# BOOST BRIDGE AUDIO AMPLIFIER

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## I INTRODUCTION

Several abbreviations used in this paper are:

- CDA = Class-D Amplifier
- BBA = Boost Bridge Amplifier
- SVCL = Single Voice Coil Loudspeaker
- DVCL = Dual Voice Coil Loudspeaker
- THD = Total Harmonic Distortion

The basic problem in all state-of-the-art linear audio amplifiers is the heat generation and low efficiency during amplification of music, requiring high power consumption, which is of specific interest for battery supplied devices in mobile phones, headphones, speakerphones, portable computers, cars, radios, cassette, DVD and CD players. This problem is successfully solved by a CDA topology [1,2,3].

The switching bridge output in CDA is connected to SVCL through the output LC filter. The switching bridge operation is controlled by the pulse-width modulated control signals *PWM*. The analog pulse-width modulator utilizes a reference triangular or a sawtooth voltage generator and a comparator, which compares the said reference voltage with an input voltage to be modulated. The digital modulator utilizes DSP and binary counters.

Since early days of CDA development, various authors tried to increase the output power delivered by the power supply at the same loudspeaker impedance. The push-pull switching power amplifier consists of two bidirectional Æuk switching power supplies [4,5]. Unfortunately, this amplifier is not optimal with respect to current and voltage stress of used switches.

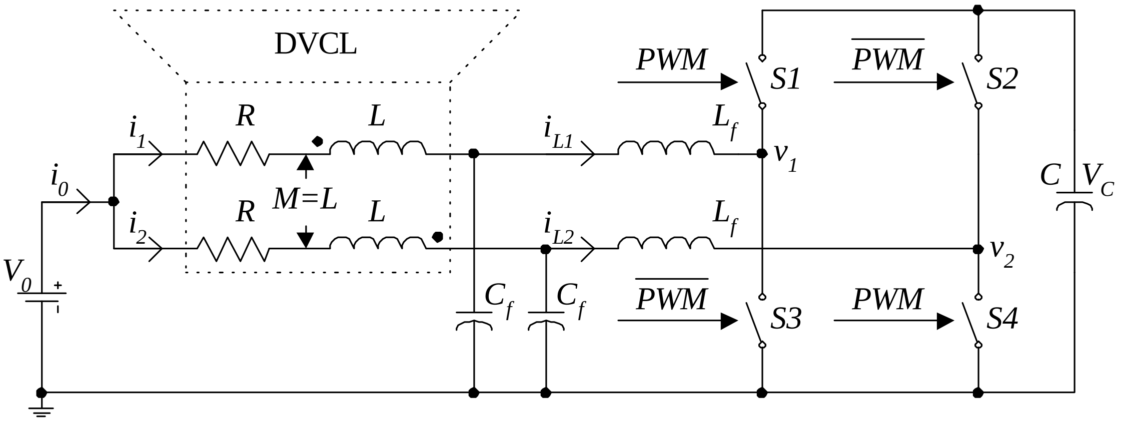


**Figure 1.** Schematic diagram of a novel boost bridge amplifier

## II BBA OPERATION

Novel BBA topology provides DVCL connection between the power supply and the output LC filter (Figure 1), which is completely opposite to CDA. The output LC filter, connected between each DVCL phase and the appropriate output of the switching bridge, additionally filters DVCL phase currents and provides necessary inductance for the voltage doubling operation.

The switching bridge operation is controlled by the pulse-width modulated control signals $PWM$ and $\overline{PWM}$, which are counter phased. Typical recommended switches are MOSFETs, IGBTs or bipolar transistors.

Power supply current is divided into two identical DC phase currents, which fluxes cancel each other according to the reference markers shown. Thus the summary DC flux and the average DC force generated by mentioned DC phase currents are zero. However, the modulated AC phase currents have opposite directions, so their fluxes will add according to the reference markers shown. The force moving the voice-coil is proportional to the difference between phase currents.

Two special features of BBA are high insensitivity to the variations of either the power supply voltage or the bridge capacitor voltage, which produce identical phase currents, so their fluxes and forces cancel each other.

The switching bridge voltage across the bridge capacitor is almost twice the power supply voltage while playing music, due to the music crest factor $CF$. Generally speaking, $CF$ is defined as a ratio of maximum peak power to rms power. $CF$ for a sine wave signal is only 3.01dB; i.e. the peak power is only 2 times higher than the rms power. The analysis of various musical genres, from classical, pop, rock to jazz, shows a variation in $CF$ from a minimum of 11dB for pop and rock to a maximum of 21dB for some classical or jazz music, i.e. the peak power is from 11.6 to 126 times higher than the rms power.

## III BBA STEADY-STATE ANALYSIS

The steady-state approximate equations describing BBA operation are derived based on the hypothesizes below:

- DVCL without back electromotive force;
- symmetrical DVCL phases;
- negligible ripple of phase currents;
- negligible ripple of the bridge capacitor voltage;
- only switch conduction loss is calculated; and
- bandwidth of the modulation signals is order of magnitude less than the LC filter cut-off frequency.

A pulse wave modulation from Figure 2 will be used as a general case correspondent to various $CF$.

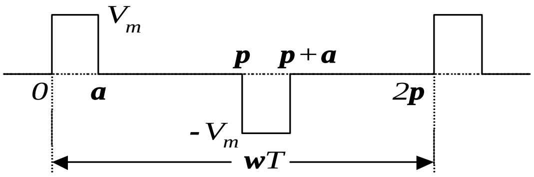


**Figure 2.** Pulse wave modulation timing

The resultant DVCL force is proportional to the difference $i_f$ between phase currents, which has only AC current term, while the power supply current $i_0$ is equal to the sum of phase currents and has only DC current term.

$$i_f = i_1 - i_2 \tag{1}$$

$$i_0 = i_1 + i_2 = I_0 \tag{2}$$

The phase currents $i_1$ and $i_2$ for a sine wave modulation can be expressed by DC and AC current terms.

$$i_{1,2} = \frac{I_0 \pm I_m \sin \boldsymbol{w}t}{2} \tag{3}$$

The power $P_R$ dissipated by DVCL for the pulse wave modulation (4) and the sine wave modulation (5) consists of DC power term $P_{DC}$ and AC power term $P_{AC}$. Both pulse wave and sine wave modulation can be handled by the same set of general equations assuming that $\frac{\boldsymbol{a}}{\boldsymbol{p}} = \frac{1}{2}$.

$$P_R = \frac{1}{T}\int_0^T \left(Ri_1^2 + Ri_2^2\right)dt = \frac{RI_0^2}{2} + \frac{RI_m^2\boldsymbol{a}}{2\boldsymbol{p}} = P_{DC} + P_{AC} \tag{4}$$

$$P_R = \frac{1}{T}\int_0^T \left(Ri_1^2 + Ri_2^2\right)dt = \frac{RI_0^2}{2} + \frac{RI_m^2}{4} = P_{DC} + P_{AC} \tag{5}$$

The switching bridge efficiency $\boldsymbol{h}$ reduces the portion of the power $P_0$ generated by the power supply, which can be dissipated by DVCL according to

$$P_0 = \frac{1}{T}\int_0^T V_0 i_0\, dt = V_0 I_0 \tag{6}$$

$$\boldsymbol{h}V_0 I_0 = \frac{RI_0^2}{2} + \frac{RI_m^2\boldsymbol{a}}{2\boldsymbol{p}} \ . \tag{7}$$

After solving the above quadratic equation, DC current $I_0$ and the overall system efficiency $\boldsymbol{h}_0$ are given by

$$I_0 = \frac{\boldsymbol{h}V_0}{R}\left[1 - \sqrt{1 - \frac{\boldsymbol{a}}{\boldsymbol{p}}\left(\frac{RI_m}{\boldsymbol{h}V_0}\right)^2}\,\right] \tag{8}$$

$$\boldsymbol{h}_0 = \frac{P_{AC}}{P_0} = \frac{\boldsymbol{h}}{2}\left[1 + \sqrt{1 - \frac{\boldsymbol{a}}{\boldsymbol{p}}\left(\frac{RI_m}{\boldsymbol{h}V_0}\right)^2}\,\right] . \tag{9}$$

The switching bridge efficiency $\boldsymbol{h}$ (11) can be derived assuming only switch conduction loss due to the ON resistance $R_{ON}$ of the switch by dividing (7) with (10).

$$V_0 I_0 = \frac{(R + R_{ON})I_0^2}{2} + \frac{(R + R_{ON})I_m^2\boldsymbol{a}}{2\boldsymbol{p}} \tag{10}$$

$$\boldsymbol{h} = \frac{R}{R + R_{ON}} \tag{11}$$

The average voltage at the switching bridge output is equal to the half of the bridge capacitor voltage in condition of an unbiased AC modulation signal.

$$V_0 = \frac{(R + R_{ON})I_0}{2} + \frac{V_C}{2} = \frac{RI_0}{2\boldsymbol{h}} + \frac{V_C}{2} \tag{12}$$

$$V_C = 2V_0 - \frac{RI_0}{\boldsymbol{h}} \tag{13}$$

Substituting (8) into (13) gives

$$V_C = V_0\left[1 + \sqrt{1 - \frac{\boldsymbol{a}}{\boldsymbol{p}}\left(\frac{RI_m}{\boldsymbol{h}V_0}\right)^2}\,\right] . \tag{14}$$

The interesting fact is that the overall system efficiency $\boldsymbol{h}_0$ can be detected by monitoring $V_C$.

$$\boldsymbol{h}_0 = \frac{\boldsymbol{h}V_C}{2V_0} \tag{15}$$

The minimum steady-state overall system efficiency $\min \boldsymbol{h}_0$ is obtained at minimum bridge capacitor voltage $\min V_C$, maximum AC current magnitude $\max I_m$ and appropriate maximum DC current $\max I_0$.

$$\max I_m = \frac{\boldsymbol{h}(\min V_C)}{R} \tag{16}$$

$$\min V_C = 2V_0 - \frac{R(\max I_0)}{\boldsymbol{h}} \tag{17}$$

$$\max I_0 = \max I_m \cdot \frac{\boldsymbol{a}}{\boldsymbol{p}} = \frac{\boldsymbol{h}V_0}{R} \cdot \frac{2\frac{\boldsymbol{a}}{\boldsymbol{p}}}{1 + \frac{\boldsymbol{a}}{\boldsymbol{p}}} \tag{18}$$

All limiting equations can be easily derived by substituting (18) into equations (4), (9), (14) and (15).

$$\min \boldsymbol{h}_0 = \frac{\boldsymbol{h}}{1 + \frac{\boldsymbol{a}}{\boldsymbol{p}}} \tag{19}$$

$$\min V_C = \frac{2V_0}{1 + \frac{\boldsymbol{a}}{\boldsymbol{p}}} \tag{20}$$

$$\max P_{DC} = 2 \cdot \frac{(\boldsymbol{h}V_0)^2}{R} \cdot \left(\frac{\frac{\boldsymbol{a}}{\boldsymbol{p}}}{1 + \frac{\boldsymbol{a}}{\boldsymbol{p}}}\right)^2 \tag{21}$$

$$\max P_{AC} = 2 \cdot \frac{(\boldsymbol{h}V_0)^2}{R} \cdot \frac{\frac{\boldsymbol{a}}{\boldsymbol{p}}}{\left(1 + \frac{\boldsymbol{a}}{\boldsymbol{p}}\right)^2} \tag{22}$$

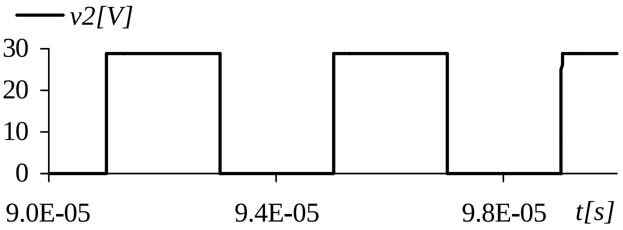
Maximum currents through the switch during both steady-state (SS) and transient (TR) conditions are the same.

$$\max I_{SWITCH}\big|_{SS} = \max I_{SWITCH}\big|_{TR} = \frac{\boldsymbol{h}V_0}{R} \tag{23}$$

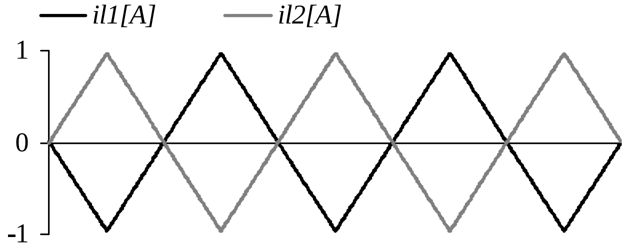
Maximum voltage across the switch is

$$\max V_{SWITCH} = 2V_0 \ . \tag{24}$$

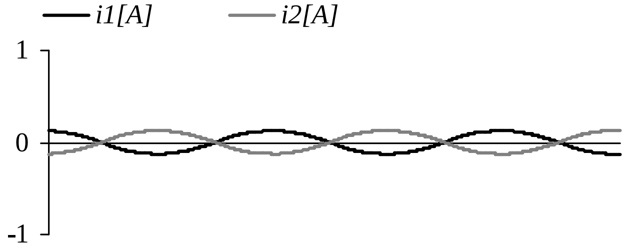
Simulated BBA timing diagrams with zero modulation signal and sine wave modulation signals are shown in Figures 3 and 4. Actual THD measurements are shown in Figures 5 and 6.



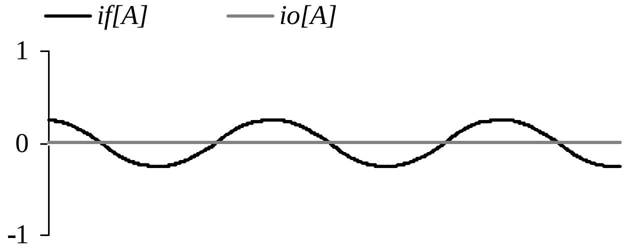
(a) output voltage $v_2$



(b) inductor’s currents $i_{L1}$ and $i_{L2}$

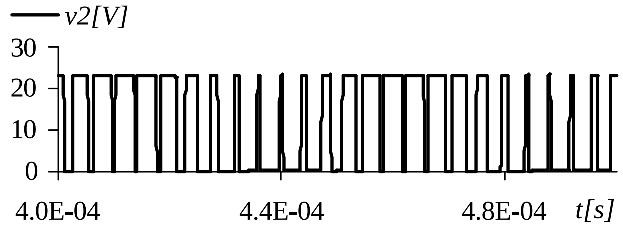


(c) phase currents $i_1$ and $i_2$

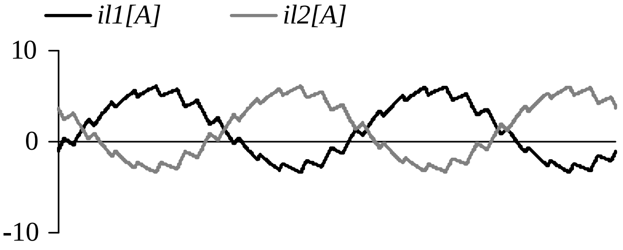


(d) force current $i_f$ and power supply current $i_0$

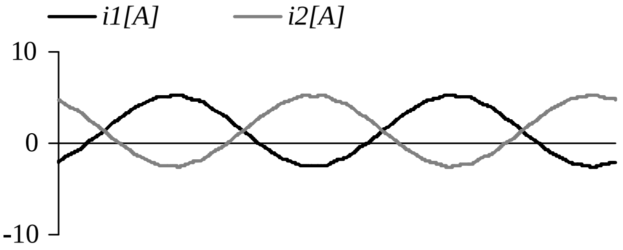
**Figure 3.** BBA idle timing diagrams



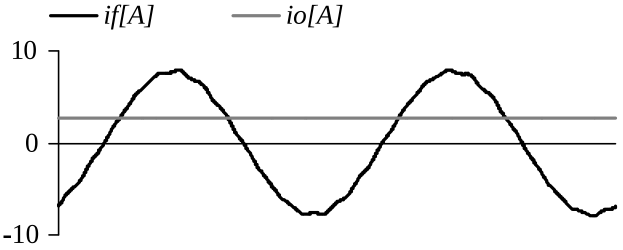
(a) output voltage $v_2$



(b) inductor’s currents $i_{L1}$ and $i_{L2}$



(c) phase currents $i_1$ and $i_2$



(d) force current $i_f$ and power supply current $i_0$

**Figure 4.** BBA sine wave timing diagrams

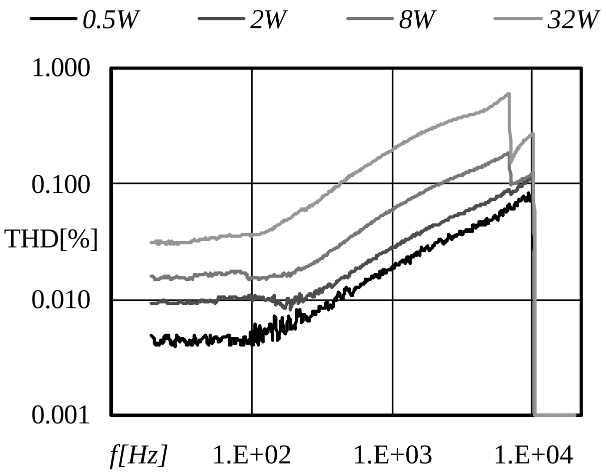


**Figure 5.** BBA THD with dual resistive load

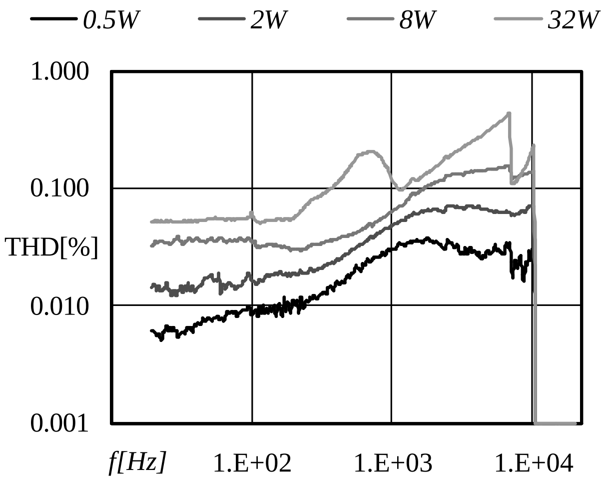


**Figure 6.** BBA THD with DVCL

Figure 7 shows the normalized overall system efficiency ratio $\mathbf{h}_0/\mathbf{h}$ for various crest factors $CF$.

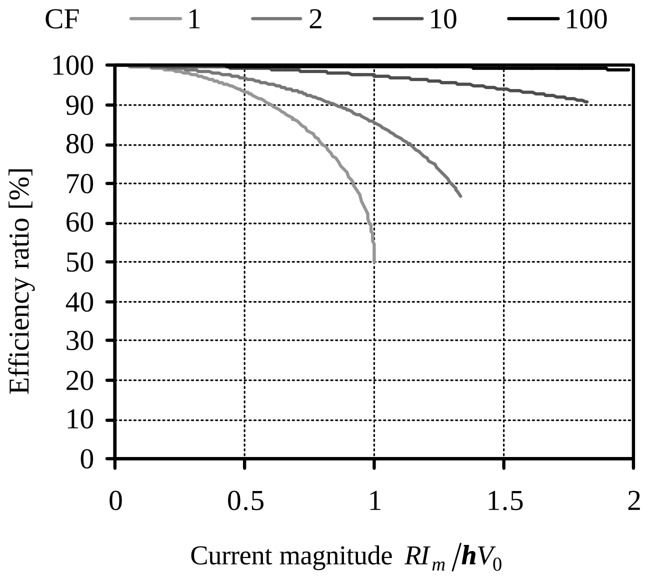


**Figure 7.** BBA efficiency ratio

Maximum bridge capacitor voltage is limited inherently to twice the value of the power supply voltage without using any feedback, in distinction to boost converters where this voltage must be carefully controlled by the negative feedback, in order to avoid switches breakthrough.

At the maximum sine wave modulation index, the bridge capacitor voltage falls to 4/3 of the power supply voltage, which limits maximum rms power of BBA to about 2 times the rms power of CDA, at the same power supply voltage and the same DVCL impedance.

On the contrary, in case of a music signal with $10 \le CF < \infty$, rms power is relatively small, so the bridge capacitor voltage is almost twice the power supply voltage. Consequently, BBA peak power for a music signal is four times greater than CDA peak power with the same power supply voltage and the same DVCL impedance. At the same time, BBA and CDA efficiencies are practically the same.

## IV EXPERIMENTAL RESULTS

BBA for the power supply voltage of 14.4V was built using HIP4080A MOSFET controller, two Si4946 dual 60V N-channel MOSFETs, the bridge capacitor $C = 4700\mathbf{m}F$ and various other components for the feedback and protection. Dual 2nd order LC filter with $L_f = 15\mathbf{m}H$ and $C_f = 1.9\mathbf{m}F$ provides $30kHz$ cut-off frequency.

The $2\Omega + 2\Omega$ DVCL serves also as an input filter, eliminating influence of the power supply noise to its own force current. For the perfectly symmetrical phases of DVCL, the theoretical power supply rejection factor (PSRR) is infinite. The experimental PSRR is linearly increasing with frequency from $-85dB$ at $1kHz$ to $-65dB$ at $20kHz$, what is more than satisfactory for car audio.

The THD measurement was performed using MultiSound Fiji PC sound card in order to utilize “brick-wall” filtering at $20kHz$ by Liberty Audiosuite Ver.3.01 software, which eliminates all ultrasonic harmonics from the THD calculation, thus producing step edges. Measured THD within full audio range from $20Hz$ to $20kHz$ at output rms power levels 0.5W, 2W, 8W and 32W is shown in Figure 5 for the $2x2\Omega$ dual resistive load and Figure 6 for the $2x(2\Omega + 50\mathbf{m}H)$ DVCL. Negligibly different THD diagrams were obtained from the same amplifier connected in the CDA topology with 28.8V power supply voltage.

In car audio applications with power supply voltage of 14.4V, nominal loudspeaker impedance of $4\Omega$ and distortion of 1%, class AB amplifier achieves 19W rms and 38W peak power, CDA provides 21W rms and 42W peak power, while BBA reaches 42W rms and 193W peak power.

## V CONCLUSION

Novel BBA has been analyzed, simulated, built and tested. BBA provides four times higher peak power at DVCL than the power, which can be achieved by a CDA from the same power supply at the same DVCL impedance. Therefore, BBA is exceptionally applicable to all battery supplied devices in mobile phones, headphones, speakerphones, portable computers, cars, radios, cassette, DVD and CD players, etc. Moreover, higher power loudspeakers are already made as DVCL, while the BBA implementation does not require any change in the state-of-the-art technology of DVCL manufacturing.

## REFERENCES

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**Abstract -** The main difference in topology of a boost bridge amplifier and state-of-the-art class-D amplifier is in the connection of a loudspeaker between a power supply and a switching bridge. The boost bridge amplifier provides four times higher peak power at the loudspeaker than the power, which can be achieved by a class-D amplifier from the same power supply. Total harmonic distortion and amplifier efficiency are appropriate to a class-D amplifier, while power supply noise rejection is increased, on the expense of negligibly increased loudspeaker dissipation.

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