A 400Hz, 3-phase 60VA Power Supply

10-10-2020 / Koos Bouwknegt

Input voltage	25…30V dc
Input current	< 10x I-out
Output voltage	3x 115 ± 5 V
Output current	0.3A rms
Distortion	< 4% THD
Sound	70 dBA
Size	10 x 10 x 10 cm
weight	1 kg

Many avionics in the fifties and sixties were powered by 27Vdc ***and*** 3-phase 115V, 400Hz ac without neutral., one phase connected to ground. The 3-phase supply was made either by an alternator or by a dynamotor, powered from the 27Vdc bus. They made a lot of noise and heat.

Today, 60 years later, such a power supply can be made with cheap components, a much higher efficiency, less noise, and very compact. I made one, based on a credit card sized 2 x 100W class-D stereo amplifier. The input is the 27Vdc bus, the output is floating 3-line *without neutral*, 3x 115V, 400Hz, 0.3A rms.
A new board generates two accurate 400Hz/ 2V sine waves with 60 degrees phase difference. These signals are amplified to 16V rms voltages (45V peak-peak), and transformed to 115V in two identical xformers.

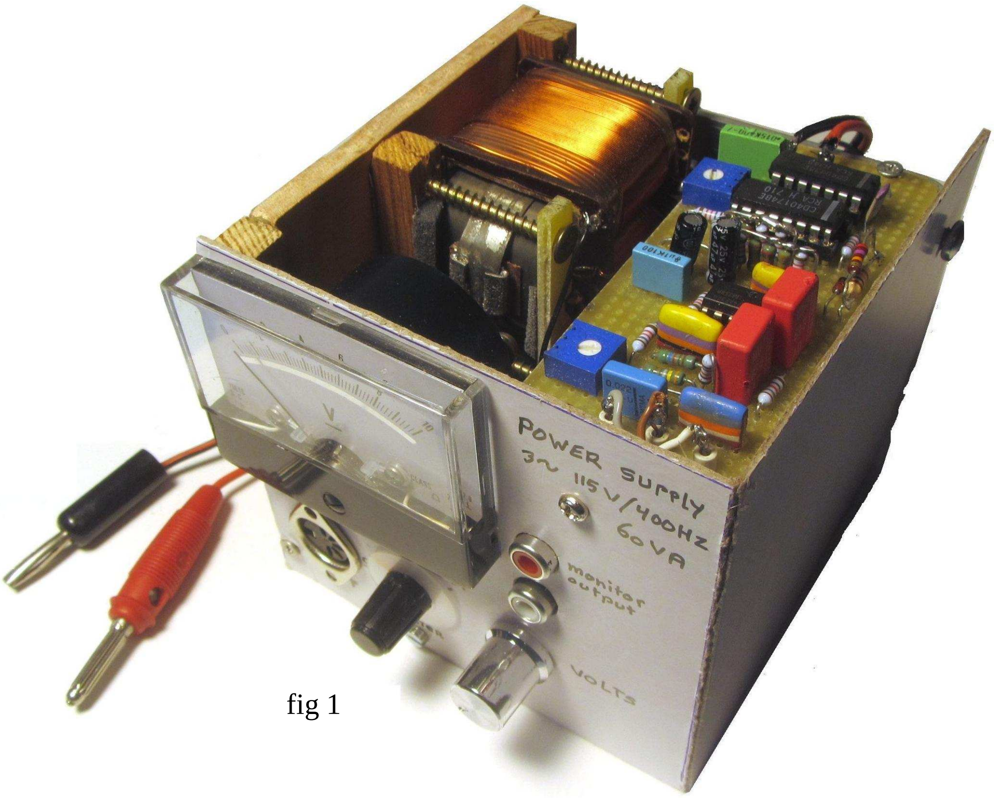


fig 1

The box is 10 x 10 x 10 cm, just 1 litre, and the mass is 1kg.

The two C-core transformers are attached to the left side of the box. On top you see the generator board, starting with a 4800Hz oscillator driving a 6 stage shift register providing 12 square waves, at 30 deg. intervals. A stepped wave is then made by proper adding these square waves to get a near sine wave. RC filtering gives it less than 1% distortion.

The class-D amplifier is in the middle of the box, and not visible on this picture.
The amplifier module is available from AliExpress for less then €10.

The amplifier is advertised as 2 x 100W (20Vrms x 5A rms each channel) for a short time.
With a fan, about 2.5A rms continuous per channel is possible. There is only one chip (TDA7498) on this module, running at 350kHz switching frequency. Each channel has a full H bridge output.
Cooling of the amplifier and the RF output filter is done with a 24V fan directly above the heatsink.

The power supply is completed with two identical transformers and a voltmeter. Four C-cores were salvaged from a single power transformer. The cores have an iron-section of 8 x 25 = 200 mm^2 , and the transfer ratio is 1 : 7.6.
A selector switch connects either the SR, RT, or TS voltages to the meter.
The output voltage is adjusted by the "volume" potmeter of the amplifier . Minor adjustments are on the generator board for balance and frequency.
The over-all efficiency is 75% (nominal 60W out is 80W dc input)

Operating principle of the waveform generator

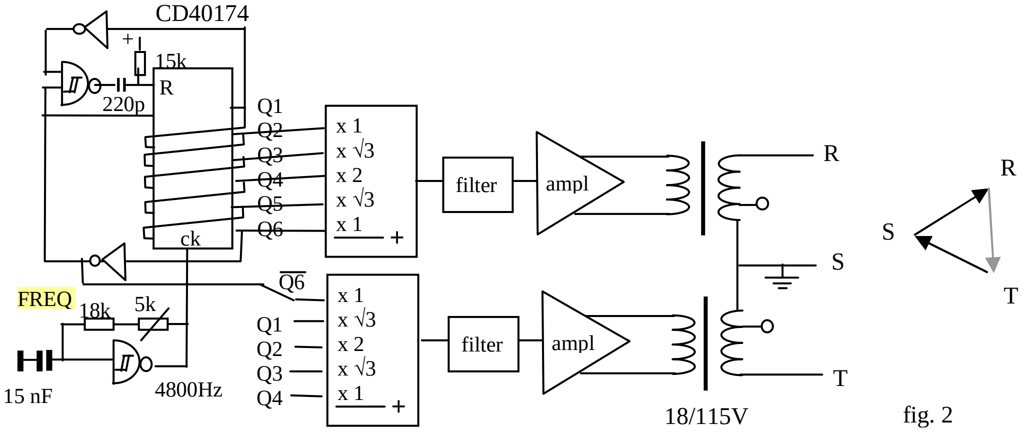


fig. 2

The hex D-latch CD40174 is clocked with 4800Hz. A pattern with 6 "zero's" and 6 "ones" walks through this shift register at every clock pulse. This gives 6 symmetrical square waves on the outputs of the shift register all with a frequency of 400Hz, and 30 degrees apart. The Reset input is used to suppress parasitic modes.
The square waves are added to get a stepped waveform, that has only the eleventh and higher harmonics. With a single RC filter, 2% total harmonic distortion (THD) is reached, with a second RC filter even 1%.

Figure 3 gives the 6 square waves from the hex-D latch, and how the two stepped waves are obtained.
Example: Wave A is Q2 + √3 Q3 + 2 Q4 + √3 Q5 + Q6

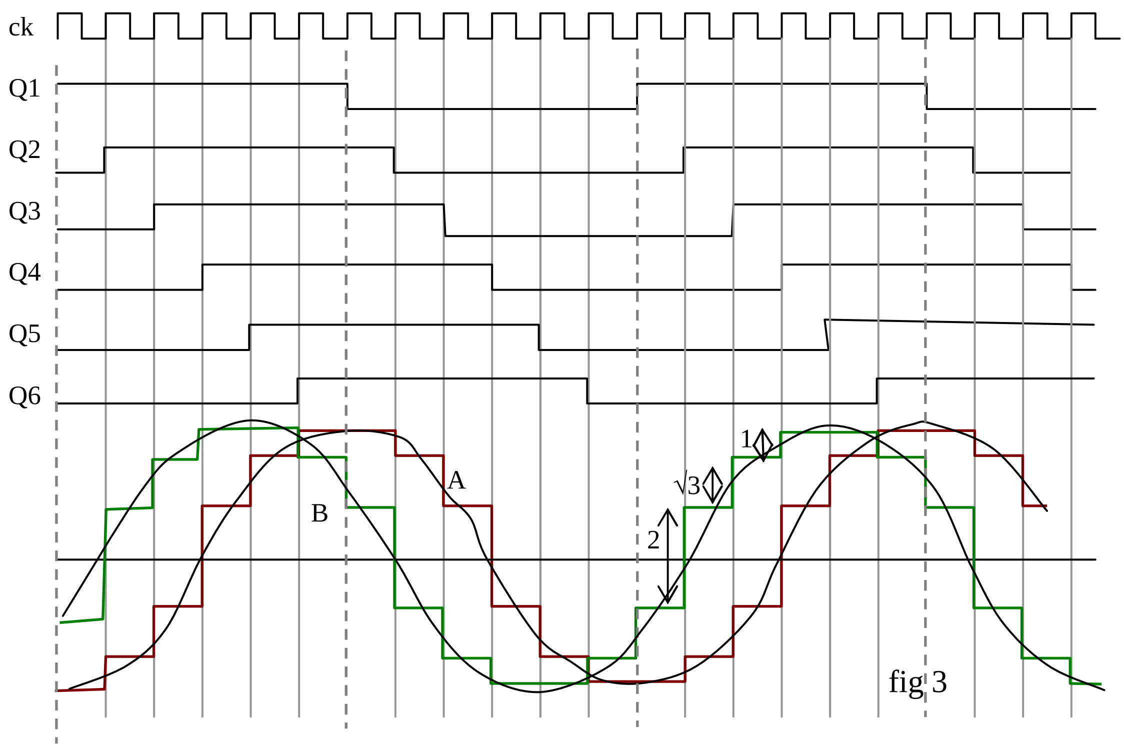


fig 3

The generator printed circuit

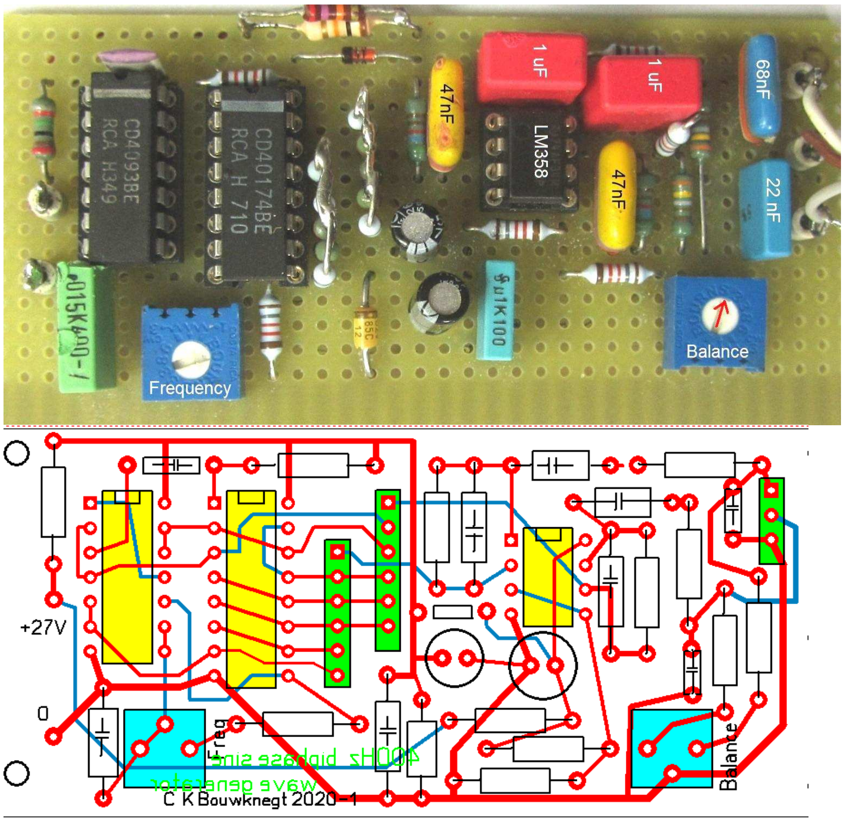


Fig. 4
Two identical resistor arrays are used to sum up the square waves. Ideally, the resistor values should have the ratio 1 : 2/√3 : 2 , example :

27k2 : 31k4 : 54 k4

More practical, I used

27k2 : 33k : 56k3

The opamp's feedback resistor is 5.6kΩ or less to prevent overdrive of these opamps at the top of the stepped waveform. The outputs are 2V rms sine waves at 400Hz.

An RC filter on the output side removes glitches, improves the waveform, and mitigates RF disturbances from the PWM final amplifier. It also serves to increase the RT output voltage.

The complete circuit is shown below. The red and green sine symbols (A and B) correspond to the waveforms in fig.3. Because the TDA7498 chip has dual PWM outputs per channel, an output transformer must be used, even if only 20Vrms is required.

Voltage adjustment is done with the "volume" pot on the amplifier. The RS and ST output voltages are made equal with the balance pot, the third, RT voltage is slightly increased by making the upper output cap 68nF. This increases the A to B phase difference from 60° to approx. 65°

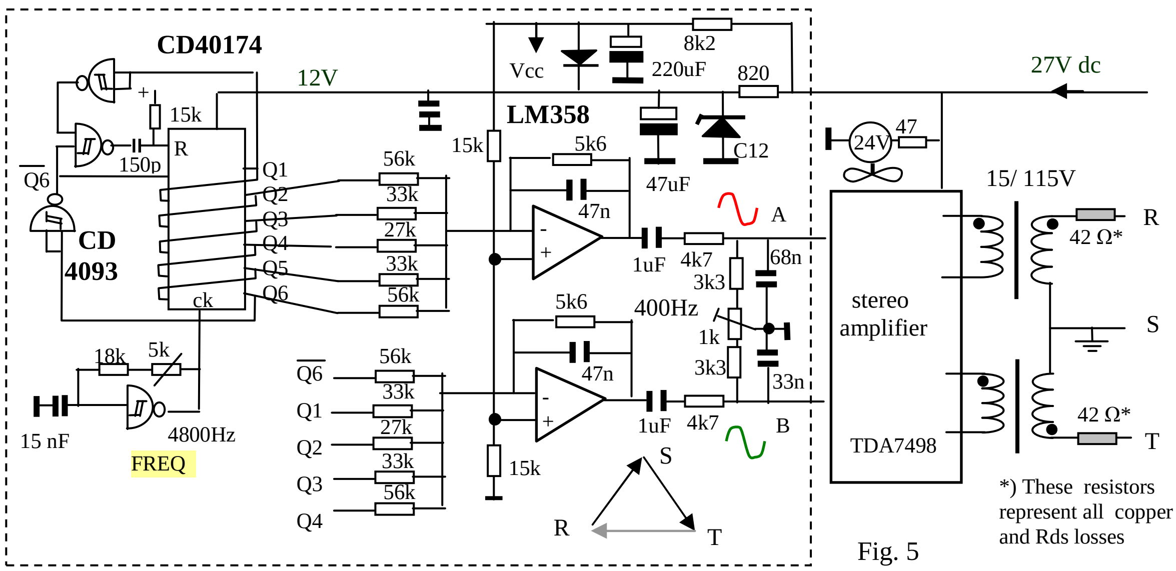
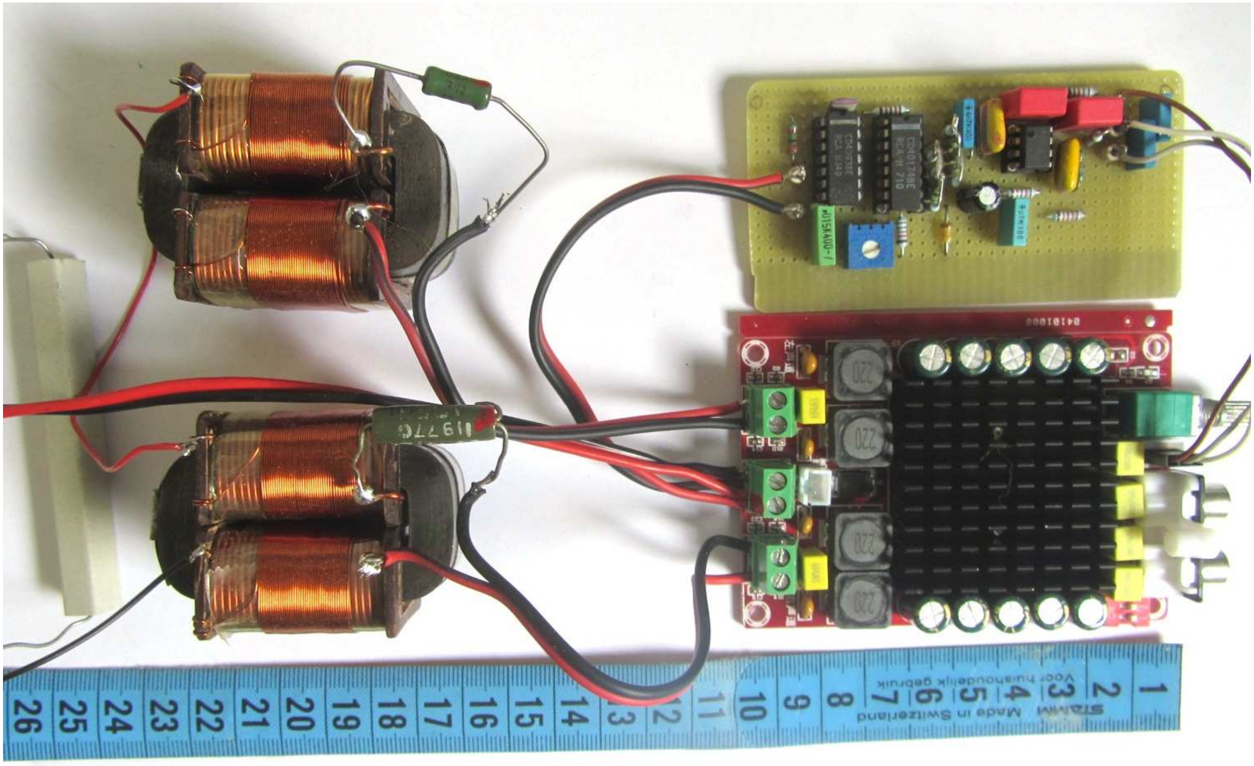


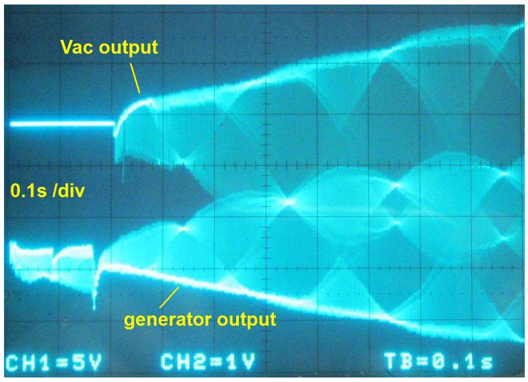
Fig. 5

Rating
The continuous nominal load for the complete system is a symmetrical load of 3 x 115Vac/ 400Hz with 0.3A continuously. This is a rating of 115 x 0.3 x √3 = **60 VA.** The nominal load is 3 resistors of 661 Ω /20W in triangle. The short time rating is 1.6x higher .

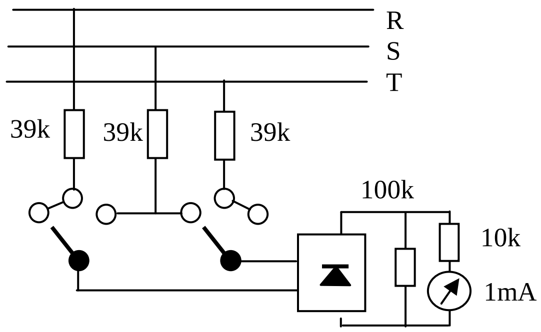
Fig. 6 The components (except the fan) shown below with (temporary) shunts to measure the current :



Symmetry
Using only two amplifiers in a 3-phase application requires transformers with a very low impedance, otherwise the RT voltage is too dependant on the load. The primary coil resistance should be < 1Ω, the secondary < 8Ω. It was impossible to find two suitable transformers, so I decided to make my own transformers with small C cores. The voltage unbalance is < 2% with symmetrical load.
With single-phase load , the unbalance can be 6%



Voltmeter



Soft start
Brute 27Vdc application to both the oscillator board and amplifier gives a loud scream in the transformers at turn-on. A softstart circuit was added to the oscillator board that gradually applies Vcc voltage to the opamps. The TDA7498 is standard muted the first 160ms after application of the 27Vdc supply.
As can be seen, the start up of the oscillator and shift register happens when the TDA7498 is still muted.

Rating

The power cube is designed for 60VA 3-phase output at 115V/ 400Hz. The line current is 0.3A, and that is also the current in the secondary of each transformer. The primary current then is 0.3 x 7.6 = 2.3A plus the magnetizing current (0.3A) is 2.6A rms (3.67A pk)

The transformers

Two equal transformers are made, with 50 primary turns, and 380 secondary turns. This is a turns ratio of 1: 7.6. Without load, this gives at least 121V undistorted output at the lowest input Vdc of 25V and 115V with a 60W balanced load. This corresponds to 16Vrms on the primary winding.

The core has 25 x 8 = 200 mm^2 iron section.
I used Ø 0.35 mm enameled wire and Ø 1.12mm.
The number of turns is simply what I could get on the bobbin in a single layer.

Primary per leg :
1 layer 25 turns, total 25 x 2 = 50 turns. width 31 mm
Secondary per leg:
2.4 layers, 75 turns each, total 75 x 2.4 x2 = 380 turns.
Two layers secondary lay on the bottom of the bobbin, then the primary in one layer, and on top (not shown) another 40 turns per leg, the legs are series connected.

From the two identical transformers, T1 has standard bobbins, T2 has home-made bobbins, that I made from 2mm pertinax. There is some difference in magnetizing current, possible due to a less flat pole faces.

	Trafo1	Trafo2
Bobbin	standard	home made
Primary turns	50	50
Secondary turns	380	380
Magnetizing current @ 16V	0.23	0.51 A rms
Main inductance (secondary side)	0.5	0.3 H
Copper resistance (,,)	6.7 Ω	6.8 Ω
Core loss @ 115V	2	2.3 W
Copper loss @ 0.3A	2	2 W
Nominal primary current	2.4A rms,	Ø 1.12 mm wire allows 2.85 A
Nominal secondary current	0.3A rms	Ø 0.35 mm wire allows 0.289 A
Core section	Afe = 8 x 25 mm = 0.0002 m^2	
Bmax = $V_{rms}.\sqrt{2} / (N.A_{fe}. \omega) = 115\sqrt{2} / (380 \times 0.0002 \times 2\pi 400Hz) = 1.05$ T peak		
Mass	292 gram	

All OK, but the sound is high above 90V output , at Vdc=25V both when loaded and in no-load.
With 27Vdc the sound is a little less and without a sharp note.

Output resistive impedance

Each transformer has 0.2Ω primary copper resistance, and 7Ω secondary copper resistance.
The amplifier output impedance (0.2Ω Rdson per FET) contributes to the losses and voltage drop under load. On each side of the transformers primary is a branch with two FETs, so 0.4Ω extra per transformer.
The total resistive part of the output impedance is $7\Omega + (0.2 + 0.4) \times 7.6^2 = 42\ \Omega$

Test results

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1. Voltages and losses

1.1 Output data without re-adjustment of voltage. Symmetric resistive load.
All with same amplifier output voltages, so different voltage drops are caused by the transformers.
Full load 3 x 687Ω was made by using the 1k and 2k2 loads in parallel.

Load	Iout	Pout	Vsr	Vrt	Vts	Loss	DC input
0	0 A~	0 W	111 V	117	115	6 W	25 V - 0.24A incl fan
3 x 2k2	0.1	18	109	113	112	7.3	24.5V - 1.0A
3 x 1k	0.18	36	105	106	107	8.3	22V - 1.9 A
3 x 687 Ω	0.26	52	105	106	108	15	26V* - 2.5A

*) stabilized power supply 26V/6A max

Observation: - The output voltage drops 8V at 0.2A, so the internal impedance of the power supply is 40Ω.
This is about the copper + fet resistances so the inductive part is negligible.
- The unbalance is highest at no-load because the unbalance was minimized at medium load.

1.2 Output data with re-adjustment of voltage. Symmetric resistive load.
All with a regulated 26.3V power supply

Load	Iout	Pout	Pin	Idc	Vsr	Vrt	Vts	Loss	Efficiency
0	0	0 W	6.6 W	0.25 A	111 V	116	116	6.6 W	-
3x 2k2	0.1 A	18.8	27.2	1.03	115	119	118	8.4	69
3x 1k	0.2	39.7	53.6	2.03	115	117	117	13.8	74
3 x 687	0.3	57.5	77	2.93	115	114	117	19.5	75

Observation: The loss can be modelled as 7W + 3 x 50Ω x $Iout^2$. The switching loss and fan consumption are constant @ fixed Vdc, even at no load, say 7W. The load dependant losses rise with the square of the output current, dissipated in a 50 ohm resistor in each line.
At 0 - 0.1 - 0.2 - 0.3A, this formula predicts 7 - 8.5 - 13 - 20 W loss

1.3 Output data with single phase loads (line-line connected)

Load	Iout	Pout	Pin	Idc	Vsr	Vrt	Vts	Loss	unbal*
1k1 SR	0.104	12.0	20	0.76	115	122	122	8 W	7V
1k1 RT	0.108	12.8	21.3	0.81	117	119	120	8.5	3
1k1 TS	0.103	11.8	20	0.76A	116	119	114	8.2	5
500Ω SR	0.224	25.1	35.2	1.34	112	120	121	10.1	9
500Ω RT	0.232	26.9	39.7	1.51	118	116	120	12.8	4
500Ω TS	0.228	26.0	36.0	1.37	115	120	114	10.0	6

*) unbal is the highest difference between line-line voltages

Observation: A single-phase load connected between the (transformed) outputs of the amplifier gives the lowest unbalance, but with the highest losses.

1.4 Output data with capacitive or inductive load

Load	Iout	Pout	Pin	Idc	Vsr	Vrt	Vts	Loss	Efficiency
0									
1uF RS									
1uF RT									

2.0 Dynamic behavior

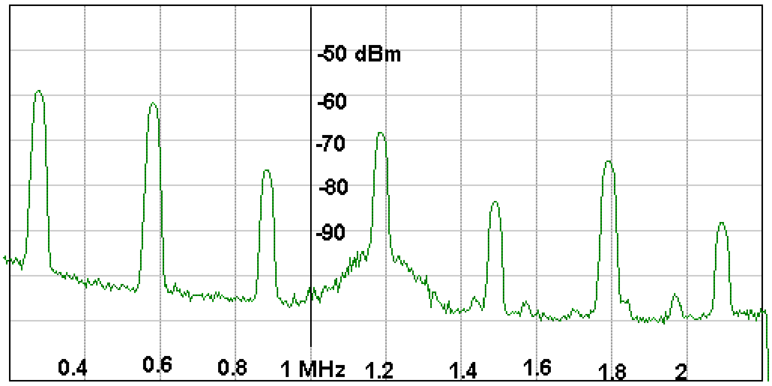
2.1 Resistive load steps

to be measured

3.0 Distortion and RFI

Distortion is below 2%, not visible on the oscilloscope.

The PWM switching frequency (300kHz) is not dominant in the radiated spectrum.
The spectrum shown is with full load. The no-load spectrum has a dominant fifth harmonic at 1.5MHz.



B 200 kHz /div Mid= 1.216 MHz 10 dBm /div Topline = -40 dBm

The box

The complete unit is a cube with 10 x 10 x 10 cm = 1 litre. Mass is 1 kg.