Development of C-Band High Power Transmitter for Doppler Weather Radar Application

Vijina VP[1], Bhaskar Chatterjee[2], L Ganesh Babu[3], TB Venkatesh[4]
[1,2] Scientist/Engineer, Radar Development Area, ISTRAC, ISRO, Bangalore
[3] Scientist/Engineer(Retd.), Radar Development Area, ISTRAC, ISRO, Bangalore
[4] Junior Engineer, Radar Development Area, ISTRAC, ISRO, Bangalore
vp_vijina@istrac.org

Abstract
This paper discusses the design and development of 250- kW Klystron based C Band transmitter at 5.625GHz for Doppler Weather Radar (DWR) appliction, using IGBT based solid state modulator as switching device. This solid state modulator is designed to deliver 20kV/80A pulsed power upto 0.006 (0.6%) duty ratio. Design of transmitter includes 1:4 pulse transformer with bi-filar winding to apply high voltage pulses to the cathode of Klystron. Power supplies designed for the transmitter are klystron filament power supply, vac-ion power supply and electromagnet power supply. Transmitter operation is automated with the design of FPGA based control electronics with monitoring and interlock activation as and when required.

Keywords: *bifilar, Doppler, insulated gate bipolar transistor, klystron, pulse transformer, solid state modulator*

I. INTRODUCTION

The Doppler Weather Radar (DWR) is an important sensor for operations and research in the atmospheric and meteorological sciences and presently is an indispensable sensor in the measurement and forecasting of atmospheric phenomena. The Doppler Weather Radar System is to provide long-range weather surveillance and is capable of detecting and estimating parameters of severe weather related phenomena that cause widespread damage to life and property in the Indian subcontinent.

In any radar, the transmitter plays a very important role and offers a greater challenge to both designers and for operators of the transmitter. The transmitter is designed for C band Doppler Weather Radar (DWR) application with the specifications shown in Table 1 using pulsed Klystron amplifier VKC-8387K as the final RF output device.

Klystron is a linear beam tube because the direction of the dc electric field that accelerates the electron beam coincides with the axis of magnetic field that focuses and confines the beam. It generates a highly concentrated high energy linear beam of electrons that interacts with the microwave structure to achieve amplification[1].

Insulated Gate Bipolar Transistor (IGBT) based solid-state modulator is used as high voltage pulse power supply for transmitter. The benefits of solid-state switching of high voltage include high reliability, significantly higher efficiency, fast and repeatable switching characteristics. To use IGBTs for high voltage switching, many such devices must be cascaded in series. The gate drives must be highly synchronized to accomplish this[2].

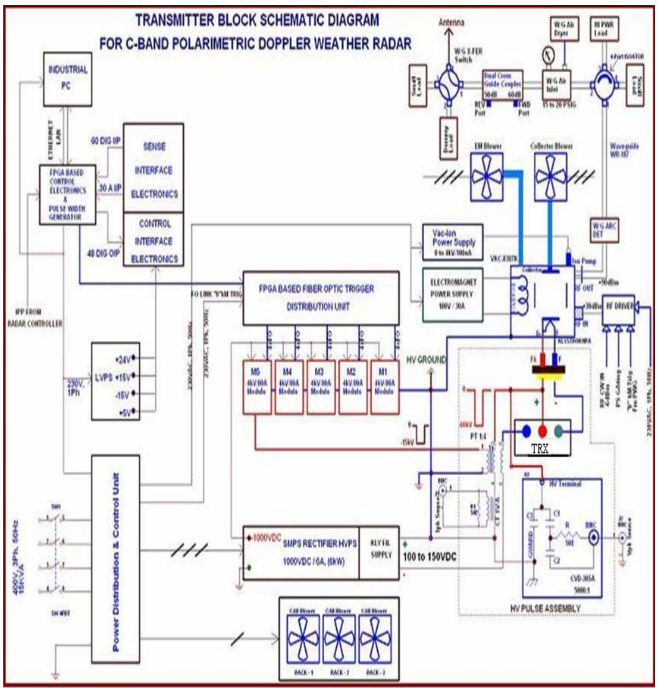
II. DESIGN APPROACH OF TRANSMITTER

Transmitter is designed with IGBT based solid state modulator in conjunction with a 1:4 pulse transformer, for applying the -44kV high voltage pulses to the cathode of the klystron high power amplifier. The high voltage pulses at cathode are floating over klystron AC filament power supply. So pulse transformer is designed with bifilar winding in order to achieve sufficient high voltage isolation for klystron filament power supply. Prior to the application of high voltage, the cathode should be heated to the required initial operating temperature. This is done by applying 6.5V/5.6A AC filament power supply for 12 minutes minimum duration. Fig. 1 shows the block diagram representation of transmitter. The klystron tube, pulse transformer and filament power supply is immersed in SHELL DIALA S3ZX-I electrical insulating oil in aluminum tank to provide high voltage isolation and cooling.

The typical beam voltage and current required for a microwave output of 250kW as given in the data sheet of the klystron tube is 44kV and 10A. The tube is cathode pulsed and the anode is grounded. The RF drive power supplied is 0.87W(29.3dBm).

TABLE 1: TRANSMITTER SPECIFICATIONS	
Type of Transmitter	Pulsed Klystron based MOPA type
Frequency	5.60 to 5.65 GHz
Instantaneous Bandwidth	50 MHz (Fixed Bandwidth)
Gain	52.5 ± 0.5dB over the band
Peak Power	250 kW min measured at the transmitter output
Average Power	1000W max
Duty ratio Beam RF	 0.006 0.004
Pulse width	0.5, 1& 2µS Selectable
PRF	100Hz to 2000Hz Selection limited to Duty
Input RF Drive to the KLYSTRON	4Watts max (+36dBm) (Adjusted as per Klystron factory test Certificate)
Input RF drive to the Tx.	-6 dBm CW
Beam power	Cathode pulsed
Modulator	IGBT based Solid-State Modular Pulse Power Supply with 1:4 Pulse Transformer
Spurious Output	-50 dBc or better
Harmonic Output	-30 dBc or better
VSWR	1.3:1 or better
RF Det Pulse Rise time & Fall times	Less than 100nS
Pulse Transformer	Bi-filar winding with 1:4 turns ratio
Output Waveguide	WR-187
Waveguide Flange	CPR 187 G with 8 holes
Waveguide air pressure	20PSIG Withstanding 15PSIG operating

Fig. 1: Block diagram of C band DWR transmitter



1. IGBT Based Solid State Modulator

The IGBT based solid state modulator is essentially functions like a pulse power supply, which eliminates a specially designed high voltage power supply (HVPS) and associated large energy stored capacitor. Mainly the design of the solid state modulator is on Line Replaceable Units (LRU) based modular technology, which has a unique topology and capable to provide high voltage pulse upto -20kV. -11kV high voltage pulse from solid state modulator is applied to the primary of pulse transformer(PT) with 1:4 primary to secondary ratio. The secondary of the PT is at -44kV which is connected to cathode of the klystron.

Solid state modulator design comprises of high voltage rectifier which generates 6kVA of DC power, the voltage of which is variable from 600V to 1000V, followed by 5 Nos. of 4kV/80A solid state modulator modules arranged in series as shown in Fig. 2. Each 4kV/80A module consists of 4 Nos. of 1kV/80A cards. Solid state modulator pulse power capacity is 20kV/80A, pulse widths upto 6.0µS and Pulse Repetition Frequency (PRF) from 100Hz to 2000Hz. The schematic of the 4kV/80A solid state modulator module is as shown in Fig. 3.

1kV DC power supply is obtained after rectification and filtering from 3-phase 400V AC input through EMI line filter. This functions as primary power source for the individual 1kV/80A pulse power supply cards.

The topology for the 1kV/80A cards is so chosen that all the cards are connected in parallel to main 1kV BUS for charging during OFF periods of the pulse stream and they are connected in series with the load for the duration of the pulse. Main IGBT and auxiliary IGBT is getting complementary trigger pulses. Capacitors connected across the 1kV section is getting charged when auxiliary IGBT is triggered and stored energy in the capacitor is discharged through the load when main IGBT is getting triggered. Necessary high voltage isolation is provided by suitable incorporation of 60kV class high voltage isolation diodes.

Fig. 2: Solid state modulator front and back view

IGBT devices have their own inherent turn on and turn off delays and the values may differ for different IGBTs of same part number. These inherent delays are to be compensated and all the 20 IGBT pulse power supply cards are to be switched ON and switched OFF simultaneously with respect to a single TTL gate drive input provided through fiber optic (F/O) link. This is achieved using a FPGA based trigger distribution unit with gate drive ON and OFF delay adjustment. Each 1kV/80A IGBT card receives their respective gate drives through fiber optic (F/O) link. The F/O link is chosen for providing HV isolation.

For the design and initial testing of 20kV/80A IGBT based solid state modulator, klystron is substituted by an equivalent resistive load with capacity 250Ω. This substitution simplifies the testing. The performance of the solid state modulator was verified with respect to the output voltage and current waveforms measured using high voltage probe and Current Transformer (CT) having sensitivity 1V/A. Fig. 4 shows the output voltage and current waveforms of solid state modulator.

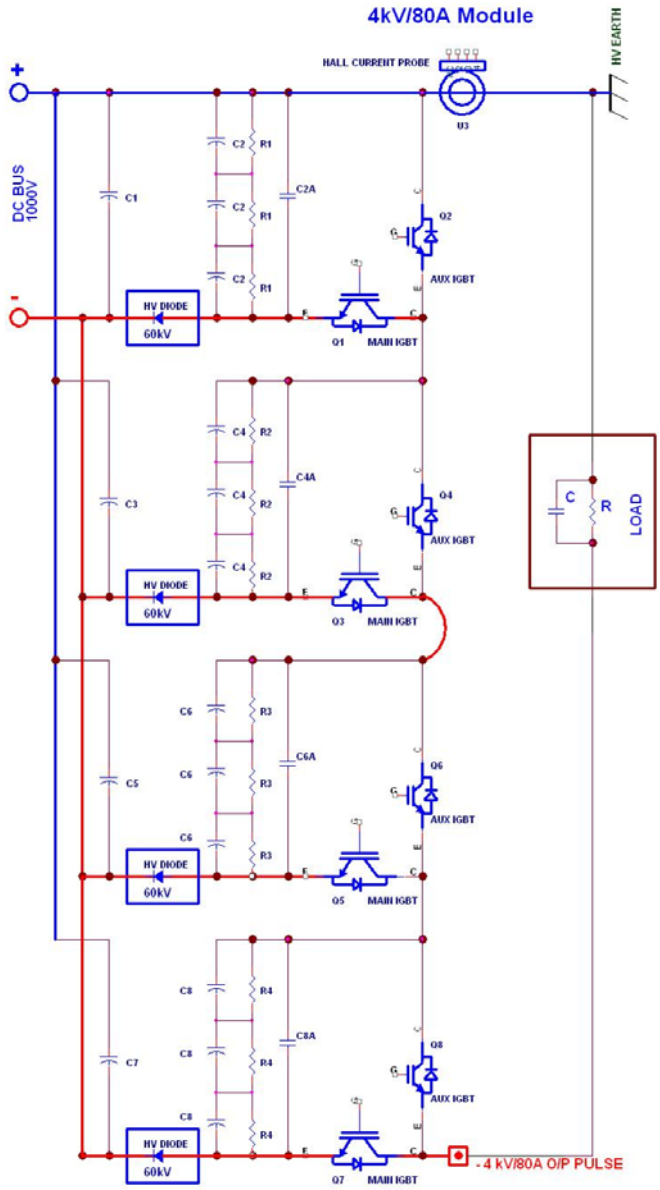


Fig. 3.:Schematic of 4kV/80A IGBT based Solid State Modulator Module

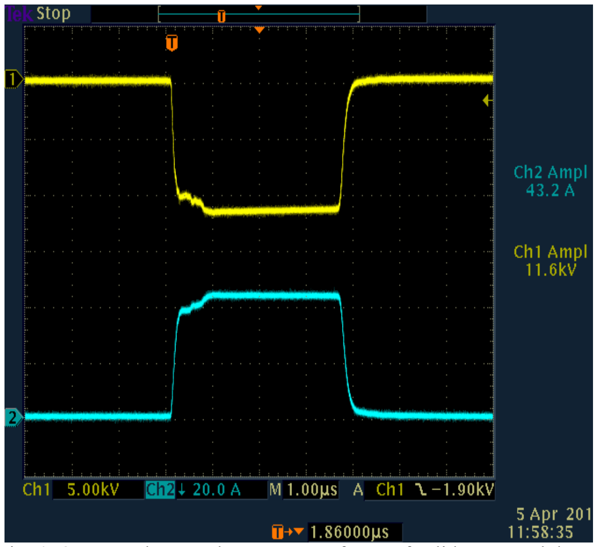


Fig. 4.:Output voltage and current waveforms of solid state modulator.

2. Pulse Transformer

In many applications of radar systems, linear accelerators or klystron/magnetron modulators a rectangular pulse shape with a fast rise time and as small as possible overshoot is required. In reality, however, parasitic elements of the pulse transformer as leakage inductance and capacitances limit the achievable rise time and result in overshoot. Thus, the design of pulse transformer is crucial for the modulator performance[3]. The rise time of transformers is the contribution of leakage inductance and parasitic output capacitance of the pulse transformer. Low rise time can be achieved by using Pulse transformer with cone winding [3]. The rise time strongly depends on the number of the secondary turns and is almost independent of the turns ratio.

From the analysis in [4], it is found that a fast rise time requires low leakage inductance and low distributed capacitance and can be realized by reducing the number of secondary turns, but it produces larger pulse droop and requires a larger core size. The rise time can be improved by tradeoffs among these parameters.

The pulse transformer designed is an isolation transformer type with two parallel primary basket windings, and with two parallel tapered secondary basket windings. Parallel primaries and secondaries are wound on each leg providing bifilar characteristics. The core is made up of 3 smaller subcores strapped together as shown in Fig. 5. Table 2 shows the important specifications of the pulse transformer.

Fig. 5: Pulse Transformer with 1:4 turns ratio

TABLE 2. SPECIFICATIONS OF PULSE TRANSFORMER	
Primary Voltage	15kV
Primary Current	60A
Secondary Voltage	60kV
Secondary Current	15A
Load Resistance at Operating Voltage	4500 Ohms
Load Capacitance	30 pF
Flat Top length	0.5µS. Minimum 20µS. Maximum at 100% Amplitude
Rise time	≤ 0.6µS.
Over Shoot	2% Maximum
Pulse repetition rate	2000pps
Primary to Secondary Voltage ratio	1:4
Droop of flattop	0.15% / µS Maximum

3. Power supplies

The power supplies used in the klystron transmitter design are klystron filament power supply, vac-ion power supply and electromagnet power supply. The filament power supply is a 6.5V/5.6A AC supply fed via two stage isolation transformers. The first isolation transformer isolates the 230V mains and gives 150V output with voltage adjustment control via the tappings. This is followed by a soft start circuit for limiting the inrush current in the cold condition of the filament. The main filament transformer which follows the first isolation transformer converts 150V AC into 6.5V AC and gives to the klystron filament.

The vac-ion pump operates continuously and absorb the gas inside the tube to continue in service for its normal life. The klystron VKC-8387K is having vac-ion vacuum pump to maintain vacuum inside the tube. Vac-ion power supply designed for this tranmitter is DC power supply with 4kV/100µA capacity. The output current is controlled by a resistor and output voltage is controlled by variac.

The electromagnet is separate from the tube and klystron is inserted into the electromagnet structure. It is required for beam focusing and to support and center the klystron tube in the correct position. This electromagnet coil requires power supply to magnetize. The electromagnet power supply designed for this transmitter is constant current power supply with steady state current settable between 20A to 27A and voltage settable between 55V to 100V. The load being the coil of an electromagnet the variability of coil resistance from cold to hot condition would necessitate appropriate voltage control to maintain a constant current operation. The normal settings for the operation of electromagnet are 65 - 75V and constant current of 23A.

III. Microwave Plumbing Scheme

A waveguide arc detector followed by a waveguide isolator connected at the output of the klystron provides the necessary protection for the tube from arcing and high VSWR load condition. The wave-guide dual directional coupler following the isolator is used to monitor the forward power from the klystron and reflected power from the antenna for VSWR measurements. In case of any abnormal operation of the transmitter the interlocks operate and switches off the beam voltage to the klystron.

It is essential to protect the waveguide plumb line from ingress of moisture and also damage against arcing in the plumb line. Hence, an appropriate air pressurization unit is used to pressurize the waveguide plumb lineto 15 PSIG.

IV. Automation Of Transmitter Operation

FPGA based Control electronics is designed to automate the transmitter operation with LAN interface with application software for monitoring and control of the transmitter in both remote and local modes of operation as shown in Fig. 6. Sufficient monitoring signals are provided to check the operating conditions of the transmitter. The high power transmitter is provided with necessary standard safety interlock circuits to protect the costly tubes and the operating personnel. Monitoring indications are provided at the transmitter rack and also at the Radar Controller display to help the operator to monitor the status of different parameters.

Fig. 6. Transmitter Graphical User Interface implemented in Microsoft Visual C++ with tool kit GTK

V. Measurements And Test Results

C band Doppler weather Radar (DWR) transmitter shown in Fig. 7 has been tested with antenna in different pulse width and PRF combinations. Klystron cathode voltage and beam current was measured in Oscilloscope as shown in Fig. 8 using Capacitive Voltage Divider (CVD) having voltage division ratio 5000:1 and Current Transformer (CT) having sensitivity 0.1V/A respectively.

The peak power and average power of the transmitter measured with power meter and found to be satisfactory. RF power is measured in Oscilloscope using RF detector with RF coupling value 73dB and around 11dBm output observed in oscilloscope for 1µS and 2µS pulse width operation as shown in Fig. 8. The pulse spectrum of transmitter output analyzed in spectrum analyzer for 1µS and 2µS pulse width operation as shown in Fig. 9. Spectral purity of transmitter output is observed by taking the spurious and harmonics measurements. No spurious signal is observed and harmonic level is >30dBc.

Fig 7: C band transmitter at TERLS, VSSC

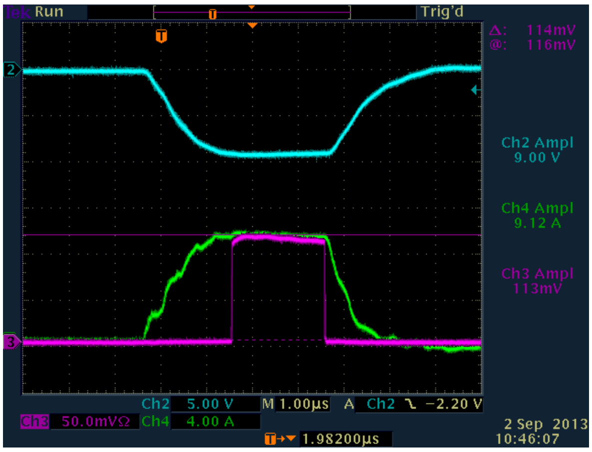


Fig.8: CRO screen shot showing klystron cathode voltage(Ch1), beam current(Ch3) and RF detector output(Ch4) for 2µS pulse width

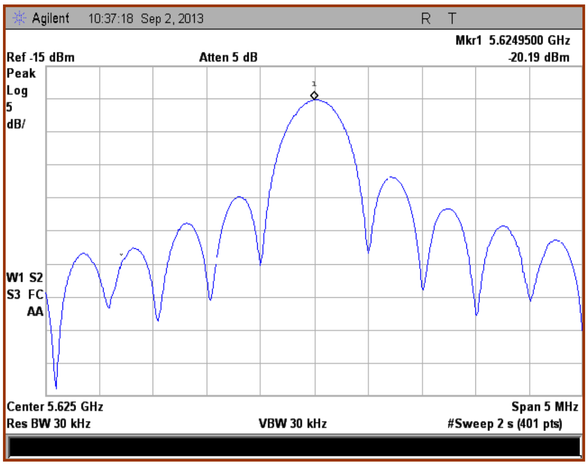


Fig. 9: Pulse spectrum of transmitter output for 2µS pulse width.

VI. Conclusion

C band DWR transmitter is developed and tested for 250kW peak power. This transmitter is integrated and tested with radar sub systems at TERLS,VSSC for forecasting storms, cyclones and other severe weather conditions. The severity of the cyclone can be quantitatively estimated more accurately to provide advance warnings for saving human lives and property.

It is able to furnish a compact, user-friendly, cost effective microwave power source with excellent Doppler capability.

Acknowledgement

The authors express sincere acknowledgements to Shri. R. Ranga Rao, Shri. T. Satyanarayana, Smt. Anitha Daniel and Shri. SNV Satyanarayana from Radar Development Area for their support and valuable inputs for the development of C-Band DWR transmitter.

References

[1] Merril I. Skolnik,"Radar Handbook," Third Edition,McGraw-Hill, 2008.

[2] M.P.J. Gaudreau, J.A. Casey, T.P. Hawkey, J.M. Mulvaney, M.A. Kempkes, P. Ver Planck," SOLID STATE MODULATOR APPLICATIONS IN LINEAR ACCELERATORS", Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

[3] D. Bortis, G. Ortiz, J.W. Kolar, J. Biela,"Design Procedure for Compact Pulse Transformers with Rectangular Pulse Shape and Fast Rise Times", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 18, No. 4; August 2011

[4] M. Akemoto, S. Gold, A. Krasnykh and R. Koontz,"PULSE TRANSFORMER R&D FOR NLC KLYSTRON PULSE MODULATOR", 11th IEEE International Pulsed Power Conference Baltimore, Maryland, USA June 29 - July 2, 1997

BIO DATA OF AUTHORS

Vijina VP - She completed her B. Tech in Electronics and Communication from Kannur University in 2005 and Mtech in computer vision & image processing from Amrita Vishwa Vidyapeetham in 2008. She joined ISRO in 2008 as Scientist/Engineer SC and presently working with Transmitter development group in Radar Development Area, ISTRAC, Bangalore. She is currently involved in development and testing of Remote Monitoring & Control Electronics, Testing and measurements of RF subsystems of high power transmitters.

Bhaskar Chatterjee – He completed B. Tech in Electronics and Communication and joined ISRO as Scientist/Engineer SC in 2009. He is currently involved in development and testing of high power transmitters in S, C and X bands.

L. Ganesh Babu - He completed Diploma in Electrical Engineering and joined IAF in Navigational Radars and Missile Guidance Radar systems from 1973-1988. Later he joined ISRO in 1990 and worked in INSAT-MCF Hassan from 1990 to 2001as INSAT Telemetry, Tracking & Command (TTC) Subsystem engineer. He was working with Transmitter Development group in Radar Development Area in ISTRAC, ISRO Bangalore from 2001-2013. He was involved in Development, Engineering, Testing of high power transmitters in S,C and X bands.

Late. TB Venkatesh – He was working in Transmitter development group in Radar Development Area, ISTRAC, Bangalore as Junior Engineer and involved in the testing and integration of transmitter subsystems in S, C, and X bands.