1 kW(dc) TWT Power Supply design.

Luis Cupido

***Abstract** – Surplus TWTs, available on the amateur markets, seem to appear in much greater number than their power supplies. Also some of the power supplies are designed for specific applications such as having exotic negative input voltages or are special such as for pulsed amplifiers, while the few good ones that show up, rapidly fall in good hands.*
The following article presents a switch mode power supply for TWT tubes. It operates directly from the sector and is capable of delivering up to 1KW DC.
This design was done for medium power TWT's but all circuits are versatile enough to accommodate up to 10kV helix and up to 8kV collector voltages. The design description is done in a way that it can be assembled for any specific TWT you may have, providing the necessary modifications.

Introduction

The TWT (Traveling Wave Tube) is an electronic tube that makes use of the interaction between a microwave signal and an electron beam to produce amplification of a microwave signal. The description of the physics or the operating principles underlying, is completely outside the scope of this article although good literature is available on the subject /1/2/3.
Most of the tubes that can be of interest to our purposes have similar configuration and employ voltages in the range of 2 to 10kV. This fact justifies the development effort to make a generic power supply that could be easily adapted to any specific TWT in this range.
A TWT requires; a powerful collector supply (in our case, a few kV), a heater supply , control grids, and a very precise helix voltage supply (in our case up to 10kV).

Collector voltages are the power source of the electron beam and are not required to be very accurate, however, the tube should not be operated far from the recommended values as the power efficiency may be affected. A 20% variation from nominal is in most cases acceptable.
Heater and grids require no different approach from any other type of beam tube, as they are use to form an electron gun (similar to the ones in CRT tubes).

The only critical issue, is in fact the helix voltage, this voltage sets the best interaction between the beam and the microwave signal. We need to understand how this voltage affects the operation, and the stability we require, to properly set a TWT in operation, specially if the operating voltages are to be determined by experimentation.
Depending on the specific tube, helix voltage changes of few percent may affect the tube gain and power output significantly, this requires a precise voltage source, preferably a feedback stabilized power supply. The helix voltage should be regulated as good as 1% but adjustable by 20% the nominal value to allow tuning for best performance.
Grid 2 voltage is, normally, derived from the helix voltage therefore it will have a stable supply. If the tube has a Grid 1, its voltage is derived from the beam current using a zener diode, so it can also be set accurately.

Description

The design presented here has:

- A collector supply with two collector connections (tubes with only one collector will not use the second collector connection).
- An helix supply with voltage feedback control, that makes the output voltage stabilized but adjustable over a wide range.
- Protection for helix over-current, and total power (collector protection can be fit if desired)

The switching frequency is 40KHz and full duty cycle is employed. The main control circuit is built around an UC3864 from Unitrode that provides all the basic functions of a SMPS. The power switching is done in a push pull configuration.

The collector supply uses two, peak-to-peak rectifiers and requires separate windings for collector 1 and collector 2. One collector configuration should use two identical, separated windings, and the collector 2 terminal is left unconnected.

The heater supply uses a simple rectifier and a monolitic regulator to set the heater voltage to the desired value, with good regulation.

The helix supply employs a four times voltage multiplier to the peak-to-peak input voltage. The helix voltage is coming from a separated transformer that has a variable input voltage.
The main transformer supplies a fixed voltage to the helix transformer trough a variable voltage gap. By changing this gap the input of the helix transformer can be varied. The voltage gap is done with a full bridge rectifier containing a variable load at its DC terminals. The helix voltage control is done by feeding back, the helix voltage information, to the variable load inside the bridge.

The complete power supply can be built using 3 PCBs. One main control board, one helix board and a collector board. The main and helix transformers are external and assembled directly to the chassis.

Main control board.

The main DC voltage is obtained directly from the sector, 220Vac or 110Vac, after being rectified and filtered (D1-D4 and C2,C3). The IC is supplied by a bootstrap secondary on the main transformer. To start the supply C17 and R3 will provide about 20mA during 20 ms, time enough for the circuit to start functioning and supplying 12V via the bootstrap secondary. D11 will prevent the supply voltage to rise above 15V during the startup.
Both R5 and C4 set the operating frequency, while C4 alone can be varied to adjust the dead time of the output switching waveforms (this is a simplified explanation, please refer to the data sheet for detailed information /4/). This values result in an oscillation frequency of 80Khz to 90KHz with 8 % to 10 % dead time. The main switching frequency is half the oscillator's frequency. Some trimming can be done increasing C4 to reach the 40KHz, if necessary.
As the UC3846 has built-in output drivers, the power FETs are interfaced directly using only a resistor divider (R9,10 and R11,12).
The total current flowing trough the FETs can be sensed at the resistors R14,15,16, which sets the peak current protection. R13, R27 and C5 will remove any spikes present at R14,15,16 to provide a clean signal to the current sensing inputs of the UC3846.
R7 and R8 will set the maximum operating current and the operation mode.
By using R7,8 both equal to 1.5Kohm, the maximum current is set to 2A and a latched shutdown is selected, that is, the power supply will not try to restart if a shutdown condition happens (such as helix or collector protection).
To increase the maximum power capability just reduce R14,15,16 accordingly.

Protections against helix and collector over current will force a shutdown by controlling the UC3846 shutdown input. Protection signals are optically isolated by U2 and U3. The input side of the opto-couplers is intended to remain at low potential or near ground voltages as U2 and U3 can be effective isolating them from the sector (220Vac or 110Vac) potential. Never connect U3 to the cathode or collector leads of the TWT. If a collector protection is desired make it using a current transformer on one of the leads of the collector wires coming from the main transformer.
R28,C15 and R29,C16 are used to remove the spikes from the protection signals to avoid shuting down the supply with transients far below the damage levels.
Some spikes on the helix current, while switching on and off the beam, can exceed the current limit by a factor of 5, although they last only a few microseconds. As they contain little energy they will not endanger the tube life and the power supply should not shut down in such events.

Also in the main control board, is the helix control circuit. It is composed of a full bridge rectifier, D12,13,14,15, and a variable load implemented with a power

darligton transistor BDX53C. The input impedance is further increased using an additional emitter follower, Q3. This way the input impedance is set only by external elements and the loop stabilization calculations and implementation become greatly simplified. Only C12, R26, in a pole-zero compensation, are required to guaranty the loop stability.
R24 and C11 make a peak-absorbing network to clean the switching waveform that is feed into the helix transformer.

Collectors supply board

This PCB comprises the collector supplies and also the heater supply, as it is usually at cathode potential. The collector supply employ two peak-to peak rectifiers in series and an additional noise filtering C24, 25 and L20, 21.
The bleeding resistors R28,29,30,31 are used to prevent the voltage of rising up to the peak of the switching overshoot, while the tube is in standby with no beam current flowing.
The value of these resistors may be set to have the collector voltages below the maximum ratings of the tube while the tube is in standby. This way the power wasted on this resistors is the minimum possible. However if we want to have the collector voltages near the nominal when the tube is in standby, a larger amount of current must flow through the resistors. Practical experimentation shown that 5 to 10mA is enough to have less than 20% rise off load.
This effect has little impact in the collector voltage variation under load since when significant current is being drawn the rectification come down to the nominal values of the input square wave, that is from top and bottom.
The heater supply uses a conventional voltage regulator that can be adjusted for the correct heater operating value by changing R30 and R31. At lower currents a small heat-sink should be fit into the regulator. However if the tube drawn currents near or above 1A a bigger regulator should be provided. Do not try to thermally connect the regulator to the box or external heat-sink as it is at cathode potential (that is helix value below ground). The isolation would have to stand far above 10kV for safety reasons.

Helix supply board

The helix supply PCB contains the helix circuits and the grid 1 and grid 2 voltage settings. The variable voltage coming from the main transformer and gap regulator is rectified in a 4 times peak-to-peak voltage multiplier. This way, a 4kV helix will require the transformer to be wound to 1kV peak to peak, that is 500V rms (remember we have square waves where rms = peak). R1 to R4 are used as bleeding resistors and help to maintain a minimum current what ever the helix current flowing.
The feedback is taken at RV1 with an offset of 180V. This offset will make the calculation of the voltage divider network easier and will increase the control loop gain. R1 and RV1 are equal in all voltage ranges.

In my design, for the maximum helix voltage desired, the transformer is driven with 100Vpp while at nominal value it may be around 80Vpp.

For the helix control loop to operate properly up to the maximum value a control margin is necessary. To guaranty this situation the main transformer is winded to supply 120Vpp to the helix circuits.
Note that the variable gap regulator will have half the peak-to-peak value on DC to control. This way, at the maximum helix voltage the voltage gap will be 8.6 V that is (120 – 100)/2 minus the diode bridge voltage drop.

The total helix voltage range can exceed a 2:1 ratio. We need to drive the helix transformer with 50Vpp to have half the maximum helix voltage and this situation corresponds to a DC gap of about 35V. This value is handled by Q4 without any problem.

Other voltage values for the helix control circuits may be used if the proper relations are maintained.

Power transformers

The transformers must be selected to work at 40KHz and handle the power required so please refer to the corresponding data-sheets before attempting to use any core. The best information I could find was on Siemens and Philips ferrite cores catalogues.
The calculation of the windings can be found in the literature, and more pratical examples are normally found on the manufacturers application notes.
The main transformer I use was an E type 3C80 core with 12x20mm section. This core was used to make a 300W dc power supply and also served for evaluating the number of volts per turn required (note that as a single turn provides more than one volt, therefore the notation is usually reverse from the one used on classical transformers).
For the 3C80 material on an E type of core with 240 mm^2 a 4 Volt peak to peak / turn was used. No air gap is used in order to maximize the number of volts per turn. For bigger 3C80 cores you can simply scale this value up according to the core cross-section and save a lot of mathematics.

While making the primary calculations do not forget to take into account the drop on the rectifier diodes, about 1.4Volt, and the loss of about 3 Volt on the saturated drain to source (or calculate it exactly from RDSon and Imax).

Example, for a 110V sector supply, each primary winding would have:

Supply voltage to drains	VDD = 110 x 1.41 – 1.4 = 154 Vdc
Switcing voltage at the drain	VDpp = 2 x (VDD – VDS_{sat}) = 302 Vpp
At 4 Vpp per turn	N = VDpp / 4 = 76 turns.

On secondary the calculations are straight forward, just divide the required peak-to-peak voltage by four (as we are using 4Vpp /turn)

For the helix transformer a small core is enough as the power consumption on helix circuits and helix itself hardly goes above 10W.
A 3C85 core with only 44mm^2 was used and winded at 3 Volt peak-to-peak per turn.
This core should be good for any design and any helix voltage.

Diagrams and component value considerations

The diagrams presented are from a power supply for a tipical 5kV helix tube, such as the RW1127 from siemens, and powered from a sector of 110Vac.
The following table summarize the components required to be changed for different tube or sector designs.

Main Board	Sector 48Vdc	Sector 110Vac	Sector 220Vac
C2 and C3	2200uF/63V	680uF/200V	330uF/400V
R3	820 R	2.7 K	5.6 K
C17	47uF/50V	22uF/180V	22uF/360V
R18 and R19	150 R / 5W ni	470 R / 5W ni	1 K / 5W ni
C13 and C14	470p / 500V cer	390p / 500V cer	270p / 1kV cer

Helix Board	2.5 - 4 kV helix	4 - 6 kV helix	6 – 10 kV helix
R1 to R4	1 M	2.2 M	4.7 M
R6, R7, R8	2M2, 2M2, 2M7	4M7, 4M7, 4M7	3x 10 M (3kV)
R11, R12, R13	2M2,2M2,0	2M2, 2M2, 2M7	4M7, 4M7, 4M7
RV2	2M2	2M7	4M7
C10 and C11	10 nF/ 3kV cer	4.7nF / 5kV cer	2.2nF /10kV cer
D1 to D8	BY584	BY584	2 x BY584
C1 to C8	100nF / 1.5kV	47nF / 2kV	22nF / 3kV

All other capacitors and diodes, namely on the collector board, should be selected for handling the correct voltages.

Concluding remarks

The power supply described in this article was tested on a few types of TWT and proved to be reliable under the most demanding situation like testing damaged tubes.

The prototypes of this supplies were always built with 110Vac input. This gave some room for errors and allowed prototyping with reduced smoke. I strongly recommend the use of 110Vac as all components on the primary side, namely the power FETs, will be operated far away from the maximum ratings.

One of the prototypes was used intensively several hours consecutively on a RW1125 and YH1102 during the November 98 microwave EME contest, without any failure or undue shutdown. The slim construction I used, that has only two small CPU fans for cooling (rotating relatively slow) operates several hours and remain nearly cold.

Several hams are already building copies of this supply and giving me useful feedback. Thanks to Hubert ON6JZ, Geert, PA3CSG, Sigi DL4OAN, and Alessandro IW5JWB for beta testing this design.

All comments and suggestions from builders will be in my web page as soon as I can make a nice compilation of all. http://escriba.cfn.ist.utl.pt/cupido.

References.

/1/ - Foundations for microwave engineering – R. Colin - McGraw Hill
/2/ - Microwave tubes – A.S. Gilmour, Jr – Artech House
/3/ - High power Microwave Sources – Artech House
/4/ - Unitrode data sheet on the web at: http://www.unitrode.com