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DESIGN NOTE

A simple and compact high-voltage switch mode power supply for streak cameras

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Abstract. The design and development of various high-voltage switch mode power supplies (SMPSs) for use with streak cameras are described. This work details −15 kV(100 μA), ±2 kV (1 mA) and ±1 kV (1 mA) SMPSs for biasing the streak and image intensifier tubes, driving the sweep circuit and positioning the photoelectron beam on the phosphor screen of the streak camera respectively. The design of the high-frequency pulse transformer—the main part of these SMPSs—is also presented.

1. Introduction

Various pulsed devices such as the photomultiplier tube, biplanar photodiode, spark gap, streak camera etc require high-voltage low-current power supplies for their operation. The streak camera in particular requires various high-voltage power supplies for biasing the streak tube (−15 kV) and intensifier tube (−7.5 kV) as well as for driving the sweep circuit (±2 kV) and positioning (±1 kV) the photoelectrons emerging from the photocathode and striking the centre of the phosphor screen. The voltage used for positioning purposes is applied on deflection plates which helps in selecting the linear portion of the sweep voltage to ensure a nearly linear sweep of photoelectrons from one end of the phosphor screen to the other. Regulated high-voltage (∼15 kV and 100 μA) power supplies made from ac line frequency (∼50 Hz) are very bulky because they use large transformers and large filter capacitors in the rectifier section. All conventional supplies make the whole streak camera system very bulky. However, it is possible to make the entire system very compact without losing any specification required by the streak camera system by using switch mode power supplies (SMPSs) [1]. This has many advantages over conventional power supplies. A SMPS has the advantage of offering good isolation between source and load as well as better efficiency. High frequency switching in SMPSs reduces the size of the filter capacitors to a few hundreds of picofarads. Self oscillating SMPSs of 1–25 W are more suitable for a streak camera because they require fewer components which then reduces the size and price of the supply drastically. These SMPSs consist of an oscillator operating at a desired frequency, a high-frequency pulse transformer and a filter rectifier system.

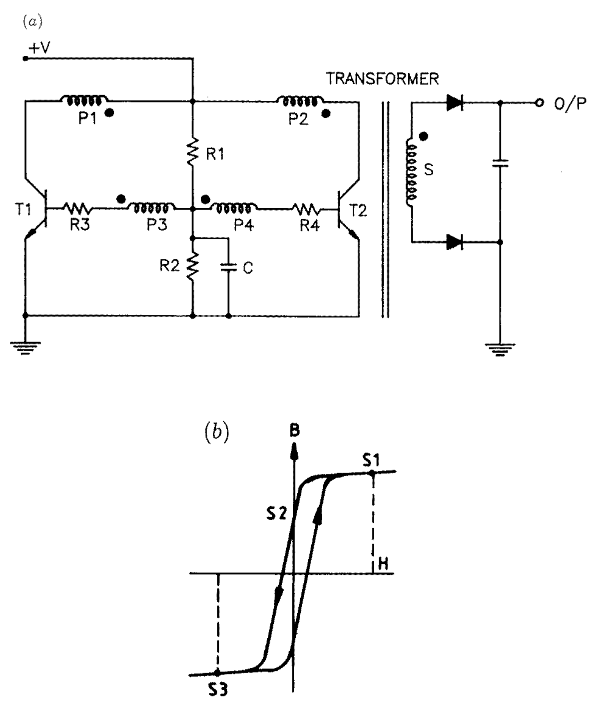

Figure 1. (*a*) Circuit diagram showing operating principle of gain limited switching. (*b*) Hysterisis loop of the core material used in gain limited switching.

In this paper we present the design and fabrication details of various SMPSs used to bias the streak camera

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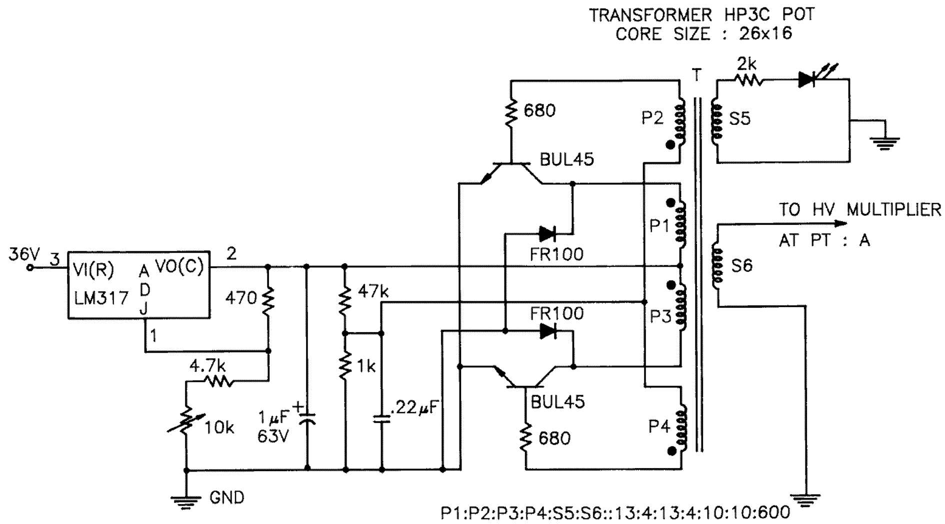

Figure 2. Circuit diagram of SMPS oscillator.

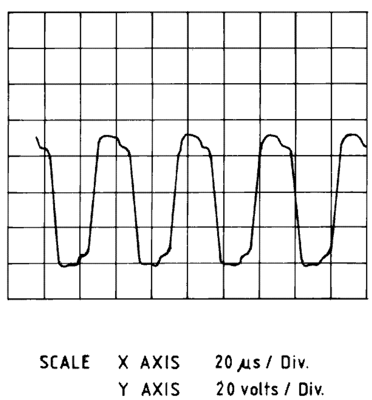

Figure 3. Oscilloscope trace showing frequency of operation of SMPS oscillator.

system [2] and an x-ray imaging device based on the combination of a phosphor screen and an image intensifier tube [3]. The switch mode oscillator, which is common to all the above mentioned power supplies, works on the principle of gain limited switching [1]. The design and fabrication of a high-voltage and high-frequency pulse transformer—the main part of SMPSs—is also reported. These SMPSs use readily available components and can be made very easily in any laboratory.

2. Oscillator and pulse transformer design

Figure 1(a) shows the operating principle of gain limited switching. Initially, when the power is switched on, current flows in R1 through the bases of transistors T1 and T2. Since two transistors with the same nominal specification do not have identical characteristics, we suppose transistor T1 starts conducting first. As this happens a positive regenerative feedback from windings P2 makes the base of T1 more positive and T2 more negative which switches T1 rapidly to its on state. In this case a supply voltage appears across windings P1 and the magnetization current flows through T1. During the on period the flux density in the core of the transformer (usually high permeability ferrite) increases towards a saturation state at point S1 as shown in figure 1(b). The core reaches its saturation state after a period which is defined by the core size, saturation flux value and number of turns in the primary. The magnetizing field H increases rapidly to point S1 providing a large increase in collector current which continues until the gain limitation in T1 prevents a further increase in collector current. Therefore the value of H at this point cannot be increased further and the required rate of change of B (magnetic field) is not sustained. As a result, the voltage on the collector of T1 rises towards supply voltage. This in turn lowers the voltage across P2 and T1 now starts to turn off. Due to a non zero slope at the top of B–H characteristics (figure 1(b)), a flyback action in the transformer from S1 to S2 takes place which reverses voltage polarity on all the windings due to the negative value of $\mathrm{d}B/\mathrm{d}t$ and a regenerative action turns T2 on and T1 off. The flux in the core now changes from S2 to S3 and the turn off action is repeated.

An oscillator for a SMPS was designed on this principle (figure 2) and proper selection of transistors and ferrite material was made. A low-loss square-loop ferrite material was chosen for high efficiency of the saturating single transformer of the oscillator. Ferrites have two significant advantages over other types of magnetic materials—high electrical resistivity which results in low eddy current losses over a wide frequency range and high permeability which results in a size reduction of the transformer. The transformer for this SMPS was designed and fabricated using HP3C core material which has a saturation magnetic flux density of 350 mT. The oscillating frequency of the self oscillating converter is decided by core saturation where the change in magnetic flux density at the end of the pulse is given by [4]

$$\Delta B = aVt_p/N_pA \tag{1}$$

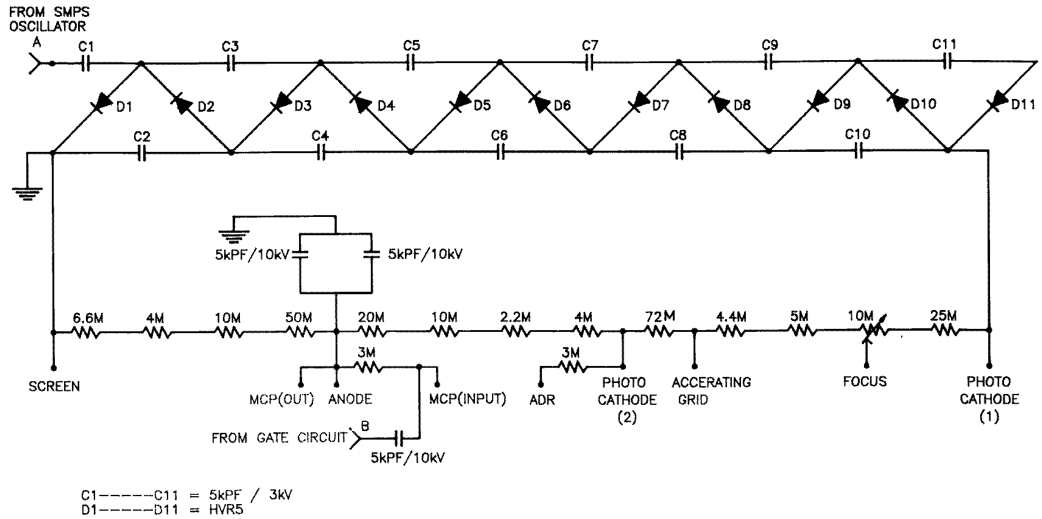

Figure 4. Circuit diagram of high-voltage multiplier and resistive divider for −15 kV SMPS for streak and image intensifier tube biasing.

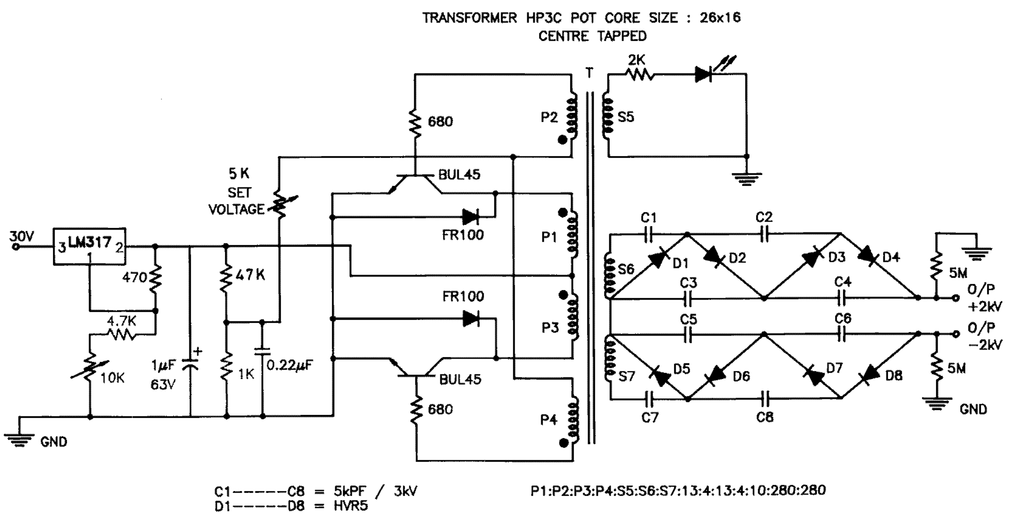

Figure 5. Circuit diagram of ±2 kV SMPS for biasing sweep circuitry of streak camera.

and

$$t_p = T/2 = 1/2f$$

where a is a constant and is usually taken as one for low power; V is the operating dc voltage of the converter; t_p, T and f are the on period, time period and the operating frequency (in Hz) of the oscillator respectively; N_p is the number of primary turns in the transformer and A is the effective area of the core material.

The power required at the output of a SMPS providing −15 kV and 100 μA current rating is $P_{out} \sim 1.5$ W. If the efficiency of the pulse transformer is assumed to be $\eta \sim 70\%$, the required input power will be $P_{in} \sim 2.14$ W. The operating voltage of the oscillator was chosen to be 30 V so as to have fewer turns in the secondary of the transformer to yield the desired step up voltage. In this case the input current is $I_{in} \sim 0.071$ A.

A ferrite pot core of HP3C material (size 26 mm × 16 mm) was used for making the transformer, which has a power handling capacity of 40 W (quite large compared to the required value). A pot core was chosen because it has a good winding flexibility and also provides better electromagnetic shielding. Besides this the air gap in between the mating surfaces on the centre posts of the core provides a fixed inductance and good temperature flexibility [5]. The operating frequency of the converter was fixed at 25 kHz ($t_p = 2 \times 10^{-5}$ s) which is limited by the recovery time of the diodes used in the rectifier section of the power supply after the secondary of the transformer. The above pot core has $A = 94$ mm^2 and total flux density change $\Delta B = 700$ mT. The number of primary turns was found to be $N_p \sim 10$ with use of equation (1). Windings P1 and P3 were made bifillar in nature using SWG30 copper enamelled wire to minimize the leakage inductance

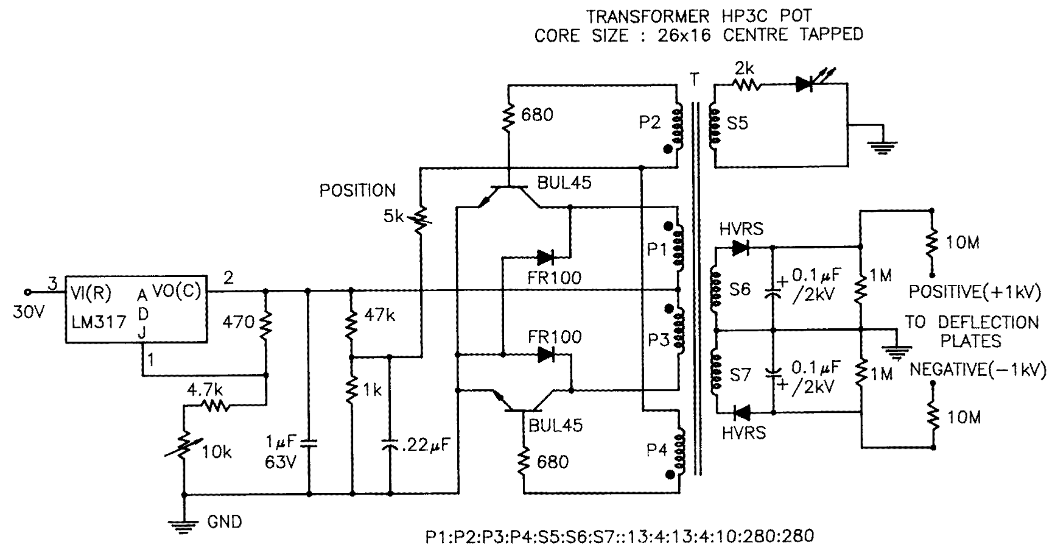

Figure 6. Circuit diagram of ±1 kV SMPS for positioning the electron beam in the streak camera.

(figure 2). The number of turns in P1 and P3 was kept to 13 to provide good winding flexibility for secondary windings which makes the interlayer capacitance uniform. However, no significant change in the operating frequency (as shown in figure 3) was observed due to this small difference between the actual and the calculated number of primary turns which seems to be due to the reflected interwinding capacitance of the secondary windings. The number of turns in the secondary was different for different power supplies; details are given in the next section. To achieve sufficient regenerative feedback for proper switching of the oscillator, the drive voltage for windings P2 and P4 in figure 2 should be at least 25% of the primary voltage which is why four turns of bifillar windings were wound just over the primary windings P1 and P3. The voltage in this oscillator was regulated by an LM317 IC from 1.2 to 40 V. A variable resistor of 10 kΩ in between output 2 and adjust 1 terminals of the LM317 IC sets the voltage to the desired value. The collector diodes FR100 were included in the circuit to provide a reverse current path whenever the reflected load current is lower than the magnetization current [1]. These diodes operate in cross connected fashion. The above mentioned oscillator circuit is common to all the power supplies. However, details of the secondary of the transformer, rectifier and doubler circuit are discussed in the next section.

3. SMPS designs

3.1. High voltage −15 kV supply for biasing streak and image intensifier tube

The streak and image intensifier tube require various high voltages for biasing. The main requirements in the streak tube are −15 kV, −13 kV to bias the photocathode and accelerating grid and focusing electrode respectively. The intensifier tube requires −7.5 kV, −7.2 kV and −5 kV for its photocathode, anti distortion ring electrode and anode respectively with respect to the phosphor screen which remains at ground potential. Even −5 kV biasing is needed at the input and output of the micro channel plate (MCP). All these biasing voltages are derived from one or two SMPSs using a suitable divider at its output. The secondary windings (S6) of the transformer in the case of a −15 kV supply consist of 600 turns of SWG38 copper enamelled wire wound over the primary windings P1, P2, P3 and P4 as shown in figure 2. The bobbin of the core can only accommodate 60 turns in one layer which is why the windings were overlapped. Teflon tape was used between the inter layer windings to ensure proper insulation. Care was taken to provide short circuit protection in the output wire coming out from the bobbin with the help of Teflon sleeves. The stepped up rms voltage at the secondary of the transformer was measured to be ∼1000 V with the help of a Tektronix high-voltage probe (model P6015) at a resistive load of 1.2 MΩ. This voltage (figure 2) was multiplied and rectified to −15 kV with the help of a multiplier section added at point A as shown in figure 4. The voltage multiplier section consists of 11 stages of a diode doubler circuit. The capacitors C_1–C_{11} filter the ac component as well as multiply the voltage available at the secondary. Various voltages were obtained at the output of the supply by using a resistive potential divider for biasing the streak and image intensifier tubes as shown in figure 4. Gating of the MCP of the image intensifier tube was achieved by applying a pulse of amplitude variable from −100 V to −1 kV of duration 600 μs at point B. This is necessary to avoid dc noise at the phosphor screen of intensifier tube. This pulse was obtained from a gate pulse generator, the details of which will be published elsewhere. This power supply can deliver a maximum current of 100 μA at −15 kV. The ripple factor in this power supply was measured to be around 2% which is acceptable for our application.

3.2. ±2 kV SMPS for biasing sweep circuitry

Another power supply of ±2 kV is required to drive the sweep circuit [6, 7] of the streak camera. This is used to charge the (120 pF) capacitors at both ends of the 13 transistor (2N5551) string; they are discharged by triggering one of the transistors in the string. This sweep circuit provided a square pulse of ∼2 kV amplitude and ≤ 1 ns rise time. This power supply consists of centre tapped secondary windings wound over the primary windings of the oscillator (figure 2). It consists of 560 turns of SWG38 copper enamelled wire centred at 280 turns. The type of insulation used in this supply is the same as used in the −15 kV supply. As shown in figure 5, the final voltage is rectified and multiplied by a two-stage multiplier. The voltage of this power supply can be varied from ±1.5 kV to ±2.3 kV with the help of a variable resistor placed at the common base terminal of the transistors as shown in figure 5. The percentage ripple of this SMPS was measured to be equal to 0.2%. This power supply can deliver a maximum current of 1 mA and is used to bias the sweep circuit of the streak camera as discussed above.

3.3. ±1 kV variable power supply for positioning the electron beam in the streak camera

A variable supply of ±1 kV is required to adjust the position of photoelectrons sweeping the phosphor screen. This voltage was directly applied on a pair of deflection plates in such a manner that the sweep voltage amplitude present on the deflection plates sweeps from −500 V to +500 V instead of 0 to ±1 kV. The presence of a proper dc voltage on the deflection plates and a proper delay in the sweep circuit with respect to the arrival of photoelectrons on the deflection plates helps in the adjustment of the sweeping range of photoelectrons on the phosphor screen. This also selects the linear portion of the sweep voltage which minimizes the error in the measurement of the streak rate of the camera at different spatial locations of the phosphor screen. Figure 6 shows the circuit diagram of the ±1 kV SMPS. It also consists of centre tapped secondary windings of 560 turns of SWG38 copper enamelled wire centred at 280 turns. The voltage at the secondary is rectified with a rectifier as shown in figure 6. The output dc voltage of this supply can be varied from ±400 V to ±1 kV with the help of a variable resistor provided at the base of the transistors. This SMPS can deliver a maximum current of 1 mA and the percentage ripple was measured to be 0.2%.

4. Conclusion

The power supplies discussed above are simple and compact in design. They also provide a good efficiency and regulation for fixed loads. All the components used in these supplies are readily available. The SMPSs operate well in the streak camera [2] and x-ray imaging device [3] built in our laboratory. The design is so simple that it can be made very easily in any laboratory.

Acknowledgment

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