Design of Rugged High Voltage Power Supplies for use in Low Noise Multimode Radar Transmitter Sub-Systems

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Abstract: This paper covers an approach to the design of High Voltage Power Supply Units for operating Travelling Wave Tube Amplifiers in Pulse Doppler Radar Transmitter Sub-Systems where ultra low noise RF Output is mandatory.

1. Introduction

A Radar Transmitter is generally required to amplify a low noise coherent RF waveform. This waveform is generally provided by a Radar RF Exciter and can be fixed frequency, frequency chirped, or phase modulated during the radar transmitter pulse. It is important that the transmitter system amplifies this pulsed signal to a high power whilst maintaining its coherence and its fidelity. To achieve this, the transmitter sub-system must add virtually no noise to the low power RF input signal as it is amplified in the SSA and TWT chain.

Consequently it is important to design the Radar Transmitter Sub-System to have very low overall added (residual) noise close to carrier. The overall added noise within the transmitter is made up of both AM and PM Noise contributions. These two parameters are fundamental to achieving the overall performance required in a pulse doppler radar system and require measurement and characterisation very early in the development of the transmitter.

To maintain coherent RF transmission in a Radar Transmitter requires that all electrode voltages to the travelling wave tube be carefully controlled. Consequently, Electronic Power Conditioners that provide these electrode voltages must maintain stability and provide a very low noise and ripple voltage to achieve this requirement.

2. Power Supply Design Requirements

A typical travelling wave tube requires a heater supply, a grid control voltage, a cathode supply and a collector supply.

The cathode voltage supply to a Travelling Wave Tube is the most difficult to control and requires special attention to ensure that it is very stable and that it achieves an ultra low voltage ripple. This is due to the effects of electrode voltage ripple producing spurious AM and PM sidebands on the RF output of the Travelling Wave Tube. These unwanted sidebands are as a direct result of phase modulation of the RF signal as it is amplified in the TWT slow wave structure.

Generally AM sidebands at the output of the TWT are 10 dB lower than the PM sidebands due to the TWT electrode AM and PM pushing figures. These pushing figures directly dictate the acceptable voltage ripple requirements for a particular transmitter close to carrier added noise requirement.

AM noise on the RF input to the travelling wave tube must also be carefully controlled by the transmitter design as this can produce both AM Noise and PM Noise due to AM to PM conversion within the travelling wave tube.

A pulsed carrier is a continuous wave carrier whose amplitude is modulated by a rectangular pulse train having a relative amplitude of one during each pulse and zero during each interpulse period.

From modulation theory it can be shown that any continuous wave whose amplitude is modulated has two sidebands, an upper and a lower sideband. Modulation theory also tells us that a portion of the total energy of the continuous wave is contained in those upper and lower sidebands. Consequently, one way of telling how the energy of a pulsed carrier is distributed is to look in the frequency domain at the sidebands produced when a continuous wave (CW) carrier is pulse modulated (as in a Radar System).

Amplitude Modulation can be expressed in the time domain as the result of multiplying the CW carrier by a rectangular pulse train. Multiplication in the time domain is analogous to the convolution of the pulsed waveform spectra and the CW waveform spectra in the frequency domain. This produces the classic (Sin X / X) waveform.

In reality the ripple voltage on each of the electrodes of the Travelling Wave Tube contributes to the overall phase noise performance of the Travelling Wave Tube output.

A heater circuit within the travelling wave tube heats the cathode, either directly or indirectly. This heater circuit is generally powered by a –6.30 volt dc supply, relative to the cathode. The cathode, due to its heating, is operated incandescent and will emit electrons from its active surface. These electrons form the beam current within the travelling wave tube. This beam current may be controlled, (gated on and off), by the grid electrode.

A negative bias voltage on the grid, relative to the cathode, will hold the beam current in cut off and a positive bias voltage will turn the beam current on. The grid is driven relative to the cathode electrode by the grid modulator circuit.

The travelling wave tube will only amplify an RF input signal whilst its beam current is flowing through the slow wave structure of the TWT.

The cathode is biased to a negative dc voltage relative to the helix electrode and this voltage accelerates the beam current from the cathode toward the collector. (Note: This is electron flow, conventional current flow is from collector to cathode).

The collector electrode purely ‘collects’ the waste beam current after its interaction with the input RF signal on the helix circuit, (RF slow wave structure).

The collector may be operated at ground, 0 volt or helix, potential but this is at the expense of overall transmitter efficiency.

By operating the collector electrode at a depressed voltage relative to the helix electrode, overall transmitter efficiency is improved. The addition of extra collectors operating at more depressed voltages further improves overall transmitter efficiency.

The Cathode to Helix voltage is the most critical power supply to the Travelling Wave Tube as it directly affects the Travelling Wave Tube beam focussing and transmission of the beam within the Travelling Wave Tube slow wave structure. The slow wave structure is the section of the Travelling Wave Tube where interaction between the Travelling Wave Tube beam current and the RF input signal, which is to be amplified, takes place. This is generally a helix structure in broadband travelling wave tubes and the beam current travels through the centre of this helix structure in a well designed tube. As the input RF signal travels down the slow wave structure (helix) beam energy is transferred to the RF signal on the slow wave structure and consequential amplification of the RF input signal occurs.

Changes to the Cathode to Helix potential directly results in beam velocity changes and consequent phase modulation of the RF output signal.

Typical values for this phase shift are of the order of 0.3 degrees per volt change on the cathode to helix supply.

Therefore, it is imperative that the Travelling Wave Tube characteristics are fully understood prior to specifying the power supply regulation, transient response and ripple performance requirements for each electrode.

If these requirements are under-specified, unsatisfactory RF performance will result. This is usually in the form of high amplitude close to carrier spurious sidebands on the RF output signal from the Travelling Wave Tube. Alternatively, over-specification results in unnecessary development cost and programme delays with no beneficial improvements in RF performance.

In a well designed Radar System the RF source, or exciter, would define the overall noise performance of the Radar transmitted signal. The Radar Transmitter, or Travelling Wave Tube Amplifier, ideally should not degrade the performance of the RF output from the RF source. To achieve this, the transmitter must have a noise performance that is at least 10 dB better than the RF source that is to be amplified.

Consequently most modern Radar Transmitters demand a very high degree of phase linearity in the Travelling Wave Tube Amplifier in all modes including High PRF, Medium PRF and Low PRF. This covers the Pulse Repetition Frequency (PRF) range to typically 160 kHz for an airborne X Band Radar Transmitter, 300 kHz for an Airborne Interceptor Radar Transmitter, and 1 MHz for a Missile Seeker application at X Band.

The Collector phase sensitivity is usually 2 to 3 orders of magnitude less than that of the

Cathode to Helix voltage. Thus the voltage ripple components on the Collector electrode(s) produce minimal spurious modulation on the RF output signal so they are generally much more easily controlled.

The spurious phase modulation of a Travelling Wave Tube is calculated using:

d∅ = dV x d∅/dE

Where,
d∅ = Required Phase Modulation on the RF output in Radians
dV = Peak AC Cathode ripple voltage
d∅/dE = Cathode Voltage Phase Pushing figure for the TWT

Radar systems requirements normally limit the amplitude of these unwanted sidebands relative to the carrier line amplitude (0 dBc).

To determine the maximum ripple voltage that can be tolerated in a transmitter system, when spurious sidebands are specified as dB below carrier (dBc), the transmitter design engineer would use:

Spurious to Carrier (dBc) = 20 Log (d∅/2)
Where,
d∅ = The peak to peak phase ripple in Radians

Hence, for a spurious phase noise of -90 dBc,
-90 dBc = 20 Log (d∅/2)
Then,
d∅ = 6.320 E –5 Radians peak to peak
= 3.624 E –3 degrees peak to peak

If the typical TWT cathode phase pushing figure is 0.3 degrees per volt, then the pulse to pulse voltage stability on the cathode to helix supply must be better than 12 milli volts radar pulse to radar pulse.

For a typical 8 kilo Watt pulse output tube this equates to 12 milli volts in 15,000 volts! (i.e. in the order of 1 part in 1 million).

This is not the total story as there is also a requirement for random noise as well as spurious sidebands or deterministic noise in a well designed Pulse Doppler Radar System. The random noise requirement can be 30 dB tighter than the spurious noise requirement, i.e. –120 dBc/Hz. Note. As this noise is random it is specified as a noise power density where the measurement bandwidth becomes important. To achieve –120 dBc/Hz, at the Travelling Wave Tube output, requires that the Cathode to Helix supply random noise is better than 1.35 E –4 volts rms. (i.e. 135 micro volts in 15,000 volts which is better than 1 part in 100 million).

3. Conclusions

The above illustration assumes that the cathode to Helix voltage is the only contributor to the overall phase noise performance of the Travelling Wave Tube. As stated above, this is not the case, as the ac voltage ripple on each electrode of the tube contributes to the overall phase noise performance of the transmitter sub-system. Hence, the effects of voltage ripple on all of the electrodes of the tube must be considered and a noise budget for each electrode contributor allocated. This demonstrates that to achieve the very small ripple voltages required to achieve the overall system performance requires careful design and layout techniques.