage provides dc to a dc-dc converter that provides isolated power to amplifiers and auxiliary circuitry. The dc-dc stage provides safety isolation and bears most of the burden of regulation. However, the pre-regulation provided by the PFC stage permits the use of smaller magnetics in the dc-dc converter, essential in this 1U design. We reviewed various dc-dc topologies and selected the 2-switch Forward Converter as a good compromise among size, cost, complexity, and efficiency factors. We sought to design the best possible implementations of these conventional power supply topologies. Synchronization and leading-edge/trailing-edge interleaving further improve EMI compliance, power density and regulation.

4. AMPLIFIER TECHNOLOGIES

Size, cost, and power efficiency considerations make class D technologies attractive for compact multichannel power amplifiers. Highly integrated solutions promise further cost savings and reduced EMI. However, integrated circuit process parameters limit power output for practical load impedances. For example, with their typical 60 volt maximum rating, readily available IC amplifiers can only provide about 30 watts[1] into an 8 ohm load. However, at the expense of doubling the number of amplifier and reconstruction filter components, the full-bridge output structure provides approximately four times more output power. In addition, the full-bridge output structure is fully differential, which has EMI advantages.

Available class D amplifier technologies differ greatly, especially with regard to the following characteristics:

- Analog versus digital inputs
- Provision for negative feedback (or lack thereof) and consequent Power Supply Rejection Ratio specification
- Integrated versus external output MOSFETs
- Distortion reduction scheme and implementation
- Output protection scheme and implementation
- Output efficiency
- Intellectual property ownership (patents, licensing)
- Availability of components in pro audio quantities
- ElectroMagnetic Interference (EMI) generation

We studied and tested integrated circuits and modules from several manufacturers before selecting integrated class D amplifier components [1] with the following characteristics:

- Excellent efficiency of up to 87% over the full frequency range, well-suited to dynamic power limiting without loss of efficiency
- Easy to integrate into microprocessor controlled system with external clock input and logic control of operational mode
- On-chip remote startup sequencing, self-test, and output and protection

[1] Assuming ±25 V supplies to provide safe margin, actual output voltage swing under load of ±22 V to allow for voltage drops in output devices and filter.

- Analog inputs permitting simple analog feedback and very good PSRR
- Fully integrated pair of amplifiers per IC for simple implementation of full-bridge configuration
- Silicon-on-sapphire integrated circuit process permitting high clock rate and zero-deadtime switching for low distortion, compact output filters with high cutoff frequency for small size and reduced sensitivity to load impedance variations
- Integrated output protection scheme providing very fast response needed to prevent output failures and load damage
- Readily available applications assistance and components
- High level of integration allowing very compact layout for low EMI

5. INTEGRATION OF POWER SUPPLY & AMPLIFIERS

To properly apply power amplifiers, system designers and installers usually need to consider all of the following:

- ac Mains requirements, including operating voltages and currents
- Inrush current/Power sequencing
- Possible adverse interactions with other equipment, affecting audio quality
- Audio dynamics control, including prevention of clipping, minimization of noise, proper gain structure, click/pop suppression, etc.
- Effects of complex load impedances
- Power and thermal requirements
- Mounting and cooling considerations
- Status reporting, fault detection and redundancy requirements
- Possible adverse interactions with other equipment Safety and EMI requirements

Our goal was to relieve the customer of as many of these concerns as possible. Ideally, the customer should be able to connect a wide range of signal sources and output loads and have the amplifier provide optimum control of signal dynamics, maximizing audio fidelity and protecting both the loads and the amplifier from all manner of abuse and misapplication. To realize these goals, we employed supervisory hardware and software to integrate the switchmode power supplies and class D amplifiers:

- A supervisory microcontroller monitors user controls, remote inputs, power supply voltages and currents and operating temperatures, and it controls PFC and power amplifier clocks and amplifier output relays.
- A Digital Signal Processor communicates with the microcontroller and controls all signals presented to the power amplifier inputs.

With its voltage, current, and temperature monitoring capabilities, the microcontroller is able to provide information to the DSP that allows it to dynamically control audio levels and frequency response as required, almost regardless of input and load characteristics.

6. POWER SUPPLY DESIGN DETAILS

While both the PFC and dc-dc topologies are conventional, we were able to include many up-to-date enhancements: Knowing that one of the principal challenges for a product of this type would be EMI compliance, we devoted a large percentage of development work to studies of how best to minimize its generation at each source. As usual, the principal controlling factors in EMI generation were: magnetic component design, component placement, and voltage and current slew rates. At the same time, it was important to maximize efficiency, in order to keep component temperature increases within bounds.

Independent Power Supply Bias and Supervision. A separate Bias Supply and Supervisory Microcontroller are in charge of clocking all high power circuits. This allows us to control the sequencing of the power conversion and amplifications circuits, insuring that these functions are not activated when operational conditions are unfavorable. For example, no clock signals are supplied to power amplifiers unless and until their rail voltages are within specifications. Similarly, power supply clock signals are removed to effect a power-off condition or in response to persistent load faults.

Power Factor Correction. The PFC boost regulator requires only 220 μF of capacitance for a 400 watt supply, simplifying inrush current limiting. Microprocessor controlled sequential start up of the PFC stage, dc-dc stage and amplifiers further reduces startup loading. The design described in this paper allows simultaneously powering more than fifteen, 400 watt amplifiers on a single 15 amp circuit[2].

The PFC boost regulator achieves very high power factor, resulting in near sinusoidal current draw.

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[2] Assuming that the amplifiers are used for speech and music signals having average power at least 12 dB below peak power.

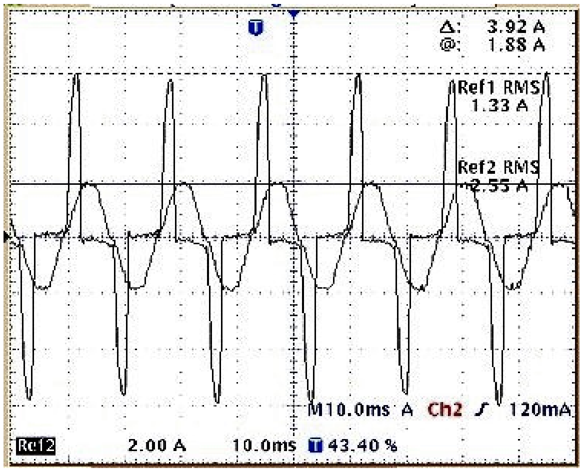

Figure 1. Conventional versus PFC mains currents for the same power input.

Figure 1 shows the current draw of a conventional power supply versus this PFC power supply, with both delivering 100 watts to a load. For the conventional supply, peak current is triple and rms current is double that of the PFC power supply.

Leading-edge/Trailing-edge Synchronization. The PFC and dc-dc stages are synchronized so that the PFC boost stage is sourcing current to a storage capacitor at the same time that the dc-dc stage draws current from that capacitor [2] This reduces ripple current in the storage capacitor, while reducing EMI currents supplied from the mains. The single IC that provides this capability [3] also incorporates essential features including soft-starting and under and overvoltage protection.

Custom Low-parasitic Magnetics. As described in the Floor Plan section, power supply components are located as far as possible from sensitive analog electronics. This puts them far to the right, both close to the chassis side and close to each other (see Figure 2 below).

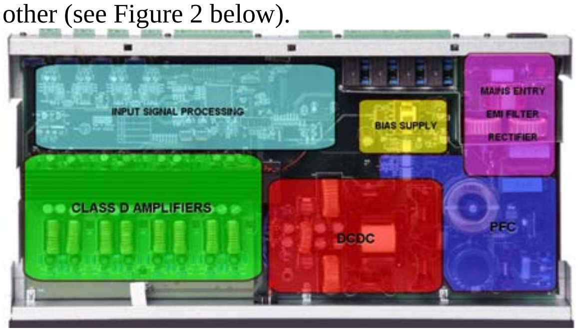

Figure 2. Multichannel Amplifier Floor Plan

Furthermore, the 1U enclosure height means that all components are relatively close to the chassis top and bottom. The chassis, which serves as earth protective ground and audio ground, carries eddy currents induced by stray magnetic fields and capacitive currents induced by the high dv/dt associated with efficient offline switchmode power supplies. These factors promoted the use of toroids for most magnetic functions. The PFC inductor is wound in two sections, connected so as to cancel the parasitic turn around the core inherent in conventionally-wound toroids. In addition, the individual windings are progressively layered to reduce parasitic capacitance. We used analyses of parasitic interactions among components to determine their locations and orientations. The high dv/dt sides of all magnetic components are positioned so as to minimize parasitic current magnitude and magnetic loop areas. This step proved to be critical for the reduction of conducted and radiated EMI.

Silicon Carbide Schottky PFC Boost Rectifier. During the development of the product, a new rectifier technology became available. High voltage Schottky barrier rectifiers processed from SiC have essentially zero reverse recovery times. The reverse recovery characteristics of the boost rectifier are an important factor in determining boost switch dissipation and EMI generation of the PFC stage. The additional cost of the SiC rectifier is offset by reduced requirements for snubbing and EMI filtering components.

EMI Reduction and Safety Isolation. Even after careful optimization of component placements and orientations, switching current harmonics and residual parasitic currents require some further shielding and filtering. Capacitors across the mains attenuate differential mode currents, but these capacitors also store energy that can create a shock hazard. Consequently, we used a combination of capacitance and inductance for the purpose. Similarly, capacitors from high dv/dt circuit nodes to protective ground (mains green wire) can be used to shunt common mode currents. However, capacitors connected from non-isolated nodes to protective ground add to the touch currents measured for compliance with shock hazard regulations. Therefore, most of the burden of filtering common mode currents falls on a high performance common mode transformer. Just as with the power supply circuitry itself, the layout and orientation of the filter components is critical. The measured harmonic currents are compared to allowable limits in Table 1.

Harmonic	Limit (mA)	Current (mA)	% of LIMIT
2	1080	11.73	1.1
3	2300	94	4.1
4	430	3.15	0.7
5	1140	38.27	3.4
6	300	3.29	1.1
7	770	23.4	3.0
8	230	2.05	0.9
9	400	15.7	3.9
10	184	2.52	1.4
11	330	8.12	2.5
12	153	2.11	1.4

Table 1. Measured Harmonic Currents versus Limits for Power Factor Corrected Supply

7. AMPLIFIER DESIGN DETAILS

Amplifier and Load Protection. Most of the available class D power amplifier 'solutions' were developed for applications in which load characteristics are known in advance. Component amplifier designers must plan for a great range of loudspeaker impedance characteristics, including series and parallel combinations, wiring and load faults, and significant departures from nominal impedance. These load variations interact with the amplifier output protection scheme, sometimes in unacceptable ways. For example, class D output stages can be protected from failure by quickly turning off all output transistors when output current reaches a threshold. However, this type of protection produces unacceptably harsh-sounding results, so a more nearly linear reduction of output power is preferable. As discussed elsewhere in this paper (see Audio Integration section) a microcontroller and a DSP control the instantaneous signal level fed to the power amplifiers, thereby holding output power at levels beneath hardware protection thresholds for all valid loads.

Hybrid Analog and Digital Signal Processing Design. The following aspects of product design practically dictated the inclusion of a DSP in the preamplification chain:

- Allowed variations in load impedance affect frequency response due to reconstruction filter characteristics in class D amplifiers
- Allowed variations in load impedance affect maximum allowable power output below hardware output/load protection thresholds
- Allowed use with distribution transformers (e.g., 70.7 V, 100 V systems) that typically saturate at low frequencies requires the incorporation of low-cut filters

Reconstruction Filters. The power amplifiers use constant frequency Pulse Width Modulation at 307 kHz. A passive filter network (see Figure 3) removes both differential and common mode components above the audio range.

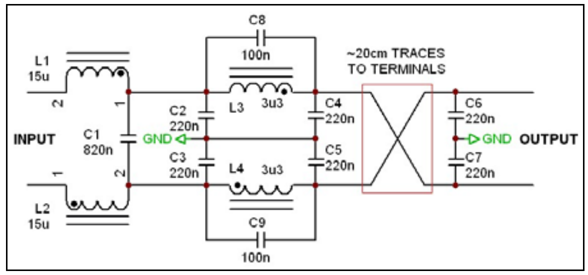

Figure 3. Simplified Schematic Diagram of Class D Amplifier Output Filters

Several features of this network are worth noting. First, shunt capacitances are connected both across the amplifier differential outputs (C1) and from each output to circuit common (C2-5). These capacitors provide shunt paths for differential and common mode currents. Second, the first stage inductors (L1, L2) are high linearity, low-loss types, as described elsewhere in this paper. Third, notch filter networks (L3-C8, L4-C9) are very effective at further reducing carrier components. Finally, some of the output shunt capacitance is positioned very close to the amplifier output terminals (C6, C7) to provide additional filtering for any common mode currents induced in amplifier output traces by nearby magnetic loops.

In spite of their small size, the integrated class D output stages have internal efficiency above 90% for 8 ohm loads. In our bridged application, with two MOSFETs in each conductive path, efficiency still exceeds 85 percent.

Early prototypes had significant additional losses in the reconstruction filter inductors. After studying a variety of possible inductor core types and constructions, we selected low-mu sintered powder toroids and single-layer windings. These inductors have excellent linearity, low core losses, and very little stray flux. Core losses reduce efficiency by less than 1 percent at full load. Single-stranded large gauge windings have low parasitic capacitance, while the associated skin effect is negligible in this low-pass application.

Circuit Layout. Printed circuit layout design is particularly critical for proper operation of the amplifiers. An adequate amount of high performance bypassing capacitance must be positioned at the chip power and reference pins, since a few nanohenries of inductance can disrupt the operation of amplifying and output protection circuitry. We worked with the chip manufacturer to optimize circuit design and layout. The manufacturer also produced several iterations of the chip design in response to the needs of various customers.

8. DETAILS OF INTEGRATED DYNAMICS PROCESSING

As outlined earlier, the microcontroller and DSP work together to guarantee that the power amplifiers and their loads are driven properly, practically regardless of operating conditions. The system monitors key amplifier operating conditions including:

- Amplifier input current and output fault status for each channel
- Root mean square signal level at each amplifier output
- Operating temperature near each amplifier
- Power supply voltages

Using the above information, the microcontroller and DSP automatically perform the following tasks:

- Estimate average load impedance
- Indicate load status (open , short, normal)
- Correctly set the voltage limiter threshold for any load, ensuring safe and reliable maximum output power and prevent current clipping.
- Set a soft-knee compressor threshold relative to the limit threshold to ensure predictable ac mains power consumption and heat generation.
- Provide meaningful headroom metering regardless of load impedance.
- Optimize fan speed
- Report fault status to a control system or another amplifier
- Remain in standby or run-mode based on control system command or fault status master amplifier
- Shut-down individual class D stages or the main power supply depending on fault status
- Drive the load or connect the load to an external source

The resulting benefits are predictable power consumption, reduced thermal stress and improved reliability into any load. These are achieved without requiring the customer to specify overly conservative designs or to perform complex calculations.

Load estimation. Load impedance is estimated using average class D supply current and rms output voltage. Each class D amplifier has a known quiescent operating current and incremental efficiency. With this knowledge, it is possible to indirectly monitor average load power by measuring average amplifier supply current. The supply rails are fixed at ±25 volts. The total average power into the amplifier is $P_{total} = (I_{avg} \times 50\ V)$. The power delivered to the load $P_{load} = (P_{total} - P_{quiescent}) \times ß$, where ß is the incremental efficiency. It follows that the estimated average load impedance $Z_{load} = V_{load}^2 / P_{load}$, where V_{load} is the rms voltage delivered to the load.

While this estimate does not reveal the actual impedance at any particular frequency, it does reflect the average impedance presented to the amplifier for a given output signal. The average impedance is used to automatically set the limiter threshold and to indicate load status

Limiter. All amplifiers have a maximum operating voltage and current beyond which clipping (voltage or current) occurs. All amplifiers have a maximum average operating power beyond which reliable operation is not possible. End users have two means of mitigating these limitations; conservative and costly over-design, or intelligent and transparent limiting to the required power levels.

Properly setting a limiter is challenging. Even with variable sensitivity, remote level control and load impedance, an integrated limiter is able to automatically, and accurately, set the limit threshold for optimum performance.

Using the estimated average load impedance to determine the appropriate peak voltage limiter threshold can eliminate current clipping. If a class D amplifier is able to deliver 11 amps peak to the load, current clipping is prevented if the limiter is set for a peak output voltage that is less than 11 times the load impedance (I×R). The minimum impedance of a well-designed speaker is typically not less than 80 percent of the average. If current is limited to 7.75 amps peak, based on the average impedance, it is possible for the impedance to drop 30 percent before current clipping occurs.

Compressor. Properly setting a compressor for the purpose of limiting the average power is equally challenging. Proper calibration requires knowledge of a variable gain structure, limiter threshold, operating temperature and likely signal dynamics. Integrating the compressor allows automating this task.

No matter how clever a design is, an amplifier must be designed to reliably and accurately deliver the required power to the load. Intelligent dynamics control dramatically reduce the likelihood that unknown variables might place an amplifier outside of the intended operating window.

Typical program material has been found to be equivalent to a pink noise source operating at an average power level one-eighth of the maximum rated power (i.e., 9 dB peak to average). This is why "normal operation" safety and EMC testing are performed at this level. Therefore, the minimum requirement is for an amplifier to operate continuously at one eighth power (12.5 watts for a 100 watt amplifier). It is then reasonable to base thermal management and ac mains power requirements on an average power level equal to one-third the maximum rated power.

Problems occur when ambient temperature goes above the design limit, program material is unusually compressed or average load impedance is less than expected. The goal of automated dynamics control is to mitigating these occurrences without resorting to a costly and overly conservative design.

If the compressor is to accurately limit long term average power to one-third maximum power, its threshold must be set relative to the limit threshold. The limiter determines the maximum peak current and load power based on estimated average load impedance. A soft-knee rms compressor with its threshold set relative to the limiter threshold may be accurately calibrated to allow the required average and maximum power, regardless of load impedance. To make the compressor as transparent as possible, a 10 dB span soft knee compressor with a ratio of 3:1 is set with an rms threshold 10 dB below the peak limit threshold (7 dB below the maximum rms signal level). The result a soft-knee response with a maximum gain reduction of 4.7 dB (about one-third power) as shown in Figure 4 below.

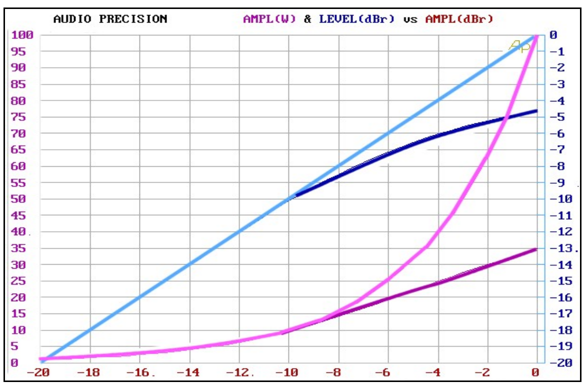

Figure 4. Average Power Compressor Characteristics

It is desirable to allow significant transients to reach full power while limiting long-term average to one-third of maximum. An attack time constant of 500 ms (1.5 seconds to reach 93 percent of maximum gain reduction for the full 7 dB step) and a release of 3 dB per second works well with most program material.

In order to accommodate bench testing, the compressor may be set to off. With this setting, the compressor remains off unless the operating temperature goes above a safe level or the total power output with all channels driven goes above a safe level for extended periods of time.

The result of integrating the compressor is an amplifier that reliably and accurately delivers the required power to the load, while exhibiting predictable thermal performance and ac mains current draw. The thermal load performance achieved with this design is illustrated by these measured values:

Standby:	370 kJ	(350 BTU)
Minimum run-mode:	3700 kJ	(3500 BTU)
Typical:	5275 kJ	(5000 BTU)
Maximum:	8025 kJ	(7600 BTU)

Integrated fault reporting and redundancy. An increasingly important feature of the integrated amplifier is the ability to report faults and load status to a control system and provide redundancy backup when faults do occur. These requirements are satisfied with only three basic additions to the design:

- Internal fault reporting
- External fault monitoring
- The ability to switch the load to an alternate input

More specifically, the following attributes allow automated fault reporting and redundancy protection:

- Fault reporting (Master)
  - Automated amplifier self-test
  - Supply monitoring (current and voltage)
  - Load monitoring
  - Report fault to control system
  - Report fault to another amplifier
- Fault monitoring (Slave)
  - Amplifier remains in standby until flag goes low
  - Remote startup/sequencing
  - Automated redundancy switching
- Automatic redundancy protection
  - Master switches load to backup input when fault occurs
  - Master reports fault to control system and/or backup amplifier
  - Slave amplifier output is connected to backup input on master
  - Slave amplifier reads fault status, turns on if fault occurs
  - Third party emergency backup system may be connected to master backup input connector

Metering. The addition of informative metering allows users to monitor status:

- Load sensitive peak headroom
- Dynamic control indicators
  - Limit
  - Compressor
  - Expander
- Fault status indicator
- Load status indicator
- Amplifier off/standby/ready indicator

While providing this information on the front panel assists users with setup and monitoring, it will soon become common practice to provide a control system with full operating status including telemetry for: average/maximum temperature, fault status, fan speed, load impedance, hours of operation etc.

9. MECHANICAL AND THERMAL DESIGN

Floor Planning. A sensible layout of components must be based on considerations of audio quality, ease of installation and use, operational reliability, and EMI. Within the confines of the 1U chassis, generators of electronic noise and heat must be located as far as possible away from potential 'victims'. Our approach to this problem was to position mains entry and power supply components on the far right, audio input circuitry on the far left, and other components in between. See Figure 5 below.

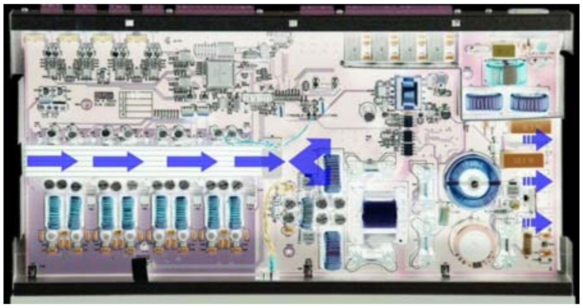

Figure 5. Airflow for the high power density audio amplifier, negative image for clarity.

Strength. The 1U chassis height presents special mechanical and thermal design problems. The product is usually supported only by the narrow rack 'ears'. Loading of these ears is proportional to product mass, sometimes includes heavy cables, and is aggravated by vibration and shock during shipment of built-up racks. Consequently, our goal was to keep product mass to a minimum.

Thermal Considerations. The 1U chassis height also means that virtually all components, including heatsinks and fans, must be less than 35 mm (1.38 in) tall. Meanwhile, rack-mounting dictates horizontal airflow. These considerations limit the choice of air-moving components to a few configurations of fans and blowers. In order to minimize size, weight, noise, and cost, our design employs a single small fan. The fan draws intake air over a small amplifier heatsink. Fan exhaust spreads over power supply components at very low velocities and exits through an EMI labyrinth shield. See Figure 5 above. As described earlier, a microcontroller monitors strategically positioned temperature sensors to control fan speed and amplifier dynamics. As internal temperatures rise, the system responds first by increasing fan speed. If temperatures continue to rise, the second level of defense is to reduce amplifier drive levels. The final defense against overtemperature is to shut down all power circuitry to allow a cooling period and/or remedial action, while providing status information to the user.

10. DISTRIBUTION TRANSFORMERS

Many multichannel audio amplifiers are installed in large venues that require the use of distribution transformers. These transformers can reduce the cost of installation by allowing the use of low-cost small diameter wiring. Their galvanic isolation properties are also sometimes required. However, due to their mediocre audio performance, large mass, and tall form-factor, the majority of distribution transformers available today are a poor match to this new power amplifier. We designed a toroidal distribution transformer with the following characteristics:

- Full power, full audio bandwidth, 100 W_{rms}, 20 Hz to 20 kHz
- 1U mounting (38 mm height)
- 1.4 kg mass

The design combines the best available tape-wound cores with multi-filar winding techniques to achieve these performance levels.

11. CONCLUSIONS

This paper describes the development of a product incorporating class D power amplifiers, switchmode power supplies, and microcontroller and DSP functions to achieve new levels of power density, installed cost reduction, ease of use, EMI compliance, and reliability.

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