APPLICATION NOTE

ANP156 | EMC-compliant power-tree design for a mixed-signal audio system

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This application note explains the development of a robust EMC-compliant power-supply architecture for a mixed-signal system with sensitive analog stages, digital signal processing, Class-D power amplifiers and tube supply.

1. INTRODUCTION: POWER INTEGRITY IN MIXED-SIGNAL AUDIO SYSTEMS

Power supply design is a key aspect of mixed-signal systems because supply quality directly affects system performance, electromagnetic compatibility (EMC) and operational reliability. This is particularly important when high-power switching stages operate close to noise-sensitive analog and digital circuitry.

The reference design presented in this application note combines Class-D power amplifiers, analog front ends, digital signal processing, Bluetooth connectivity and a tube-based preamplifier. These functional blocks require different supply voltages, load currents and filtering concepts. Figure 1 and Figure 2 show the block diagram and the PCB arrangement of the audio system.

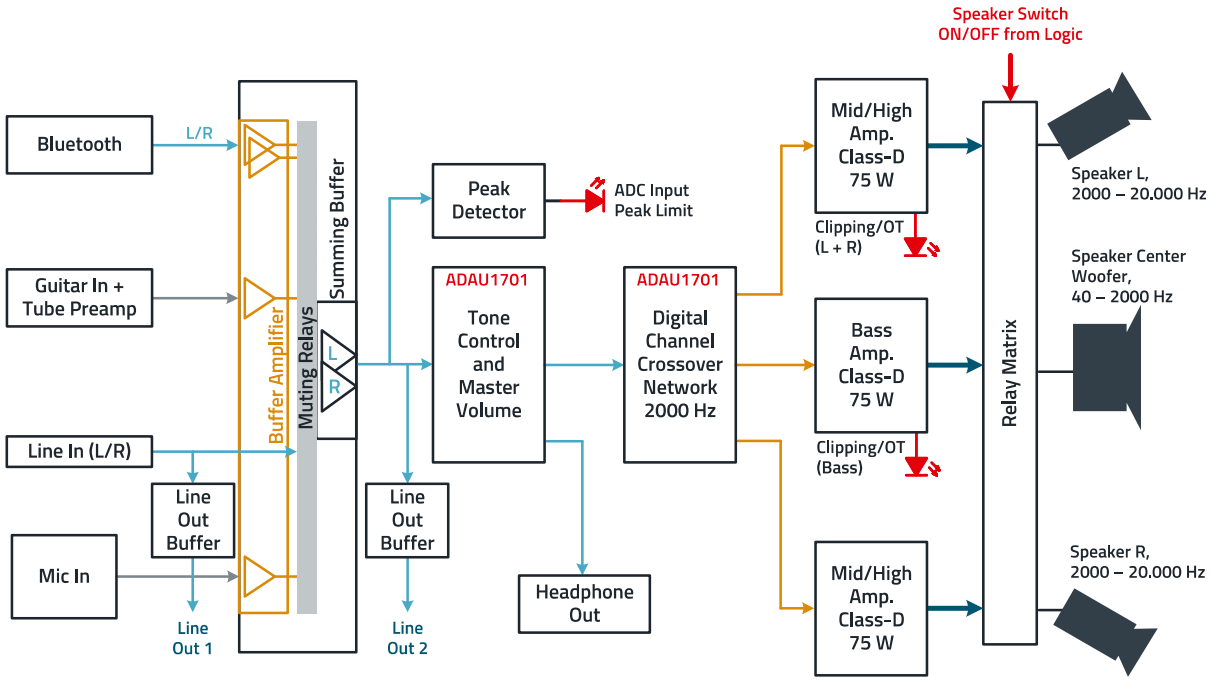


Figure 1: The overall signal flow of the audio system from the different input sources through analog signal conditioning and digital signal processing to the Class-D power amplifiers and speakers.

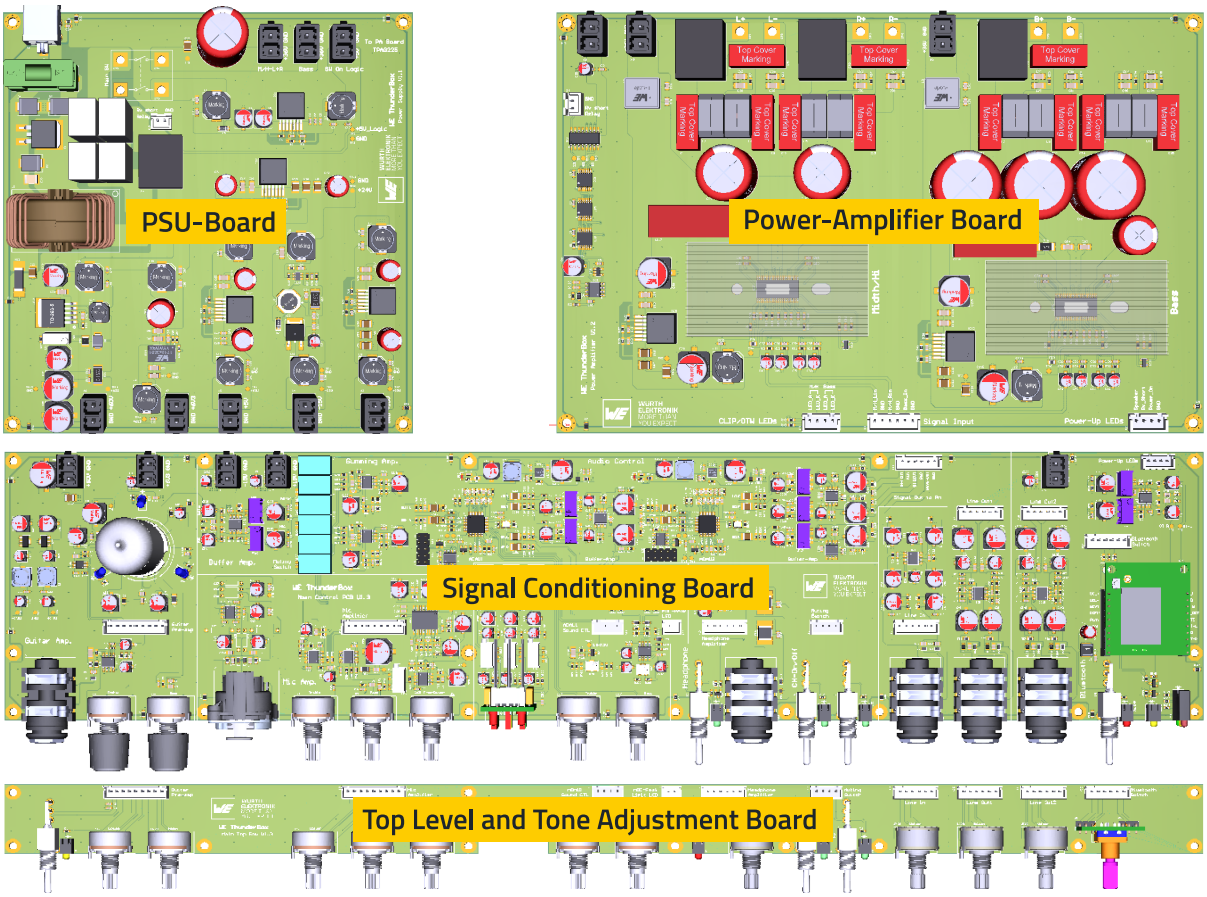


Figure 2: The PCB arrangement of the complete audio system.

This Application Note focuses on the central power-supply board (the PSU-board in Figure 2) and its integration into the complete system. The design of the power tree, DC/DC conversion stages, filtering and inrush-current limiting is discussed. The measured ripple and LF/RF noise of the individual supply rails are also presented.

2. SYSTEM OVERVIEW AND POWER REQUIREMENTS

The reference design combines power, analog and digital loads with different requirements regarding voltage level, current capability and necessary supply quality. The power architecture therefore uses dedicated supply rails for the individual functional blocks.

Hence, the power supply architecture follows a hierarchical concept with centralized power distribution and dedicated voltage conversion for the individual load groups. The 36 VDC input forms the main supply level while the required auxiliary rails are generated in subsequent conversion stages, as illustrated in Figure 3.

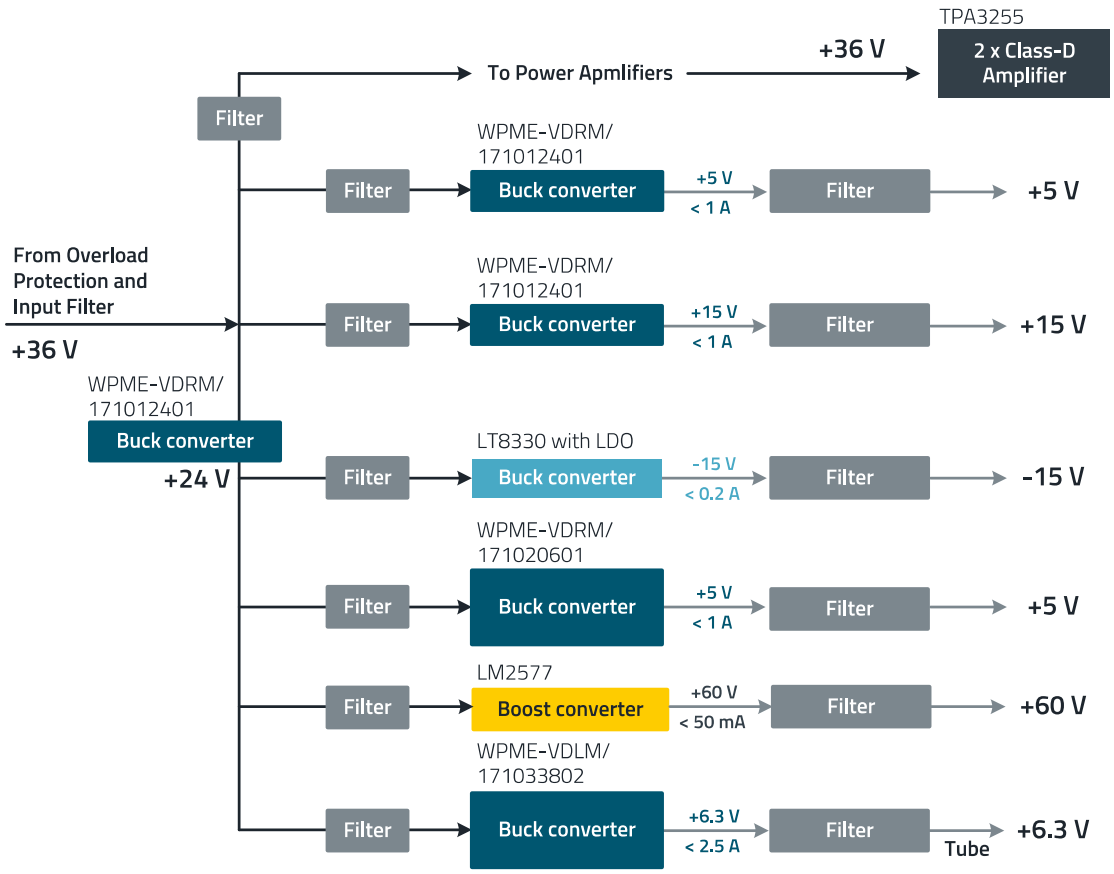


Figure 3: The power-tree architecture of the mixed-signal audio system. The 36 V input supplies the Class-D power amplifiers directly while the remaining supply rails are generated by dedicated DC/DC conversion and filtering stages.

This architecture provides three main benefits:

- separation of high-power, analog and digital supply domains,
- local adaptation of voltage level and filtering to the respective load,
- reduction of shared supply impedances and interference between functional blocks.

The +36 V rail directly supplies the Class-D power amplifiers and serves as the input for the first conversion stages. The input is equipped with an efficient filter featuring transient and reverse polarity protection. The +24 V rail acts as an intermediate supply for several downstream converters. The downstream supply rails do not operate at their maximum load. The +24 V intermediate rail is therefore dimensioned according to the expected combined operating load rather than the sum of all individual maximum rail currents.

Sensitive analog, digital and tube-related loads are supplied through dedicated paths each with its own individual filtering and decoupling. This limits the propagation of switching disturbances and reduces mutual interaction between the different supply domains.

3. LOAD GROUPS

The main load groups supplied by the power-supply board are:

- Class-D power amplifiers,
- analog preamplifier stages,
- DSPs (ADAU1701),
- Bluetooth module,
- tube heater,

- tube anode supply,
- control logic, relays and indicators.

3.1 Supply Rails

Rail	Loads	Main Requirements
+5 V	DSPs, Bluetooth, digital circuitry	Local HF decoupling
+5 V Logic	Control logic, relays, indicators	Stable during system start-up
+6.3 V	ECC83 tube heater	Low ripple, adequate current capability
-15 V	Analog preamplifier stages	Low ripple, low LF/HF-noise, low voltage tolerance
+15 V	Analog preamplifier stages	Low ripple, low LF/HF-noise, low voltage tolerance
+24 V	Downstream converters	Decoupled intermediate supply
+36 V_{MAIN}	Class-D power amplifiers	High current capability and load dynamics
+60 V	ECC83 anode (tube amplifier)	Low current, effective filtering for low LF/HF noise

Table 1: The individual supply rails, their associated loads and the main power-supply requirements of the mixed-signal audio system.

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The +3.3 V supply required by the ADAU1701 DSPs is generated locally from the +5 V rail on the main audio board, close to the DSPs. It is therefore not part of the power-supply board considered in this application note.

The resulting supply structure forms the basis of the hierarchical power-tree architecture described in the following section.

4. DC/DC CONVERTERS AND RAIL GENERATION

Rail	Function	Converter / Module	Description
+5 V	Digital auxiliary supply	WPME-VDRM171020601	Buck converter, 24 V to 5 V
+5 V Logic	Control logic and relay supply	WPME-VDRM 171012401	Buck converter, 6 V to 42 V input, up to 1 A output current, 200 kHz to 800 kHz switching frequency
+6.3 V	ECC83 heater supply	WPME-VDLM 171033802	Buck converter, up to 3 A output current and adjustable switching frequency
–15 V	Negative analog supply	LT8330 with WE-TDC 74489440068 and MC79M15	Inverting converter generating approximately –19 V with linear post-regulation to –15 V
+15 V	Positive analog supply	WPME-VDRM 171012401	Buck converter, 36 V to 15 V
+24 V	Intermediate supply for downstream converters	WPME-VDRM 171012401	Buck converter for 36 V to 24 V conversion, up to 1 A output current, 494 kHz switching frequency
+60 V	ECC83 anode supply	LM2577SX-ADJ with WE-PD 7447773101	Boost converter, approximately 52 kHz switching frequency and 100 µH power inductor

Table 2: DC/DC converters used for the individual supply rails.

The auxiliary supply rails are derived from the 36 V input using dedicated conversion stages selected according to the required voltage level, load current, efficiency and supply-quality requirements. Table 2 summarizes the converter stages implemented on the power-supply board.

The converter selection is based on the following main parameters:

- input and output voltage range,
- required output current and load reserve,
- switching frequency,
- conversion efficiency,

- output ripple,
- transient response,
- thermal performance and,
- protection functions.

These parameters have to be considered together because converter selection involves trade-offs among efficiency, supply quality and EMC performance. In sensitive supply paths, additional filtering or linear post-regulation may be required even when the DC/DC converter itself meets the basic voltage and current requirements.

The converter stages are complemented by individual input and output filters according to the requirements of the respective supply rail. The corresponding protection, filtering and decoupling concepts are discussed in sections 5 and 6.

5. INPUT PROTECTION AND 36 V EMI FILTER

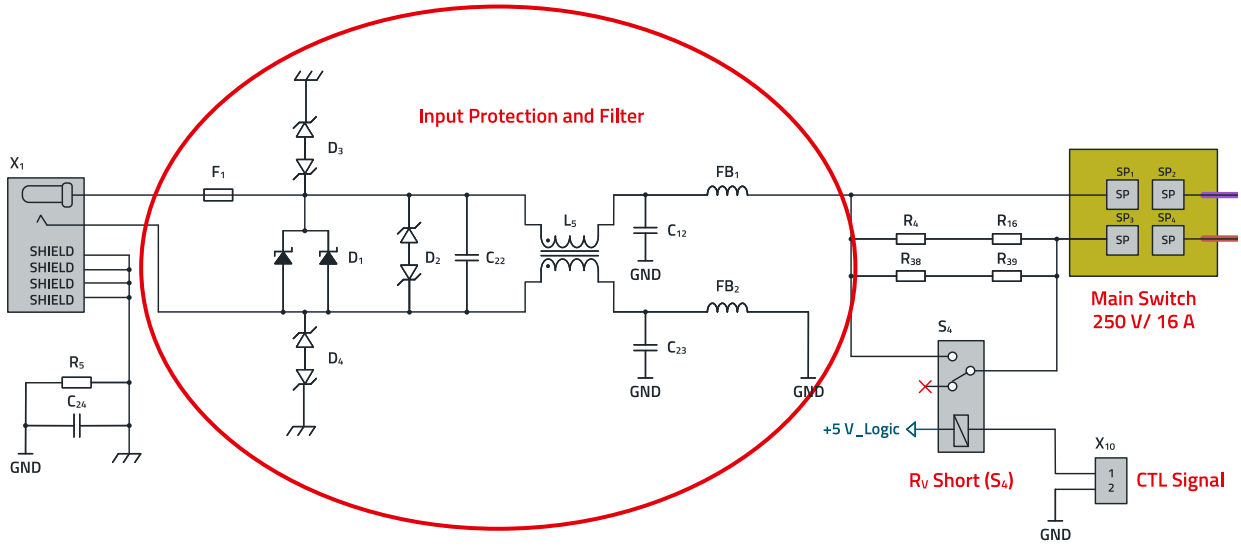


Figure 4: The schematic concept of the 36 V input protection and EMI filter. The input stage combines transient and reverse-polarity protection with common-mode and differential-mode filtering before the 36 V rail is distributed to the downstream power stages.

The 36 V input interface is protected and filtered before the supply is distributed to the internal power stages. The input network combines transient protection, reverse-polarity protection and multi-stage EMI filtering. The implemented input section on the power-supply board is shown in Figure 4.

5.1 Transient and Reverse-Polarity Protection

The filter and protection stage is located directly at the 36 V input to protect the downstream converter stages against external disturbances and reverse-polarity conditions. The TVS diode (D_2) limits transient overvoltages above 42 V caused by effects such as hot-plug events, burst or surge while Schottky diodes provide reverse-polarity protection.

The protection stage therefore has to be coordinated with the allowable input-voltage range of the downstream converter stages, particularly with respect to transient overvoltages at the 36 V input.

5.2 Differential- and Common-Mode Filtering

The 36 V input filter combines a common-mode choke (L_5), capacitors (C_{22}, C_{12} and C_{23}) and ferrite beads (FB_1 and FB_2) to attenuate both common-mode (CM) and differential-mode (DM) disturbances over a broad frequency range. The individual components contribute differently depending on the disturbance mode, frequency and direction of propagation.

The common-mode choke L_5 has an inductance of 2 × 2.5 mH and provides the main series impedance for common-mode disturbances. For common-mode disturbances generated by the internal electronics and propagating toward the input, the choke acts with the parasitic capacitances of Schottky diodes D_3 and D_4, which are approximately 700 pF per diode. These capacitive paths provide a return path for high-frequency common-mode currents while L_5 presents a high impedance in the supply conductors.

L_5 also contributes to differential-mode filtering through its differential-mode impedance, which is mainly determined by the leakage inductance of the common-mode choke. For differential-mode disturbances entering from the external 36 V supply, C_{12} and C_{23} together with the downstream bulk capacitances at the inputs of the DC/DC converters form part of the filtering network. Differential-mode disturbances generated within the system and propagating toward the input are additionally attenuated by C_{22}.

Ferrite beads FB_1 and FB_2 complement the choke at higher frequencies. The multilayer power-suppression beads exhibit a predominantly resistive impedance of approximately 80 Ω at 50 MHz, increasing to approximately 180 Ω at 1 GHz. They therefore provide additional attenuation of high-frequency disturbances propagating in either direction.

No single component provides sufficient attenuation over the complete relevant frequency range. The common-mode choke, capacitors and ferrite beads are therefore combined to form a broadband input filter. The dominant contribution of the individual filter elements is summarized in Table 3.

Frequency Range	Dominant Filter Element
Up to approximately 50 MHz	Common-mode choke with respective capacitors
Above approximately 50 MHz	Ferrite beads and HF capacitors
Broadband	Combined effect of all filter stages

Table 3: The dominant filter elements of the 36 V input filter and the frequency ranges in which they primarily contribute to disturbance attenuation.

The common-mode impedance of L_5 increases strongly with frequency and reaches approximately 9 kΩ around 500 kHz. This characteristic supports effective attenuation of high-frequency common-mode currents.

The R_5/C_{24} network provides a configurable connection between the functional ground (GND) and the chassis or shield ground (SGND), allowing different grounding configurations to be evaluated during EMC testing. Depending on the required coupling between circuit ground and chassis, the network can be adapted accordingly. For a more detailed discussion of grounding and chassis coupling, refer to Reference Design Notes RD016 and RD022.

The physical implementation is equally important. Short connections, wide copper areas and a continuous ground/chassis reference minimize parasitic inductance and prevent the filter components from being bypassed by unintended high-frequency coupling.

6. FILTERING, DECOUPLING AND PCB IMPLEMENTATION

The individual supply rails require different filtering concepts depending on switching frequency, load behavior and sensitivity of the connected circuitry. The filter stages therefore combine ripple suppression, load decoupling and local energy storage according to the requirements of the respective rail.

6.1 Input and Output Filtering of the Individual Rails

The practical implementation of three different DC/DC converter and filter concepts on the power-supply board is shown in Figure 5. The highlighted sections correspond to the +5 V Logic, –15 V and +60 V supply rails. Each converter uses a different input and output filter topology, selected according to the voltage level, load characteristics, switching-converter topology and required suppression of conducted switching noise.

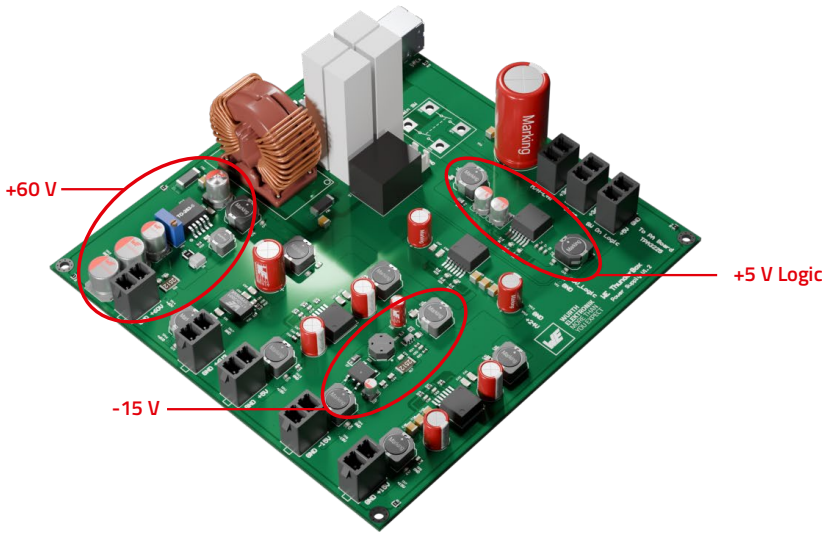


Figure 5: Practical implementation of the +5 V Logic, – 15 V and +60 V DC/DC converter stages, illustrating the different input and output filter topologies used for the individual supply rails.

Figure 6 shows the corresponding circuit diagrams and allows the individual filter components and their arrangement to be examined in detail. The examples illustrate how the input and output filtering is adapted to the specific requirements of each supply rail. Although the basic objective is the same - limiting the propagation of switching noise - the required component values, filter order and circuit topology differ considerably depending on the converter and its operating conditions.

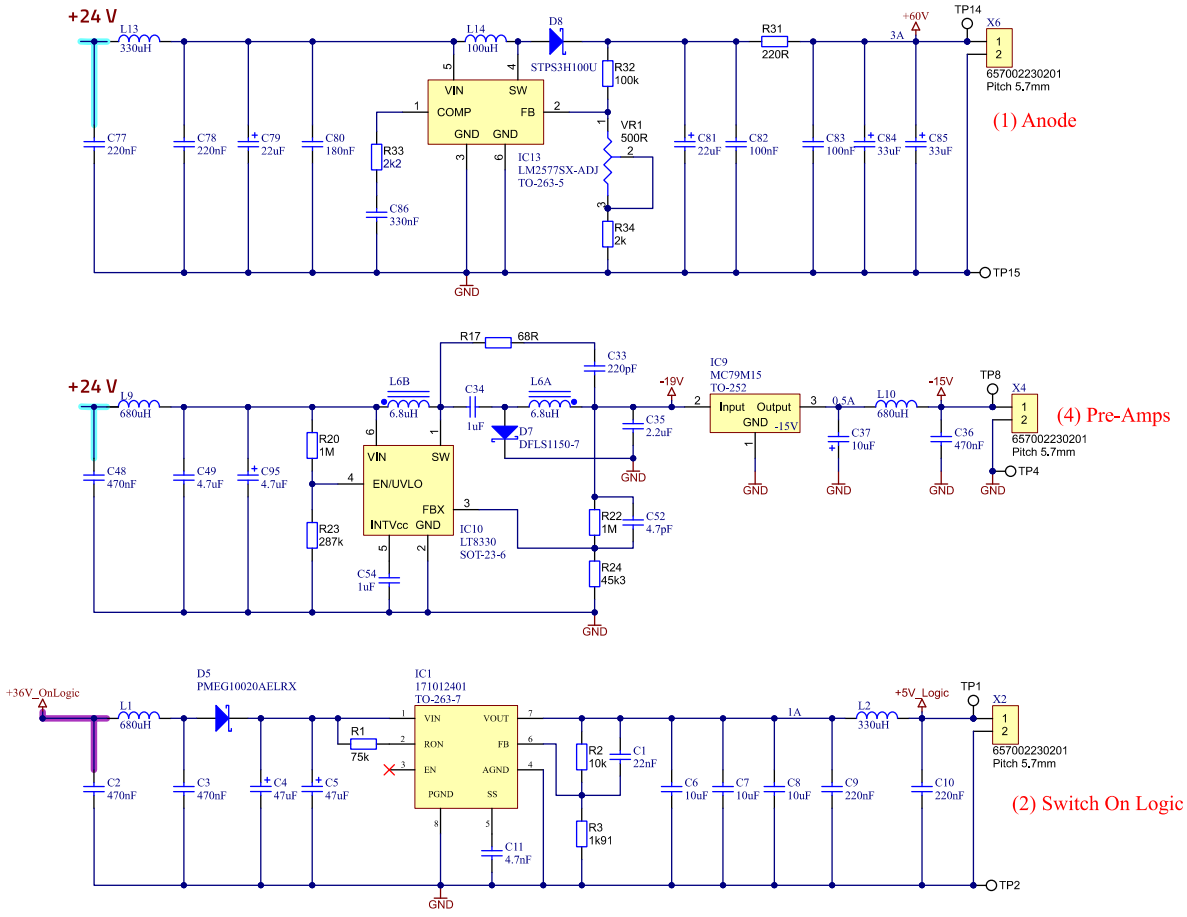


Figure 6: The schematic diagrams of the +5 V Logic, – 15 V and +60 V converter and filter stages.

The +60 V anode supply is generated from the +24 V rail by the LM2577SX-ADJ boost converter (IC_{13}). At the converter input, C_{77}, L_{13} and C_{78}/C_{79}/C_{80} form a C-L-C π-filter with L_{13} (330 µH). The filter attenuates disturbances arriving from the +24 V rail and reduces the propagation of switching-frequency disturbances generated by the boost converter back onto the +24 V supply. L_{14} (100 µH) serves as the power inductor of the boost converter. Together with D_8 and the output capacitors C_{81} and C_{82}, it forms the main power-conversion stage for generating the +60 V rail. At the converter output, R_{31} (220 Ω) together with C_{83}, C_{84} and C_{85} forms a damped RC low-pass filter. The resistive output filter avoids a pronounced LC resonance and provides additional attenuation of switching ripple and high-frequency disturbances. This approach is particularly suitable for the +60 V anode supply because the anode current is comparatively low. The voltage drop and power dissipation across R_{31} therefore remain acceptable while the sensitive analog circuitry benefits from a significantly cleaner and well-damped supply voltage.

The –15 V analog supply is generated from the +24 V rail using an inverting Ćuk converter followed by linear post-regulation and output filtering. For easier readability, this area is shown again in Figure 7. At the input, C_{48}, L_9 and C_{49} form a C-L-C π-filter with L_9 (680 µH). This filter attenuates disturbances arriving from the +24 V rail and reduces switching-frequency disturbances generated by the LT8330 from propagating back onto the +24 V supply. The LT8330 (IC_{10}) operates at a fixed switching frequency of 2 MHz. L_{6A} and L_{6B} are the two 6.8 µH windings of a coupled inductor. Together with the energy-transfer capacitor C_{34} and diode D_7, they form the main Ćuk power-conversion stage. The topology generates an intermediate voltage of about –19 V and provides comparatively low input- and output-current ripple because inductors are present on both sides of the energy-transfer capacitor.

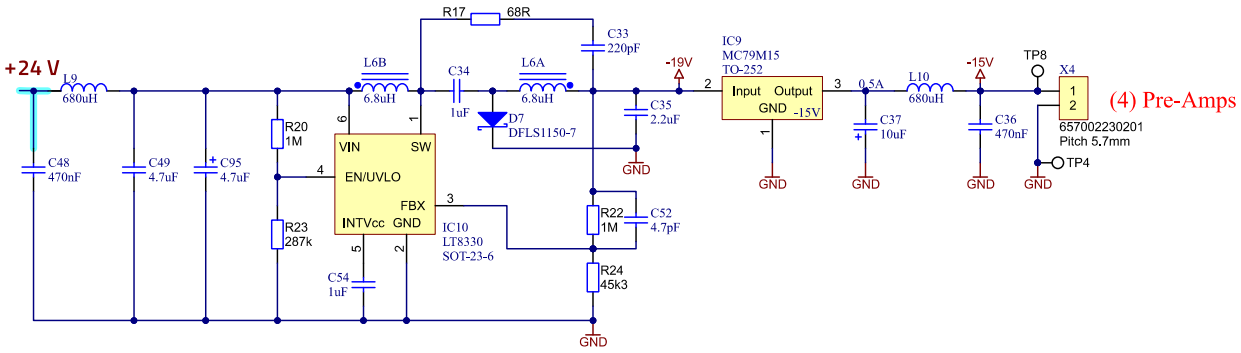


Figure 7: The -15 V supply realized with an inverting Ćuk converter followed by linear post-regulation and output filtering.

The –19 V intermediate voltage is then regulated to –15 V by the MC79M15 (IC_9) linear regulator. This provides a stable analog supply and additional attenuation of converter ripple and low-frequency disturbances. Since the power-supply rejection of a linear regulator decreases at higher frequencies, C_{37}, L_{10} and C_{36} form an additional C-L-C π-filter after the regulator. The nominal resonance frequency of the output-side LC section can be estimated using

$$f_0 = \frac{1}{2 \cdot \pi \sqrt{L_{10} \cdot C_{36}}}$$

With L_{10} (680 µH) and C_{36} (470 nF), the resulting resonance frequency is 8.9 kHz. The final filter provides additional attenuation of higher-frequency disturbances before the –15 V rail reaches the sensitive preamplifier circuitry.

The +5 V Logic supply is generated from the switched +36 V rail by the Würth Elektronik WPME-VDRM 171012401 (IC_1) synchronous buck power module as shown in Figure 8. The module integrates the switching regulator, MOSFETs and a 15 µH power inductor and uses a Constant-On-Time (COT) low-ripple hysteretic control scheme. Its switching frequency can be adjusted from 200 kHz to 800 kHz. At the input, C_2, L_1 and C_3 form a C-L-C π-filter L_1 (680 µH) while C_4 and C_5 provide additional bulk capacitance. The input filter attenuates disturbances from the +36 V rail and reduces the propagation of converter-generated switching disturbances back toward the upstream supply. At the converter output, C_6 to C_9, L_2 (330 µH) and C_{10} form the post-filter. This stage attenuates residual switching ripple and high-frequency differential-mode disturbances before the +5 V Logic rail supplies the control logic, relays and indicators.

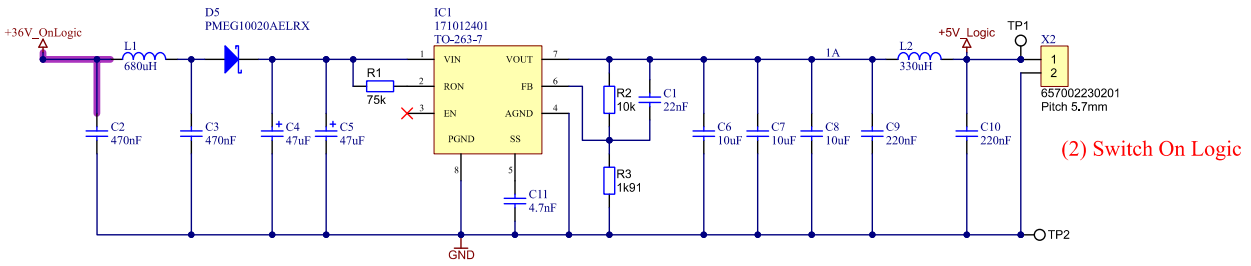


Figure 8: The +5 V Logic supply with WPME-VDRM synchronous buck power module.

Some information to the selected inductor WE-PD- type: The WE-PD can be used both as a power inductor in DC/DC converters and as a series inductive element in differential-mode filters. In converter applications, the main selection criteria are ripple current, peak current, DCR, losses and saturation margin. In filter applications, the focus shifts toward frequency-dependent impedance, attenuation, self-resonant frequency (SRF) and damping behavior. A particular advantage of the WE-PD in filter applications is its comparatively high impedance over a broad frequency range while maintaining a high DC current capability. This allows effective differential-mode filtering even in power lines carrying significant DC current, without the inductor approaching saturation too quickly.

6.2 Local Decoupling

In addition to the filtering implemented on the central power-supply board, further decoupling and filtering is applied locally at the individual loads on the respective circuit boards.

Local decoupling complements the filtering of the central power supply by providing a low-impedance supply path directly at the individual circuits. Its main purpose is to supply the transient current required by switching and analogue components locally and to provide additional attenuation of low- and high-frequency disturbances on the power-supply path.

The local filters reduce supply-voltage fluctuations through their load-side capacitors, which provide the transient current close to the IC. The series inductors provide a high impedance to higher-frequency disturbances and limit the corresponding AC current flowing between the local load and the upstream power-supply network. In this way, the high-frequency current is largely confined to the local loop between the load and its decoupling capacitors.

At the same time, the filters provide bidirectional isolation: they attenuate disturbances arriving from the power supply and help prevent disturbances generated by the local circuit from propagating through the common power-distribution network and coupling into other circuits.

The effectiveness of local decoupling is primarily determined by the impedance over the relevant frequency range. Component characteristics, parasitic inductance of PCB traces and vias, and particularly component placement determine the actual high-frequency performance. For this reason, the load-side decoupling capacitors should be placed as close as practical to the supply and ground terminals of the load, with short, low-inductance current paths. An example of a local decoupling is shown in Figure 9, which is the DC/DC supply for a digital signal processor (DSP, ADAU1701).

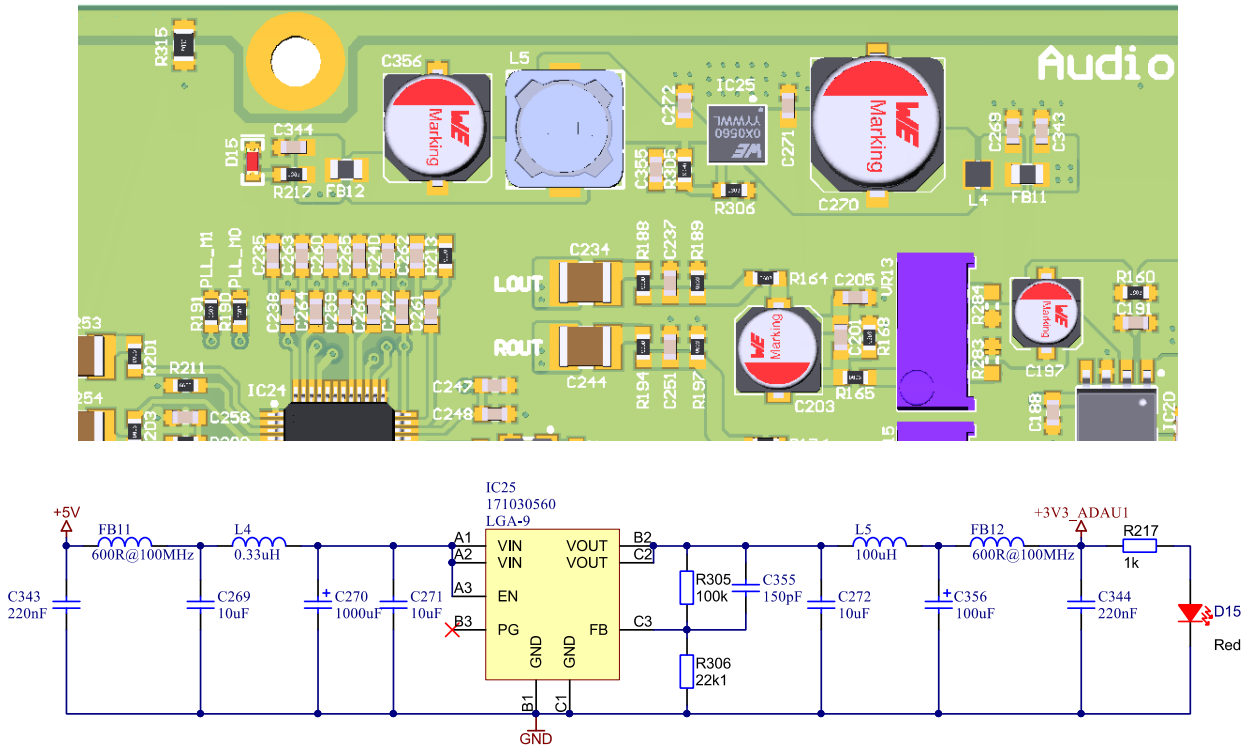


Figure 9: The local +3.3 V supply circuit for the ADAU1701, including the input and output filter stages.

6.3 Circuit and Layout Implementation

The +3.3 V supply for the ADAU1701 (Figure 9) provides an example of how the filtering concept of the central power-supply board is continued locally at a sensitive load. It is generated locally from the +5 V rail by the WPME-VDMM 171030560 DC/DC converter module (IC_{25}). The converter is surrounded by dedicated input and output filtering to prevent switching disturbances from propagating into the +5 V supply and to provide a low-noise +3.3 V rail for the sensitive mixed-signal circuitry on the audio main board.

At the input, C_{343}, FB_{11}, L_4, C_{269}, C_{270} and C_{271} form a multi-stage filter. FB_{11} provides high-frequency attenuation, while L_4 together with the capacitors provides additional differential-mode filtering at lower frequencies. The combination of different capacitor values and technologies provides a low supply impedance over a broader frequency range than a single capacitor could achieve.

At the converter output, C_{272}, L_5, C_{356}, FB_{12} and C_{344} form the local post-filter. The 100 µH WE-PD inductor L_5 provides substantial impedance over a wide frequency range, while C_{272} and C_{356} provide the main capacitive filtering. FB_{12} and C_{344} extend the attenuation toward higher frequencies, resulting in a clean +3.3 V supply for the ADAU1701 and limiting the propagation of converter-generated switching noise.

6.4 Physical Implementation

The PCB layout follows the electrical structure of the filter very closely. The components are arranged in a linear sequence from the +5 V input, through the input filter and DC/DC converter, to the filtered +3.3 V output. This is important because it prevents the filter stages from being bypassed by long parallel supply paths or unnecessary coupling between the unfiltered input and filtered output.

The capacitors are distributed on both sides of these series elements according to their function, thereby providing local energy storage and low-impedance paths for switching-frequency and high-frequency noise components. Particular attention is given to keeping the critical connections between IC_{25}, its local capacitors and the first filter elements short and compact. This reduces parasitic inductance and minimizes the loop area of the high-frequency switching currents, thereby limiting conducted

and radiated EMI. The compact arrangement around the DC/DC converter (IC_{25}) also minimizes the area of the high-di/dt current paths.

The layout therefore implements a clear "source-filter-converter-filter-load/IC" structure. This physical separation, together with short connections and a low-impedance ground reference, is essential: even correctly calculated filter components can provide poor high-frequency attenuation if input and output nodes are coupled through the PCB layout.

6.5 Grounding and Return-Current Paths

Figure 10 shows the grounding concept used for the +15 V DC/DC converter. A continuous GND plane provides a low-impedance reference and avoids unnecessary interruptions of the return-current paths. The input and output capacitors are connected to the converter and GND by short, direct connections, thereby minimizing the loop area and parasitic inductance of the relevant high frequency current paths.

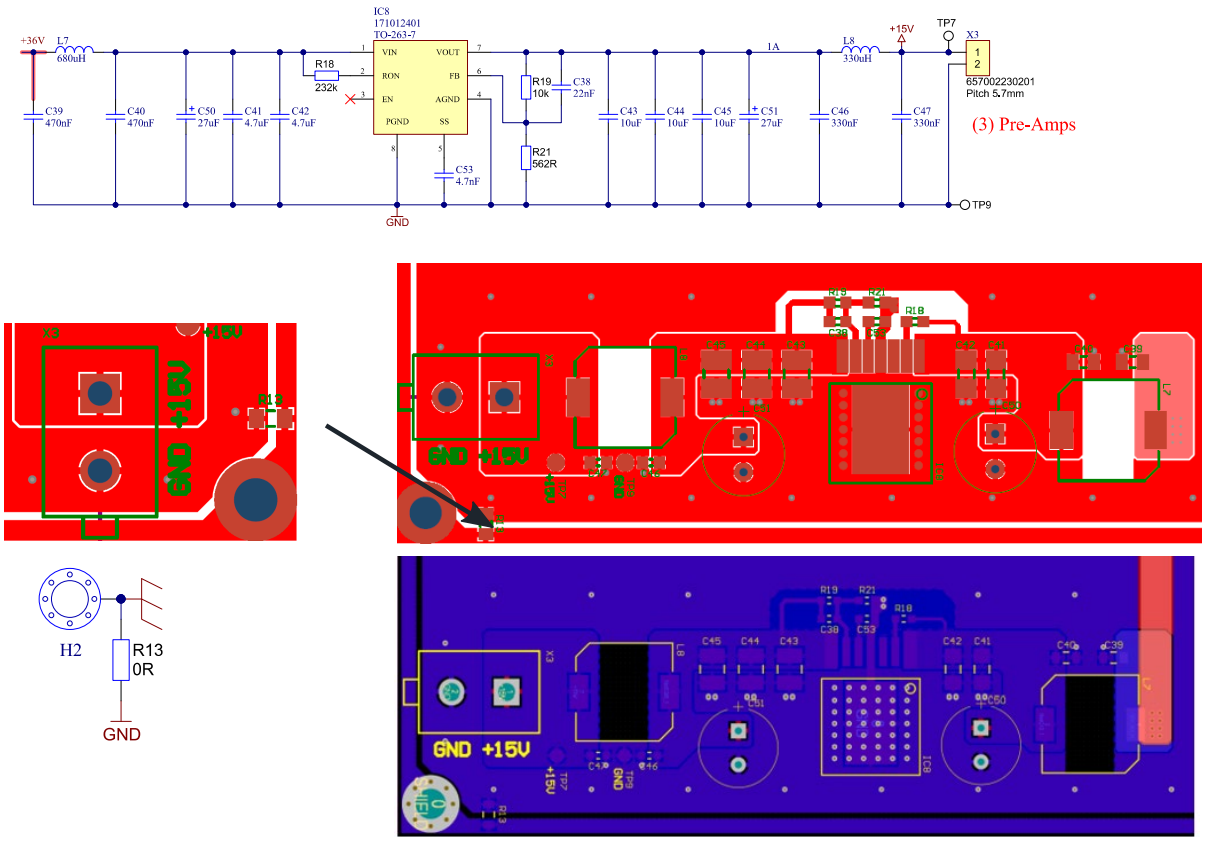


Figure 10: An example of the ground-plane and layer implementation of the +15 V DC/DC converter, including the local return-current paths and the connection between circuit GND and chassis/shield ground.

The GND plane is locally kept clear underneath the WE-PD inductors. Due to the shielded construction of the WE-PD series, such a keep-out area is not strictly required. However, it can be advantageous because it reduces capacitive coupling between the inductor winding and the ground plane, thereby limiting the injection of high-frequency common-mode currents into the ground structure.

The circuit GND is connected to the shield/chassis ground (SGND) through R_{13}, providing a defined connection between the electronic ground and the enclosure. The appropriate coupling element depends on the expected disturbance mechanism: a direct or resistive connection can be used where DC or low-frequency potential equalization is required, while a capacitor can provide high-frequency coupling without a DC connection. Where high-frequency equalizing currents should be limited, an SMD

ferrite can alternatively be used to increase the impedance at higher frequencies. As mentioned before, for a detailed explanation, please refer to Reference Design Notes RD016 and RD022.

In summary, this example illustrates three important grounding measures: a continuous reference plane, compact converter current loops and a controlled impedance between circuit GND and chassis/shield ground. These measures complement the supply filtering without unnecessarily splitting the ground plane.

From an EMC perspective, grounding should be considered in terms of impedances. At higher frequencies, the return-current path is increasingly determined by parasitic inductance and electromagnetic coupling. A continuous reference plane minimizes return-path impedance and loop area, while intentional connections between circuit ground and chassis define how common-mode currents are controlled. Consequently, grounding is an integral part of the high-frequency current-path design rather than simply a connection to a common zero-volt potential.

7. POWER-UP, INRUSH LIMITING AND SHUTDOWN SEQUENCE

The power-supply concept includes a defined power-up and shutdown sequence to limit the initial charging current of the amplifier buffer capacitors and to ensure controlled connection and disconnection of the loudspeakers. The large bulk capacitors are located on the Class-D amplifier boards and are therefore charged through the inrush-limiting resistor R_V when the main power switch is activated. This limits the initial current drawn from the external 36 V supply and reduces the electrical stress on the switch, PCB conductors, connectors and power components.

During the initial charging phase, the main 36 V supply reaches the amplifier boards through R_V. After approximately 1.1 s, the bypass relay closes and shorts R_V, allowing the amplifiers to operate directly from the low-impedance 36 V supply without additional series resistance.

The individual DC/DC converters are not actively sequenced against each other; the system-level start-up sequence is determined by the inrush-current bypass timing and the subsequent delayed activation of the loudspeaker relays.

Figure 11 summarizes the complete sequence from inrush-limited charging and relay bypass during power-up to delayed loudspeaker connection and rapid loudspeaker disconnection during power-down.

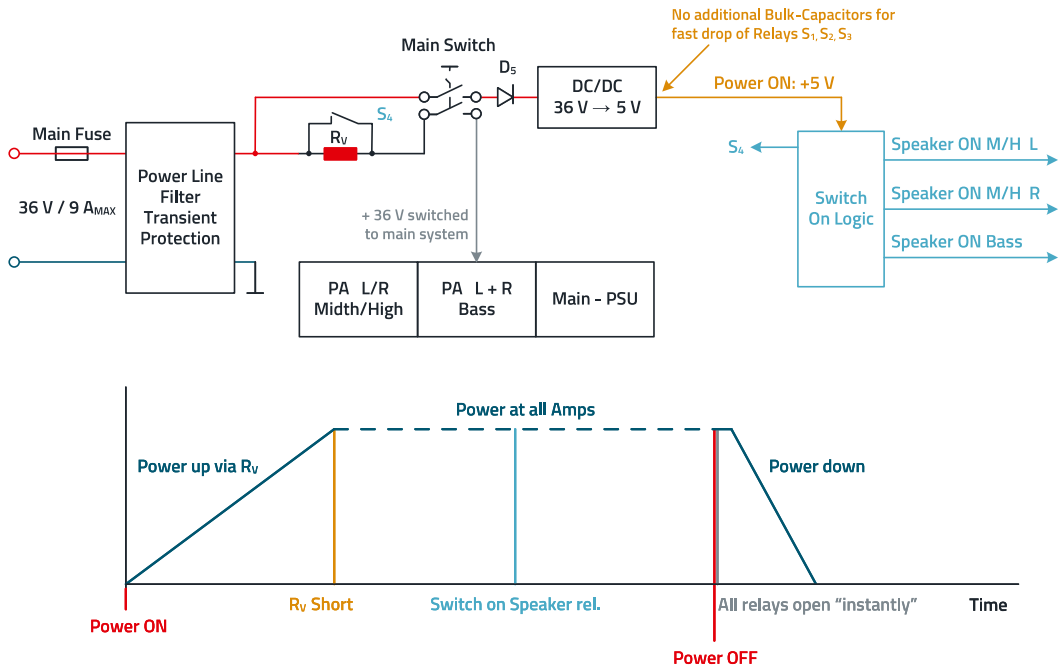


Figure 11: The power-up and shutdown sequence of the system, including inrush-current limiting, bypass of the series resistor and the delayed connection and rapid disconnection of the speakers.

A separate 36 V to 5 V DC/DC converter supplies the switch-on logic. No additional large bulk capacitance is used on this auxiliary +5 V rail, allowing it to respond rapidly to the state of the main power switch. After the main supply has stabilized and the system initialization is complete, the switch-on logic activates the loudspeaker relays, connecting the bass and left/right mid/high-frequency loudspeakers to their respective amplifiers.

The shutdown sequence is intentionally faster than the natural discharge of the main amplifier supply. This function is not controlled by a dedicated undervoltage-lockout (UVLO) threshold. Instead, the auxiliary +5 V logic supply contains only limited stored energy and therefore decays rapidly when the main switch is opened. As a result, the loudspeaker relays are released while energy is still stored in the main 36 V amplifier buffer capacitors. The amplifiers therefore remain electrically supplied during the short relay-release interval, preventing uncontrolled output transients from reaching the loudspeakers during power-down.

From a system-design perspective, the power-up and power-down sequences must be considered separately. During power-up, the priority is to limit inrush current and allow the supply rails and amplifier operating points to stabilize before the loudspeakers are connected. During power-down, the priority is reversed: the loudspeakers should be disconnected before the amplifier supply rails collapse, thereby preventing audible transients and undefined amplifier states from reaching the loudspeakers.

Diode D_5 provides reverse-current isolation between the input of the auxiliary 36 V to 5 V converter and the switched +36 V main supply. During power-up, activation of the power amplifiers can cause a temporary high-current load step and a corresponding voltage drop on the +36 V rail. If the main rail voltage falls below the locally maintained voltage at the input of the +5 V converter, D_5 becomes reverse-biased and prevents the local input capacitors C_4/C_5 from discharging back into the main 36 V system. The energy stored in C_4/C_5 can therefore support the +5 V converter during short supply dips, improving the stability of the switch-on logic during amplifier start-up.

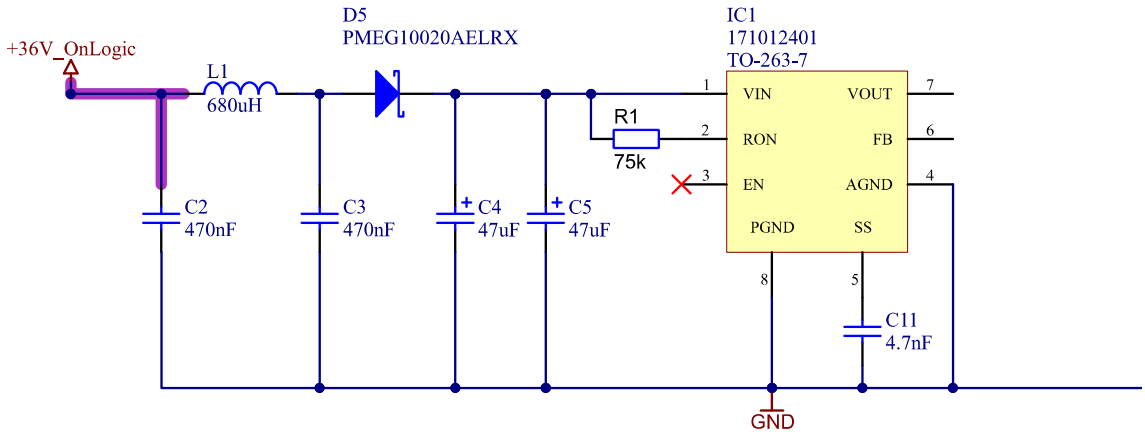


Figure 12: The input stage of the +5 V Logic converter. Diode D_5 provides reverse-current isolation while C_4 and C_5 provide local energy storage at the converter input.

8. POWER SUPPLY RIPPLE AND EFFICIENCY

The individual supply rails were characterized in terms of peak-to-peak ripple and conversion efficiency under representative resistive loads. Ripple measurements were performed using standard oscilloscope probes, with the signals recorded before and after the respective output filters. Particular attention was paid to the oscilloscope probe ground connections and their routing to minimize potential interference pickup. The influence of the ground leads was experimentally checked and found to have no measurable effect on the ripple results.

For additional frequency-domain investigations, a dedicated AC-coupled measurement probe was connected to a spectrum analyzer. This probe consists of a 470 nF, 250 VDC X7R MLCC (WCAP-CSMH 885342211003) connected in series with the measured supply rail and a 1 kΩ resistor connected between the capacitor output and ground. The RC network blocks the DC

component of the supply voltage while allowing the superimposed AC noise components to be analyzed. These spectral measurements are not presented in this report.

The measurement setup, including the oscilloscope probes, dedicated spectrum analyzer probe and resistive loads, is shown in Figure 13.

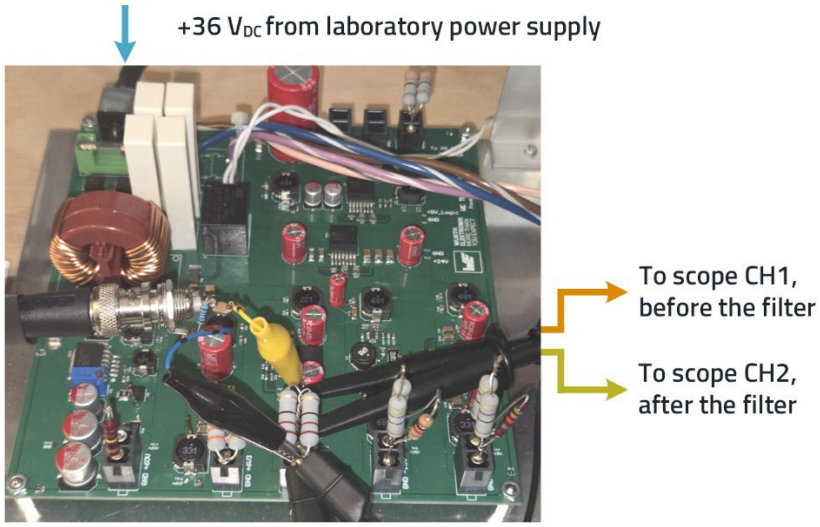


Figure 13: Measurement setup for the characterization of the individual supply rails, showing the oscilloscope connections for ripple measurements before and after the output filters, the dedicated AC-coupled probe for supplementary spectrum analyzer measurements, and the resistive loads.

For the oscilloscope measurements (refer to Figure 14), the yellow trace represents the voltage before the respective filter stage while the blue trace represents the voltage at the filter output. The vertical scales of the oscilloscope channels were adjusted individually for the different measurements to obtain sufficient resolution of the ripple waveform. Therefore, the displayed trace amplitudes in Figure 14 should not be compared directly based on their visual appearance.

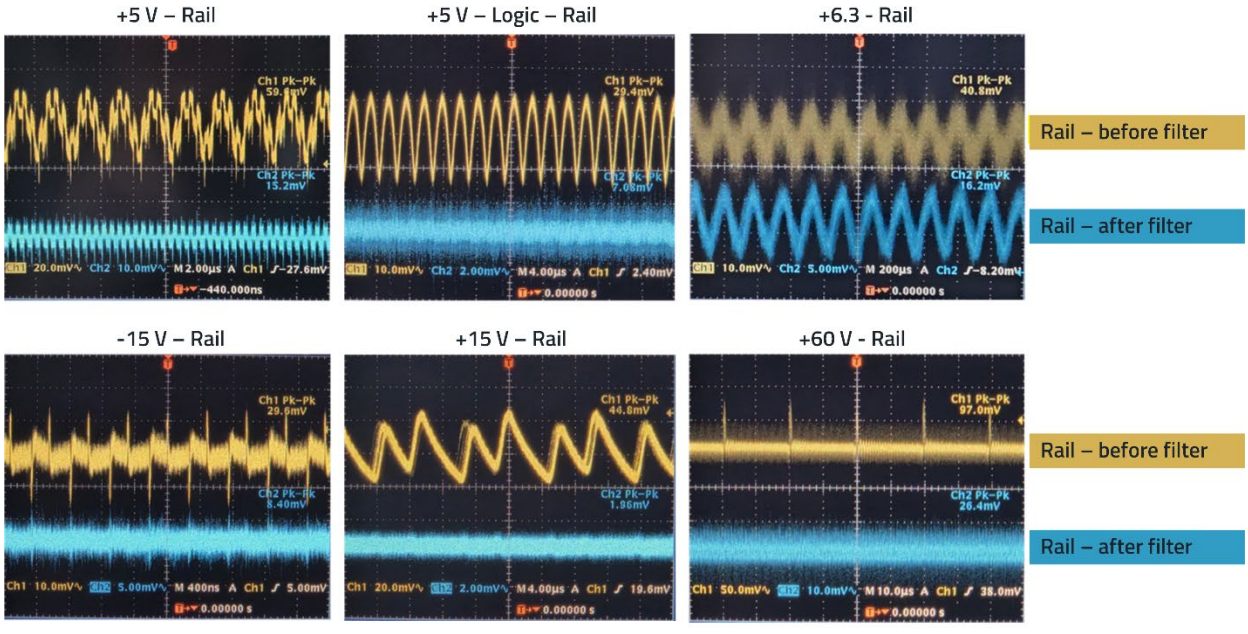


Figure 14: The measured ripple waveforms before and after the respective filter stages for the individual supply rails under the specified resistive loads.

The quantitative comparison is based on the measured peak-to-peak values summarized in Table 4.

Rail	Load	Ripple pk-pk	Attenuation
+5 V	10.6 Ω	58.8 mV → 15.2 mV	11.7 dB
+5 V Logic	17.78 Ω	28.4 mV → 8.64 mV	10.3 dB
+6.3 V	16.96 Ω	36.2 mV → 14.8 mV	7.8 dB
-15 V	86.8 Ω	29.6 mV → 8.40 mV	10.9 dB
+15 V	86.8 Ω	45.2 mV → 2.16 mV	26.4 dB
+60 V	100 kΩ	97.0 mV → 26.0 mV	11.4 dB

Table 4: The measured peak-to-peak ripple and the filter attenuation of the individual supply rails under the specified resistive load conditions.

The measurements show a reduction of the peak-to-peak ripple on all evaluated supply rails, with the +15 V and -15 V rails providing the lowest ripple for the smooth operation of the sensitive amplifiers.

9. DESIGN RECOMMENDATIONS

The reference design demonstrates that power integrity in mixed-signal systems has to be addressed at system level. Converter selection, filtering, decoupling and PCB implementation must be coordinated according to the requirements of the respective load.

The following design recommendations can be derived:

- Separate high-current, analog and digital loads into dedicated supply domains with controlled coupling between them.
- Select the converter according to voltage range, load current, efficiency, transient behavior and required supply quality.
- Adapt the filter topology and component values to the respective rail instead of applying one common filter concept throughout the system.
- Combine filter stages to cover different frequency ranges where attenuation over a broad frequency range is required.
- Place high-frequency decoupling as close as possible to the corresponding load.
- Keep switching-current loops short and provide continuous, low-impedance return paths.
- Minimize shared return-current paths between noisy and sensitive circuit sections.
- Avoid undamped high-Q filter structures where resonances may reduce stability or increase interference, consider the frequency-dependent impedance and parasitic behavior of the components.
- Evaluate ripple and efficiency under representative operating conditions rather than relying only on converter data-sheet values.
- Verify the implemented filtering directly on the actual hardware.

10. CONCLUSION

The presented reference design demonstrates a practical power-supply architecture for a mixed-signal audio system with substantially different load requirements. The measurements confirm that the rail-specific filter stages reduce the residual peak-to-peak ripple while the measured efficiencies illustrate the influence of converter topology and operating point.

The results underline that power distribution, filtering, decoupling and PCB implementation have to be considered as a coordinated system. The presented design approach can also be transferred to other mixed-signal applications in which switching power stages operate close to sensitive analog and digital circuitry.

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REVISION HISTORY

Document Version	Release Date	Changes
ANP156a	2026/11/03	Initial release of the application note
ANP156b	2026/11/05	+5 V logic rail added in Figure 3, Table 2 and Figure 10 updated, Information about max. load of downstream supply rails added in chapter 2.

Note: *The current version of the document and the release date are indicated in the footer of each page of this document.*