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1 About the HPHV shunt regulator

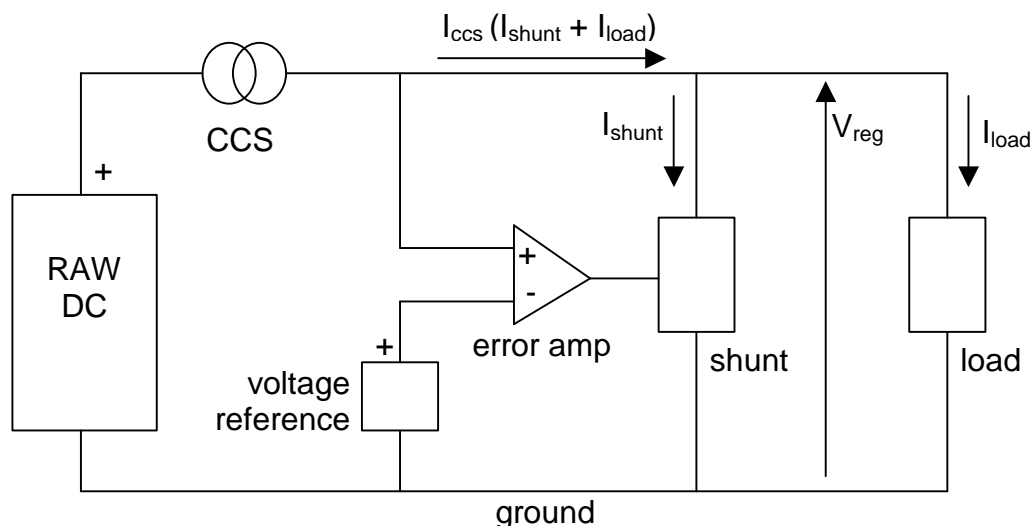
The HPHV shunt regulator is a very high performance circuit designed to provide a low impedance power supply for a tube circuit. The circuit is optimized for a constant phase response within the audioband as well as very low noise.

In order to reduce the stress that tubes face during startup, the regulator slowly raises the output voltage when starting. Full (sonic) stability is reached after about 5 minutes.

The shunt regulator has two parts: the constant current source (CCS) and the shunt (regulator). The CCS provides a constant current to the shunt and to the load. In effect this creates a high impedance (isolation) between the raw dc supply and the shunt/load.

The shunt regulates the voltage supplied to the load by adjusting the current through the shunt. The error amp measures the voltage at the shunt/load and compares this voltage with a reference voltage. If the two voltages differ, the error amp will cause the shunt to conduct more or less current. This will (re-)set the voltage at the shunt/load to the correct level. This happens very fast, in fact, much faster than any audio signal.

Due to the topology, the shunt regulator provides a very short path to ground for the load.



2 The circuit

The shunt regulator basically has two parts: the constant current source and the shunt.

2.1 The constant current source (CCS)

The CCS consists of T2 and U2. U2 (TL431) is a shunt regulator (in a 3 pin device) that will always try to keep a constant potential (voltage) between its anode and its reference. It does this by adjusting the potential (voltage) across itself (anode-cathode).

T1 and R4 form a CCS (high impedance), so the cathode of U2 is free to move and well isolated from the raw dc supply. The cathode of U2 sets the bias of T2 (gate potential through grid stopper R5). So by setting the voltage across itself, U2 sets the bias of T2 which, in turn, sets the current through R16 & R6. As U2 will try to keep the voltage between its anode and reference constant, the current through the CCS is kept constant. This provides high (AC) isolation between the raw dc supply and the load. In order to function correctly, the CCS needs about 20VDC across it.

The TL431 has a reference voltage of 2.5V. Let's assume R16 is set midway (50R). The total resistance of R16 & R6 is $50R + 20R = 70R$. U2 will adjust the current so that it sees 2.5V between its anode and reference. In this case, it will set the current at $2.5V / 70R = 0.036A$ (36mA). R6 limits the maximum current at $2.5V / 20R = 0.125A$ (125mA).

2.2 The shunt

The shunt consists of T4¹ (the shunt) and U1 (the error amp). By setting the grid-potential of T4, U1 tries to keep the potential (voltage) between its two inputs the same (it acts on the **difference** between its two inputs).

The inverting input is connected to a voltage reference, composed of T3 (CCS) and U3 (shunt reg). The CCS allows the cathode of U3 to move freely and provides a

¹ Mosfet shunt option.

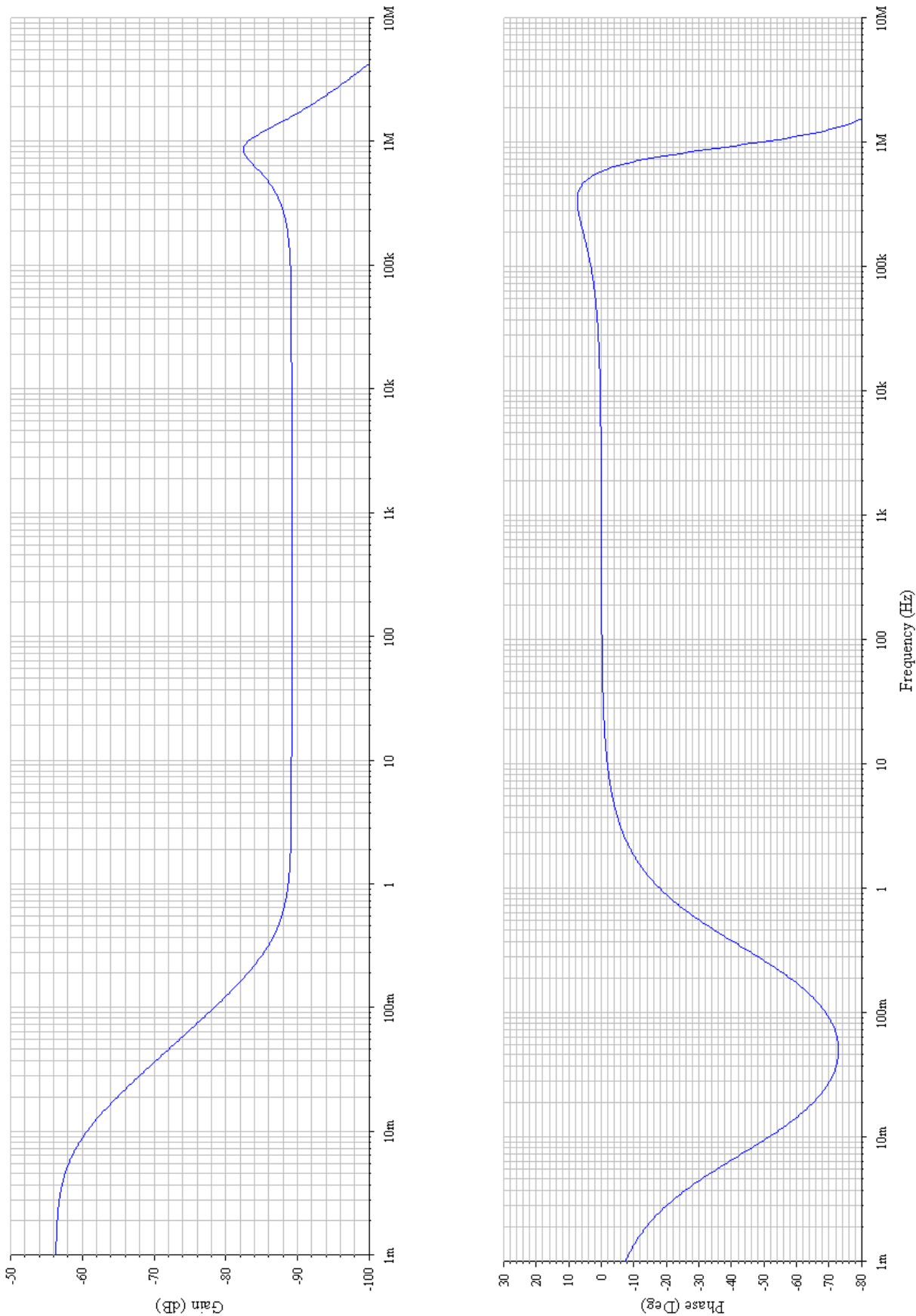
high impedance (isolation) between U3 and the (regulated) DC rail. The voltage reference is set at (approximately) 7VDC, so U1 wants to see 7V at its **other** (non-inverting) input. This input is coupled (AC via C2 and DC via the voltage divider R19/R18/R3/R17) to the output of the shunt reg (V_{reg}).

If V_{reg} changes (causing unequal potential between the inputs of U1), U1 will react by adjusting its output. The output of U1 sets the bias of T4, controlling the current through the shunt (setting V_{reg}). The AC coupled input (i.e. error signal) is amplified about 100 times by U1 (the DC gain is set with R8 and R13). Since U1 (OPA655P) has a gain-bandwidth product of 240MHz, it is able to handle the signal well beyond the full audioband, causing very little phase shift within the audioband.

DUE TO THE SPECIAL (DUAL) POWER PINS/CONNECTIONS OF THE OPA655P, DO NOT SUBSTITUTE THIS DEVICE WITH ANOTHER OPAMP.

The low-end response of the regulator is determined by the C2 and R15. The combination of 1uF and 470K causes a -2dB point below 1Hz. Due to the long RC-time of C2 and R15, V_{reg} rises very slowly after applying power (prolonging tube life).

At higher frequencies (about >150KHz), the gain of the amp is reduced by C13 so that the opamp always has ample feedback (providing linearity at these higher frequencies). In effect, the amp is rolled off with -2dB around 375KHz. At even higher frequencies, C4 becomes dominant and provides a low impedance path to ground (at these frequencies, the gain of the opamp is severely reduced by C13). C13 also damps any potential (HF) oscillation.



Simulated response

Due to the high gain-bandwidth product of the OPA655, the regulator has a very constant phase angle within the audioband (20-20kHz), The phase-angle is never more than 2 degrees. I find that excellent phase response is essential to (sonic) imaging and stability.

This kind of performance can only be achieved by using extraordinary components. The Burr-Brown OPA655 is a very special amp, definitively never designed to be used as a error amp in a shunt regulator for tube circuits, but it sure does a great job (BB OPA655 datasheet):

The OPA655 combines a very wideband, unity gain stable, voltage feedback op amp with a FET input stage to offer an ultra high dynamic range amplifier for ADC buffering and transimpedance applications. Extremely low harmonic distortion along with excellent pulse settling characteristics will support even the most demanding ADC input buffer requirements.

The broad unity gain stable bandwidth and FET input allows exceptional performance in high speed, low noise integrators.

The high input impedance and low bias current provided by the FET input is further supported by the ultra-low $6\text{nV}/\sqrt{\text{Hz}}$ input voltage noise to achieve a very low integrated noise in wideband photodiode transimpedance applications.

Broad transimpedance bandwidths are achievable given the OPA655's high 240MHz gain bandwidth product.

If you want more info on the OPA655, download the datasheet from the Burr-Brown site:

<http://focus.ti.com/docs/prod/productfolder.jhtml?genericPartNumber=OPA655>

R8, R13 and C13 form the feedback network for U1 setting the (DC & HF) gain of the error amp. T5 and R21 form a CCS that force the output of U1 into class A (better sonics). R1 provides isolation for the output of U1 from the gate capacitance of T4.

U4 and its associated parts provide U1 and U3 with clean DC rail. L1 and L2 provide HF isolation from the raw dc supplies.

In order to monitor the current through the shunt, the voltage at test point I can be measured. The shunt current (mA) equals this voltage (mV) divided by 10. In order for the shunt regulator to work correctly, the shunt current should be at least 0.2 times the load current.