Design of Low Phase noise compact TWT based Transmitter for airborne application

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Abstract
This paper presents the design issues and challenges in the realization of compact, low phase noise Travelling Wave Tube (TWT) based transmitter for air borne application. The transmitter has been designed in Ku Band delivering a peak RF Power of 250W (min) and an average power of 75W(min) across the band. The transmitter has been designed for Synthetic aperture Radar(SAR) application requiring high spectral purity of -80dBc/Hz @ 100Hz offset. The transmitter is currently realized in a volume of 0.012m^3 and weight of 12kgs, with a final targeted weight of 9kgs. The low phase noise requirement translates into stringent voltage regulation requirement (typically 20mv on 9kV) on the cathode high voltage power supply for the TWT. Further transmitter being for airborne application calls for low weight, compact size and Low power consumption. The transmitter has been designed to meet environmental requirements as per MIL-STD-810E, EMI/EMC as per MIL-STD-461E and power supply requirements as per MIL-STD-704E. The paper describes in detail design for achieving low phase noise, approach for efficient thermal design and high voltage engineering aspects. The paper also provides general guidelines for meeting the quality requirements as per airborne standards. A FPGA card is used for status transfer and remote operation of transmitter.

Key words: Phase noise, TWT, high voltage, FPGA

I. INTRODUCTION

RADAR Transmitters using microwave tubes amplify the RF signals from few milliwatts to few hundreds of watts and several kilowatts. The requirement of high stability, large band width and large gain can generally be met by Master oscillator power amplifier(MOPA) type transmitter using coherent amplifier like TWT as final power amplifier. Transmitters using TWT as the basic RF amplifier needs high quality power supply in terms of voltage regulation to achieve the spectral purity required for the Synthetic Aperture RADAR(SAR) application. Further Airborne Radar transmitters are to be realized in compact weight and volume, working reliably in stringent environmental conditions. So the High Voltage Power Supply (HVPS) needs to be highly efficient.

Power supplies for Radar transmitters have to supply pulsed loads and thus require high energy storage capacitors at the output. These power supplies are designed using high frequency converter topologies to achieve precise output voltage regulation, improved performance and to realize in compact size. Post regulator connected in the helix line of the TWT is a crucial element in the HVPS to meet the phase noise requirement, which also aids in the reduction of the output energy storage capacitor requirement.

HVPS is a phase modulated series resonant converter (PMSRC) with a single inverter and a tapped High voltage High frequency (HVHF) transformer supplying cathode and two depressed collectors of the TWT. The cathode voltage is regulated very precisely by phase modulation of the inverter and the collector voltages are maintained by the cross regulation of the HVHF transformer.

Solid encapsulation technique is used to provide the necessary insulation. Potting materials are used considering the dielectric strength, thermal conductivity and the density of the encapsulating material in various modules.

The paper also presents the approach used to reduce the size of the Grid modulator and control and protection strategy employed for the transmitter. A FPGA board is used for status transfer and remote operation. Schemes employed to ensure reliable operation of the FPGA board in the transmitter has been described considering the high EMI/EMC environment.

II. SYSTEM DESCRIPTION

Some of the important specifications of the transmitter are given in Table 1.

Parameter	Specs
RF Peak Power output	250 W
Duty cycle	30%
RF Frequency	Ku-Band
Phase noise	-80dBc/Hz @ 100Hz offset
RF input	0±2 dBm
Input Power	28V DC
Size	300mm(D)X250mm(H)X150mm(L)
Weight	15 kg max

Table 1

The specifications for the HVPS and the Grid modulator of the transmitter are derived from the power supply requirements of the TWT electrodes, which decide the TWT performance in terms of the spectral purity of RF output. The voltage variations from pulse to pulse of the TWT electrodes and the phase sensitivities of the TWT electrode voltages contribute the phase noise in the RF output. Phase noise performance to a large extent is decided by the regulation of the cathode supply of TWT. To achieve the required phase noise performance of -80dBC/Hz, a cathode voltage regulation of the order of 0.0001% is required in this transmitter. Since TWT's can tolerate much higher variation in collector voltage without degrading the phase noise performance, the High voltage power supply topology selected is a single phase modulated SRC powering a tapped high voltage high frequency transformer with cathode voltage regulated and the two collector voltages maintained by the cross regulation of the transformer.

The voltage droop on the electrodes of the TWT with-in the pulse and the amplitude sensitivities of the TWT electrodes will collectively decides the RF amplitude flatness of the output. To meet the RF amplitude flatness requirement of the system large energy storage capacitors are required on the TWT electrodes which not only increase the size and weight, but also the large energy stored can cause permanent damage to the TWT in the event of arcing. Hence in this transmitter the capacitor values are selected so that the energy stored is well below the TWT limit and the droop on the cathode supply is controlled by the use of linear post regulator.

High voltage power supply, Helix Series regulator, modulator and control circuits form the major subunits of any transmitter. The approach for realization of these units in a compact volume is discussed below.

1. *High voltage power supply*

A DC-DC converter with an inbuilt EMI filter is at the front end and is the primary power source to the transmitter. DC-DC converter filters the standard 28VDC aircraft power supply and converts to a regulated 270VDC. The conditioned DC of 270V from the DC- DC convertor is used as input to the PMSRC, which converts this to required voltages demanded by TWT having required pulse to pulse regulation. The regulated 270VDC from the DC-DC converter output enables to reduce the size and optimize the SRC elements. Further this also enables to reduce the size of the transformer as it is operating at higher voltage.

DC DC converter has been designed to meet the Power supply requirements as per MIL-STD-704E and EMI/EMC as per MIL-STD-461E. Some of the major design considerations are listed below:

- Converter is designed for operation from 18VDC to 32VDC
- All power supply, filter components are selected for 60VDC
- The control loop has been designed for stability, considering the ripple voltages and currents injected during MIL 704E tests
- The converter is provided with common mode and differential mode EMI filter to meet MIL 461E requirements
- All the input power and signal lines are protected with over voltage clamps

The specifications of the High voltage power supply are derived from the TWT requirements. The PMSRC is a full bridge resonant inverter operating at 100 kHz using MoSFETs as switching devices followed by step-up transformer, HV diode bridges and Energy storage capacitor. Series Resonant topology is selected basically for the following reasons

- Zero voltage switching (ZVS) is achievable. Hence, switching losses can be reduced.
- The circuit is basically short circuit protected as the transmitter is short circuit prone.
- Some of the non-idealities of the HV transformer like leakage inductance can be absorbed

The input 270VDC voltage is converted into high voltages of -9kVDC, -4.4kVDC, -6.2kVDC as required by the TWT electrodes. Fig.1 shows the block diagram of the TWT Power supply. The transformer has been designed with Low leakage inductance and good cross regulation to maintain collector voltages of TWT within acceptable limits from no load to full load.

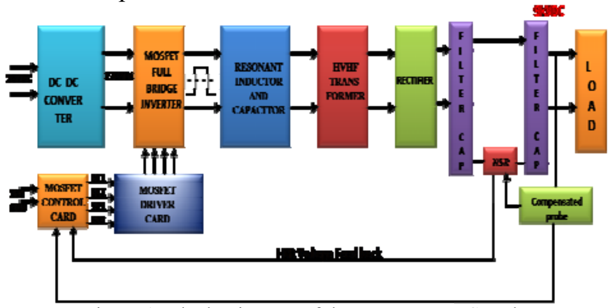

Figure 1. Block Diagram of the TWT Power Supply

Multiple section secondary winding is used to reduce the inter-winding capacitance of the transformer. Each section voltage is rectified and stacked. The HV transformer, HV rectifier and the storage capacitors are encapsulated in a solid dielectric with sufficient thermal conductivity to extract the heat generated in the modules.

2. *Helix Series Regulator (HSR)*

Helix Series Regulator (HSR) is a post regulator used in series with the helix of TWT, used for fine regulation of the cathode voltage of the TWT. The Post regulator's series pass element is in the return path of the cathode voltage and is close to the ground potential. The active voltage regulation minimizes the energy storage capacitor necessary to support the helix voltage over the pulse length and therefore reduces the system size and weight.

The series pass element is a MoSFET, operated in active region. Series regulator is modelled considering the series pass element`s (MoSFET`s) Coss,rds andgm. The non-idealities of the output capacitor are also considered. The electrical model of the HSR is given in Fig.2 where,

C_{gs} - Gate to source capacitance of the MoSFET
Coss- Output capacitance of the MoSFET
g_m- Trans-conductance of the MoSFET given by
$\Delta I_D/\Delta V_{GS}$ at constant V_{DS}
r_{ds}-Output resistance of the MoSFET given by
$\Delta V_{DS}/\Delta I_D$ at constant V_{GS}
G_{ea}- Gain of the Error amplifier
Z_0- Equivalent load at the output and is approximately

$$Z_o \approx \left(\left(R_C + \frac{1}{SC_0} \right) \middle\| \frac{1}{SC_{0ss}} \middle\| R_L \right)$$

R_L- Load Resistance

R_{oa}-Resultant resistance at the output of the error amplifier.

C_0- Output load Capacitance

R_c- ESR of the load capacitance

A suitable controller is designed to compensate the droop during pulse ON and ripple correction during pulse OFF. Cathode voltage Droop with a body current of 18mA without HSR regulator is measured as 18V(Fig.3) and <2V(Fig.4) with HSR regulator. The HSR element is protected by suitable transient absorbers and spark gaps across it to prevent damage in the event of a TWT Helix arc.

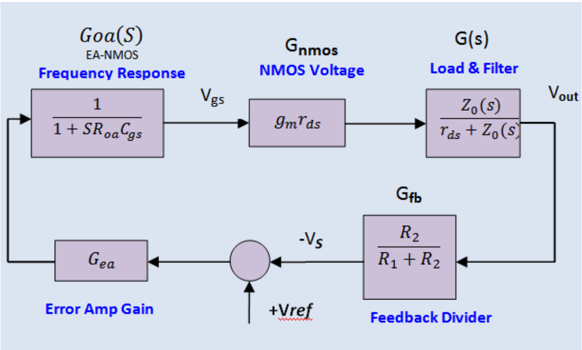

Figure 2. Electrical model of the HSR loop

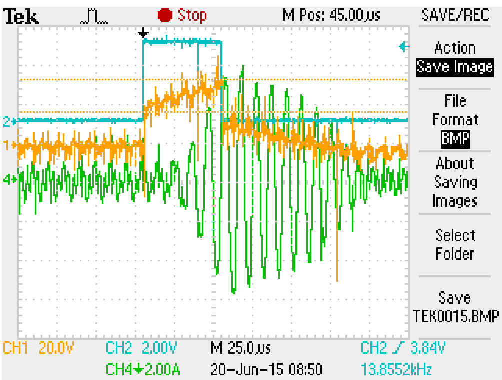

Figure 3. TWT pulsing with 50µSec,30% duty cycle. CH1 Cathode Voltage ,CH2 Grid Pulse TWT, CH4 Inverter current (5.8A peak)

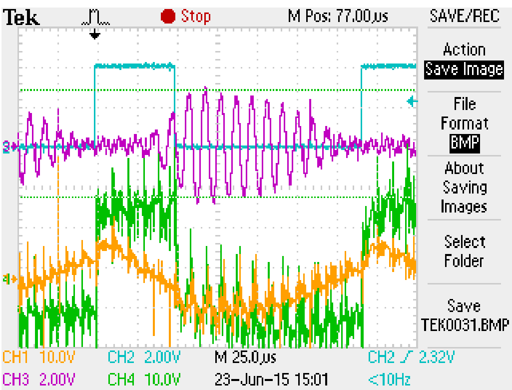

Figure 4. TWT pulsing with 50µSec,30% duty cycle. CH1 Voltage across HSR MoSFET ,CH2 Grid Pulse TWT, CH3 Inverter current (5.8A peak),CH4 Cathode Voltage.

3. *Modulator*

The Grid is a low voltage control electrode to control the electron beam of the TWT thereby controlling the RF output. Modulator generates the control electrode voltages and the filament voltage as required by the TWT and also pulses the TWT grid as per the pulse width and PRF requirements of the transmitter. Above all, the voltages generated by the modulator are floating at a very high potential of the cathode i.e.,-9kVDC.

Grid Modulator is solid encapsulated to provide the necessary isolation and the potting material is selected considering the heat removal from the potting. The parameters like Grid bias voltage, Grid drive voltage are transferred using optical links. All the power supplies are realized using multi output flyback converter operating at 100 kHz and the required voltage regulation is achieved by the post regulator at each output.

The Fly back converter is provided with current control to protect against short circuit and limit the surge current through TWT heater during cold start. RF MoSFET based push pull switch is used for Grid pulsing between positive and negative supplies. The switch is provided with a passive bypass to ensure availability of Grid bias to TWT in the event of failure of the switch.

4. *Control Circuits*

The Control unit enables the sequential switching ON of the transmitter, continuous monitoring and real time interlocking of control parameters. It also classifies the fault and puts the transmitter inappropriate state. The control board uses fast acting voltage latch comparators, for detection and storage of faults. The speed of the comparator latch is within 2 or 3 microseconds.

FPGA is used to transfer the status and parameters of transmitter to the Radar controller through RS422 serial interface. Transmitters being an EMI environment, control circuits are designed to work reliably and digital circuits to prevent nuisance operation of protection circuits and FPGA board. Given below are few of the points considered for fail safe operation of the control circuits.

- All samples are taken through RC filters and terminated with transient absorbers at PCB input.
- Multi layer PCB board is used
- High currents are provided with shortest path lengths in the transmitter to reduce the inductance effects.
- Isolated power supplies for the FPGA
- All communication with FPGA through optical isolation.

5. *High Voltage Engineering*

Solid encapsulation techniques have been used in the transmitter for HV insulation requirements. The breakdown strengths of the dielectric have been sufficiently de-rated to ensure reliable operation at high altitude. Series current limiting resistors have been used at the output of the High voltage power supply to protect the power supply components and TWT in the event of High voltage arc. Following factors are considered in the selection of the potting material:

- Dielectric strength of the material to provide required insulation under worst environmental conditions

- Thermal conductivity to enable heat removal
- Low co-efficient of thermal expansion, thereby preventing stresses on encapsulation electronic components during thermal cycling.

Copper heat spreaders have been used to remove the concentrated heat below the TWT collector.

III. RESULTS

Compact airborne transmitter is realized and tested for its full duty and performance. Transmitter has been realized in the targeted volume of 300mm(D)X250mm(H)X150mm(L) a weight of 12kgs. Currently the transmitter has been tested to its full duty of 30%. TWT cathode current, Inverter voltage and Inverter current waveforms for 50µSec and 30% duty cycle operation is shown in Fig.5.

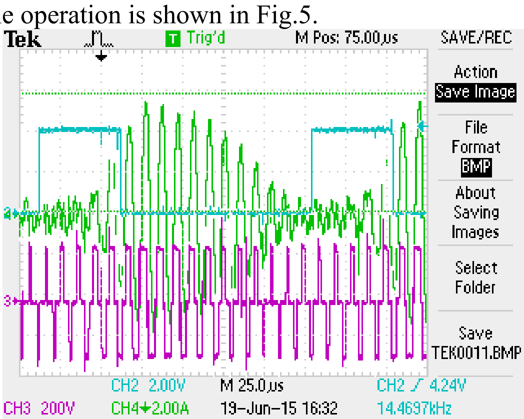

Figure 5. TWT pulsing at 50µSec30% duty cycle. CH2 Grid Pulse TWT, CH3 O/P voltage of the inverter, CH4 inverter current (5.8A peak)

The output spectrum of the transmitter was measured with and without HSR circuit with a RF input drive from a R&S RF source with 0dBm RF input and with input spectrum measured as-72dBc/Hz @100Hz offset. Spectral purity improvement by over 10 dB was observed due to use of post regulator. Spectrum was measured as -70dBc/Hz @ 100Hz offset(Fig.6) with HSR and -60dBc/Hz @ 100Hz offset(Fig.7) without HSR circuit. Final RF spectrum measurements at full duty will be carried out with RF input from exciter with near carrier noise of -85dBc/Hz @ 100Hz offset.

CONCLUSION

A Compact TWT based Airborne Transmitter using state of art technology for Synthetic Aperture Radar has been realized. The transmitter has been tested upto full duty cycle of 30%. The transmitter will be qualified for airborne application and for EMI/EMC requirements as per MIL-STD 461E.

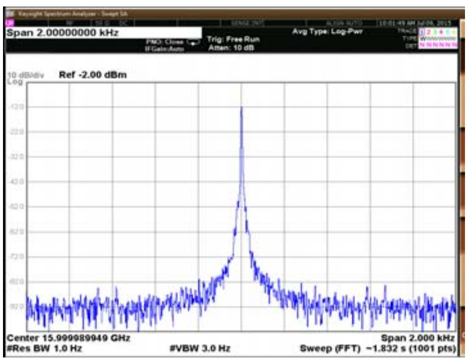

Figure 6. RF output Spectrum with HSR circuit.

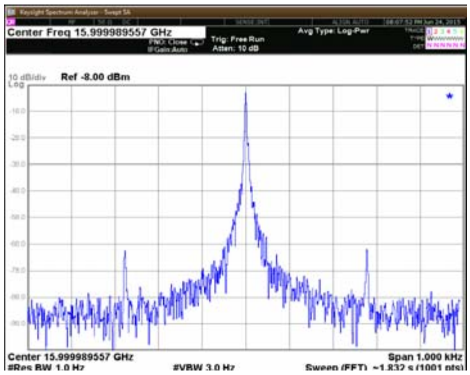

Figure 7. RF output Spectrum without HSR circuit.

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