

Push/pull output stages with paralleled constant current sources

In his article „Leaving class A“ Nelson Pass describes the advantage of constant current sources, that work in parallel to one (the lower) side of a push pull output stage and thus deliver single-ended bias current to the other (the upper) side. In the product literature he describes that he uses this method in his new amplifiers XA.8 and in the XS. In addition the symmetry of bridged amplifiers is used to lower distortion.

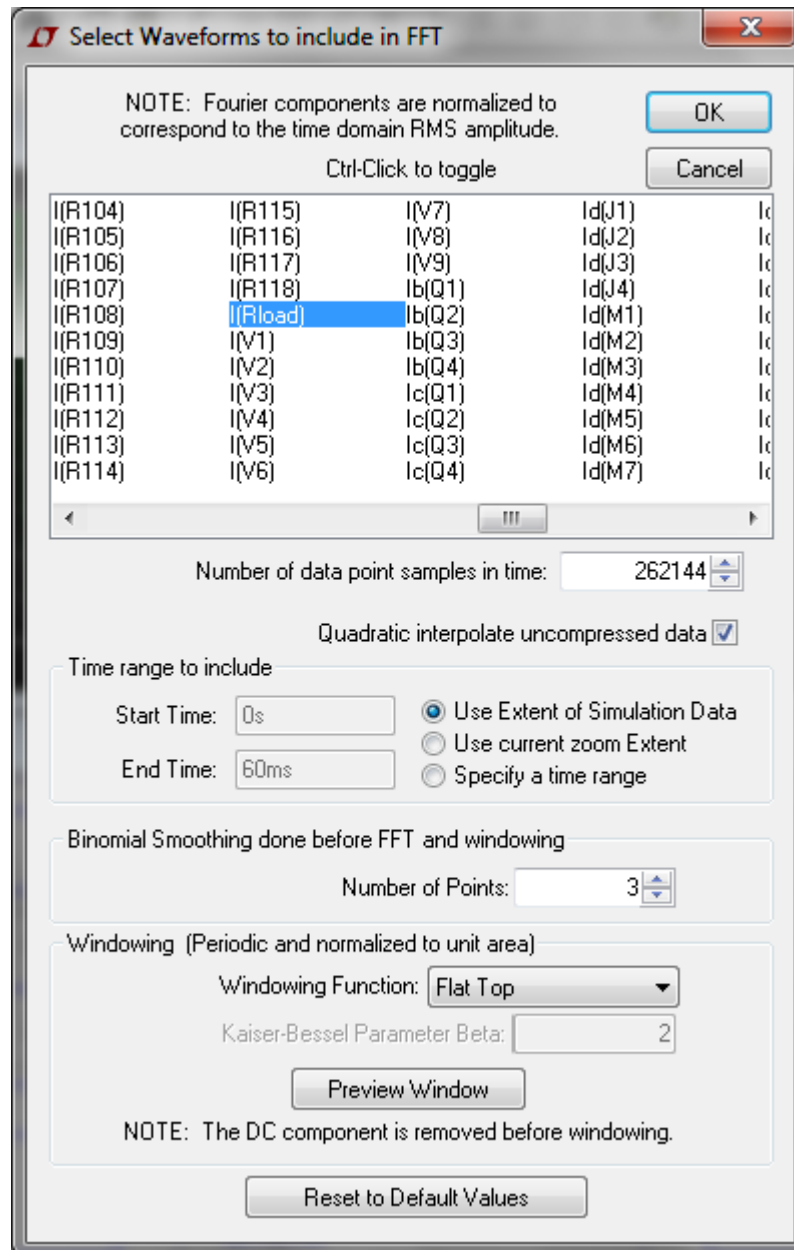
In this text, these methods are theoretically examined and simulated with LTSpice to find out how the methods can be used in an amplifier. It is unknown how similar the information in this text are to the real XA.8 and XS amplifiers. This information is only a guess that is derived from public available material from Nelson Pass like product literature, data sheets and postings in www.diyaudio.com. The intention behind this text is to know enough of the methods to be able to use them in a controlled manner in own, self designed amplifiers – building amplifiers makes (even) more fun when we know what we do.

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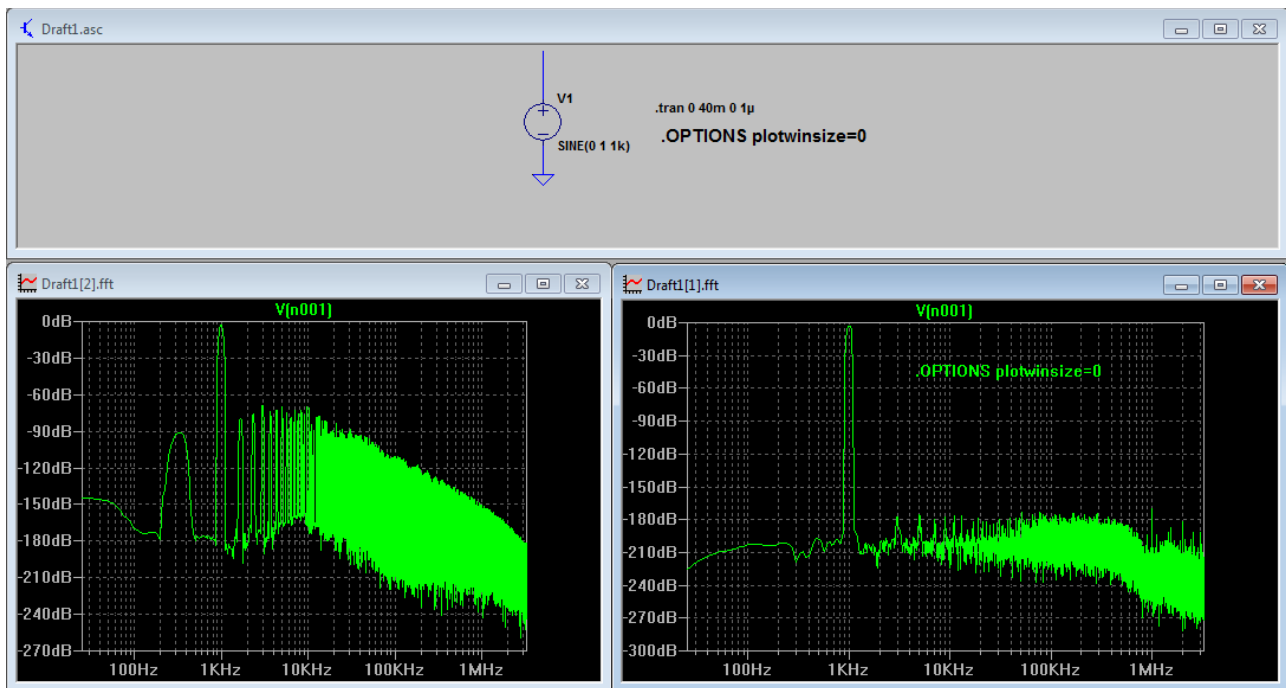
1 Evaluation of the distortion spectrum

1 Important settings in LTSpice



Flat Top does not look good, but gives the most accurate values of the amount of the distortions. To avoid that the components become very wide a relatively long simulation time is necessary (e.g. a lot of data and thus a high precision). To achieve that the setting `.tran 0 60m 0 3μ` is used.

In addition also the Spice directive `.OPTIONS plotwinsize=0` must be used. Otherwise the spectrum shows strange simulation faults and even a pure sine signal does not have a clean spectrum. Draft[2] (left, lower section of the picture) was generated without `.OPTIONS plotwinsize=0`, Draft[1] (right, lower section of the picture) was generated with `.OPTIONS plotwinsize=0`, in both cases circuitry Draft1.asc was used:



To avoid that the capacitors in the signal path have any influence on the simulation results at lower frequencies their capacitance is set to gigantic and otherwise exaggerated 1F.

LTSpice shows values of $1V_{eff}$ or $1A_{eff}$ as 0dB. So to display k1 as 0dB, measure the peak value of the signal, divide it by square root of 2 ($= 1.4$) and use the resultant value as a divider of the signal name that is displayed on top of the fft window, for example see picture below: $I(Rload)/3$.

Versions of LTSpice published since about mid of January 2015 offer an improved simulation of the MOSFET behavior at small gate-source voltages (below the threshold voltage, thus called "subthres") and small drain currents. To be able to use the improved accuracy the LTSpice file standard.mos needs to be extended by the models that use the additional, new parameter ksubthres. It is possible to add the parameter to existing models because it seems not to interfere with other parameters.

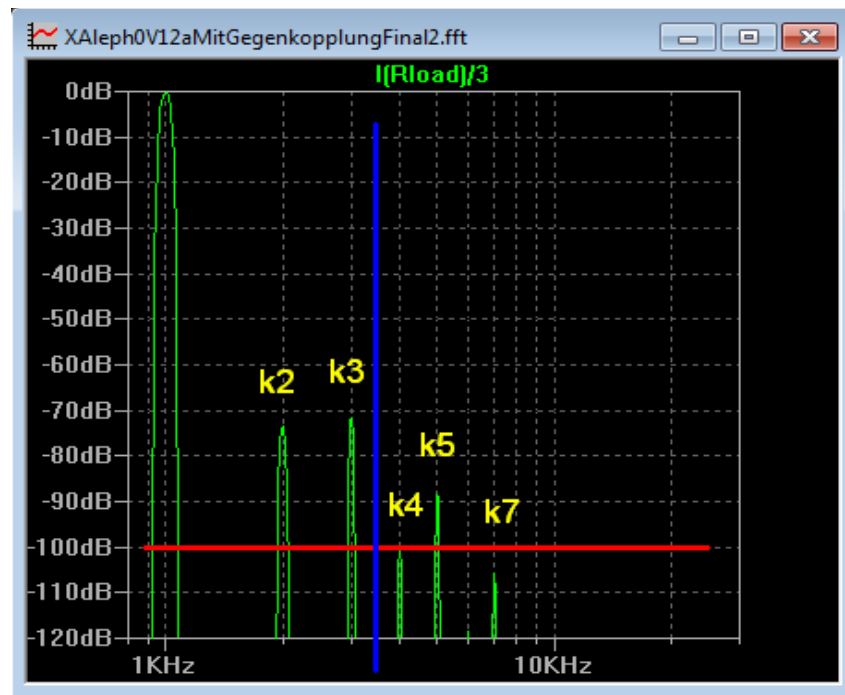
Here is an example of the ksubthres parameter sets of the IRFP240 and the IRFP9240. To select these models in the simulation, the transistor names need to be changed to irfp240Ckst and irfp9240Ckst. Here only an extract of the parameters is given, the full set was published in www.diyaudio.com by Bob Cordell. Please read his posting #43 for details:

<http://www.diyaudio.com/forums/software-tools/266655-better-power-mosfet-models-ltspice-5.html>

```
.model irfp240Ckst VDMOS( <insert here standard parameters of the irfp240> ksubthres=190m)
.model irfp9240Ckst VDMOS( <insert here standard parameters of the irfp9240> ksubthres=107m)
```

2 Scaling & interpretation of the values

The spectrum should be scaled to reasonable ranges, because only relevant information should be shown: 0...-120dB, 10 dB scaling, 800Hz...30kHz, logarithmic scale:



- red line: everything below is regarded as inaudible or irrelevant (we have to set a limit for our goal somewhere or we will never finish the work)
- blue line: all distortion components k4,k5,k6,k7,... spoil the sound , they should stay below -100dB .
- k2 brings warmth and soul, k3 dynamic. At lower levels k2 should be about 10dBs greater than k3. At higher levels k3 may become larger than k2, presumably because its attack seems to fit well to higher sound pressure levels and because of the transfer characteristics of a stable system (which can be approximated by a polynomial regression $y = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3$) k3 rises with the 3. power of the signal strength and k2 only with the 2. power and that means this behavior is natural (further information in ShortInfoHarmonicDistortion20141226.pdf, see post #149) . Please see also the article by Nelson Pass “Harmonic Distortion and Sound”.
- To show how the distortion distribution looks like, in this text the scale's lower limit level is often set to -160dB instead of -120dB. That makes it easier to see what's going on and it helps to understand, but these low levels should not be used to reject a schematic.

2 Push/pull output stages in bridge configuration with paralleled constant current sources

1 *Error compensation of both halves of the bridge according to the Susy concept*

The basic idea of the Susy concept is that both halves of a bridge amplifier create identical distortions so that the differential output signal (that means the load / the loudspeaker is

connected to the live outputs of both halves) does not see the distortion signals. For further details please look into Nelson's patent (Amplifier with gain stages coupled for differential error correction Patent US 5376899).

To make that work both halves of the bridged amplifier need to be identical.

Although both halves create anti phase signals, the distortions cancel to about 10% (= -20dB) (compared to each single output regarded alone).

In the picture below the blue differential signal of the bridged amplifier is a lot lower than the green output signal of one of the 2 halves.



The reasons are:

1. Because the bridge is a differential stage of type 1 it cancels all even order harmonics. In spite of that they are present in this picture because the circuitry used here uses a trick to preserve k_2 , see in one of the following chapters.
2. The odd order harmonics are also reduced. They have in common, that they correspond to a compressed positive and negative amplitude. Guess: So a limited positive amplitude could be canceled by a limited positive or a negative amplitude of the other half of the bridge. (Todo: Examine the phase of the odd order harmonics.)

2 Constant current sources parallel to the output devices

According to information in the product literature and www.diyaudio.com the XS and the XA.8 amplifiers use the output stage of the Aleph 0 V1.2 in a modified form (but not the controlled current sources of the Aleph 0 V1.4..1.6 or that of the Aleph2,3,4,5...).

In his article „Leaving class A“ Nelson Pass describes the advantage of constant current sources, that work in parallel to one (the lower) side of a push pull output stage.

3 Place constant current sources parallel to the n- or the p- channel MOSFETs?

Where should the constant current source be placed? Parallel to the p- or the n-channel MOSFETs?

Same on both halves of the bridge? Or on one half parallel to the p-channel MOSFETs and parallel to the n-channel MOSFETs of the other half? In the last case it would be very easy to achieve lots of k_2 .

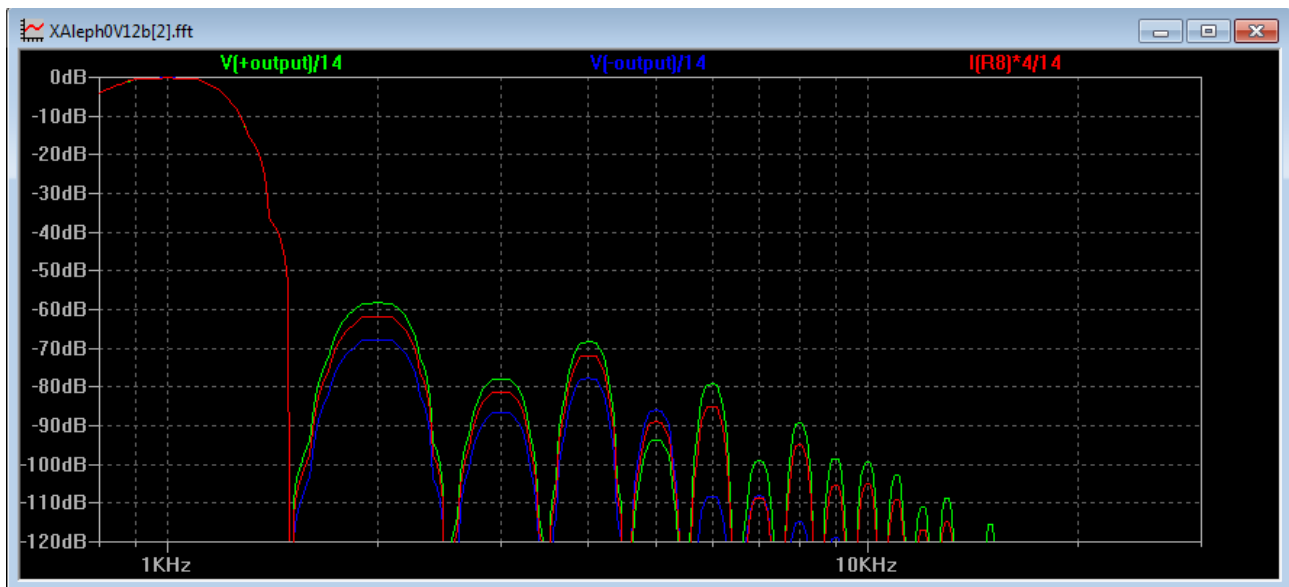
To examine that last case the circuitry XAleph0V12b.asc was used.

- It uses 8 pairs of MOSFETs and the constant current source like the Aleph 0 V1.2 but the rest of the circuitry is different.
- It was not possible in simulation with 8 pairs of IRFP240 and IRFP9240 to increase k_2 with moderate amount of constant current when the current source was connected parallel to the IRFP240. Only at 3.5 A a comparable spectrum showed up (see picture below) like in the circuitry in which a 2A constant current source was connected parallel to the IRFP9240 MOSFETs (current through the 8 IRFP240 together 2.2A, current through the IRFP9240 together 200mA, two times 40V – circuitry with 3.5A constant current source parallel to the IRFP240: current through the 8 IRFP240 together 0,1A, current through the IRFP9240 together 3.6A, two times 40V).
- To get the 3.5A in the simulation it is easiest to delete the complete circuitry of the constant current source and replace it with a single LTSpice ideal current source. The difference of the impact to the distortion spectrum of an ideal constant current source and one made of single transistors is extremely small at least at 1kHz signal frequency. It seems to be not worth to implement a precision constant current source, a simple one will do the job with the same result. It has to be checked if that is also true at higher frequencies, where the drain gate capacitance of the MOSFET which is part of the constant current source causes an additional current which lowers the output impedance of the current source. If that decrease in impedance impairs the performance of the amplifier is not known yet. A first analysis about that is given in one of the next chapters (“Standard and precision constant current sources”).

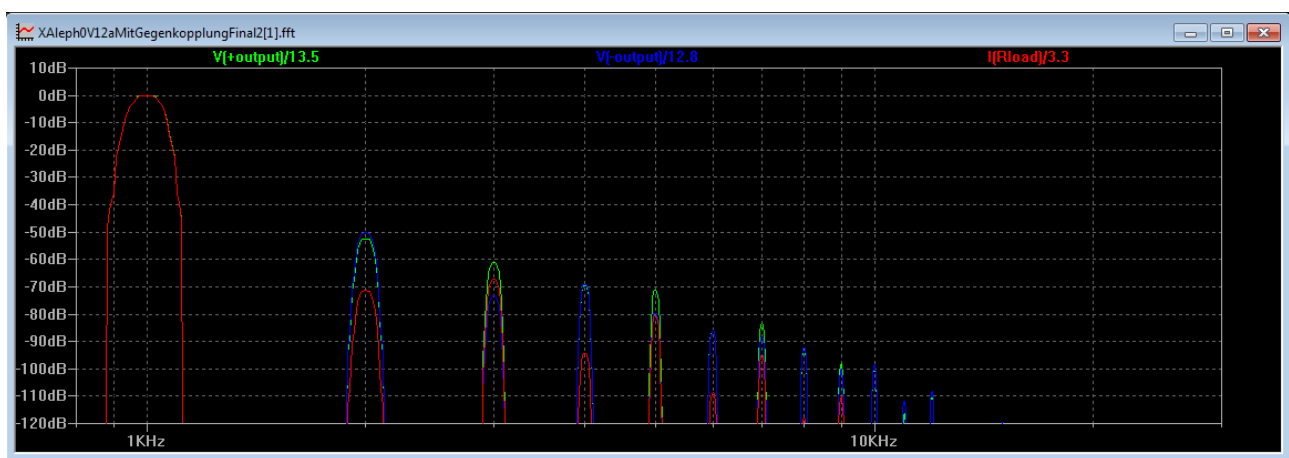
Here is the result:

The following picture shows both output voltages and the current through the load R8. (The output voltage was 20V at each output, hence 40Vpp over the load. Source resistors 0.5 Ohm each.)

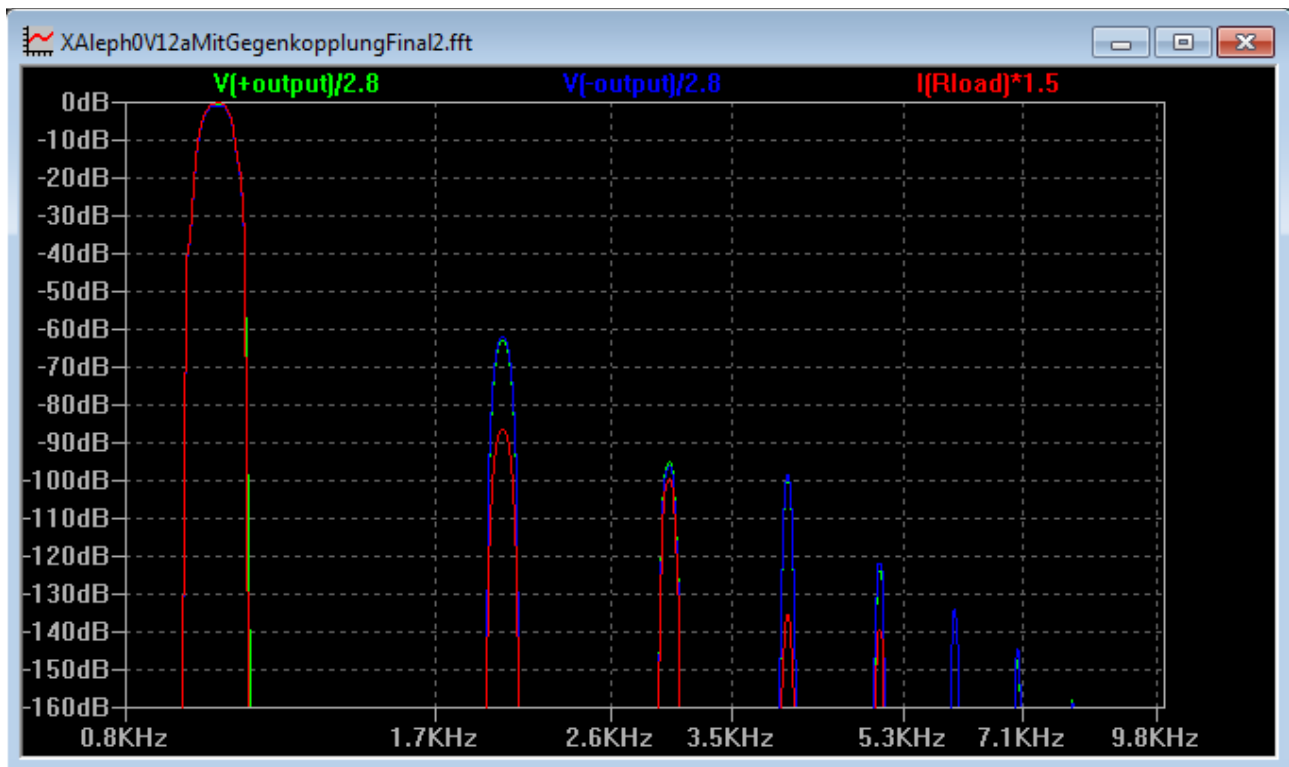
The result of the bridge output (red) is worse(!) as the blue output (that is the one with 3.5A current source). The cancellation of the higher order distortion components does not work well, because the 2 halves of the bridge are not identical in their transfer characteristic. It does not make sense to build such a bridge amplifier (one with a constant current source in parallel to the n-channel MOSFETs on one bridge half and with a constant current source in parallel to the p-channel MOSFETs on the other bridge half), because half the effort (the non-bridge amplifier) leads to a better result!



In addition, because the necessary constant current for the same result is lower, when the current source is connected in parallel to the p-channel MOSFETs, that is the best suitable variant. That was implemented in XAleph0V12aMitGegenkopplungFinal2.asc. Simulation done here with the same output voltage but only two times 25V operating voltage. Both halves of the bridge have nearly identical distortion patterns and the differential output signal of the bridge (red) has massively lower distortions compared to each of both outputs (blue & green) alone:



At 8Vpp output voltage:



4 **Choosing the bias for the n- and the p-channel MOSFETs and the constant current source**

The bias settings for the p-channel MOSFETs (=IRFP9240) can be grouped by the way they work into following classes:

1. $I = 0$:
The transistors are normally in the off-state and start to conduct only just before the moment when the current of the constant current source is not sufficient anymore to deliver the increasing output current. That is the case, when the n-channel MOSFETs (= IRFP240) are just to enter the off-state. That means at lower to middle output levels the p-channel MOSFETs are virtually not existent. They kick in only at higher output current levels. This operating mode seems to be very suitable, because the constant current sources seamlessly deliver clean current. Switching distortions occur only at very high levels where they disturb the less. Up to this point the output stage behaves single ended. The disadvantage is that the p-channel MOSFETs are not available for controlling the output signal at low levels.
2. $I = 10...20\%$ of the bias of the output stage:
This is roughly the setting of the Aleph 0. The constant current is accordingly set to 80...90%. The transistors are usually operated very close to the off-state and will also switch at very low levels. But these transistors have a very strong soft clipping characteristic, so that the switching distortions are very small the more so as the parallel connected constant current source damps the switching distortions. As a benefit the p-channel MOSFETs are available for controlling the output signal at low levels.
3. $I = 50\%$ of the bias of the output stage:
That is a variation of the setting $I = 10...20\%$. The spectrum seems to be cleaner in the

higher order distortions at higher levels. At lower levels it is very similar. Decision between the two in listing tests. For the setting $I = 50\%$ the constant current has to be reduced from 1.7A/1.95 (left/right half of the bridge) to 0.95A/1.1A and the bias voltage has to be increased from 8.16V/8.17V to 8.33V/8.34V (simulation values, will be of course different in real circuits!) to keep the current through the n-channel MOSFETs of the push pull stage and thus the whole amplifier constant. Therefore it is very convenient when there is an ampere meter at the front of the amplifier ...

4. $I = 90\%$ of the bias of the output stage:

This seems to be the setting of the XA.5 amplifiers. The constant current is accordingly set to 10% and thus can only support the linearity of the output stage to a smaller degree. Switching distortions occur only at high levels.

5. $I = 100\%$ of the bias of the output stage:

That is the standard push/pull stage. It has not got the advantage of the additional constant current, so it is not regarded here.

Simulation results with a bias of the n-channel MOSFETs at 270mA each:

Unfortunately simulation results were not stored, so this is from memory:

Setting $I=0$ delivered astonishingly more distortions as the setting $I = 10\ldots 20\%$. Nelson Pass says in his article „Leaving Class A“ that a high constant current roughly reduces distortion by 50%. In the simulations before it was shown that the constant current had to be raised up to 2A respectively 3.5A until the best distortion spectrum was received. Hence the setting $I = 10\ldots 20\%$ is also better as the setting $I = 90\%$.

The amount of the current of the output stage is a compromise and is chosen by the accepted power consumption and heat, the expected load and the number of output devices.

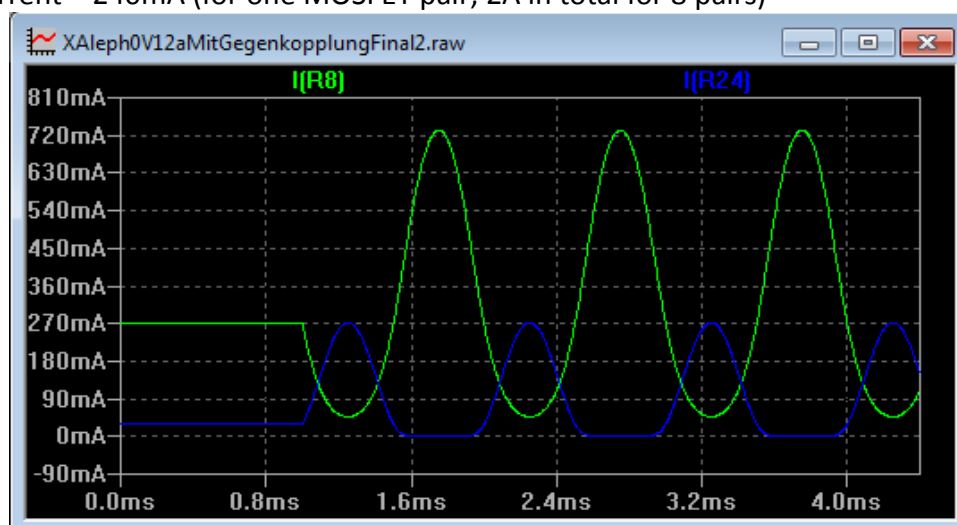
In the newer Passlabs amplifiers 250...300mA and 7W ..15W in each MOSFET seem to be used.

Setting $I = 10\ldots 20\%$:

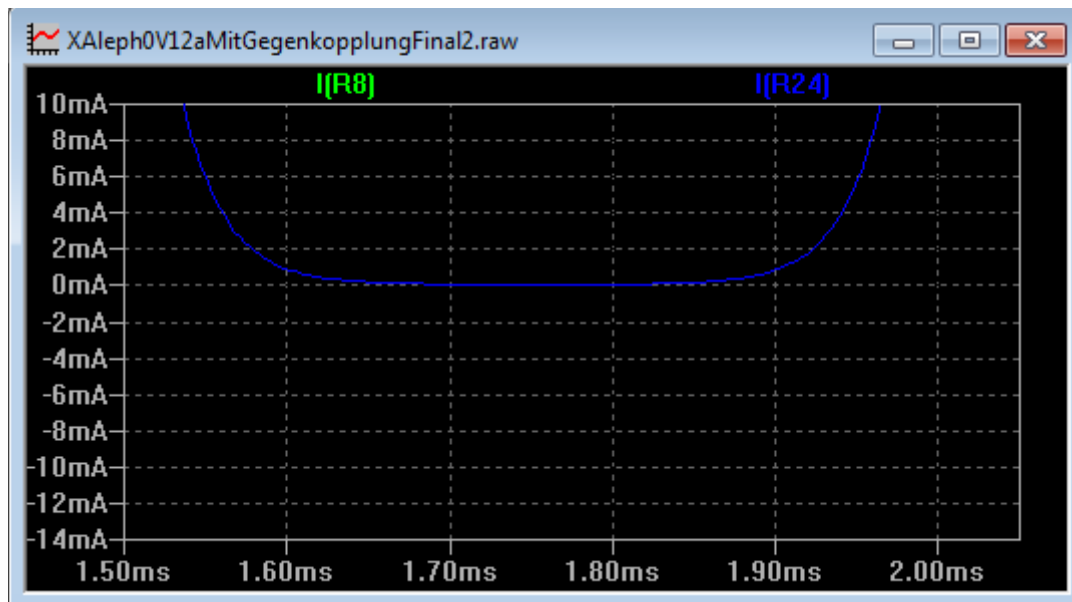
$I(R8)$ = current through the n-channel MOSFET

$I(R24)$ = current through the p-channel MOSFET

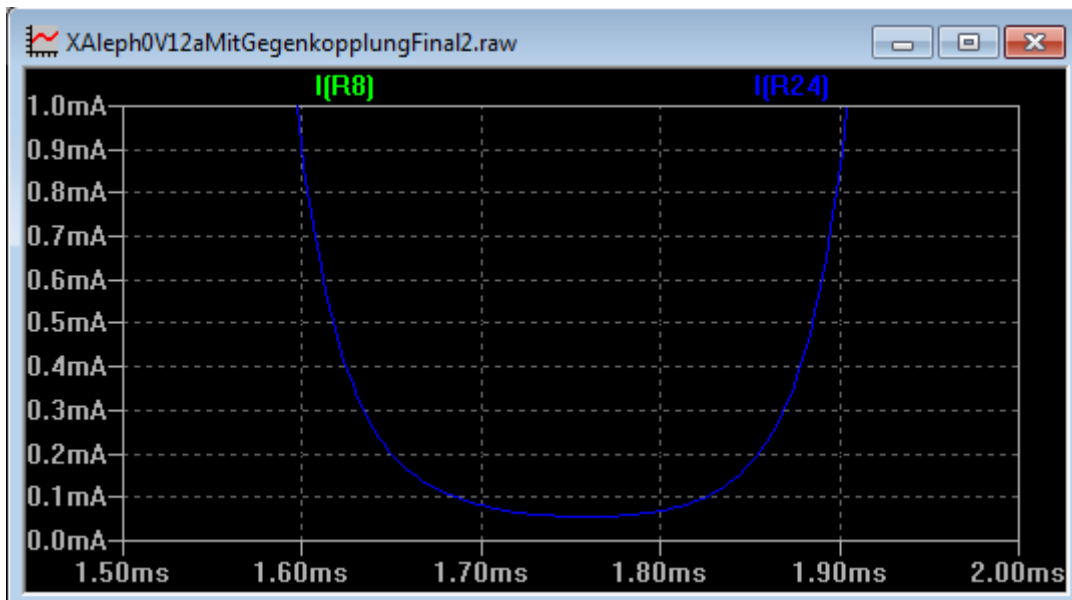
constant current = 240mA (for one MOSFET pair; 2A in total for 8 pairs)



Detail zoom soft clipping:



Further zoomed in:



The transistor does not switch off!

5 Preserve K_2 in output signal of the bridge

When the Susy concept is applied in a bridge configuration of an amplifier it cancels all even order distortions (including k_2) and some of the higher order odd harmonics. But to tune the sound the second order harmonic ($= k_2$) should not be canceled. A solution to solve the contradiction is to

- make the transfer characteristic of both halves of the bridge identical (so they have identical nonlinearities)
- but to make the gain of the amplifier different for the positive and the negative output of the bridge.

Gain of the push pull stage

In a stage with parallel output devices the mentioned trimming is very easy achieved by simply deleting one or more transistors:

For a given output voltage an according output current must be delivered by the amplifier into the load resistor. To deliver 24V on an 8 Ohm load, a MOSFET with a transconductance

of 1A/V needs to see an input voltage of $24\text{V} + (24\text{V}/80\Omega) / (1\text{A/V}) + 4\text{V}(=V_{th}) = 31\text{V}$. If 10 MOSFETs are used in parallel their necessary input voltage is $24\text{V} + (24\text{V}/80\Omega) / (10\text{A/V}) + 4\text{V}(=V_{th}) = 28.3\text{V}$, because the transconductance is 10 times higher. The gain of such a buffer is not exactly 1 but only roughly and can be controlled by the number of parallel transistors. To make transfer characteristic of the circuitry as identical as possible to the one without the deleted MOSFETs, the current of the constant current source needs to be reduced to set the bias in every MOSFET of the push/pull stage to the same value as before the removal of the MOSFET(s).

It is another option only to change the constant current in one of the halves of the bridge instead deleting one or more MOSFETs, because the change in constant current causes a change in the gain of the output stage, but only indirectly: The constant current shifts the working area of the transistor in the characteristics diagram. The transconductance is only changed when the transconductance is different in the shifted area. Unknown how reliably that works stable over time, aging and temperature. It is far more secure and reliable to delete one or more transistors. Deleting MOSFETs looks strange but works better.

If I remember correctly Nelson Pass said many years ago that the transconductance of the transistors varies less than the threshold voltage. Thus when matching all n-channel MOSFETs of both halves of the bridge together to the same threshold voltage it should be very unlikely that the transistors on each half together have the same transconductance, although the number of MOSFETs in both halves is different.

6 Workflow of defining the parameters of an Aleph 0 like output stage

1. To get a high gain (that helps to reduce distortion) and to reduce the modulation of the transistor characteristics by the load current (that creates distortion) as many as possible MOSFETs should be paralleled. The number is limited by the generated heat and the capacitive load that the driver stage sees when driving the paralleled MOSFETs.
2. At an operating voltage of 25V the bias of 250...300mA seems to be optimal for the IRFP240 (as shown above, in XAleph0V12b.asc with 8 parallel MOSFETs the optimal bias was 2A, which equals to 250mA in each MOSFET). For the IRFP9240 the optimum current seems to be $3.5A/8 = 440mA$. When reliability is not a concern the current can be further increased but at least from simulation results the improvement is only small.
3. The transistors IRFP240 and IRFP9240 show their best results when operated at $I_d > 50mA$ and $U_{ds} > 13V$. At no time the transistor should be operated below these values, otherwise the distortion will rise a lot. As long as the heat sink holds the temperature below 25...30K above room temperature, the transistors can be operated with very high reliability at 7W each (this seems to be the case in the XA.5 and XA.8 amplifiers), 13W is still very reliable (used in many Alephs), 25W less reliable and 50W experimental. In all cases very good thermal contact between the transistors and the heatsink is necessary, because reliability heavily depends from temperature of the die that should therefore be kept low. On the other hand, push pull output stages with the IRFP240/IRFP9240 are reported to sound better when they get a little bit of temperature, which is achieved when the heatsink temperature is 25...30K above ambient temperature.
4. Calculate peak class A output current and output voltage like it is shown in chapter "Guess: Schematic of the output stage of the XA30.8" where also the following steps are described. With these values calculate the maximum acceptable power dissipation per channel, for example 250W. At ca. 6W in each transistor the amplifier needs $250W/6W/transistor = ca. 40$ transistors. These 40 MOSFETs are split on both halves of the bridge and there split again into 10 n-channel MOSFETs for the push pull stage, 10 MOSFETs for the constant current source (preferably but not necessarily n-channel MOSFETs). Added to that are additional 10 p-channel MOSFETs on each half, that are irrelevant in regard to heat dissipation because of the low bias (ca. 10...20% of the constant current) .
5. Estimate in simulation or listening tests the number of the n-channel MOSFETs that have to be deleted in the half of the bridge, that delivers the inverted output signal.
6. Set the current of the constant current source to the same value in every push/pull MOSFET as before the removal of the MOSFET(s).
7. Set the bias so high, that at a desired output power the p-channel MOSFETs just don't conduct less than 10...50mA. That is a compromise. Note well, that in the Aleph 0 output stage the p-channel MOSFET has a very strong soft clipping characteristic. Hence there is a huge output power range where the current has got roughly this value.

7 Simulating an X350 with Aleph 0 like modified output stage

Nelson Pass didn't publish the schematic of the X350, but he mentioned that it nearly exactly is what it is shown in the Susy patent (or was it the X600?).

With that information a simulation in LTSpice was created and complemented to best knowledge to get a realistic schematic.

The X350 doesn't use constant current sources parallel to the output transistors. But the circuitry has a very low complexity and is therefore simulated and adapted very easily.

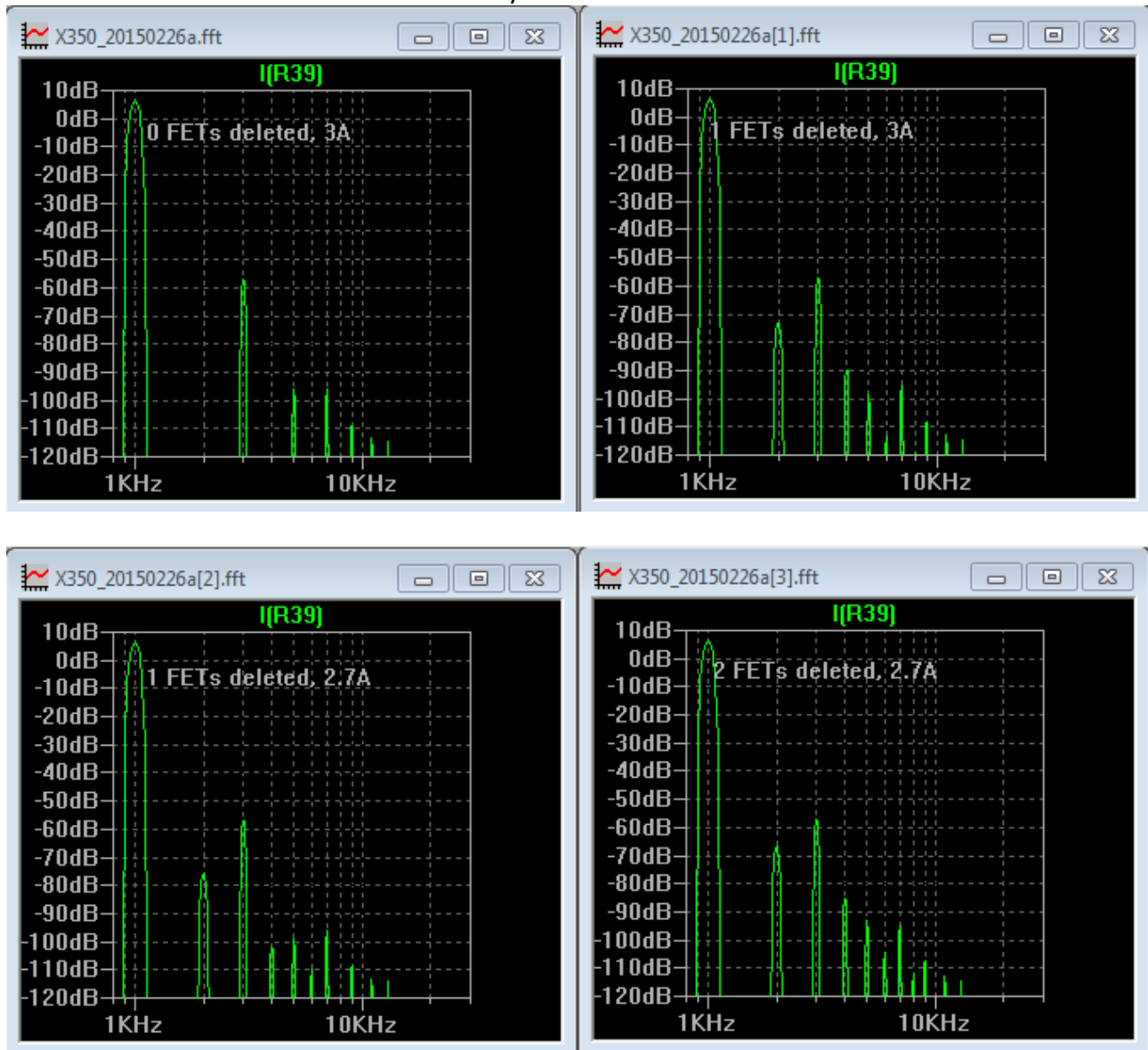
That's why the X350 was used here to test the described method. To achieve this simply each half of the bridge was extended with a constant current source.

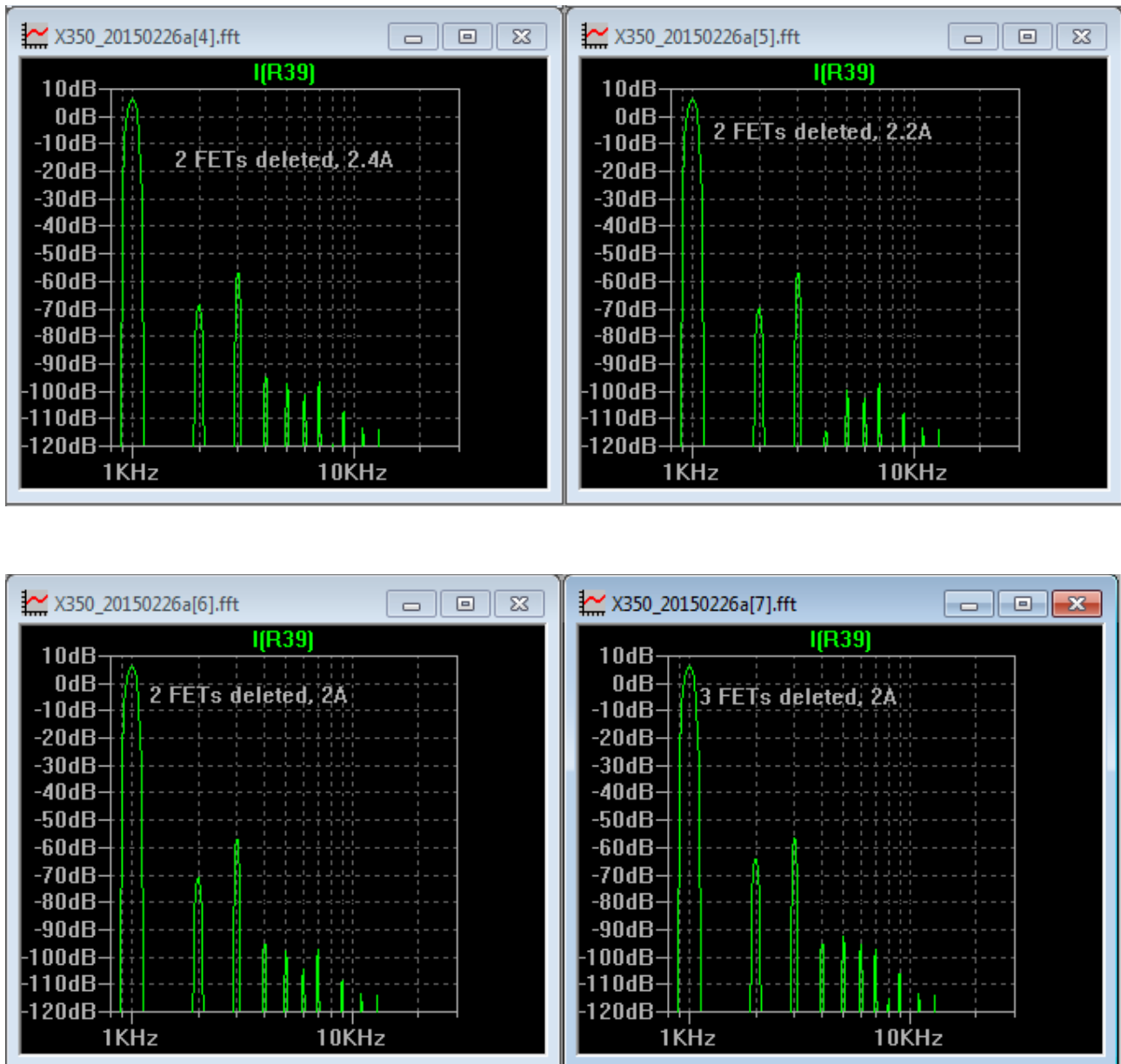
Because the Aleph 0 with 8 parallel MOSFETs uses a 2A constant current source, the current for the X350 with 12 parallel MOSFETs was set to 3A accordingly. That gives the afore mentioned optimal current of 250mA in each n-channel MOSFET.

When no MOSFET is deleted, that means if both halves of the bridge use 12 MOSFETs all even order distortions will be canceled as expected and shown in the picture below. The text in the picture tells how many transistors were deleted and the value of the constant current source. Of course only one half of the bridge was changed (the left one which delivers the negative or inverting output signal because the negative amplitude shall be limited, see ShortInfoHarmonicDistortion20141226.pdf), because both halves need to have a different gain as described before.

The bias and the constant current should be made adjustable and it should be made possible to deactivate single MOSFETs.

By the way, it has nearly no effect to delete p-channel MOSFETs of the other half of the bridge because their currents are so small that they do not contribute to it so much at lower levels.





8 Guess: Schematic of the output stage of the XA30.8

With the official available data and the information in this text the following guess of a schematic of the output stage of the XA30.8 was made. The input and driver stage are made of ideal LTSpice elements to see in simulation only the behavior of the output stage.

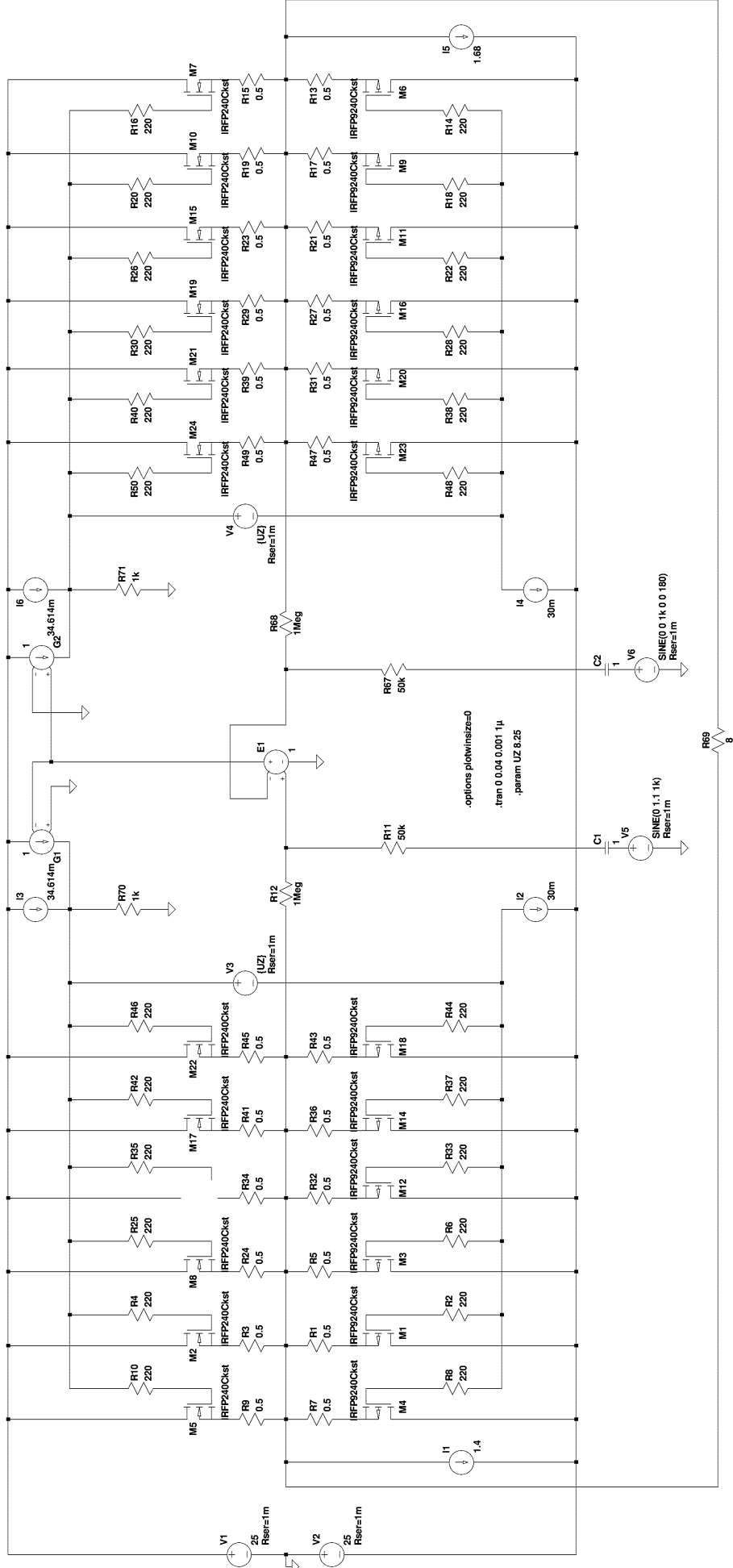
The XA30.8 delivers in class A $30W_{\text{eff}}$ which equals $60W_{\text{peak}}$. Square root ($60W_{\text{peak}}/80\Omega$) = $2.8A_{\text{peak}}$

So the smaller of the 2 constant current sources has to deliver $2.8A_{\text{peak}} / 2 = 1.4A_{\text{peak}}$.

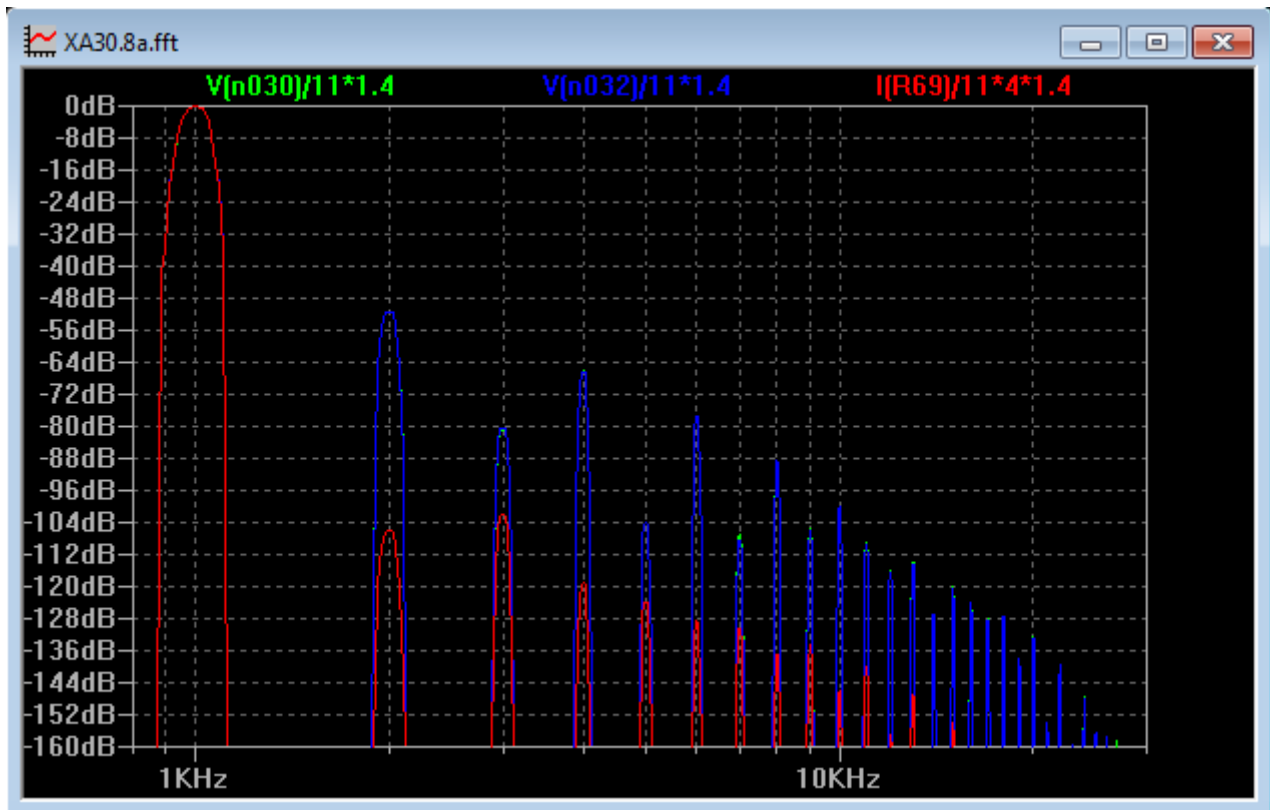
The peak output voltage at $2.8A$ is $80\Omega \cdot 2.8A = 22.4V$, so each half of the bridge has to deliver $11.2V$. As mentioned before, for highest quality the drain source voltage should never become smaller than $13V$, we add the $13V$ to the $11.2V$ which gives $24.2V$, round up to $25V$.

The n-channels of each half of the push/pull stage thus will have to dissipate $25V \cdot 1.4A = 35W$. If the dissipation of each MOSFET should be 7W, 5 MOSFETs have to be used in parallel in the half of the bridge with reduced amount of MOSFETs to dissipate 35W. Each of the n-channel MOSFETs of the push/pull stage will be set to a bias of $1.4A/5 = 280mA$ which is also well in the optimal range of 250..300mA. So with these values we have a good match in power dissipation and in bias current. As can be seen from the information above, a good distortion pattern is generated if 1 of 6 MOSFETs is deleted. Therefore in the other half of the bridge where none of the MOSFETs is deleted, 6 n-channel MOSFETs have to be used, each conducting the same current as on the side with the 5 MOSFETs, 280mA which gives $6 \cdot 280mA = 1.68A$ in total for the constant current source. But there is one thing to add: the current of the p-Channel MOSFETs. We set them to 10% of the value of the constant current source, which gives 28mA bias for each p-channel MOSFET. This adds to the amount of current caused by the constant current source, 280mA, so we get $280mA + 28mA = 308mA$ in each n-channel MOSFET. Power dissipation goes up to $25V \cdot 308mA = 7.7W$ which is pretty much in tolerance. By the way, total power consumption becomes: $(1.68A + 1.4A) \cdot 110\% \cdot (2 \cdot 25V) = 169W$, for a stereo amplifier $2 \cdot 169W = 338W$. (110% because of the 10% added current of the p-channel MOSFETs.) Heat sinks (which temperature is 25K higher than ambient) need to be $25K/338W = 0.07K/W$! If an appropriate driver stage is used, the drain source voltage can become as low as 4V for acceptable quality, which gives $25V - 4V = 21V$ peak output voltage for each half of the amplifier and $2 \cdot 21V = 42V$ that the whole amplifier can deliver to the load, which at 8 Ohms equals $220W_{peak} = 110W_{eff}$. But that's not class A anymore.

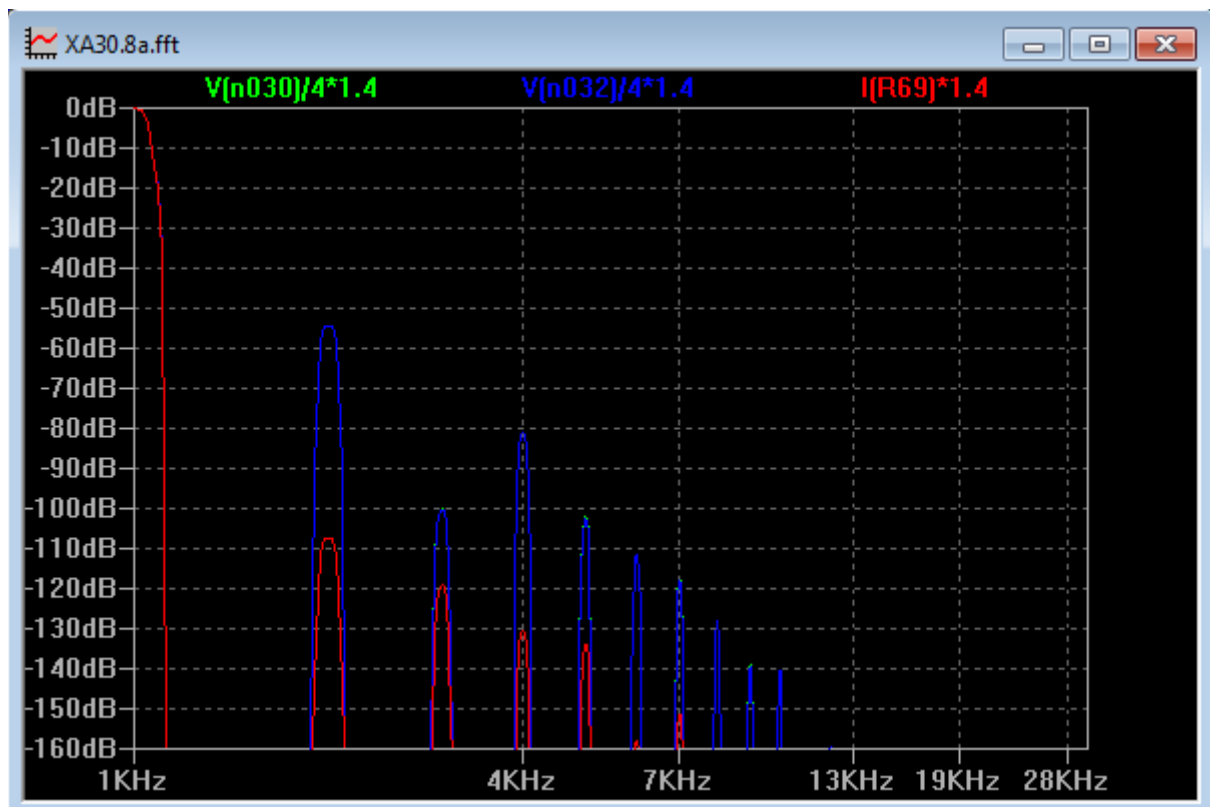
(Of course it would also be possible to use 7 instead of 6 paralleled MOSFETs which would result in 256mA in each n-channel MOSFET, which gives 6.4W and 23mA in the p-channel MOSFETs. The constant current source for the reduced half stays at 1.4A, but the other constant current source would have to be set to $233mA \cdot 7 = 1.63A$. That makes not a big difference, but the gain of the two halves becomes more similar and thus the effect of deleting of the MOSFET becomes smaller which is less ideal. All in all, the solution with 6 paralleled MOSFETs seems to be a better choice.)



Spectrum at 60Wpeak@8Ohm (notice: ideal input and driver stage used, e.g. real amplifier is likely to be a little bit less impressive), green, blue = signals of both halves of the bridge, red = current through loudspeaker – impressive distortion cancellation:



Spectrum at 8Wpeak@8Ohm (notice: ideal input and driver stage used, e.g. real amplifier is likely to be a little bit less impressive):



3 Standard and precision constant current sources

As mentioned above, the difference of the impact to the distortion spectrum of an ideal constant current source and one made of single transistors is extremely small at least at 1kHz signal frequency. It seems to be not worth to implement a superior constant current source, a simple one will do the job with the same result. It has to be checked if that is also true at higher frequencies, where the drain gate capacitance of the MOSFET which is part of the constant current source causes an additional current which lowers the output impedance of the current source. If that decrease in impedance impairs the performance of the amplifier is not known yet. A short discussion about that is given here.

To examine that, 3 constant current sources are compared here. Circuitry is shown below, each current source boxed. V7 is the powersupply voltage set to 25V. VoutputAmp is the output stage of the amplifier. It creates a voltage swing of 16V. Attention: When it's amplitude is increased, the precision current sources run into limitation and do not deliver a clean current anymore! RoutAmp1,...,RoutAmp3 simulate the output impedance of the amplifier. With 0.8Ohm they are very high to make effects of errors in the constant currents easy visible. They equal a damping factor of 5 (not 10 because there is also the other half which is not shown here that also adds 0.8Ohm; $80\text{Ohm}/(2*0.8\text{Ohm})=5$).

1. Standard constant current source.

The MOSFET's current flows through R11. If it's voltage becomes too high, the bipolar transistor's collector voltage will drop and thus the MOSFET's input voltage is reduced, that reduces the MOSFET's current. Problem is that the output voltage of the amplifier heavily modulates the drain voltage of the MOSFET. Because of its drain gate capacitance this voltage swing causes a big gate current that modulates the bipolar's control signal to the MOSFET. It is visible in R16. So there are two errors: a.) the additional drain gate current that overlays the drain current and b.) the disturbance of the control loop caused by that current. That current is called here "errorcurrent"

2. Precision Constant Current Source Bipolar Output Transistor

To solve the problem of the drain gate current, in this circuitry

- the MOSFET is replaced by a bipolar transistor which collector base capacitance is smaller and thus the errorcurrent is smaller
- this errorcurrent is kept away from the control loop. Instead it is fed via U7 and R85 into the current sensing resistor R72. So the error created by the errorcurrent is fed into the input of the control loop. The bipolar transistor is replaced by U1, simply because U1 has far more gain and is temperature compensated. Q44 lowers the output impedance of U1 which results in a rock solid regulation. Q33 takes the job of the MOSFET and sets the output current. It's a relatively small transistor for linear applications. At two times 25V power supply the TIP35C is within its safe operating area. The extremely low ohmic resistors (like $1\mu\text{Ohm}$) are only inserted to make it easy to measure the current in this wire.

3. Precision Constant Current Source MOSFET Output Transistor

When building an amplifier with many paralleled output MOSFET, the MOSFETs need to be matched and thus it is necessary to buy a large amount of MOSFETs (I would guess 2 to 3 times the number necessary for the amp) and use only those that have a good match.

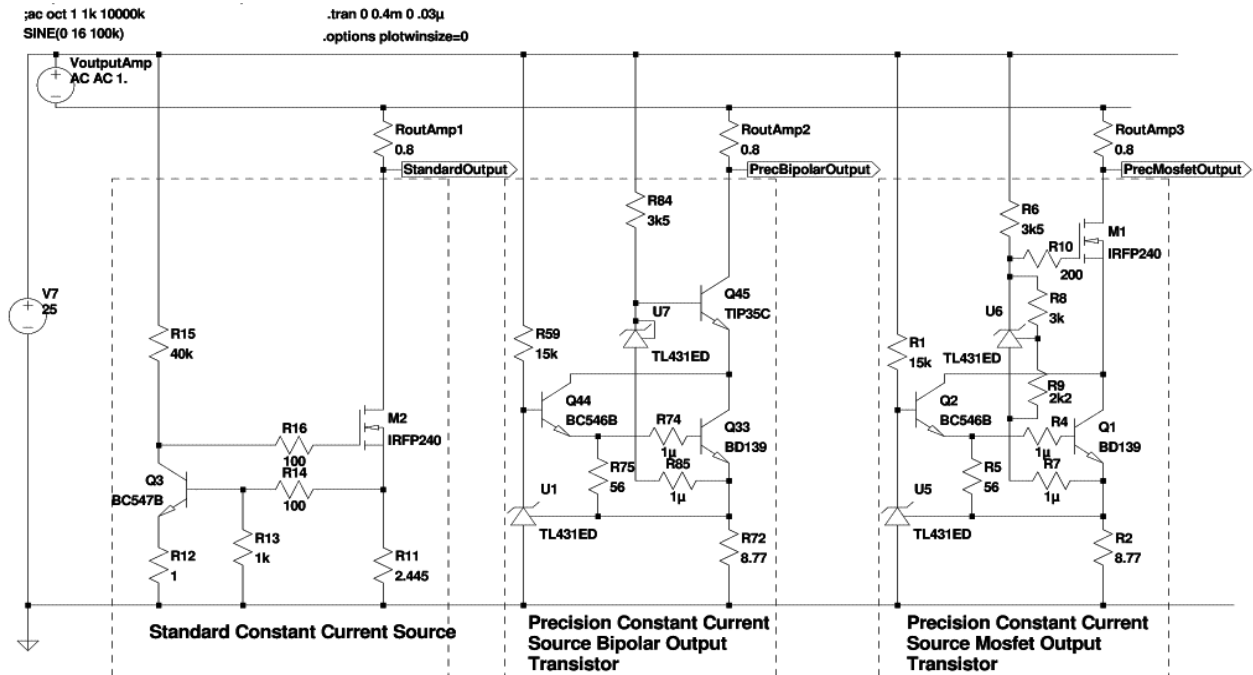
What to do with the rest? Each of the constant current sources here has its own control loop that works nice with unmatched MOSFETs. So this variant is derived from

"Precision Constant Current Source Bipolar Output Transistor" to make the use of the MOSFETs possible.

Because the gate source voltage (4V) is higher than the base emitter voltage of the bipolar transistor, the voltage of U6 is increased accordingly.

The output current of the 3 variants are examined at an amplifier output signal of 16V output swing and 1kHz, 10kHz and 100kHz. 100kHz to check if the sources run wild at high frequencies that cause big problems for the amplifier. At 1kHz also the distortion spectrum at the amplifiers output (labels "StandardOutput", "PrecBipolarOutput", "PrecMosfetOutput") are shown to get an impression of how "much" the current errors add errors to the output signal. Then the same is repeated at 20V output swing.

Here is the circuitry:

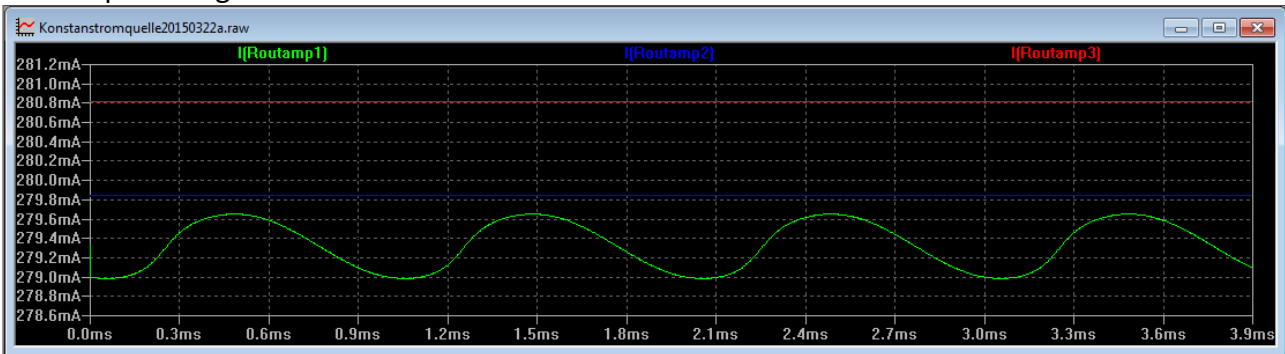


The output current of the 3 variants are examined at an amplifier output signal of

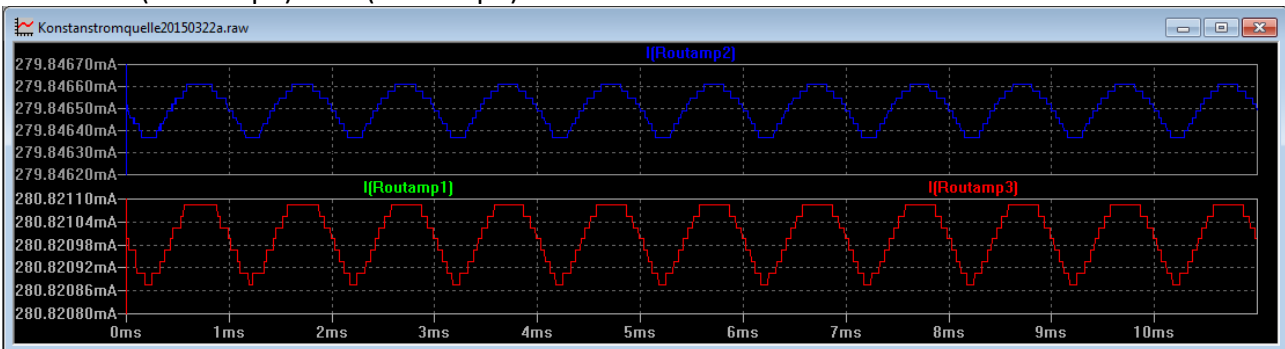
- 16V output swing and 1kHz
- 16V output swing and 10kHz
- 16V output swing and 100kHz
- 16V output swing and 1kHz distortion spectrum
- 20V output swing and 1kHz
- 20V output swing and 10kHz
- 20V output swing and 100kHz
- 20V output swing and 1kHz distortion spectrum

Caution: Different scales used!

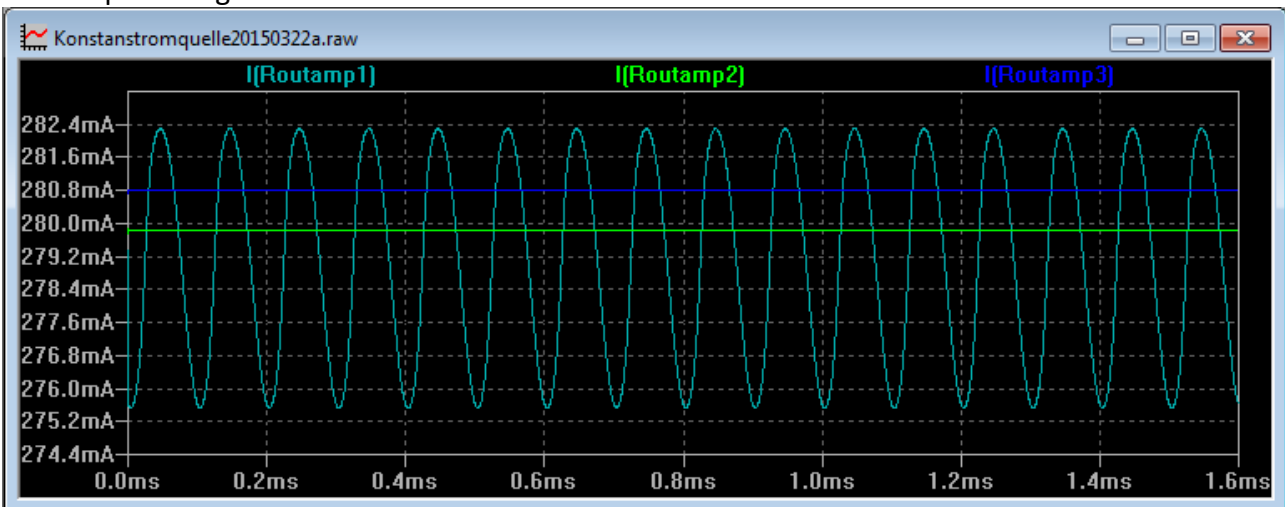
16V output swing and 1kHz:



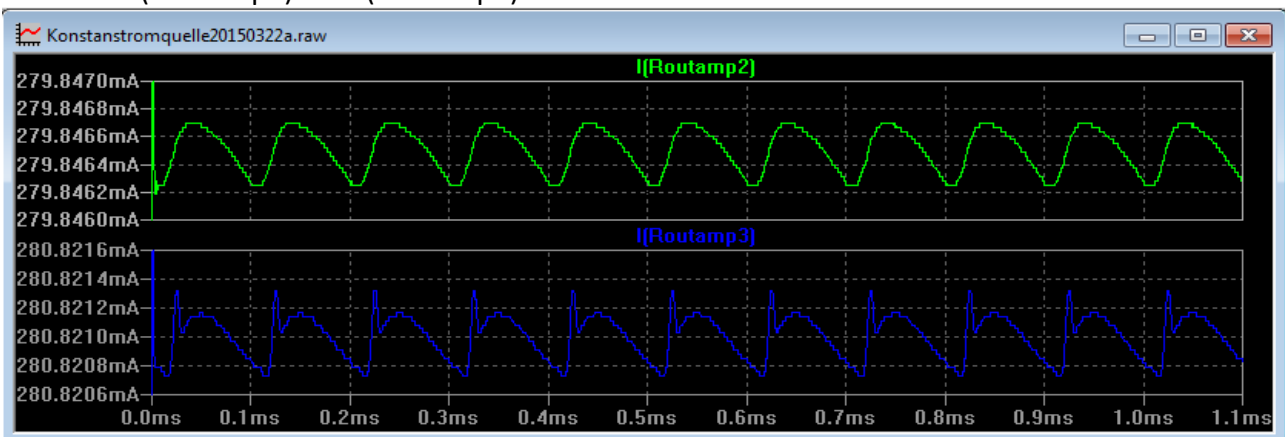
Details of $I(Routamp2)$ and $I(Routamp3)$:



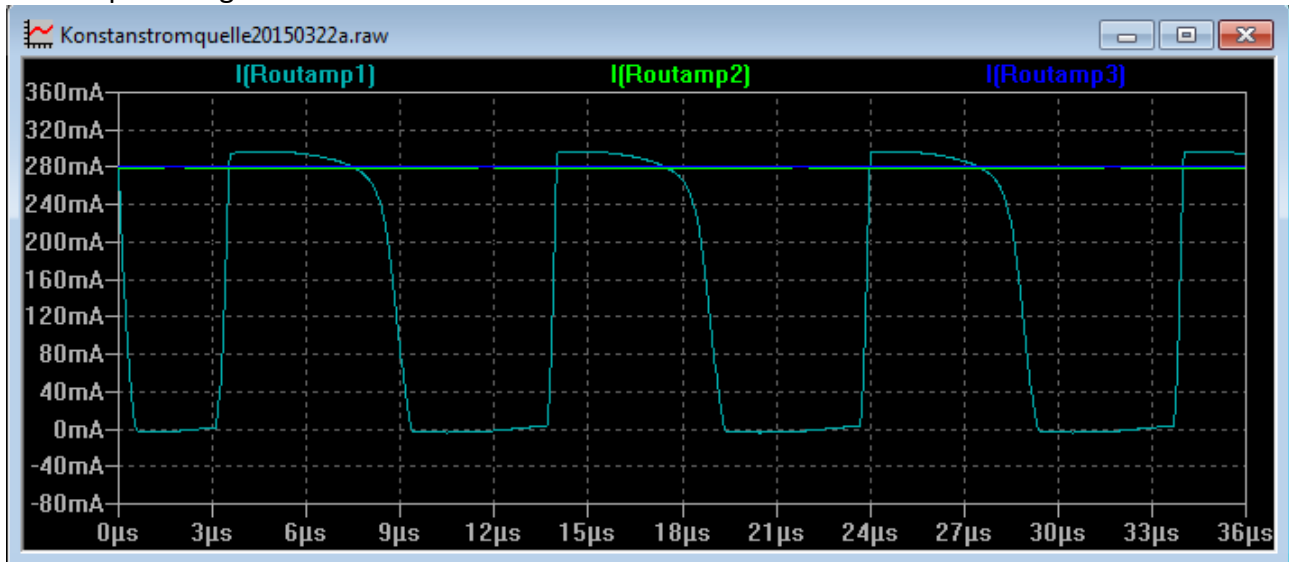
16V output swing and 10kHz:



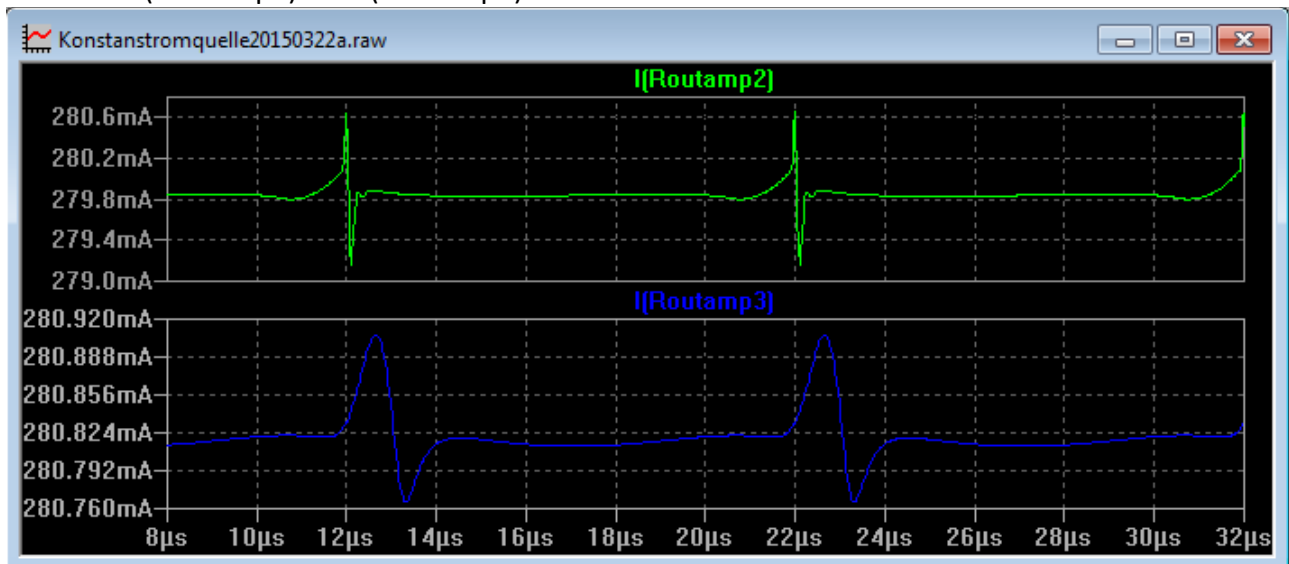
Details of $I(Routamp2)$ and $I(Routamp3)$:



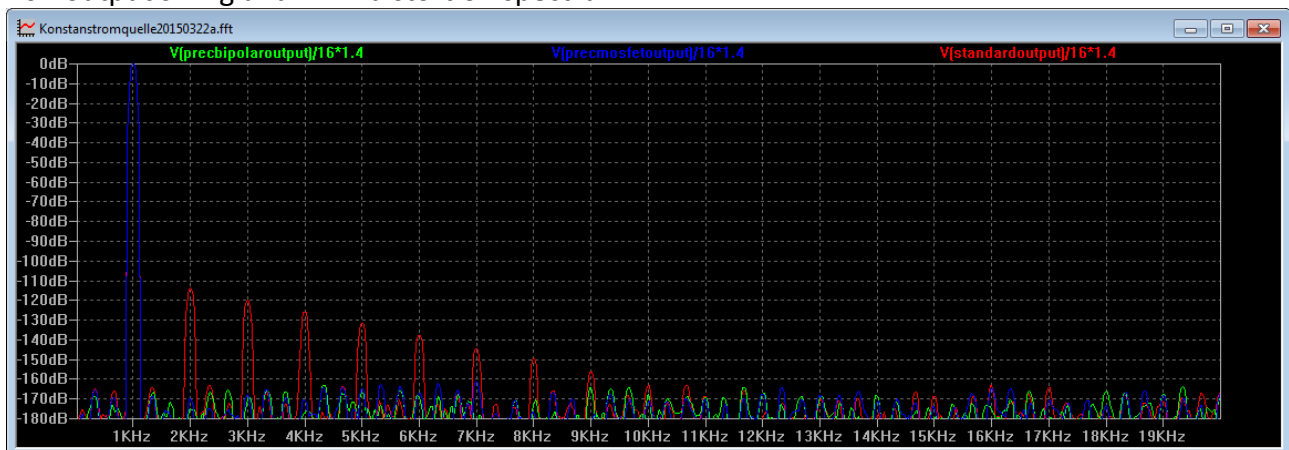
16V output swing and 100kHz:



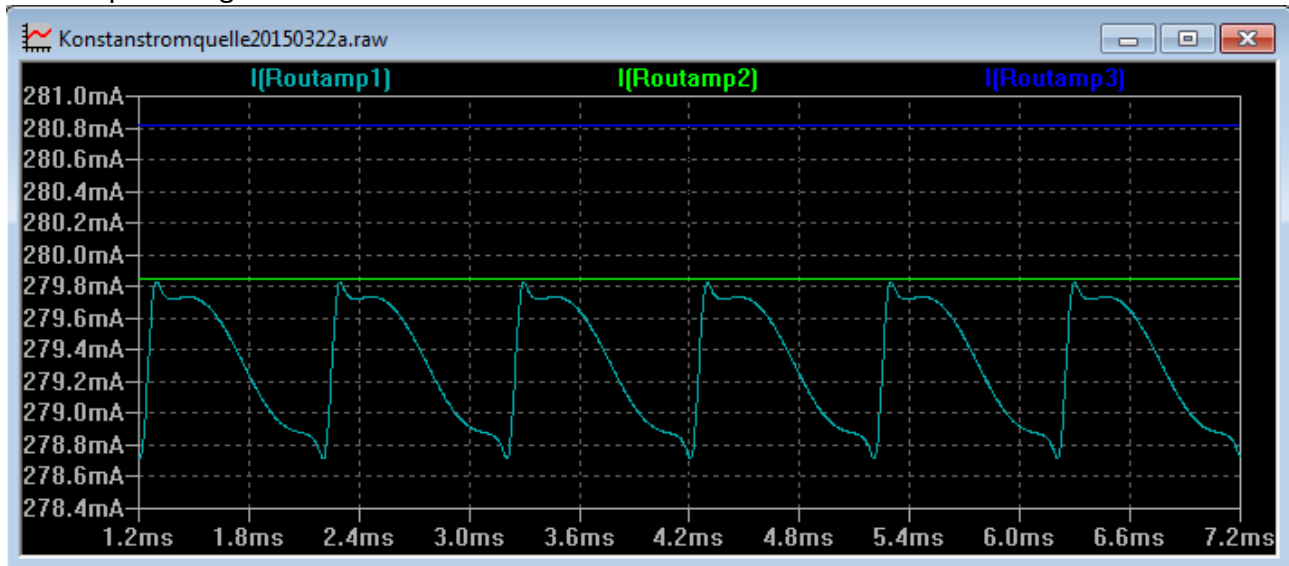
Details of $I(Routamp2)$ and $I(Routamp3)$:



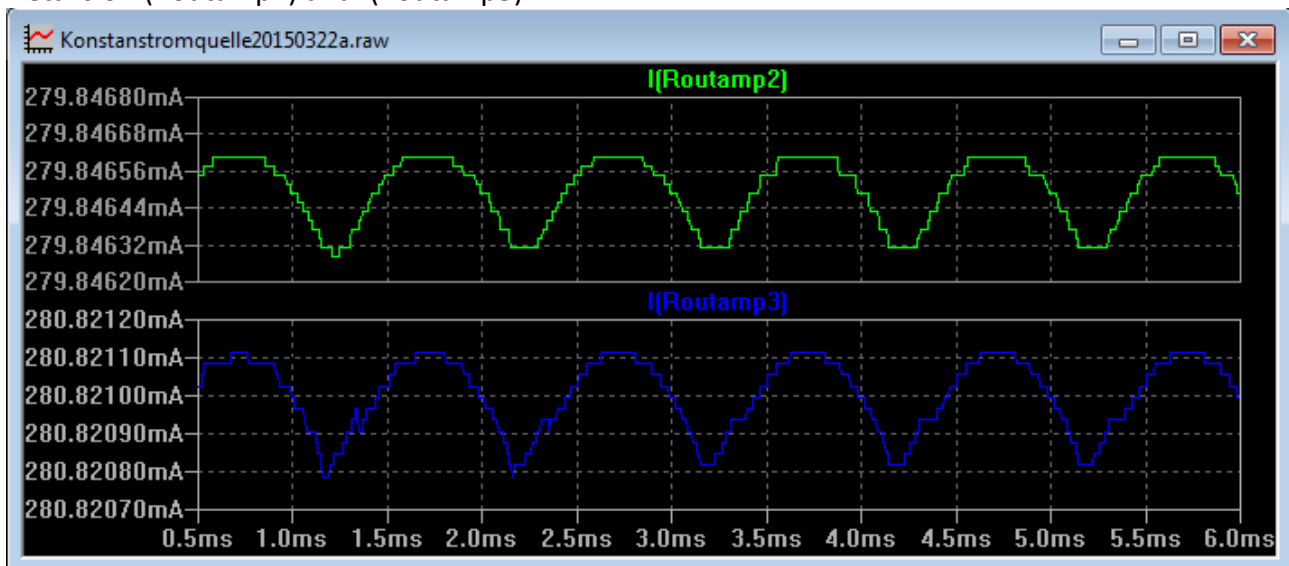
16V output swing and 1kHz distortion spectrum:



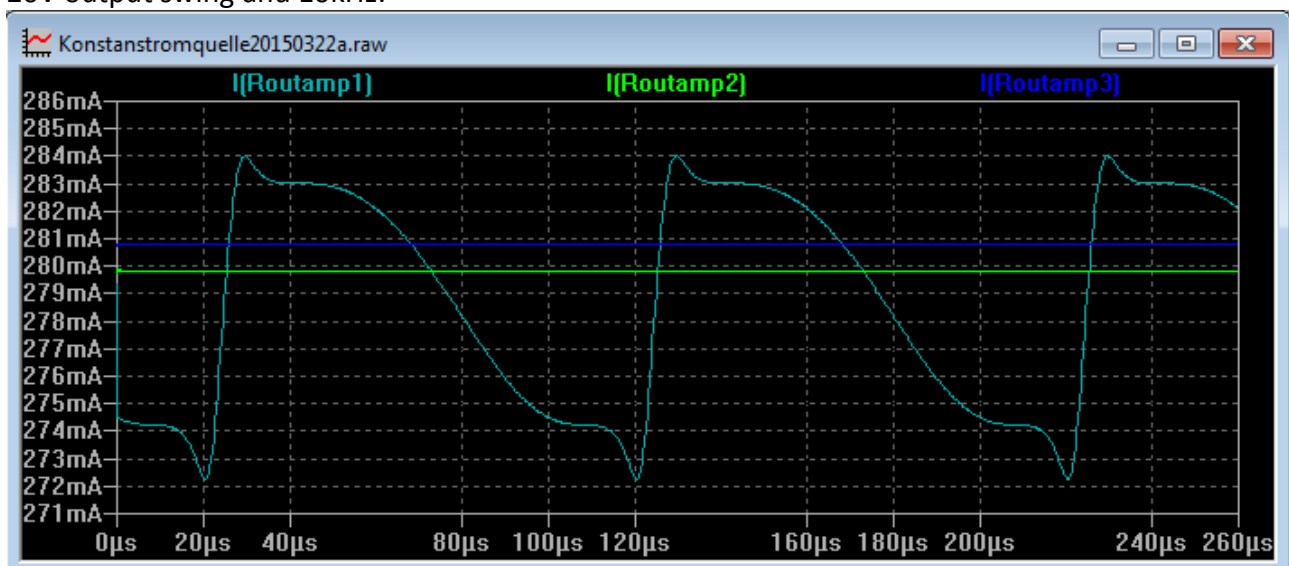
20V output swing and 1kHz:



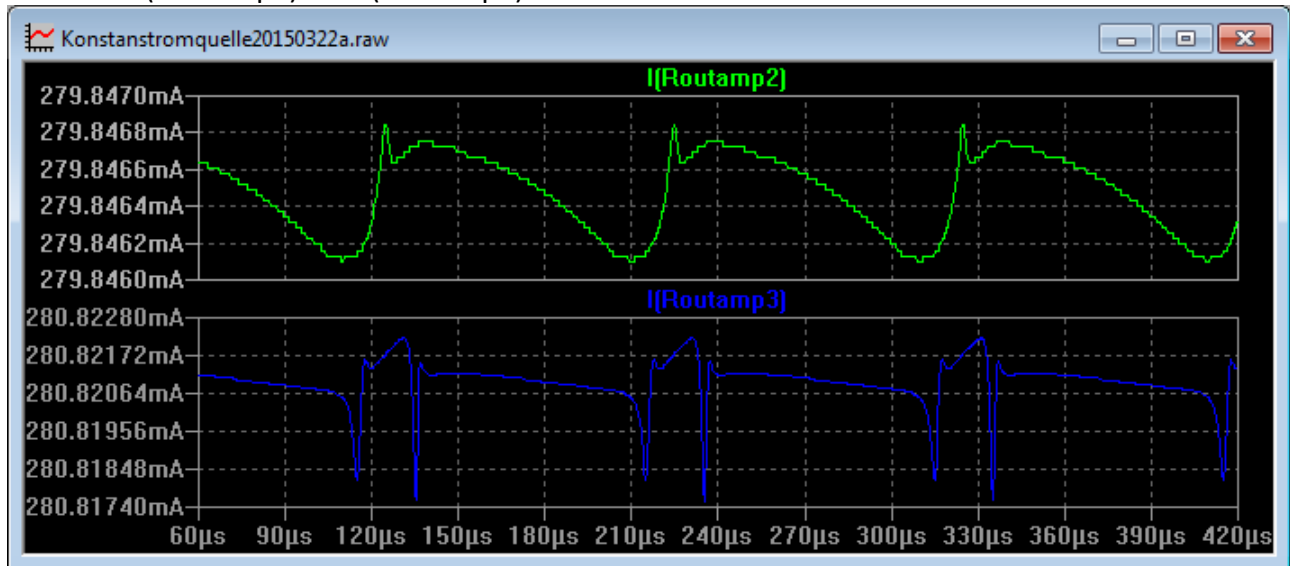
Details of I(Routamp2) and I(Routamp3):



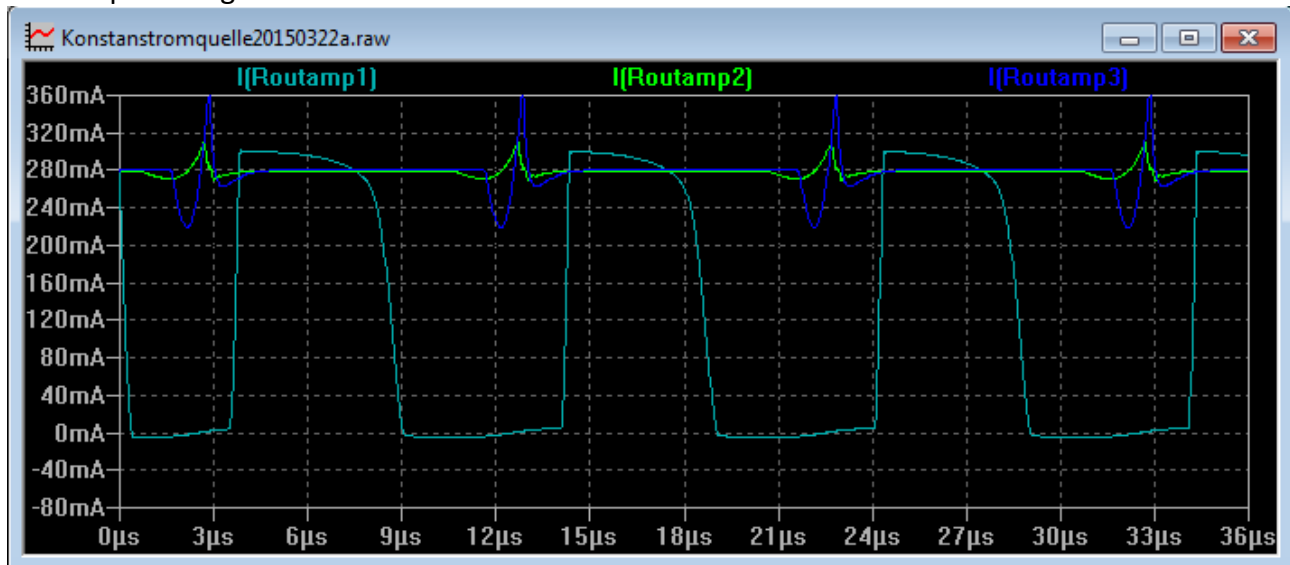
20V output swing and 10kHz:



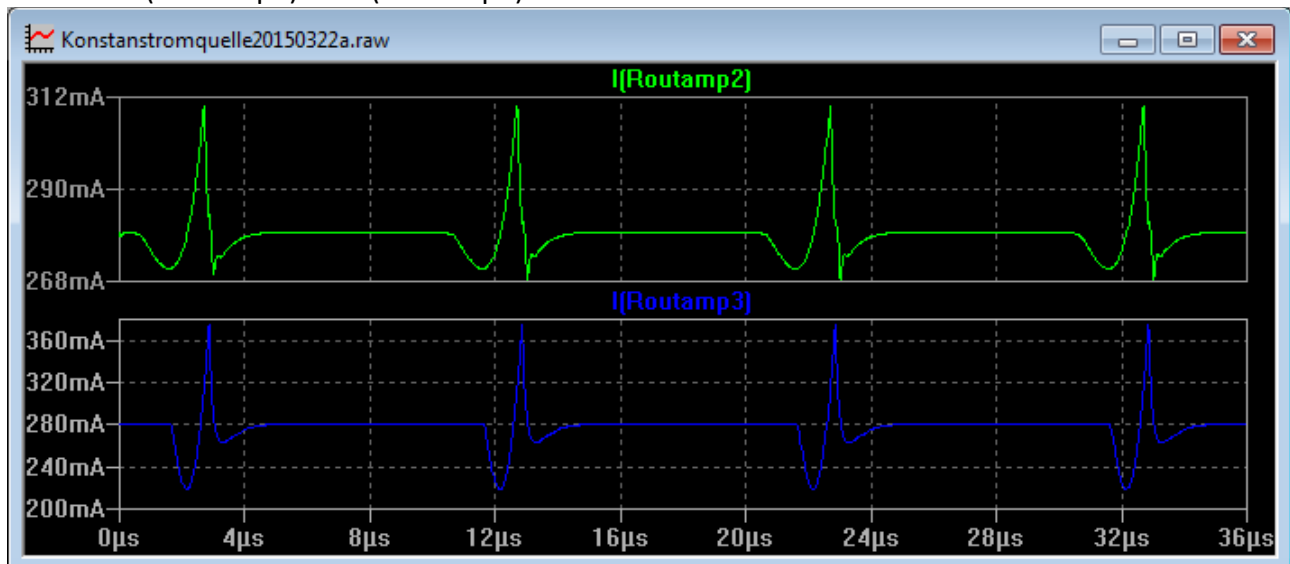
Details of I(Routamp2) and I(Routamp3):



20V output swing and 100kHz:



Details of I(Routamp2) and I(Routamp3):



20V output swing and 1kHz distortion spectrum:

