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Development of Airborne High Density High Voltage Power Supply for Traveling Wave Tubes

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ABSTRACT

This paper describes the development and testing results of a high density High Voltage Power Supply (HVPS) that drives microwave Traveling Wave Tubes (TWTs) of phased array transmitters for airborne EW systems. The HVPS is designed to consist of a number of modules connected in series. Among them, especially, the high-density pulse transformer module including the resonant circuit is newly designed to make the HVPS much more reliable. In addition, this paper describes the development of high voltage solid-state modulation using fast switching devices (FETs) and also represents the test results of a modulator module.

Keywords: high voltage power supply, traveling wave tube, high density pulse transformer, modulator

1. Introduction

In the fields of Electronic Warfare (EW) Applications, the phased array transmitter is regarded as being more important than ever. In radars, phased arrays should be controlled to effectively track multiple targets by instantly switching from one target (or threat) to another. When used as a phased array transmitting antenna, the signal to be transmitted is divided among the antennas, and the phase of the signal to each antenna is adjusted so that all of the signals will be in phase when viewed from some selected direction and will thus add to a constructively sharp beam. It follows that they will be out of phase, when viewed from any other angle and will thus add less constructively. This actually forms a pattern of the antenna beam. Another advantage in using a phased array transmitter is the relative ease of generating a higher output of effective radiated power (ERP) than using a single antenna transmitter. This is possible by using a microwave oscillator that makes an individual antenna beam [1].

The Traveling Wave Tube (TWT) is one source of driving phased array antennas. The TWT is frequently used in EW broadband microwave devices. In order to drive TWTs, quite stable DC input voltages (-4kV and -2kV in this paper) generated by HVPS are demanded. This is because any maladjustment of the input high voltages from HVPS to each tube can cause an undesired phase mismatch among TWT outputs, consequently it will make it difficult to steer beam streaming from transmitters in certain directions (like pointing in the direction of a jamming source). Therefore, it is considered critical to maintain the stability of input high voltages to the TWT so the HVPS must be designed to have little ripple/spike noise in the of DC high voltage. In addition, other requirements in the development of HVPS are demanded

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such as possessing a light weight, high efficiency, and high reliability as well as small size in airborne applications [2].

In connection with these issues, some new ideas are devised such as: (1) zero current switching (ZCS) resonant circuit of power transform module, (2) highly efficient high density pulse transformer of HVPS. Additionally, it is described that the beam switching of pulse modulation of TWTs can be performed using a power modulator to switch the cathode beam on and off. In this study, we use focus electrode (FE) type power modulators that provide off-bias voltage (-1kV) to cathode the TWT. In order to control the FE voltage for a beam modulation, the FET is required to have a fast on/off-switching time and a short response time, so even if the TWTs are arcing, it will be possible to protect the HVPS and transmit the beam partially.

Based on this discussion about the requirements of an airborne HVPS, in the following section we will now proceed to describe the developments of a high density high voltage module, the high density pulse transformer, the modulator using FETs that control high voltage beams and cut high voltage switches off when the faults occur.

2. Traveling Wave Tube Characteristics

The TWT is an RF amplifier used to enlarge a small microwave input signal by hundreds of thousands of times. Because the TWT is known to have many advantages, such as broadband capability with high gain, high reliability and a long lifetime, it has been broadly used in areas including EW, radar and broadcasting. The HVPS furnishes the required operating voltages and currents to all inputs of the TWT; Cathode, Collector, Heater, and Focus electrode.

As mentioned in the previous section, any ripple or noise of DC high voltage from the HVPS will cause a pushing effect on the phase of the TWT's output signal. After all, the phased array transmitter would lose a control capability of beam streaming techniques so the HVPS requires good cathode voltage smoothing.

If there is any change in the cathode voltage from HVPS, it will reflect on the electron velocity, μ of the TWT as

$$\mu = \sqrt{\frac{2eV}{m}} \tag{1}$$

where, e is the electron charge, V is the cathode voltage and m is the electron mass. As mentioned before any change in cathode high voltage will have an effect on the phase velocity and change the direction of the antenna beam. In a CW radar transmitter, the spectral purity that is required at the RF output of the tube will be specified.

Finding the phase pushing characteristics of the tube will make it possible to define the allowable ripple voltage of the electrode. In this paper, the cathode phase sensitivity of the TWTs is defined as

$$d\theta / \theta = \frac{1}{3} dV / V \tag{2}$$

where, θ is the electrical length of the slow wave structure of the TWT and is typically about 15 times or more of the wavelength. From the Equation (2), if we apply the phase pushing factor to the TWT that is driving this transmitter, the cathode voltage variations would be 0.9~2.7[°/V] at the frequency range of the TWT.

3. Design of High Voltage Power Supply Modules

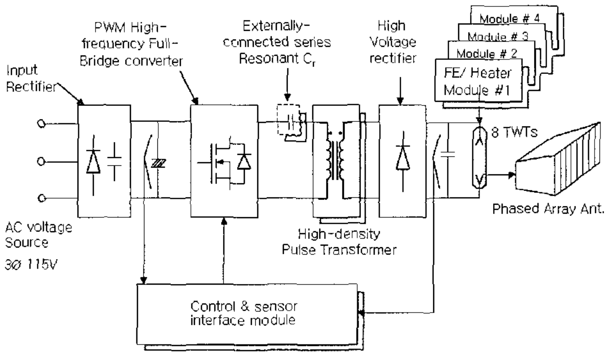


Fig. 1 Configuration of the HVPS for the TWTs

From what we have seen in the previous sections, limited output of the high voltage ripple in driving the TWTs of the phased array transmitter is highly expected. The ripple of output voltage also includes voltage spikes and consequently it must be considered to reduce the switching noise of power modules during the beginning of the design stages. Additionally, the power supply should be developed to have the characteristics of small-sized volume and high density with high efficiency for the application of airborne platforms. Fig. 1 shows the configuration of a high-density high voltage power supply for TWTs of a phased array transmitter and the total output power of HVPS is designed for 3kW. As shown in Fig. 1, the HVPS has five modules: input rectifier, ZCS resonant converter, high voltage pulse transformer and rectifier, modulator and logic control module. The last module is called a modulator module and is made up of four sub-modules. A series of five modules composed of HVPS are functionally separated as the following. The first module rectifies three phase 400Hz 115Vac of aircraft power lines, which supplies a +265Vdc bus voltage. This bus voltage provides DC power to the input of PWM high frequency, full-bridge ZCS resonant converter in the power transition module. Hence, this DC power will be switched at 100kHz switching frequency by the controlled duty cycles to become AC power for driving the step-up high density pulse transformer whose outputs are then rectified through the high voltage diodes and capacitors to provide the required high voltages for the TWTs.

The control circuit and sensor interface module senses the high voltage outputs of the high voltage rectifier and its value will feedback to the converter module. This converter module, using the PWM switching method, provides the power to the output port and manipulates the duty cycles. Another function of this module is to control all kinds of fault signals and to interface with all related modules. Especially this module will be set up fully separated from the high voltage sections, in order to avoid a breakdown of the high voltage insulation. The last module is composed of 4 sub-modules in which each module generates the Focus Electrode (FE) voltage and the heater voltage. Each sub-module is connected to two TWTs. Hence, the total number of TWTs of this phased array transmitter is eight.

In the following sections, there will be more details about the design concept and its operation of each sub-module of the HVPS.

3.1 Resonant ZCS converter

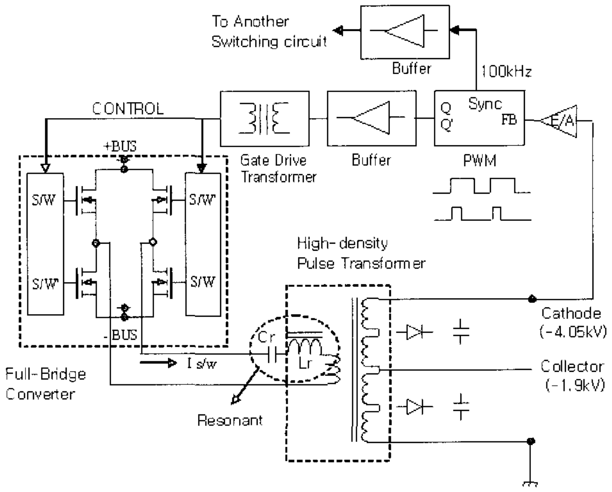


Fig. 2 Schematic of Full-Bridge resonant converter and Control loop

In order to stabilize the DC high voltage, it is necessary to reduce the ripple of the DC voltage and the switching noise of the power supply. One method of reducing the output ripple of the DC voltage is to enlarge the value of the high voltage capacitors. However, the larger the volume of the capacitance, results in a smaller permitted HVPS space. In addition, another problem with a very large capacitor is that during the TWT arcing, the amount of energy stored in the capacitor is enough to destroy the TWT unless a very fast action crowbar circuit is used to divert this energy from the tube. As a result, we should limit the value of the output capacitor to 0.6uF or less in this paper.

Fig. 2 illustrates the schematic of a Full-Bridge resonant converter and control loop for the HVPS. The converter has a series resonant circuit that is used to reduce the switching noise of the FET's. Generally, many of the HVPS adopt these resonant circuits. But they have problems such as limited space arrangement of components for an airborne application and the generated heat of a resonant inductor. In light of these considerations this paper provides a ZCS resonant circuit that combines the inner leakage inductance (L_r) of a pulse transformer with the externally connected series capacitor (C_r) to the transformer's primary winding [3].

$$f_r = \frac{1}{2\pi\sqrt{L_rC_r}} \qquad (3)$$

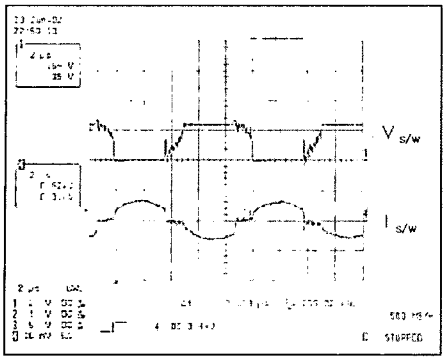


Fig. 3 Resonant voltage and current waveform as experimental results (time scale is 2us/div)

The value of the designed resonant frequency (f_r) is 93kHz, which is calculated by the Equation (3). For example, if the converter operating frequency (f_o) is confirmed, the leakage inductance of the pulse transformer has a fixed value. Therefore, if we select an adequate value of the resonant capacitor C_r, the final value of the resonant frequency f_r will be calculated. In this paper, we decided to operate at frequency f_o at 100kHz. The reason why we selected the less value of f_r than f_o is the lagging current. This results in a slight difference between the turn on/off time of current/voltage so that the switching loss could be zero. Electrical parameters and performance of the Full-Bridge resonant converter are summarized in Table 1.

Table 1 Designed Full-Bridge resonant converter

Operating frequency	100 kHz
Resonant frequency	93 kHz
Leakage inductance	1.95 μH
Series capacitor	1.5 μF
Input voltage	265 Vdc
Output power	3.25 kW

Fig. 3 shows resonant switching waveforms as experimental results. The upper waveform demonstrates the switching voltage of the pulse transformer's primary side. It is the AC pulse type of the rectified input Bus voltage (265Vdc_peak). The lower waveform shows the sinusoidal waveform of the resonant current through the switching device (FET). It is quite clear that the time when the voltage turned off, the current starts from zero. For that reason, we verified the decrease in switching loss and noise as a function of the ZCS resonant circuit.

3.2 High density high voltage pulse transformer

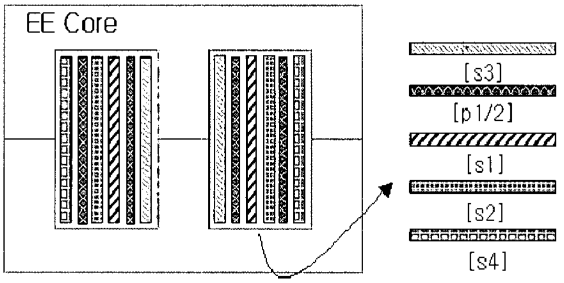


Fig. 4 Schematic diagram of a high-density pulse transformer

The pulse transformer of a high density HVPS for a TWT amplifier has a very important role in designing HVPS airborne applications. The high voltage transformer has a high turn ratio which means a large volume is needed. In comparing the high voltage transformer with ordinary transformers, some problems are apparent. In other words, the high turn ratio increases the leakage inductance of a pulse transformer and enlarges the peak values of the self-resonant current with stray capacitance. This will affect hard to design high-density high voltage pulse transformers. Due to this, we must limit the turn ratio values.

In order to reduce the volume and weight of the high voltage pulse transformer for an airborne application, it is necessary to increase the switching frequency of the resonant converter. A higher switching frequency means a smaller volume for the pulse transformer. After all, the power density of the transformer has also increased. Under fixed conditions, such as the size of the power supply (or the transformer volume) and the turns ratio of the input/output sides, the switching frequency must be as high as possible to acquire the highest power density. But the increased switching frequency causes problems such as switching noise and higher operating temperatures in the power module.

So far, very little has been studied in the development of 100kHz high-density high voltage pulse transformers that can handle output power over 3kW for driving a TWT amplifier [4]. In order to solve the above-mentioned problems, some techniques are applied in this paper: (1) dividing the secondary winding into four, which reduces values such as stray capacitance, leakage inductance, and proximity effects of winding layers; (2) special arrangement of windings as shown in Fig. 4 so that the magneto-motive forces between primary and secondary are balanced. Analogously, the stacked-layer winding and the leakage inductance, referred to the primary, is given by

$$L = \frac{KN_p^2 l_m}{ws^2}\left[\sum t + \sum \frac{h_p + h_s}{3}\right] \quad \mathrm{H} \qquad (4)$$

where l_m, h, t, and w are linear dimensions in centimeters: N_p is the number of primary turns (leakage reflected to the primary), s is a function of winding interleaving and K is a constant number. As noted by s^2 in the denominator, interleaving of the windings will substantially reduce the leakage inductance. This technique, as shown in Fig. 4 would normally require additional insulation between windings and would reduce the window available for the conductors [5].

The core should be selected to satisfy operating frequency and temperature. The core volume is not allowed to exceed 400cm^3. This paper selects the Magnetic ferrite EE type core 47228 with R material. Calculating the plots of winding, core, and total transformer losses as a function of flux density, we verify results where by the operating ranges of flux density are 1500~2000G and the handling output power is large enough to drive the HVPS. Using the following Equation (5) and (6), the values of the primary and secondary turns are calculated

$$N_p = \frac{(V_{dc} - 2V_q) \times \dfrac{D}{2f} \times 10^8}{A_e \times dB} \qquad (5)$$

$$N_s = N \times N_p \qquad (6)$$

where, A_e is the effective cross sectional area of core, dB is flux change (=2B$_{\max}$), V_{dc} is input Bus voltages, and N is a turn ratio of the pulse transformer. As a result of calculating equations and simulating the parameters, the developed high-density pulse transformer has a volume of 250cm^3, handling output power over 3kW and a power density of 14.1W/cm^3. Finally, Fig. 5 shows each of the measured secondary winding waveforms. It displays the perfect 100kHz AC pulse waveforms without any resonance on the turn on/off time.

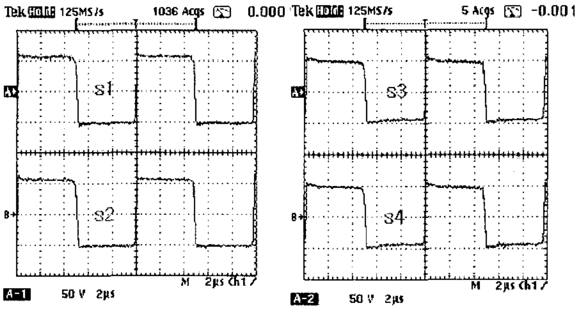


Fig. 5 Secondary output high voltage waveforms of the pulse transformer(When the operating flux density is 2,000G)

3.3 FE modulator

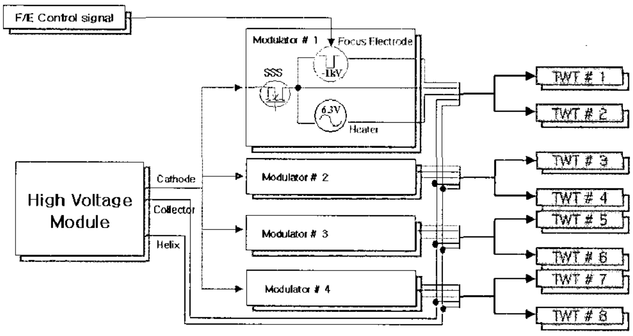
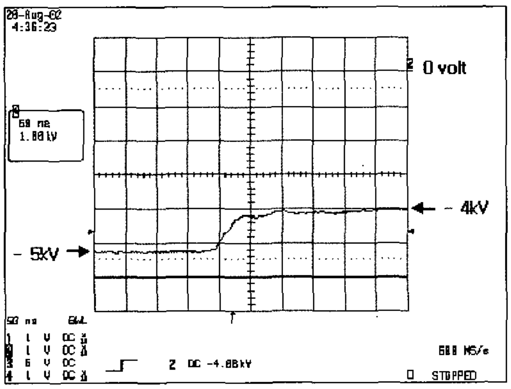


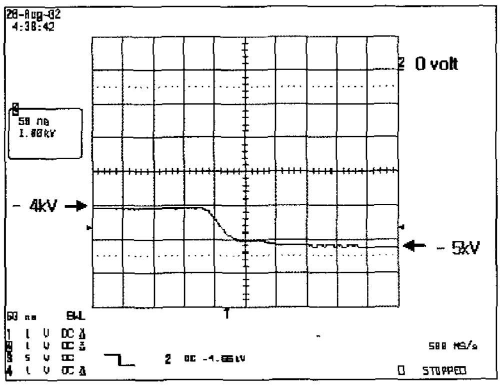
Fig. 6 The interface schematic of modulator-modules with the TWTs

As shown in Fig. 6, one modulator controls the 2 TWTs by the FE control signals and provides the voltage to the TWTs from high voltage module. Each modulator's sub-modules consists of 3 parts: (1) one is the generation of focus electrode voltage to −1kVdc(beam off) and 0Vdc(beam on) with respect to the cathode voltage, which is controlled by the FE control signal, (2) another one offers the heater voltage for driving the TWT's heater filament, which heats the cathode up to its operating temperature, (3) the last one is a high voltage cut-off switch that prevents damage to the tube during arcing and under voltage protection circuit for the 'beam off' voltage.

The FE on/off voltage can swing the levels of 0~1kVdc on the high speed switching time. In order to satisfy these switch requirements, high-speed MOSFET devices with a drain to source breakdown voltage of 1kV are used. Furthermore, dual use of switches during on/off switching time minimizes the switching response time within 100ns as shown in Fig. 7 that shows; (a) the –4kVdc FE on time and (b) the –5kVdc (with respect to cathode voltage) FE off time.



(a) FE voltage ON



(b) FE voltage OFF

Fig. 7 Waveforms of the Focus Electrode voltage

When the TWT internally arcs or the TWT's power supply instantaneously shorts it is impossible to drive the TWT's transmitters. So we must sense the short circuits and cut off the cathode high voltage (-5kVdc). The newly developed short circuit's sensor is not an ordinary voltage sensor that senses output voltage but the current sensor could detect the helix over current. This sensor has a high sensitivity and a good response time. We used several MOSFETs in series when the cathode voltage cut out. The total number of FETs is 6. Each FET has a 1k voltage rating. A resistor is connected to each FET's source point. When arcing occurs, the high current flows into these resistors so that the voltages of the resistors are negative. As a result, the negative voltage makes the FET's gate drive invalid in a short time. Additionally, the current sensor senses the over current using a magnetic core and sends the arcing time to the gate drive controller. The complete FET turn off time lasted 300ms. If the turn-off actions are repeated 3 times, the controllers completely turn off the cathode voltage.

The test results of a forced arcing verified the cut-off switching time as having a characteristic high-speed response time within 200 ns, which did not interfere with the other modules. Due to this, other beams could then be partially transmitted. Fig. 8 displays one sub-module of the FE modulator that shows a high compact assembled module.

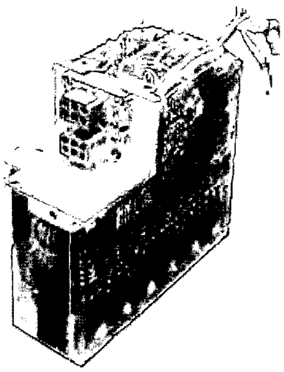


Fig. 8 One sub-module of FE modulator

4. Conclusions

Up to now, we have looked at the development of a high-density high voltage power supply applied to an airborne phased array transmitter with 8 TWTs. The discussion has included how to reduce the switching noise of the converter, how to increase the pulse transformer's efficiency and how to increase switching characteristics of modulators. The converter's switching noise can be reduced by the resonant circuit of the ZCS converter that combines the leakage inductance of the pulse transformer with the externally connected serial capacitors to the transformer primary winding. The newly developed pulse transformer is implemented in a relatively small volume with minimized losses and an increased power density at 100 kHz switching frequency. The efficiency of the pulse transformer is measured at 90%. The FE modulator's on/off switching time and cut-off switching times are improved by using high-speed MOSFET and newly designed circuits which are far shorter than those found in older types. Separated sub-modulator modules are designed to transmit the RF beam partially.

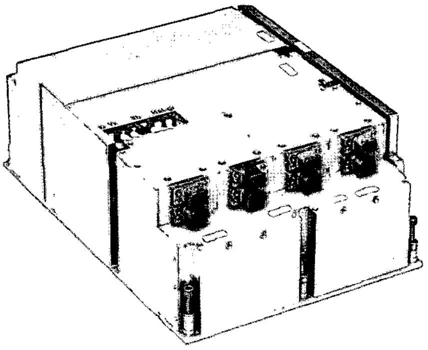


Fig. 9 The developed 3kW airborne HVPS for the TWTs

Fig. 9 shows the final assembly of a developed high-density airborne HVPS that has a volume of 390 in^3, the output power of 3kW, and the power density of 6.5W/inch^3. And Fig. 10 shows the developed airborne high-density transmitter. Finally, we have verified the effectiveness of this HVPS through environmental tests under temperature conditions of –40~+85°C at an altitude of 55,000ft with relative humidity of 95%.

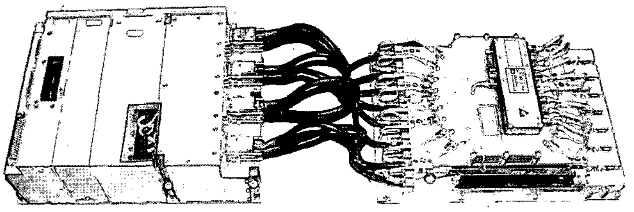


Fig. 10 The airborne high-density transmitter

References

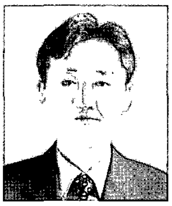
[1] Y.J. Park, K.S. Lee, S.C. Lyu, "Development of High Voltage Solid-State Modulation Power Supply for the Electronic Warfare Applications", *KIMST proceedings of 2002 annual conference*, 4 Sep 2002, Daejeon, pp.731-734.

[2] L. Sivan, *Microwave Tube Transmitters*, Chapman & Hall, 1994, Ch 2.

[3] J.Sun, M. Nakaoke, H. Takano, "High-Voltage Transformer Parasitic Resonant PWM DC-DC High-Power Converter and Their Performance Evaluations", *ISIE 1997, Proceedings of IEEE International Symposium* on Vol. 2, 7-11 July 1997, pp 572-577.

[4] S.C. Kim, S.H. Nam, D.T. Kim and S.H. Jeong, "High Power Density, High Frequency and High Voltage Pulse Transformer", *PPPS 2001*, Digest of Technical papers, Volume : 1, 17-22 June 2001, pp 808-811.

[5] Ralph E. Tarter, P.E., *Solid-State Power Conversion Handbook*, John Wiley & Sons, Inc, 1993, Ch 3.



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