Design of High voltage power supply and modulator for compact C-Band High Power Radar Transmitter

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Abstract

This paper presents the design issues and challenges in the realization of state of art compact high voltage power supply and grid modulator for high performance TWT based C Band Transmitter. The design goal was to achieve stable operation of the transmitter having spectrum purity of near carrier noise of -75dBc/Hz at 100 Hz away from the carrier while delivering 70 kW (minimum) of peak power and 3 kW of average power across the bandwidth of 400MHz at C-Band. These requirements translates into High Voltage Power Supply (HVPS) design, i.e., Cathode voltage of -39 kVDC and Collector voltage of 27kVDC with stringent cathode pulse to pulse regulation of the order of 0.0004%, under adverse environmental conditions which includes operation at altitudes of 16000feet. High voltage power supply is the most critical unit in TWT based transmitters. The realization of the pre-regulator using power factor controlled interleaved boost converter, realization of compact HVPS with single tapped high voltage high frequency transformer are discussed in detail. Design of compact modulator for the TWT is also discussed in detail.

Key words: Interleaved Boost converter, cross regulation.

I INTRODUCTION

Radar transmitters with high stability and high gain use coherent amplifiers. One such amplifier is a Travelling Wave Tube Amplifier (TWTA). This paper presents the challenges involved in the design of a compact high voltage power supply of a Travelling Wave Tube (TWT) based transmitter.

High gain TWTAs require a very high peak power of few tens of kW and high voltages of tens of kilovolts. The power supply should be capable of delivering this high power at high voltages in adverse EMI environment. The performance specifications of these supplies are very stringent demanding very good regulation on pulse to pulse basis (0.0004%) with good efficiency.

State of art techniques like high switching frequency inverter, PFC based interleaved boost converter as pre regulator and single tapped High Voltage High Frequency (HVHF) transformer resulted in a compact high voltage power supply for a C-Band TWT based Transmitter with peak RF output power of 70kW meeting very stringent performance specifications.

The cathode and collector power supply for the TWT is realized by a single inverter and tapped transformer fed from a pre regulator. Cathode voltage is regulated by phase modulation technique and the collector voltage is maintained by the cross regulation of the HVHF transformer. Phase Modulated Series Resonant Converter (PM-SRC) operating at 50 kHz, with Zero Voltage Switching (ZVS) is used as the inverter circuit topology for its compactness, flexibility, efficiency and better dynamics. The design realization of the Boost converter, PM-SRC and cross regulation of HVHF transformer and realization of high frequency modulator are discussed in detail.

II SYSTEM DESCRIPTION

Transmitter for Weapon locating Radar is realized in volume of 1.2m^3 and a weight of 575Kg, which constitutes of the High Voltage Power supply, Control and protection Unit (CPC), modulator and the microwave components. Compact high Voltage power Supply is realized for the C-band transmitter with the following main specifications.

Parameter	**Specifications**
Output Power	20 kW
Input Voltage	3 Phase 415V, 50Hz
Input THD	30%
DC Ripple(Pre-regulator)	<3V on full load
DC regulation(Pre-regulator)	<0.5%
Cathode voltage and regulation	-39kVDC,<0.0004% Pulse to pulse
Collector voltage	27kVDC ±1kV

The main blocks in which the compact high voltage Power supply is realized is given in Fig.1 The High voltage power supply is realized with a phase modulated series resonant inverter, fed by a PFC based Boost regulator, followed by a HVHF transformer with a inbuilt rectifier feeding High voltage energy storage capacitors.

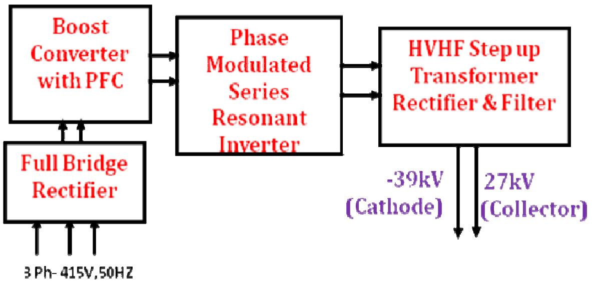

Fig.1. Basic blocks of High Voltage Power Supply

1. PFC based Boost Converter Pre-Regulator

The conventional AC-DC converter with passive power factor correction using a LC filter will be bulky to deliver high power of 25kW meeting the performance requirements. So, to make the power supply compact without any performance degradation the conventional AC-DC converter is replaced with a rectifier and 20 kHz PFC based pre-regulator giving a regulated output at 700VDC.

Boost converter has become one of the best choices for power factor correction as the input current is continuous and the output voltage is always greater than input peak voltage. As it is a high power application three phase power factor correction has to be employed, where the scheme becomes complex and even more complex when interleaved [1] [2].

The proposed topology for the AC-DC converter is shown in Fig.2.

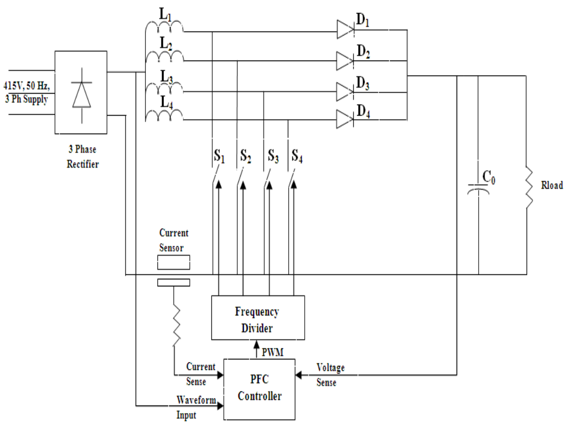

Fig.2. PFC based Boost Convertor Topology

PFC based Boost converter can be made possible to operate in two different ways viz., Continuous current mode and discontinuous current mode. In continuous current mode of operation though the switching losses in the switching devices are high, the ripple current in the inductor is less which results in lower core loss in the inductor and in case of discontinuous current mode of operation, the switching losses are less because of Zero current switching during turn ON of the switch but the ripple current in the series inductor is high compared to that of the continuous current mode of operation which results in more core loss in the inductor. Discontinuous current mode with Zero Current switching technique is employed in this power supply.

This can also be operated in Continuous current mode when the silicon diode in boost converter is replaced by SiC Schottky diode [6] as it has virtual zero reverse recovery current. The reverse recovery charge in the SiC Schottky diode is extremely low as it is only the result of junction capacitance and not stored charge. Unlike the silicon diode, the reverse recovery characteristics of SiC Schottkys are independent of di/dt, forward current and junction temperature. The use of SIC diode can significantly reduce the turn on losses in the switching device.

The output voltage of the pre regulator required is 700V which calls for the Boost converter to operate with a duty cycle range of 0.11 and 0.28. For a boost converter operating with this duty cycle 4-stage Interleaving is the optimized solution in terms of input ripple current reduction and output Capacitor ripple current reduction. The graphs for input ripple current cancellation and output capacitor ripple current cancellations with respect to duty cycle are given below in Fig.3 and Fig.4 respectively [8].

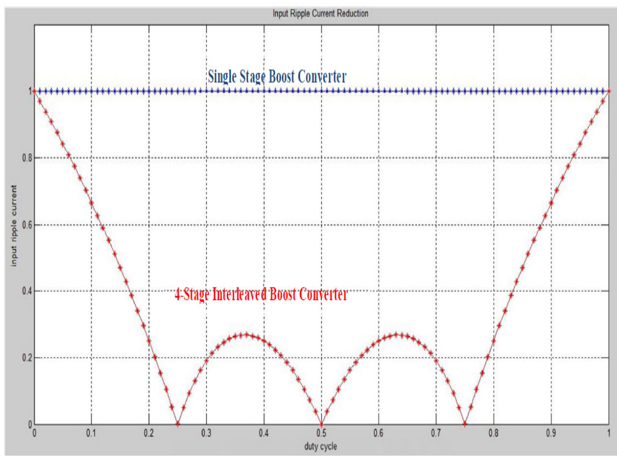

Fig.3. Input Ripple Current Reduction with Duty

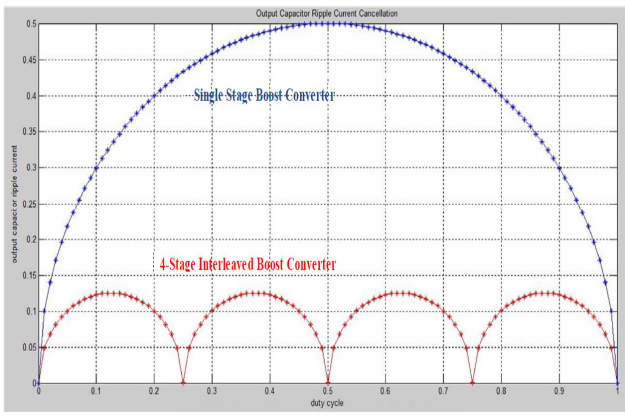

Fig.4. Output Capacitor Ripple Current cancellation

2. Design of the Boost Converter

The three phase supply415V, 50Hz is given to a three phase diode bridge rectifier and the output is given to a 4-stage interleaved boost converter. The boost converter is designed for 25KW power and switching frequency of 20 KHz.with output regulated at 700V

The value of inductor and capacitor of the interleaved Boost converter is given by the equations 1 and 2 respectively.

Inductor, L1 = L2 = L3 = L4

$$= \frac{Vin\_min^2 * \eta * Ts}{I\% \, (Pout\_max/4)} \times \frac{Vout-(Vin\_min*\sqrt{2})}{Vout} \quad \ldots (1)$$

where, Vin_min = Minimum input voltage
Vout = Output DC voltage
Ts= Time period of the PWM switching
Pout_max = Maximum output power
η = Efficiency
I% = Ratio of accepted peak to peak inductor current ripple (typical value 20-40%)

$$\text{Capacitor, } C = \frac{D_{max} * Ts}{R_{load} * \%\, Ripple} \quad \ldots\ldots\ldots\ldots\ldots.. \quad (2)$$

where, Dmax = maximum duty cycle
Ts = Time period of the PWM switching
%Ripple = allowable output voltage ripple

Input supply current simulated and measured are shown in Fig.5. The peak current drawn is 50A with an RMS value of 34A. Input THD is measured to be 30%.

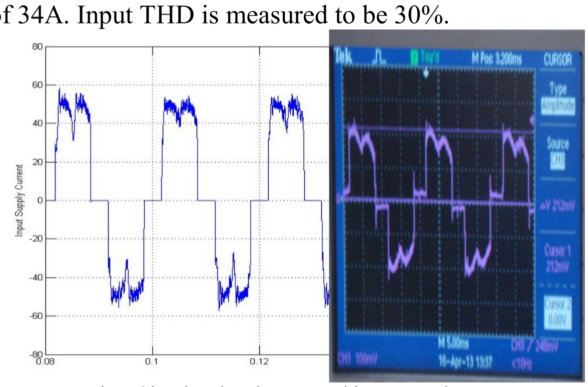

Fig.5.Simulated and measured input supply current

Four stage interleaved Boost converter is realized in DCM mode and the voltage and current waveforms of the device along with the switching pulses are shown in Fig. 6 and the magnified portion of the switching waveforms in Fig.7

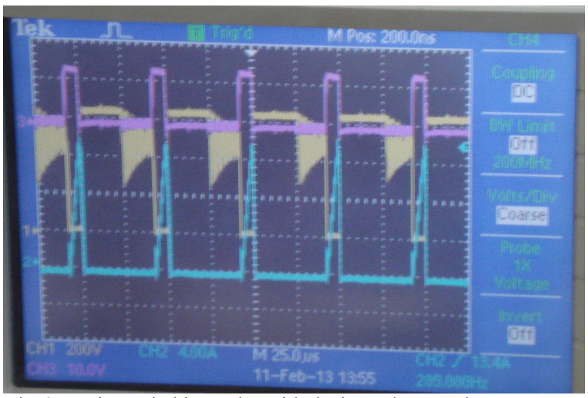

Fig.6. Device switching pulse with device voltage and current waveforms

The PFC based pre regulator operating at high frequency enabled the size reduction of the filter bank. PFC control also enables the use of a smaller EMI filter at the input.

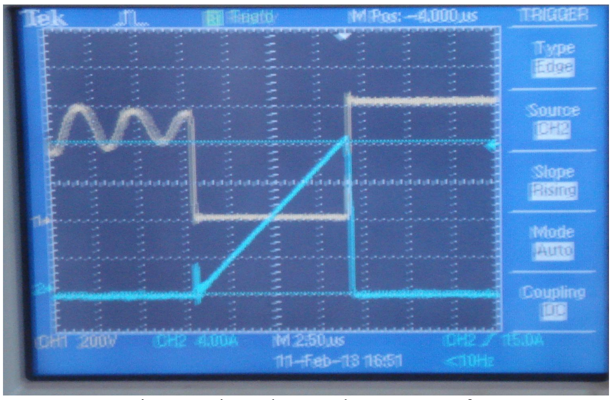

Fig.7. Device voltage and current waveforms

The regulated output voltage of 700VDC from the pre regulator is fed to a full bridge inverter with a series resonant topology. The switching devices used are ultra fast IGBTs operating at 50 kHz. As the output voltage of the AC-DC unit is regulated the design of the resonant components of the PM- SRC can be optimized. The realized inverter is given in Fig.8.

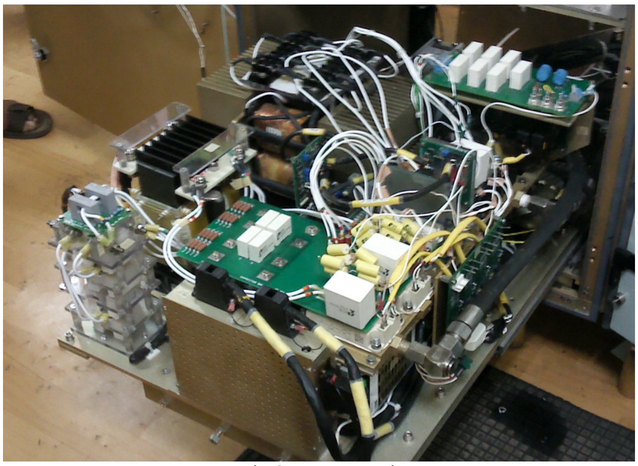

Fig.8.Inverter Unit

3. *HVHF Transformer*

The square wave voltage from the inverter is stepped up by a single HVHF transformer with an inbuilt rectifier with a tapped output to feed both cathode and the collector of the TWT. The secondary winding of the HVHF transformer comprises of 28 sections, each section voltage is rectified and stacked to get the required output voltages of -39kVDC for cathode and 27kVDC for the collector (w.r.t cathode) fed through the high voltage energy storage capacitors.

Phase noise performance of the transmitter majorly depends on the regulation of the cathode supply of TWT. The collector can tolerate much higher variation in voltage without degrading the phase noise performance. So, to achieve the required phase noise performance a cathode voltage regulation of the order of 0.0004% is required in this transmitter. High voltage power supply topology with a phase modulated SRC powering a tapped high voltage high frequency transformer is selected. Cathode voltage is sensed and regulated and the collector voltage is maintained within the required limits by the cross regulation of the transformer.

The high voltage cathode sample is fed to the feedback loop of the control circuit through a compensated probe, which produces phase shifted gate pulses for the IGBTs resulting in the controlled primary voltage to the HVHF transformer and in-turn the regulated output.

4. Cross Regulation of HVHF transformer

The Cathode output voltage of the rectifier stack in the HVHF transformer is sensed and regulated to the desired value by the feedback control loop of the PM-SRC. The tapped output is not directly regulated, but are maintained within tolerable limits with respect to the principle output voltage by the coupling between the transformer windings which is called cross regulation.

Cross regulation can be caused by many factors such as transformer internal resistance, capacitance between coils which causes the different coupling coefficients between the coils which in-turn results in the leakage inductance. The cross regulation becomes noticeable when the difference in the output power between the secondary windings of the tapped transformer is large.

The cross regulation in the multi-output transformer [7][8] is affected by the leakage inductances of the transformer windings. Proper winding patterns of the transformer windings will lead to the improvement of the cross regulation.

The value of leakage inductance depends on the winding geometry in a transformer core. Changing the position of the winding will change the value of the effective leakage inductance. For better cross regulation, the leakage inductances between the primary and secondary windings should be small and the leakage inductance among the secondary windings should be maximized to reduce the effect of load changes. The realized HVHF transformer is shown in Fig.9.

Fig.9 HVHF Transformer

With the incorporation techniques discussed above the HVPS unit is realized in a weight and volume of 114Kg and 0.161m^3.

5. Modulator

Modulator switches ON and OFF the beam of the TWT. Two types of modulators are in use

- High power modulator
- Low power modulator

In high power modulation also called as cathode modulation, high instantaneous powers are involved since both the full beam voltage and current have to be switched simultaneously. Low power modulators exploit a control electrode such as grid, a focus electrode or an anode.

TWT's generally use grid modulation, for switching ON and OFF the beam. Grid modulation can be achieved through Floating deck modulator (FDM) where all the voltages generated are floating on the cathode potential of few tens of kilovolts.

An isolation transformer provides input to FDM floating on cathode potential of -39kVDC. To realize a compact FDM and to reduce the size of the isolation transformer, operating frequency of the isolation transformer is enhanced to 30 kHz by a auxiliary converter and 100kHz fly back converters are realized for generating grid and filament voltages in FDM.

The auxiliary converter comprises of a 3 phase half bridge diode rectifier generating 325VDC form 415V, 3phase 50Hz mains followed by a buck convertor operating at 60KHz with a output of 200VDC. A free running half bridge inverter operating at 30kHz generates a 100V square-wave voltage. A high frequency isolation transformer operating at 30KHz provides AC input to the modulator thereby reducing the size of the input filters of the FDM.

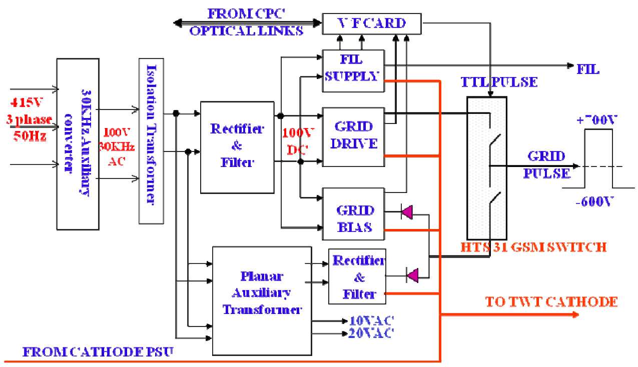

Fig.10 Basic Block diagram of FDM

The basic block diagram of the FDM scheme used in the transmitter is given Fig.10. FDM is used to generate the grid pulses to switch ON and OFF the TWT beam at the pulse width and the PRF rate as required by the Radar system, along with the filament and grid voltages required by the TWT. All supplies are short circuit protected. The grid pulsing is achieved using a fast solid state High voltage push pull switch (Mosfet based). A passive bypass is provided for the push pull switch so as ensure that grid bias voltage is applied to Grid in the event of switch failure. The filament and Grid samples are transmitted to control and protection unit on optical links for protection requirements.FDM is realized in a weight and volume of 13Kg and 0.014m^3.

III. RESULTS

Compact transmitter has been realized in the targeted volume of $1.2m^3$ and a weight of 570kgs. Currently the transmitter has been tested up to 2% duty cycle. TWT cathode current and Inverter current waveforms for 2% duty cycle operation is shown in Fig.11.

Fig.11. Beam current, Detected RF and inverter Current Waveforms

IV CONCLUSION

PFC based Boost converter has been realized and tested for full load of 25kW meeting all performance requirements. THD can be further improved with other PFC based boost converter topologies[5][6].The compact high voltage power supply is realized in a weight and volume of 114Kg and $0.161m^3$ respectively.

Compact FDM is realized in a weight and volume of 13Kg and $0.014m^3$ respectively and tested for its full performance.

Transmitter is tested upto 2% duty and testing is under progress to complete 5% duty cycle operation.

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