Resonant Power Supply Suits Audio Systems

By Dr. Mahesh de Silva, Senior Applications Engineer,
CamSemi, Cambridge, U.K.

A power supply with a novel resonant topology enables an audio system with the efficiency, no-load and size advantages of SMPS, but very low-generated EMI.

Audio equipment manufacturers are under growing market and commercial pressures to improve the efficiency and no-load power dissipation in products that currently rely on linear power supplies. Linear power supplies are ideal for audio applications, because the mains frequency transformer generates low electromagnetic emissions, and because of the minimal design time typically required for low-cost applications with relaxed voltage regulation, ripple and protection specifications. However, linear supplies suffer from low average efficiency and high no-load power, so they struggle to meet today's main regulatory requirements, such as ENERGY STAR and California Energy Commission (CEC).

A typical 12-W linear power supply, for example, has an average efficiency of about 63%, whereas the proposed ENERGY STAR V2.0 requirement, scheduled for implementation later this year, is 77.8%. The no-load power dissipation of around 1.5 W also fails to meet the 300 mW demanded by the standard. Bulky linear supplies, particularly at higher powers, are also getting increasingly expensive because of steep rises in global commodity prices, such as copper and steel used in the line-frequency transformer.

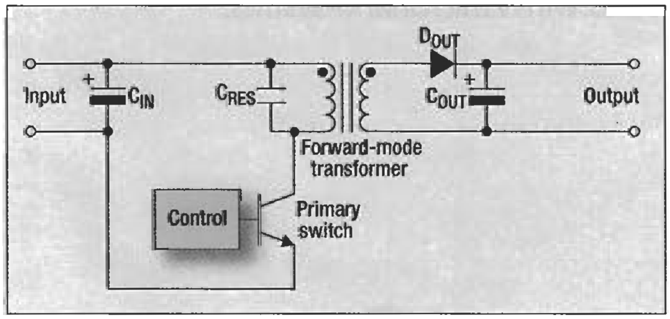


Fig. 1. *Key components of the RDFC resonant topology include a bipolar junction transistor as the primary switch and resonant capacitor (C_{RES}), which resonates with the transformer magnetizing inductance to achieve fully resonant switching.*

Although low electromagnetic interference (EMI) is often cited as the single most attractive feature of linear supplies for the audio market, the presence of twice the mains frequency ac component at the rectified output can cause audible hum in some applications. This usually gets worse with increasing load and reduced input voltage, which causes the audio quality to deteriorate.

SMPS for Audio Applications

To overcome these efficiency and EMI difficulties, audio power-supply manufacturers are actively looking to replace linear supplies. Specifically, they are focusing increased attention on common switch-mode power-supply (SMPS) topologies such as flyback and ringing choke converter. Both topologies offer higher efficiency, lower standby power and additional features such as overvoltage, overcurrent and overtemperature protection. SMPS also provides tight load and line regulation, which relaxes the requirement for post-regulation circuitry. And with tightly controlled output V-I characteristics, these alternative approaches can be programmed to deliver the peak load capability that many audio systems demand.

On the other hand, SMPS suffers from higher bill-of-materials (BOM) cost and longer design times, making them a much less attractive option as linear replacements in low-cost, high-volume applications. The presence of excessive electromagnetic noise due to fast switching transients is also a major hurdle, because the resulting conducted and radiated emissions interfere considerably with the audio signal. To overcome this, expensive electromagnetic compatibility (EMC) suppression filters are normally required along with EMI reduction techniques in the core of the SMPS controller.

One SMPS design technique involves using a sync pulse from the audio system to dynamically shift the operating frequency away from the instantaneous radio frequency, thereby reducing interference. Switching-frequency dithering or spread-spectrum modulation is another commonly employed method to spread the spectral energy of noise while maintaining the system's overall efficiency. However, even with extensive filtering and sophisticated control techniques, it can be extremely difficult to achieve the very low EMI required by most audio systems to deliver targeted signal-to-noise ratios.

Resonant Topology Replacement

Resonant topologies offer a commercially viable power-supply alternative to overcome the limitations of linear and common SMPS topologies, while meeting the latest efficiency, no-load power and EMI requirements. By switching at near-zero voltage and current, this approach minimizes switching losses to deliver high efficiency and generate minimal EMI because of their sinusoidal switching waveforms. But until recently, resonant topologies have not been exploited commercially for low-power applications in the consumer electronics market because of inherent difficulties in control and the resulting high BOM cost.

A novel single-switch resonant discontinuous forward-converter (RDFC) topology offers the efficiency, no-load and size advantages of SMPS without the cost penalty, as well as additional safety and protection features. More importantly for audio and other EMI-sensitive applications, such as cordless-phone adapters and modem/router power supplies, the topology offers resonant power conversion with naturally low EMI.

As no energy is stored within the forward-mode transformer during switching, a forward-converter topology also allows a reduction in the transformer core size. This delivers a cost benefit in itself, while removing the need for a secondary freewheeling diode and choke to make the solution much more commercially attractive at low power.

Fig. 1 shows the key components of the RDFC topology. The input capacitor (C_{IN}) smooths the rectified ac voltage at the input and applies it to the forward-mode transformer. Closing the primary switch transfers power from the primary to the secondary during the same conduction phase. The current waveform through the primary transistor consists of current through the leakage inductance and magnetizing inductance. The leakage current component usually dominates and also appears across the secondary diode.

When the primary switch is closed, the total current through the transformer diverts to the resonant capacitance (C_{RES}), which includes the transformer winding capacitance and primary transistor output capacitance. C_{RES} forms a resonant circuit with the transformer leakage inductance

(L_{LEAK}) followed by the magnetizing inductance (L_{MAG}).

Resonant frequencies are given by Eqs. 1 and 2:

$$f_{RES1} = \frac{1}{2\pi\sqrt{L_{Leak} \times C_{RES}}} \qquad \text{(Eq. 1)}$$

$$f_{RES2} = \frac{1}{2\pi\sqrt{L_{MAG} \times C_{RES}}}, \qquad \text{(Eq. 2)}$$

where f_{RES1} equals the resonant frequency due to the transformer leakage inductance, f_{RES2} equals the resonant frequency due to the transformer magnetizing inductance, L_{LEAK} equals the transformer leakage inductance, L_{MAG} equals the transformer magnetizing inductance and C_{RES} equals the transformer resonant capacitance.

The leakage inductance is much smaller than the magnetizing inductance, so the resonant frequency in Eq. 1 is higher than that of Eq. 2.

A mixed-signal control IC developed by CamSemi ensures the RDFC circuitry operates at optimum performance levels with load variations. The resultant C2470 family of controllers achieves this through three main control mechanisms:

- Resonant control senses the resonance waveform to identify the near-zero turn-on and turn-off voltages and to determine the optimum on-time in the next switching cycle.

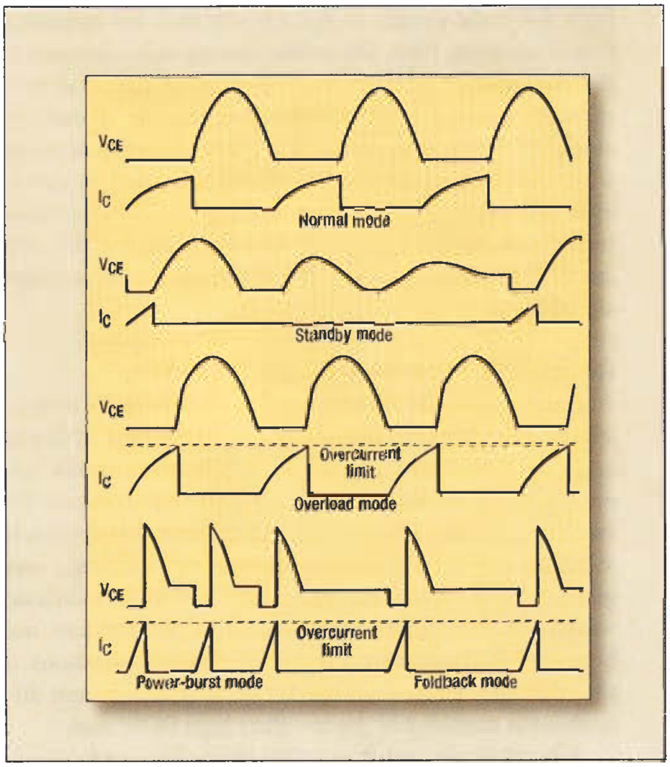


Fig. 2. *Different operating modes within the RDFC power supply guarantee fully resonant operation at all significant loads to deliver optimized efficiency and reduced EMI.*

- Power control is achieved by sensing the switch current and limiting it under overload conditions or reducing the on-time at low-load conditions to minimize no-load power loss.
- Base-drive control dynamically maintains the on-state voltage of the power transistor at an optimum voltage to reduce conduction losses and minimize turn-off time to lower switching losses.

The RDFC controller uses a combination of these three control mechanisms to define five main operating modes of the power supply (Fig. 2):

- Normal mode provides fully resonant switching and has a fixed duty cycle for power delivery from around 20% to 100% load.
- Standby mode is entered as the load decreases. The controller enters this mode by reducing the on-time and increasing the off-time.
- Overload mode occurs under high-output loads. It limits the peak switch current and reduces the on-time, while maintaining fully resonant operation.
- Foldback mode occurs under excessive output loads and reduces the on-time to a minimum, while increasing the off-time to protect the power supply in short-circuit conditions.
- Power-burst mode has an increased duty cycle. The controller enters this mode periodically during the foldback mode to allow the power supply to recover from a short-circuit condition.

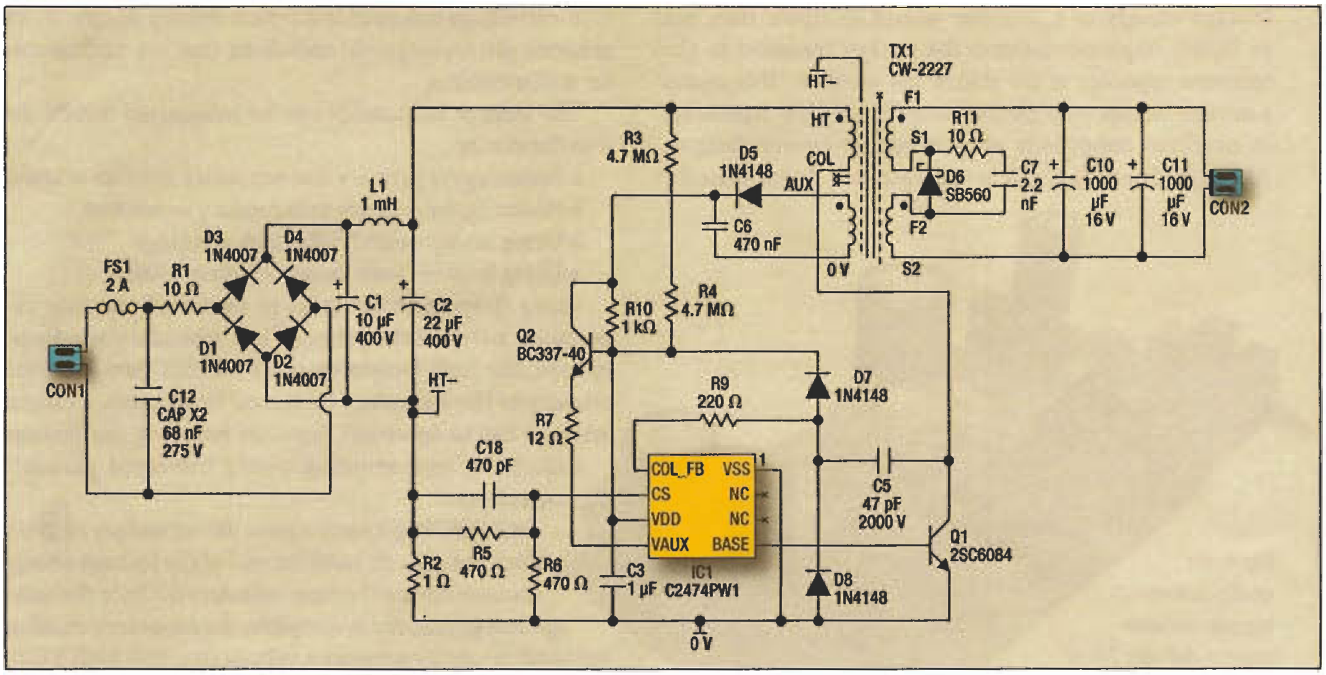


Fig. 3. *The RDFC circuit employs the C2474PW1 member of the controller IC family housed in a PDIP-8 package.*

Minimizing EMI

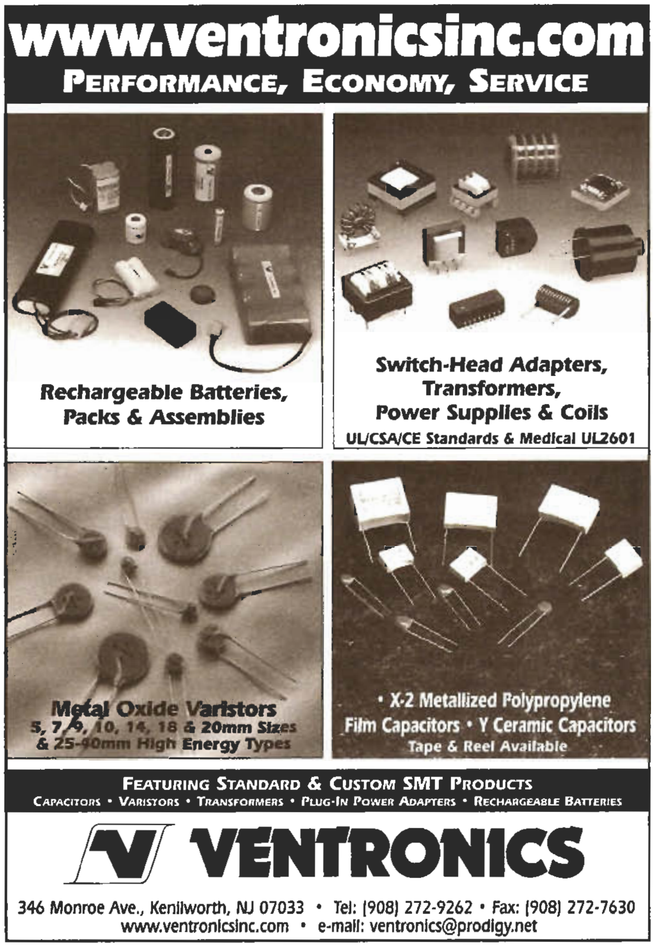
The RDFC topology generates very low EMI to meet the tight specifications of audio applications, but with minimum design effort or need for extra components. The topology's sinusoidal switching waveform eliminates fast switching transients and the consequent electromagnetic emissions. As Fig. 2 shows, the topology maintains fully resonant operation during all significant loads, which ensures low noise levels.

The resonant waveform in RDFC is superimposed on the unregulated input voltage. Fluctuations of the input voltage due to mains ripple cause the resonant waveform to move up and down resulting in an off-time fluctuation. Duty cycle is fixed, so this off-time fluctuation causes switching-frequency dithering, leading to further improvement in EMI performance.

Both of these features help to deliver a switching power supply with electromagnetic emissions that are 15 dB to 20 dB lower than a similarly rated SMPS. Expensive EMC filters are not required up to 20 W for almost all consumer applications, and in most cases, there is no need for a Y2 capacitor between the primary and secondary sides. Eliminating the Y2 capacitor further improves the audio quality by minimizing mains hum on the secondary side of the transformer that is directly connected to the audio system.

Despite the EMI benefits of resonant switching and frequency dithering, electromagnetic emissions are still present in RDFC implementations at a low level because of non-ideal transformer behavior. Eliminating leakage inductance in a transformer completely is hard to achieve from a practical perspective, despite careful design and construction.

Leakage inductance in a switching power converter stores a significant amount of energy during the on-state of the primary switch. In a typical flyback solution, the



leakage energy of a snubber would dissipate this, but in RDFC implementations, the energy transfers to the resonant capacitor at the end of the on-state. This causes a notable voltage step during turn-off, which is significant in overload conditions or with higher-power designs. Although this voltage rise is usually much slower than the turn-off voltage transient in a typical flyback design, it can generate electromagnetic emissions that are undesirable for audio systems.

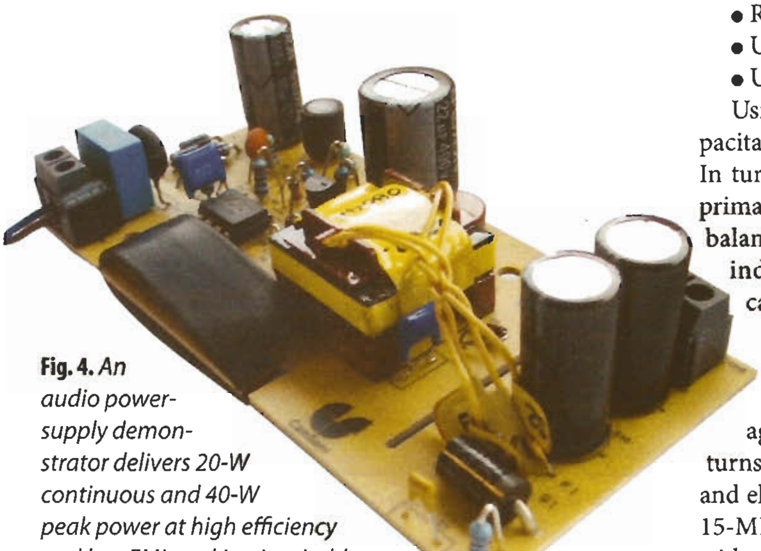
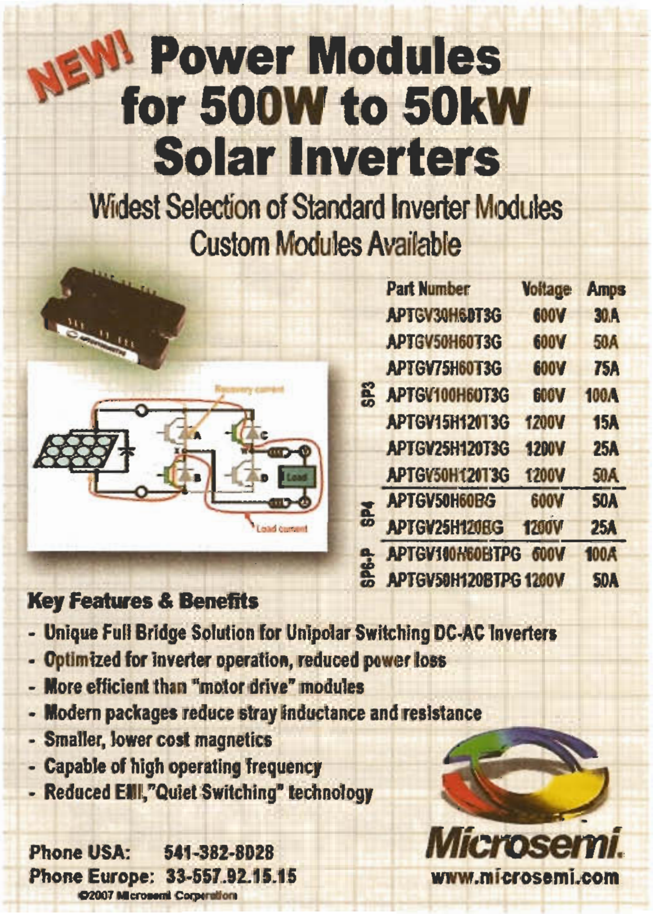


Fig. 4. *An audio power-supply demonstrator delivers 20-W continuous and 40-W peak power at high efficiency and low EMI, making it suitable for low-cost audio products with CD players and FM radios.*



The leakage inductance can be minimized within the transformer by:

- Reducing the primary and secondary number of layers
- Reducing the primary to secondary separation
- Using neatly wound full-width windings
- Using bobbins with longer winding widths.

Using these methods leads to increased parasitic capacitance between the primary and secondary windings. In turn, the high-frequency noise current flow from the primary to the secondary increases. In all cases, a careful balance has to be struck between reducing the leakage inductance and avoiding overly increased parasitic capacitances.

In RDFC implementations, the secondary rectifier does not turn off until the end of the leakage energy transfer during the turn-off interval. Once the leakage energy transfer is complete, the secondary rectifier turns off to rapidly generate a voltage step with high dV/dt and electromagnetic emissions, usually in the 12-MHz to 15-MHz range. This noise can be successfully eliminated with an R-C snubber across the secondary rectifier and with minor effect on the power supply's efficiency.

Transformer noise reduction or cancellation techniques also can be employed to reduce electromagnetic emissions still further. The most popular technique for cutting common-mode conducted emissions within the topology is to place a wound or foil screen between the primary and secondary windings. High-frequency current that flows out of the primary winding through the primary-to-secondary parasitic capacitance is now collected by the screen and returned to the supply conductors. The auxiliary winding, which provides the V_{DD}-pin supply, also can be used effectively as a screen between the primary and secondary windings — in other words, to eliminate the need for an extra screen winding or foil, thus reducing the BOM cost.

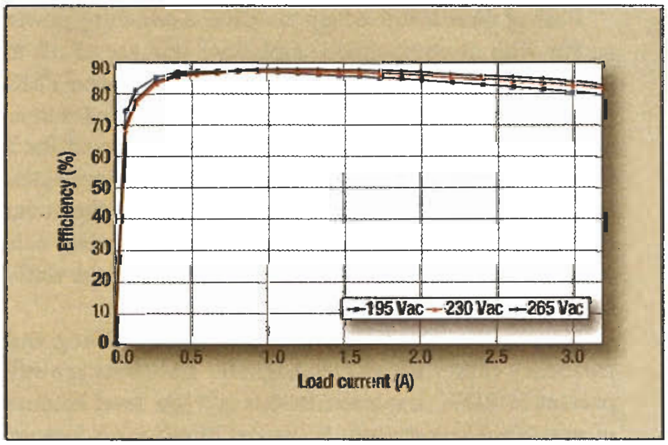


Fig. 5. *High-conversion efficiency is maintained throughout the load range with 70% at 80 mA, 88% at rated load of 1.6 A and 81% at peak load of 3.2 A.*

Design Example

Fig. 3 shows the off-line audio power-supply circuit. Fig. 4 is the demonstrator based on the RDFC topology and a C2470 controller, operating from a 230-Vac nominal input and delivering 20-W continuous and 40-W peak power on a single 12-V output rail. The unit has a very low component count and uses a smaller transformer than a flyback solution of a similar specification. In addition, lower rms output current, due to the shape of the on-state current, reduces the ripple current requirement of the output capacitors, compared with those in more conventional SMPS topologies.

EMC reduction is achieved from the improved transformer design plus the use of a secondary snubber, a shield around the primary switch and a small X2 capacitor. The transformer has foil screens on either side of the balanced split secondary winding to allow cancellation of the secondary-side common-mode noise currents and to minimize primary-to-secondary noise-current flow through the parasitic capacitance. A shield around the primary switch contains the noise radiated from the tab of the TO-220 package connected to the collector of the transistor.

The table lists key specifications for this design example including a high average efficiency of 88% and low no-load power dissipation of 180 mW, both of which meet the proposed ENERGY STAR V2.0 regulations with a significant margin. The efficiency versus the output current graph in Fig. 5 shows the low-load efficiency with a minimum of 70% efficiency at 5% load, ideal for audio systems operating well below the rated power level.

Fig. 6 shows the worst-case conducted EMI results for the power supply with the negative output rail connected to earth. These plots illustrate that a margin of at least 20 dB below the EN55022 quasi-peak and average limits is achievable with this design.

The resonant topology and EMI reduction techniques discussed here are ideal for consumer audio products with CD players and FM radios, but for applications with AM receivers, a further reduction in EMI is required. This can be achieved by a combination of optimizing the transformer design, careful selection of EMC filters and additional shielding of specific components that generate radiated emissions. Fig. 7 shows the results for a typical AM-compliant RDFC power-supply design with these modifications implemented. The EMI generated is below 15 dBμV, making it hard to measure using an industry-standard EMC receiver. **PETech**

Description	Typical
Line input voltage	230 V
Line frequency	50 Hz
Switching frequency	60 kHz
Output voltage	12.5 V
Output ripple voltage at line frequency	0.78 V
Output ripple voltage at switching frequency	180 mV
Continuous output power	20 W
Peak output power	40 W
Average efficiency	88%
No-load consumption	180 mW

Table. *Key specifications of example design.*

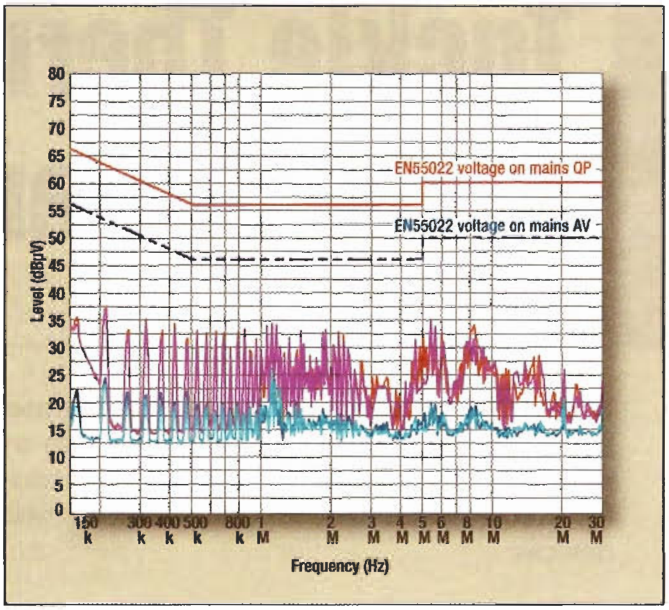


Fig. 6. *Worst-case conducted EMI performance measured with the negative output rail earthed shows greater than a 20-dB margin throughout the EN55022 measurement range of 150 kHz to 30 MHz.*

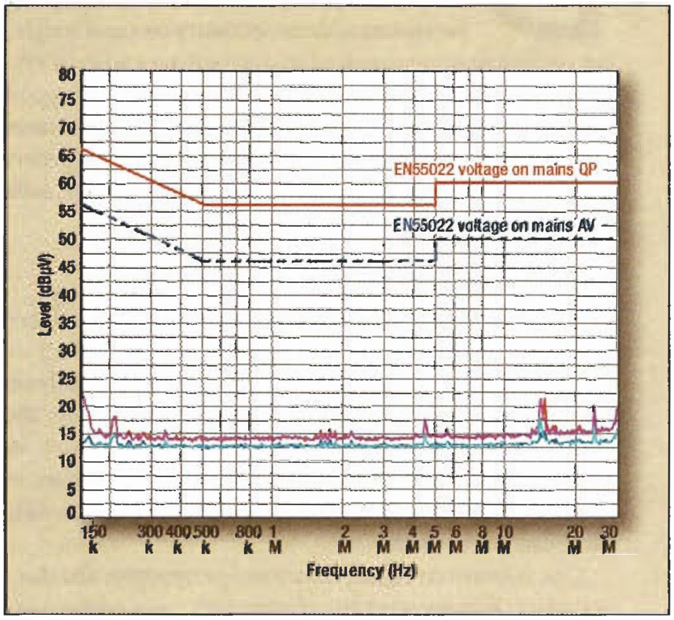


Fig. 7. *An AM-compliant RDFC design produces very low EMI, barely noticeable above the noise floor of the industry-standard EMC receiver.*