I J C T A, 9(15), 2016, pp. 7187-7195

100 kHz High Voltage Power Supply for Travelling Wave Tube

Lakshmypriya K.A.* and Deepa K.**

ABSTRACT

Travelling Wave Tube (TWT) is a high gain microwave amplifier used in RADAR transmitters. TWTs require a highly sophisticated high voltage power supply for powering its electrodes viz., cathode and collectors. The high voltage power supply should have low output ripple and good regulation(few hundreds of millivolts) on cathode to obtain good RF performance and the power supply needs to be short circuit protected. This paper presents the high voltage power supply designed for a TWT based radar transmitter with electrode voltages of -9kV, -4.4kV and -6.2kVDC. Input voltage of the high voltage power supply (HVPS) is 65VDC. The high voltage output is achieved with a series resonant converter operating at a high frequency of 100 kHz. The inverter output is stepped up by a high voltage high frequency transformer. The transformer output after rectification is filtered and fed to TWT. The output voltage is regulated using phase shift control. This work is further extended in the implementation of the designed high voltage power supply in hardware.

Keywords: high voltage power supply; series resonant converter; pulsed load; phase shift control

1. INTRODUCTION

Transmitter in RADAR applications, use microwave tubes for the purpose of amplifying RF signals from few millwatts to several kilowatts. Radar transmitters require precisely regulated high voltage power supplies and these power supplies are subjected to pulsed loads. To realize these high voltage power supplies in a compact size and to precisely regulate the output, it is essential to design these power supplies using high frequency converter topologies[1].

Resonant high frequency converters are widely employed in many applications due to their lossless switching properties [2 -3]. With an adequate modulation and control technique, the zero-voltage switching (ZVS) can be guaranteed over a wider range, increasing significantly the power density. Addition of an inductor to the series resonant converter (SRC) yields different resonant topologies that significantly improve the no-load characteristic of the SRC. One of the resulting topologies is called CLL-T(capacitor inductor inductor), which offers the possibility of magnetic-component integration in a high-frequency transformer.

This HV power supply generates the high voltages -9kV,-6.2kV and -4.4kV DC from an input of 65VDC. Power Supply is realized using an inverter followed by a series resonant tank which feeds a tapped high voltage high frequency (HVHF) transformer [4]and the output of which is rectified and filtered to get the required voltages for the TWT [5]. The inverter is realized using a phase modulated series resonant converter in full bridge topology using MOSFET as switching devices [6]and the load is a TWT, with cathode and two depressed collectors. To validate the proposed design of the converter simulation studies have to be carried out. The present work mainly focuses on the dynamic analysis of the dc-dc CLL-T resonant converter. Furthermore, based on the developed model, a nonlinear feedback controller that uses the sliding motion

* M Tech Scholar, Power Electronics, *Email: lakshmypriyaka@yahoo.com*

** Assistant Professor, Dept. of EEE, Amrita School of Engineering, Bengaluru, Amrita Vishwa Vidyapeetham, Amrita University, India.

principles and the input-output linearization approach is designed, providing simple implementation, fast transient response and robustness against power-stage parameter variations.

2. SYSTEM CONFIGURATION

This section deals with the details of the High voltage power supply designed for the TWT based transmitter. The specifications for which the power supply is designed are given in Table 1.

Table 1
HVPS specifications

Parameter	*Specification*
Power output (average)	450W
Output Cathode Voltage	-9kVDC
Output Collector 1 Voltage	-6.2kVDC
Output Collector 2 Voltage	-4.4kVDC
Switching Frequency	100kHz
Efficiency	>85%
DC Input	65VDC ± 1%

The prime power of 28VDC as per MIL standard 704D, available in the aircraft is boosted up and regulated to give 65VDC, which is the input to this HVPS.Fig. 1 shows the block diagram of the proposed high voltage power supply unit. A series resonant converter (SRC) configuration is selected for the inverter to take the advantage of the inherent short circuit protection as the load is prone for arcing[7]. SRC is the preferred configuration to incorporate Zero Voltage Switching (ZVS) technique to reduce the switching losses in the devices, which is prominent at high switching frequencies. As an added advantage the parasitic inductance of the transformer, which limits power flow, becomes part of the resonant inductance in this SRC configuration [8].

The output of the SRC is fed to a HVHF square wave transformer with a multiple secondary sections. The outputs are rectified,cascaded and filtered to generate the voltages required by the TWT. The HVHF transformer is designed to have six secondary sections in this case [9].

3. DESIGN METHODOLOGY

This section presents the design of the PMSRC for the specifications given in table1.The focus of the design here is on selecting a suitable operating point to realize the HV powers supply in a very compact size and weight. Given below is the detail design of each block.

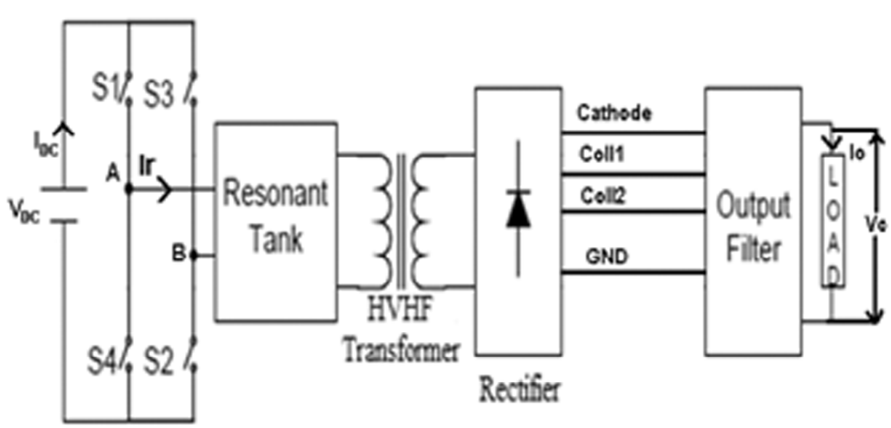

Figure 1: Block diagram of the system

3.1. Series Resonant Converter

The primary advantage of the PM-SRC is the constant switching frequency. The output side does not require filter inductor. The power supply is short circuit protected as the converter is operated away from the resonant frequency [10]. Appropriate selection of the load factor (*Q*) and K = fs/fr is critical in the converter design, where fs is the switching frequency and fr is the resonant frequency of the converter.

Selection of the operating point is an iterative process. For example, the HV transformer parasites have to be known to choose the operating point; on the other hand, the operating point is needed to design the transformer. The transformer parasites depends on the no.of secondary turns of the transformer and the winding configuration.Since the output voltage is constant, a suitable voltage gain can be selected. The voltage gain of the converter is 0.85. A switching frequency between 1.1*fr* and 1.2*fr* is seen to be a good trade off among peak voltage and current stress on the inverter switches, delivered power andPeak current of the inverter.

Table 2. gives the design values for different K values. Realization of resonant inductor for values of K less than 1.2 is not possible because realizing a HVHF transformer with leakage inductance of less than 2μH is practically not possible. Hence optimal design values are chosen for K=1.2.

Table 2
Selection of operating point

K	*fr (kHz)*	*Vgain*	*Q*	*Lr (μH)*	*Cr(μF)*
1.1	90.90	0.85	1.6	0.9	3
1.2	83.33	0.85	1.69	12.16	0.29
1.3	76.92	0.85	1.8	14	0.3

The operating point is selected with k = 1.2 and Q = 1.69 and the values for the tank resonant elements are obtained as 12.16μH and 0.3μF.

As the inductor consists of a magnetic circuit and an electric circuit, the design requires:

- The size of the wire to be used for the electric circuit, to carry the rated current safely.
- The size and shape of the magnetic core to be selected such that
  - o The peak flux is carried safely by the core without saturation
  - o The core should accommodate the conductor of the required size and turns
- The number of turns of the electric circuit to obtain the desired inductance

EELP 43 core with N87 magnetic material is selected for the Inductor and is designed to have 3 turns to give the required inductance of 12μH. The resonant inductor is realized as a planar inductor to get high power density. 0.3μF,high rms current polypropylene capacitor is selected as the resonant capacitorto support the switching frequency currents.

3.2. High voltage high frequency transformer

HVHF transformer gives mains isolation and the desired high voltage outputs. Design of the HV transformer is the most challenging issue in this power supply as the transformer is the largest single component and reducing its size is very important for the compactness of the power supply. Increasing the switching frequency reduces the size of magnetic components but the expertise involves managing the number of secondary turns and high peak secondary voltages and currents.

Power ferrites are employed as the magnetic material due to the high resistivity and low eddy current losses under high frequency. The power handling capacity of the transformer core is determined by its area product. The area product of the transformer required is 20836mm^4 and PM 74/59 core is selected. The window area of the core is extremely importantas it has to accommodate the required number of turns.Once a core is chosen, the calculation of primary and secondary turns and wire size is readily accomplished.

Number of primary turns,

$$N_p = \frac{V_p}{4 \times f \times B_m \times A_c} \tag{1}$$

$$= 2$$

Number of secondary turns, Ns = 326

Magnetizing inductance, $L_m = N_p^2 A_L = 40\ \mu H$ (2)

The magnetizing inductance L_m should be $\geq 3L_r$ to retain the voltage gain of the SRCwhen the HVHF transformer is connected.The effect of L_m on voltage gain is given in Table 3. Magnetizing inductance of the transformer is selected as, $L_m = N_p^2 A_L$ or $3L_{-r}$ whichever is higher.

Table 3
Selection of l_m

Case	Vo(kVDC)	Vprim(V)	Gain
Lm=Lr	7	40	0.61
Lm=2Lr	9	44	0.67
Lm=3Lr	9	55.8	0.85
Lm=4Lr	9	56.1	0.855
Lm=5Lr	9	57.2	0.86

In the high frequency transformer design, litz wire is used for primary winding so as to make the skin effect feeble.For secondary winding, a high voltage cable with ainsulation of 13kV and with a minimum overall diameter is selected to fit in the available window area of the core.

Leakage inductance is measured as 0.8uH from Frequency Response analyzer.The leakage inductance of the transformer is absorbed in to the resonant inductance. The parasitic capacitances can result in parallel resonances with magnetizing inductance of the transformer due to more number of secondary turns and therefore it is kept as low as 13.8nF by proper winding configuration and multiple secondary sections.

3.3. High Voltage rectifierstage

Each secondary section of the HVHF transformer is followed by a diode full bridge rectifier circuit. Fast recovery avalanche rectifier diodes are used in stack to realize the high voltage rectifier unit. Each section gives a rectified output of 1.5kVDC these outputs are cascaded to get the required DC voltage which in turn is connected to a high voltage energy storage capacitors.

This high voltage energy storage capacitors droops during the on period of the pulsed load and is charged back by the inverter during the off period of the pulsed load. Bleeder resistors are connected across the capacitors for discharging when the power supply is off. Cathode output voltage is regulated precisely by feeding the cathode sample to the control circuit of PMSRC.The block diagram of the closed loop HVPS circuit is shown in Fig. 2.

4. CONTROL CIRCUIT

In this section,design of the closed loop control circuit to regulate the cathode voltage is discussed. Phase modulation technique is selected since it provides precise output voltage regulation under varying line and

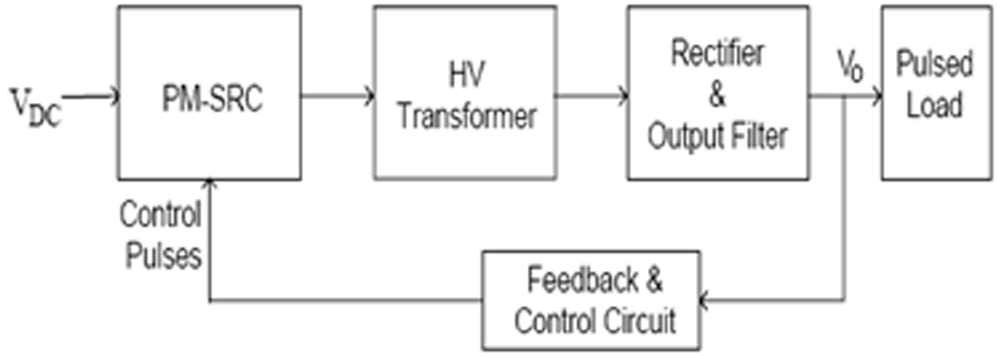

Figure 2: Closed loop block diagram

load conditions [11, 12].In this method, the output of the full bridge inverter is controlled by offsetting the conduction time of diagonally opposite switches of the inverter.

The phase shift control technique is implemented through BiCMOS advanced Phase shift PWM controller IC UC1895 operating at constant switching frequency pulse width modulation. Collector tap voltages are maintained within the specified limits by cross regulation of the transformer.

To design the closed loop controller, the open loopstep response of the plantis obtained and plant transfer function is derived from the step responsefor full load condition. The control loop requirements are derived from

- Allowable steady state error
- Settling time
- Transient overshoot in the event of disturbances or command changes

PI controller is designed to meet the required bandwidth and steady state error. Simulation of PI controller was carried out in MATLAB simulink.

The step response of the HVPS under load condition is shown in Fig. 3. Its transfer function is as below

$$G(s) = \frac{G}{1+s\tau} = \frac{1891}{0.006844s+1} \tag{3}$$

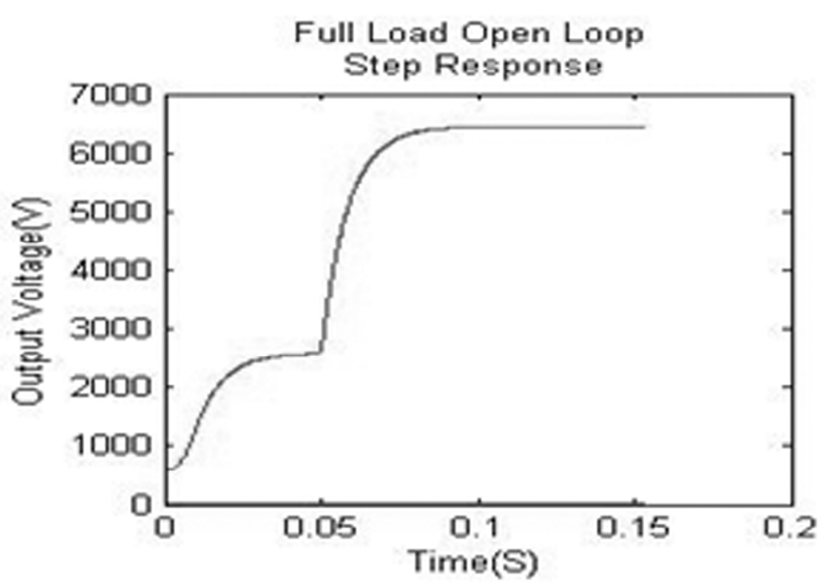

Figure 3: Step response

Where, G = Gain from controller output to the power supply output

τ = Time constant of open loop system

For closed loop operation, PI controller is selectedwith transfer function as

$$H(s) = K\left(\frac{1+s\tau}{s\tau}\right) \tag{4}$$

Hence, the loop transfer function is

$$G(s)H(s) = \frac{G.K_p}{s\tau} = \frac{G.K_i}{s} \tag{5}$$

where, Kp and Ki are proportional and integral gains.

DC gain of the closed loop system = $G.K_p$ (6)

Bandwidth of the closed loop system = $G.K_i$ (7)

From the above response curve G and τ can be computed.

The transfer function of the overall system with PI controller is found to be

$$G = \frac{94.55s + 3152}{0.002053s^2 + 0.03s} \tag{8}$$

Bode plot of the closed loop system is given in Fig. 4. From the Bode plot of the G(s)H(s), bandwidth is 23 kHz with the phase margin of 90º and thus the closed loop system is stable.

5. SIMULATION RESULTS

Simulations are carried out in OrCAD Capture IDE and MATLAB simulink. Simulation waveforms of the bridge voltage and the inverter tank current under closed loop operation are shown in Fig. 5 and cathode output voltage and current waveforms are shown in Fig 6.

The change in the output voltage under varying load and line conditions has been studied. The MATLAB results of the output voltage for changes in supply voltage with pulsed load are shown in Fig. 7 and Fig. 8 respectively.

6. HARDWARE RESULTS

The HVPS was realized and tested under no-load and full-load under open-loop condition and the results are given in Table 4. along with the bridge voltage and inverter current wave forms in Fig 9. The efficiency

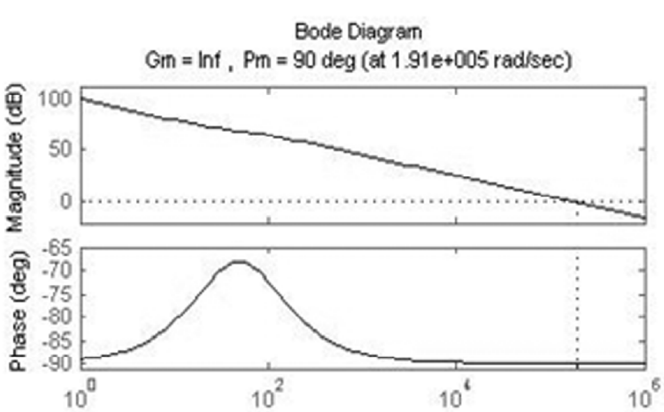

Figure 4: Bode plot

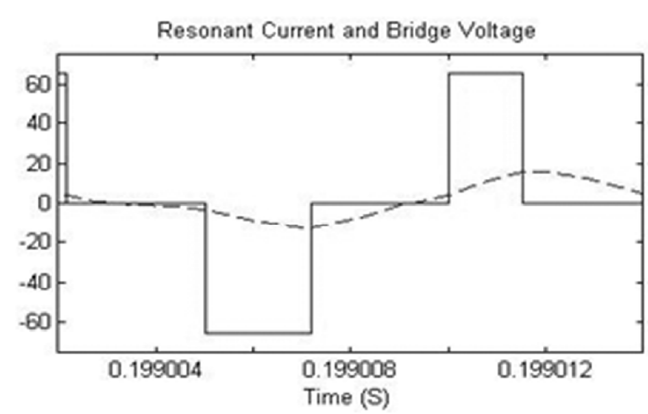

Figure 5:Bridge voltage and inverter current under No-load with closed loop

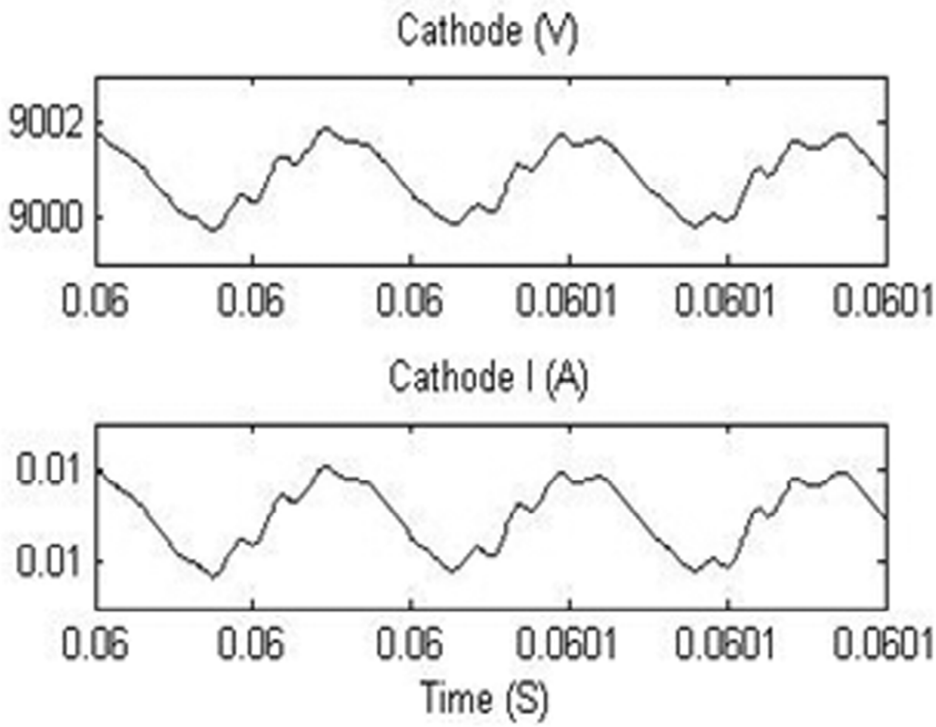

Figure 6: Cathode output voltage and current under No-load with closed loop

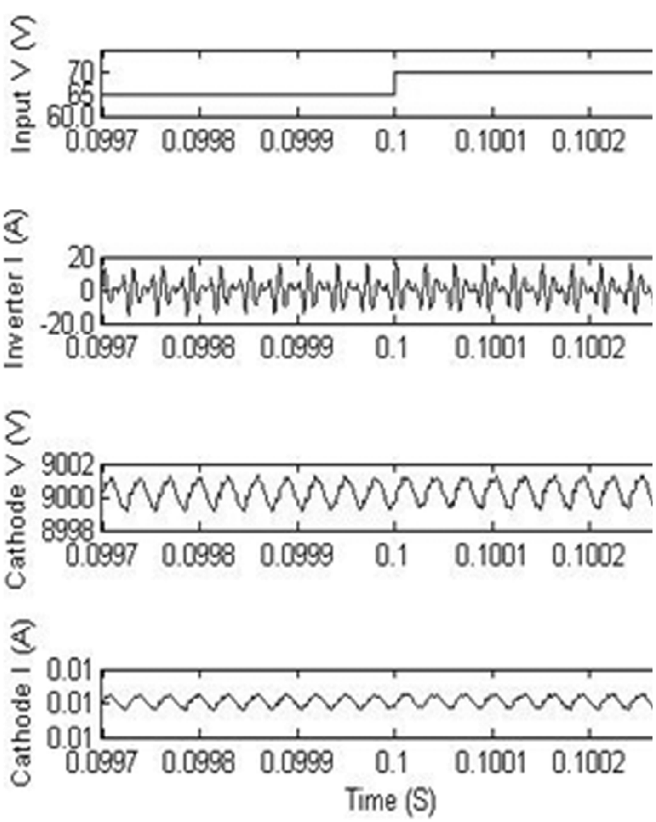

Figure 7: Step change in supply voltage

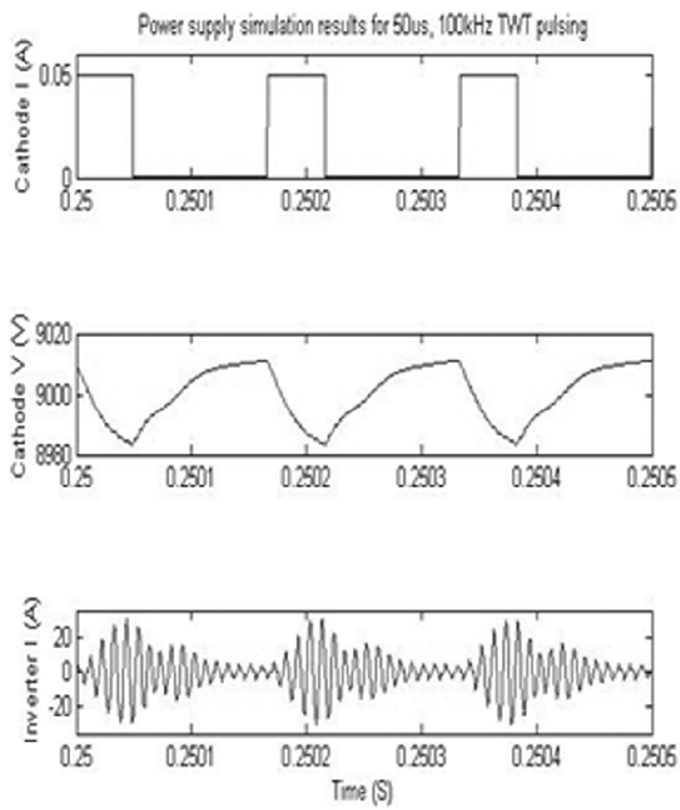

Figure 8: Output during pulsed load

at -9kVDC was measured to be 89%. Under closed loop, no-load line regulation was measured and is found to be satisfactory. The waveforms of the bridge voltage, inverter current and the output voltage for different line voltages are shown in Fig. 10 and Fig. 11.

Table 4
Results of full-load test

VDCV	*IDC A*	$V_{AB}V$	*Ir(A)peak*	*VO kV*	*IomA*	*η(%)*
11.6	2.2	11.6	3.24	2	9	70.5
28.0	5	28	7.5	4	31	85.5
43.4	7.6	43.4	11.5	6	49	88.9
52.3	8.9	52.3	13.8	7	60	89.9
65.0	11.0	65.0	16.5	9	72	90.6

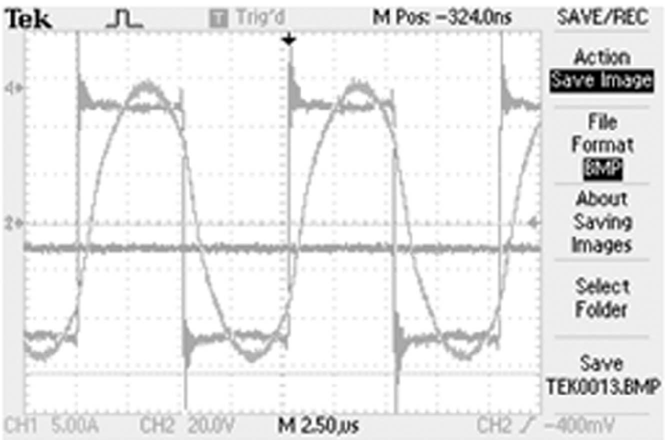

Figure 9: Bridge voltage and inverter current for full-load under open loop

Figure 10: Bridge voltage and inverter current under No- load line regulation at 25VDC input

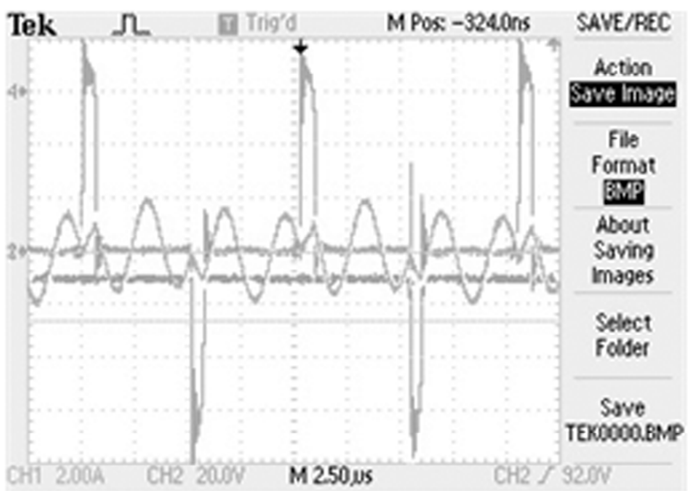

Figure 11: Bridge voltage and inverter current under No- load line regulation at 65VDC input

7. CONCLUSION

In this paper, the design of a 100 kHz, PMSRC based high voltage power supply for RADAR transmitter is presented. The high voltage power supply is designed to give output voltages of -9kVDC, -6.6kVDC and -4.2kVDC.Non-idealities of HVHF transformer like leakage inductance and winding capacitance which put severe restrictions on the selection of switching frequency and load factor of the inverter are discussed. The PMSRC with full bridge topology is designed, verified through simulation and tested for full-load and full power of 450W. A PI controller is designed for the phase shift controller to regulate the output voltage.The power supply is tested for its regulation for line variations and the performance is found to be satisfactory. Power supply testing is in progress for pulsed load condition.

REFERENCES

[1] N.V. Bijeev, Anju Malhotra, Virender Kumar, Surinder Singh, K.S. Dasgupta, Rajesh N. Motta, B. Venugopal, Sandhyarani, O.K. Jinan and B.K. Jayakumar, "Design and realization challenges of power supplies for space TWT," IEEE Transactions On Power Electronics, vol. 15, no. 3, pp. 536–544, May 2011.

[2] K.Deepa, Sanitha Mary Kurian, M. Vijaya Kumar, "Improvement of Efficiency in an Active Clamp ZVS Multi-output Flyback Converter with Voltage Doubler by Using UC3825 Analog Controller, International Journal of Applied Engineering Research, Volume 10, Number 1 (2015) pp. 1671-1685.

[3] Deepa Kaliyaperumal, Hridya Merin Saju, M. Vijaya Kumar, "High Efficiency Single Output ZVS–ZCS Voltage Doubled Flyback Converter", Journal of The Institution of Engineers (India): Series B Electrical, Electronics & Telecommunication and Computer Engineering, DOI 10.1007/s40031-014-0161-5.

[4] Athira S and Deepa K, "Modified Bidirectional Converter with Current Fed Inverter", International Journal of Power Electronics and Drive Systems (IJPEDS)", Vol 6, No 2, June 2015, pp.387-395.

[5] S. R. Jang, H. J. Ryoo, J. S. Kim and S. H. Ahn, "Design and analysis of series resonant converter for 30kW industrial magnetron," IEEE Transactions On Power Electronics, vol. 15, no. 3, pp. 536–544, May 2000.

[6] Nitai Pal, Pradip Kumar Sadhu ,Dola Sinha and AtanuBandyopadhyay, "Selection of power semiconductor switches – a tool to reduce switching & conduction losses of high frequency hybrid resonant inverter fed induction cooker," International Journal of Computer and Electrical Engineering, Vol. 3, No. 2, April, 2011.

[7] Leopoldo Rossetto and Giorgio Spbzzi, "Series resonant converter with wide load range," Industry Applications Conference, Thirty-Third IAS Annual Meeting. The 1998 IEEE , vol. 2, pp. 1326-1331, 12-15 Oct. 1998.

[8] Biju S. Nathan and V.Ramanarayanan, "Designing for zero-voltage switching in phase modulated series resonant converters," Indian Institute of Science Journal, July-Aug. 2000.

[9] S. C. Kim, S. H. Nam, H. M. Keon, and D. S.Park, "Development of a high frequency and high-voltage pulse transformer for a TWT HVPS," Pulsed Power Conference, Digest of Technical Papers, Vol. 2, 15-18 June 2003.

[10] Biju S. Nathan and V. Rammarayanan, "Analysis, simulation and design of series resonant converter for high voltage applications, "Industrial Technology 2000. Proceedings of IEEE International Conference, Vol. 1, 19-22 Jan. 2000.

[11] Em-Soo Kim, Tae-JinKim,Young-Bok Byun, Tae-GeunKoo,Yoon-Ho Kim, "High power full bridge DC/DC converter using Digital-To Phase-Shift PWM Circuit," IEEE Power Electronics Specialists Conference, 2001.

[12] F. C. Schwartz, "An improved method of resonant current pulse modulation for power converters," IEEE Power Electronics Specialists Conf., 1975 Rec., pp. 194-204