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Class D Amplifier with Ripple Steering

Abstract

Class D amplifiers are used for their high efficiency, but they have some undesirable characteristics, one of these being the residual switching frequency ripple. This paper shows a method of switching frequency ripple reduction by means of ripple steering. With this technique a second output is constructed, into which the switching ripple is steered, substantially relieving the main output from a major artifact of Class D operation.

white paper

Introduction

A Class D amplifier is basically a switchmode power supply modified to operate in four quadrants at high frequencies. A half bridge Class D amplifier and its basic waveforms are shown in Figures 1 and 2. A squarewave is generated by the switching devices, which is smoothed by the LC filter L1, C1. For minimum residual switching frequency ripple the LC filter should have a low cutoff frequency. For maximum audio output signal bandwidth the LC filter should have a high cutoff frequency. The tradeoff is simple to analyze using linear methods.

A method of reducing the residual switching frequency ripple is shown by a concept known as ripple steering. In this method, a second output is constructed that consists of a second LC filter with a high ripple current that is used solely for the purpose of eliminating the ripple current in the main output. This second output uses the main output's power inductor, which is modified by one of several means, as well as a discrete uncoupled inductor and a small capacitor.

The power inductor may be modified by the addition of a small secondary winding with a termination in common with the primary inductor winding's switched node, by the addition of a smaller bucking secondary winding with a termination in common with the main inductor's output node, or by the addition of a tap in the power inductor's primary winding.

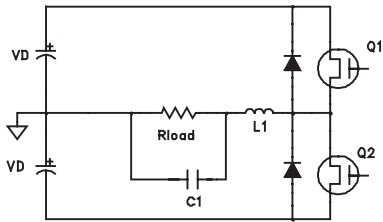


Figure 1: Conventional Class D Half Bridge

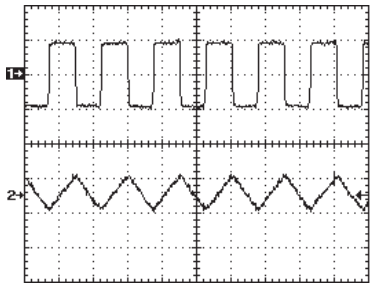


Figure 2: Class D L1 Voltage (Ch 1, 50 V/div) and L1 Current (Ch 2, 1 A/div)

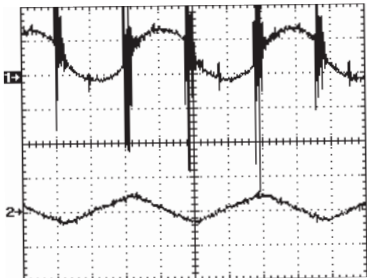


Figure 3: Class D C1 Voltage (Ch 1, 100 mV/div.) and L1 Current (Ch 2, 1 A/div.)

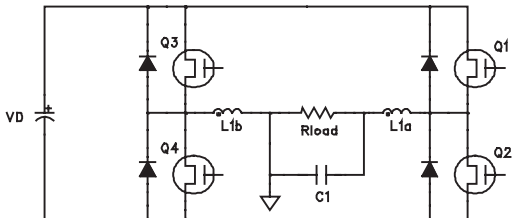


Figure 4: Conventional Class D Full Bridge

Conventional Class D Operation

Figure 1 shows a half bridge Class D amplifier. The associated waveforms are shown in Figure 2. In this circuit an LC filter is driven by a squarewave at the switching frequency and the output voltage changes slowly in comparison to the switching frequency. The voltage across L1 is shown in Figure 2, Ch1. The integration of the squarewave voltage into a triangle wave current is done by L1, with L1 current shown in Figure 2, Ch2. This triangle wave current is integrated into a quasi-sine wave voltage by the output capacitor C1, as shown in Figure 3, Ch1.

In practice the voltage ripple on the output capacitor ripple voltage on a full bandwidth Class D amplifier can approach 1Vpp with a fundamental of several hundred kHz, making it extremely prone to interfering with other electronic equipment, especially AM radio receivers. Modulation schemes in which the switching frequency is variable are particularly troublesome. In order to reduce this ripple an LC series trap circuit is often used across C1. This approach has several disadvantages. First, the Q of the LC trap must be extremely high in order to effectively shunt current away from C1, whose impedance at the switching frequency is already well below an ohm. Second, the trap is only effective at a single frequency. The higher the Q, the less effective the trap will be if the switching frequency is variable. The trap is also not very effective at attenuating harmonics of the switching frequency; although these are usually 20dB down from the fundamental in relative terms, they can still present problems if their magnitude is too large in absolute terms. Another standard method of reducing ripple would be to add a second order filter to the output. The disadvantages of this method are that the inductor must be sized to handle the full output current, and the filter may add distortion due to nonlinearity in the devices used, and the filtered output is outside of the control of any feedback loop.

For completeness, a full bridge conventional Class D amplifier is shown in Figure 4. The two inductors are shown as L1a and L1b, and these may be implemented as two discrete inductors, or a single coupled inductor as long as the dot orientation is as shown. The output in this case is shown with one side grounded, but this is not necessary for operation. Waveforms are similar to that of the half bridge.

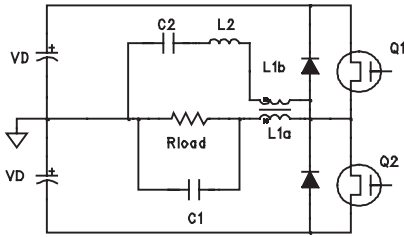


Figure 5: Ripple Steering Class D Half Bridge

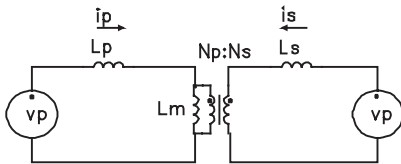


Figure 6: AC equivalent circuit

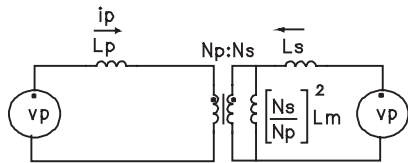


Figure 7: Coupled Inductor with Lm Reflected

Ripple Steering Class D in Theory

To achieve zero ripple current conditions for the main output inductor winding a second output is constructed by adding a second LC filter driven from the same switching node as shown in Figure 5. The output capacitors are separate but the inductors are coupled, having finite uncoupled inductance L2. The DC output voltages on C1 and C2 must both equal the DC voltage on the switching node. For the purpose of switching ripple analysis we need to consider only the AC circuit, and we can redraw the circuit as shown in Figure 6, in which the coupled inductor L1a/L1b is shown as an ideal transformer with turns ratio Np:Ns having a finite magnetizing inductance Lm and finite uncoupled inductances Lp on the primary side and Ls on the secondary side. In practice, Ls will be the combination of coupled inductor leakage inductance and a larger discrete inductor; this is labeled L2 in Figure 5.

The two sides of the inductor are driven with separate AC voltage sources, each of magnitude vp. These are the AC voltage waveforms that appear across each of the coupled inductor windings, including uncoupled inductance. The primary winding sees the differential voltage between the switching node and the main output capacitor C1, while the secondary winding sees the differential between the switching node and the second output C2. Since the voltage on C1 is equal to that of C2 to a first order, each winding drive voltage is equal to vp. vp may have any waveshape and spectrum.

We can see that if the voltage across NP is made equal to vp, then there will be no AC voltage across Lp, which means no AC current flow through Lp. Under these conditions we achieve a zero AC current ripple component for the primary winding of the inductor, meaning zero ripple in the main output.

First Lm is reflected to the secondary side as shown in Figure 7. We can see that there is an inductive voltage divider formed by Ls and the reflected Lm. This divider places a fraction of vp across Ns, as represented by Equation 1.

$$VN_s = v_p \cdot \frac{L_m \cdot \left(\frac{N_s}{N_p}\right)^2}{L_s + L_m \cdot \left(\frac{N_s}{N_p}\right)^2} \quad \mathbf{1}$$

The voltage across N_p is scaled up from the voltage across N_s by the turns ratio N_p/N_s , as represented in Equation (2). When the reduction caused by the inductive divider is equal to the increase caused by the turns ratio, the voltage across N_p will be equal to v_p . Thus there will be no voltage drop across L_p , therefore no ripple current through L_2 .

$$VN_p = \left(\frac{N_p}{N_s}\right) \cdot v_p \cdot \frac{L_m \cdot \left(\frac{N_s}{N_p}\right)^2}{L_s + L_m \cdot \left(\frac{N_s}{N_p}\right)^2} \quad \text{2}$$

Taking Equation 2, setting $V_N = v_p$ and simplifying yields Equation (3). Under these conditions there will be zero ripple current in the main output.

$$L_s = L_m \cdot \left(\frac{N_s}{N_p} - \left(\frac{N_s}{N_p}\right)^2\right) \quad \text{3}$$

If Equation 3 is followed, the optimum value of L_s can be found given the conventional Class D output inductance and the turns ratio of the additional winding. L_s will be comprised of coupled inductor leakage inductance, stray layout inductance, and discrete inductance L_2 . For accurate control of L_s , the discrete L_2 should be the largest component of L_s .

The full bridge version shown in Figure 8 can be arrived at by symmetry, adding a ripple steering circuit to each half bridge, then consolidating series capacitors and inductors so that only one of each is necessary. The coupled inductor windings L_{1a} , L_{1b} , L_{1c} and L_{1d} can all exist on the same core as a single integrated magnetic structure, and only a single uncoupled inductor L_2 and secondary output capacitor C_2 are needed. Alternately, two coupled inductors could be used, L_{1a} - L_{1c} and L_{1b} - L_{1d} .

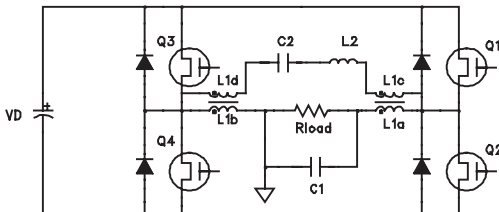


Figure 8: Ripple Steering Class D Full Bridge

Ripple Steering Class D in Practice

A circuit was constructed to demonstrate Ripple Steering Class D; it is a full bridge running at 130 kHz from a 100-200 VDC supply, optimized for high power and low audio bandwidth. The main Class D output filter is comprised of a 200 uH inductor L1 and a 5 uF film capacitor C1. The zero ripple winding was first wound with $N_p = 30$, $N_s = 24$, $L_m = 200$ uH, so $L_s = 32$ uH as given by Eq. (6). The L_s was apportioned as approximately 8 uH leakage inductance and 25 uH discrete inductance, L2. C2 was varied from 5 uF to 1 uF with no impact on ripple steering operation. When C2 was reduced to the point that the voltage ripple became too high, ripple steering operation was impaired.

The circuit was optimized for high power and a low bandwidth, and so has a relatively low switching frequency of 130 kHz. The values of inductance and capacitance reflect this low switching frequency; they are much larger than low power full bandwidth circuits would use. A switch was installed in series with L2 in order to switch easily between Class D and Ripple Steering Class D.

Figures 9 and 13 show the voltages across the main inductor L1a in both configurations. As predicted, the Ripple Steering Class D has almost zero switching frequency ripple. With tight control over tolerances, the ripple could be made arbitrarily close to zero.

Figures 10 and 14 show the voltages on the output capacitors under idle conditions. Again, the quasi-sinewave present on the Class D has been greatly reduced in the Ripple Steering Class D.

Figures 11 and 15 show the output capacitor voltages and the inductor currents in the two configurations, but with output voltage being modulated by an audio signal. The modulator in this experiment was run open loop, with no feedback of any kind, hence the slightly visibly distorted audio voltage waveform.

Figures 12 and 16 show the same with a 20 kHz audio signal.

The additional winding needs to handle only the ripple current, which is on the order of 10% of the main winding current. This makes it possible to wind with a much smaller wire gauge than the main winding. Capacitor C1 is now relieved from handling any switching ripple, however C2 must be rated to handle the ripple current.

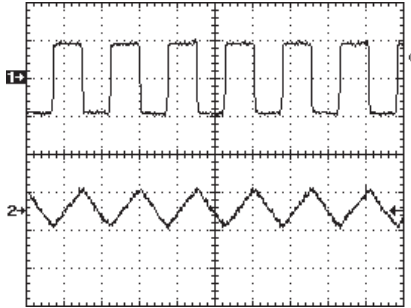


Figure 9: Class D L1a Voltage (Ch 1, 50 V/div.) and L1a Current (Ch 2, 1 A/div.)

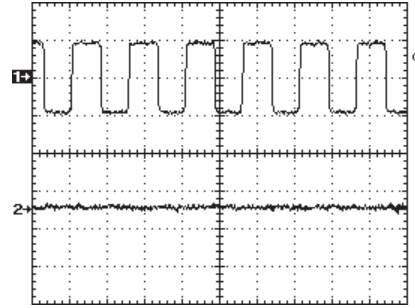


Figure 13: Ripple Steering Class D L1a Voltage (Ch 1, 50 V/div.) and L1a Current (Ch 2, 1 A/div.)

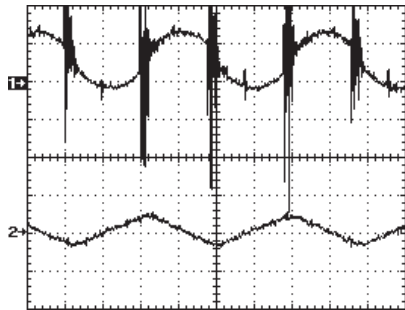


Figure 10: Class D C1 Voltage (Ch 1, 100 mV/div.) and L1a Current (Ch 2, 1 A/div.)

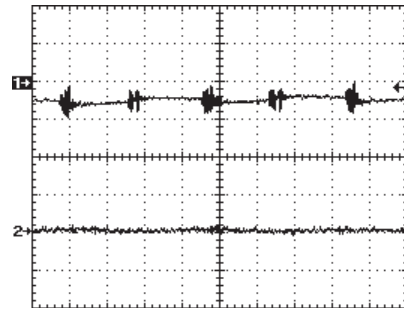


Figure 14: Ripple Steering Class D C1 Voltage (Ch 1, 100 mV/div., 20 MHz BW) and L1a Current (Ch 2, 1 A/div.)

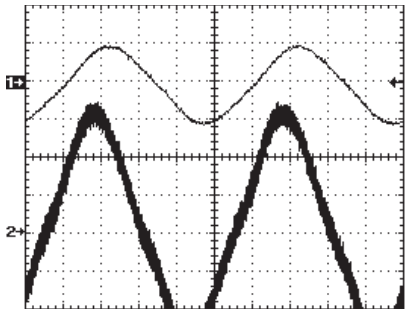


Figure 11: Class D C1 Voltage (Ch 1, 20 V/div.) and L1a Current (Ch 2, 1 A/div.)

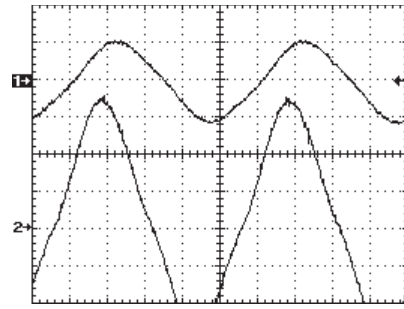


Figure 15: Ripple Steering Class D C1 Voltage (Ch 1, 20 V/div.) and L1a Current (Ch 2, 1 A/div.)

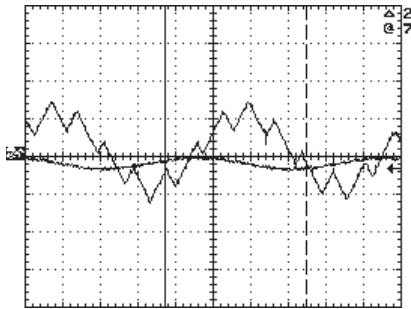


Figure 12: Class D C1 Voltage (Ch 1, 5 V/div.) and L1a Current (Ch 2, 1 A/div.) with Low Level 20 kHz Audio

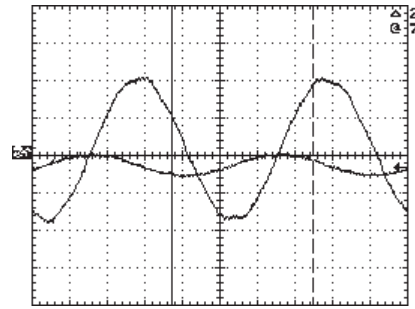


Figure 16: Ripple Steering Class D C1 Voltage (Ch 1, 5 V/div.) and L1a Current (Ch 2, 1 A/div.) with Low Level 20 kHz Audio

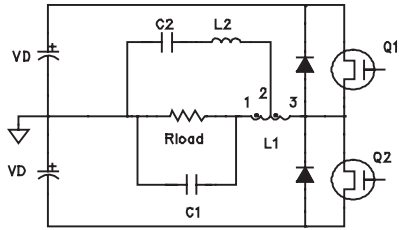


Figure 17: Ripple Steering Class D Half Bridge with Tapped Inductor

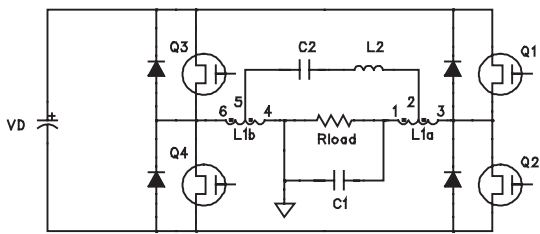


Figure 18: Ripple Steering Class D Full Bridge with Tapped Inductors

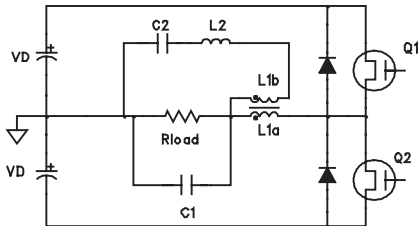


Figure 19: Ripple Steering Class D Half Bridge with Bucking Coupled Inductor

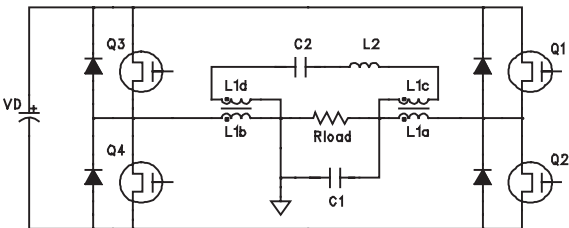


Figure 20: Ripple Steering Class D Full Bridge with Bucking Coupled Inductors

Alternate Topologies for Ripple Steering Class D

The implementation of Ripple Steering Class D has so far been discussed by the addition of a secondary winding of almost the same number of turns as the primary winding. Magnetically, there are other ways to achieve the same behavior. Since one side of each coupled inductor is tied together, the voltage on the output side of the secondary inductor will be determined by the turns ratio. This voltage ratio may also be realized by the addition of a simple tap on the main inductor winding, as shown in figures 17 and 18. This may be an easier winding to manufacture. In this case, N_p would be the turns on L1 from pins 1-3, and N_s would be the turns on L1 from pins 2-3. The previous experiment used $N_p = 30$, $N_s = 24$; in this case $N(1-3) = 30$, $N(2-3) = 24$, so $N(1-2) = 6$.

Another way to achieve the same result is to add a coupling winding from the output side of the main inductor, winding backwards in a bucking fashion, as shown in figures 19 and 20. This also produces the same voltage ratio, but with far fewer turns added, these turns optionally being of a much smaller ampacity with respect to the main winding. This method may be better for external leakage field reduction on the coupled inductor if a toroidal core is used. This is because the smaller bucking winding can occupy a smaller portion of the toroid circumference, such that each winding, L1a and L1b, both have almost the ideal 360 degree winding coverage, which will reduce leakage flux.

In each of these methods the leakage inductance of the coupled inductor will change, but it is advantageous to keep leakage inductance small with respect to discrete inductor L2 in any case so small manufacturing variations will not affect circuit behavior.

Conclusions

A Class D amplifier with greatly reduced residual switching frequency - Ripple Steering Class D has been shown in theory and in practice. The amplifier produces less EMI than a conventional solution by means of steering the ripple to a second output. Several winding topologies were presented.

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