High Voltage Generation and Control Circuit for Space X-ray Instrumentation

Ananthalakshmy K.
PG Student
ICE Dept., MIT, Manipal
India
e-mail: ananthalakshmy.k@gmail.com

Abstract - The work concentrates on the design of a high voltage supply for X-ray detectors. A dc to dc converter is designed that can convert the low voltage of the raw bus to a value high enough to make the detector work. It is optimized to have a low mass and power. The design also satisfies some stringent requirements such as corona proof, power bus protection, and the automatic reduction of high voltage (HV) applied to the detector when satellite enters into high charge concentrated regions in the sky, in its trajectory. The HV unit is used in space applications so it has to be compact, light in weight and has to consume low power. It must be able to withstand the widely varying temperatures and the harsh radiation conditions of space. The design produces voltages in the range ±200 to 2000 volt. The HV bias circuit can be used for different kinds of detector with only slight modifications in the circuit.

Keywords: X-ray detectors, high voltage bias.

I. INTRODUCTION

X-ray astronomy is an observational branch of astronomy which deals with the study of X-ray emission from celestial objects. It is one of the extensively growing branches of astronomy. X-ray radiation is absorbed by the Earth's atmosphere, so instruments for detection must be taken to high altitudes by balloons, sounding rockets, and satellites. The X-rays emitted from a particular source interacts with the material of the detector producing signals that can be analyzed to study the X-ray source. X-ray detectors are of various types. Many conventional and new detector technologies require the application of intermediate to very high voltages. Examples of the detectors requiring high voltage bias are gas filled chambers and scintillators coupled to photomultiplier tubes. Some special semiconductors such as Cadmium Telluride, Cadmium Zinc Telluride are operated at intermediate high voltages. Applications which include micro channel plate as the basic detector would require high voltage (HV) up to 3kV.

The project work concentrates on the design of a compact high voltage bias for X-ray detectors used in X-ray astronomy and astrophysics. Here a dc to dc converter is designed that can convert the low voltage of the raw bus to a value high enough to make the detector work. The design is aimed to produce compact and efficient HV bias that can produce voltages in the range 200 to 2000V, thus useful for different types of detectors.

The high voltage unit designed is used for space based experiments. An apt method for dc-dc conversion was designed based on the requirements. The whole circuit was divided into various sub circuits for ease of design and simulation. Each sub circuit contains different units. The software simulation of each unit was done in the PSpice simulation tool.

II. DESIGN SPECIFICATIONS

The HV unit design is aimed to give voltage in the range 200 to 2000V. The lower ranges of HV can be used in semiconductors. The medium ranges for gas detectors and the higher ranges for scintillators + PMT. The specifications that are given change with the type of detector used. Consider SDD as an example. It stands for Silicon Drift Detector which is a type of semiconductor detector. The various design specifications for SDD are given below.

a) Electrical Specifications:

These are the maximum values like current, voltage etc. that the detector can withstand without getting damaged. The specifications given below are for SDD detector. These values may change for different detector and the HV design can be modified accordingly.

\[\text{Table 1: Electrical Specifications}\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td>-200 to -300</td>
<td>V</td>
</tr>
<tr>
<td>Load Current</td>
<td>+25</td>
<td>µA</td>
</tr>
<tr>
<td>Ripple</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Regulation</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;1</td>
<td>mW</td>
</tr>
</tbody>
</table>

b) Simulation Tool:

SPICE is the most suitable simulation tool for the implementation of this HV circuit. SPICE is a powerful general purpose analog and mixed-mode circuit simulator that is used to verify circuit designs and to predict the circuit behavior. This is of particular importance for integrated circuits.

III. EXPERIMENTAL SETUP

The high voltage bias circuit consists of mainly 3 sub circuits – HV generation unit, HV regulation unit and HV control unit.

a) Generation Unit:

The HV generation consists of an oscillator, a transformer, a voltage multiplier and a filter. The oscillator circuit converts the applied dc into an appropriate ac signal which acts as input to the transformer. It mainly uses the push pull action of 2 transistors. The transformer provides isolation and ac voltage step up. A saturable core transformer with primary, secondary and feedback winding is used here. The voltage multiplier converts the ac output from the transformer to a very high value dc. It consists of certain number of diode-capacitor stages that provides the required voltage multiplication. Its output is a pulsating dc thus voltage multiplier
also rectifies the applied ac voltage. The dc is further smooth-
ened using the filter circuit.

b) Regulation Unit:
The HV regulation unit consists of a transistor series pass reg-
ulator. It is made of 2 transistors forming a Darlington pair. It
provides a constant output voltage regardless of load and line
variation.

c) Control Unit :
The control action is provided by a voltage divider, a multi-
plexer and an error amplifier along with the series pass tran-
sistor circuit. The voltage divider provides a small portion of
the HV output for feedback. The multiplexer output acts as the
reference. By introducing programmability we can vary the
reference voltage as required. The error amplifier compares
the output with the reference signal and rectifies the errors.
Another sub circuits is the low voltage dc-dc converter. The
LV dc-dc converts the raw bus voltage (about 26-42V) into a
regulated dc value of around 7 volt. The overall action con-
sists of converting a low dc voltage (around 26-42V dc) into a
high value ( 200-2000V dc). Here dc to ac conversion, step up
of ac, and ac to dc back conversion actions take place. The
following block diagram illustrates the circuit:

IV. PSPICE SIMULATION CIRCUITS

The various circuits that have been created and simulated in
the PSpice simulation tool are shown below.

a) Voltage Multiplier:
Fig. 2 shows a voltage multiplier circuit. This type of circuit is
called a Cockroft Walton voltage multiplier. It is a multistage
diode-capacitor device that can give a high voltage at low
current and low cost. Voltage multiplier can be a doubler,
tripler, quadrupler etc giving twice, thrice or 4 times the input
peak voltage. The output can be odd or even multiples of the
input depending on the number of stages. The number of stages
of the voltage multiplier is decided according to the voltage
multiplication required. In figure a 2.5 stage voltage multiplier
consisting of 5 Capacitor and 5 diodes is shown. A filter cir-
cuit can also be seen. In the actual circuit input to voltage
multiplier is the secondary voltage of transformer. For the
PSpice simulation a sine wave source has been used.

1) Working:
During the 1st half of the 1st cycle diode D1 if forward biased.
Thus C1 is charge to the peak value of the supply voltage. In
the second half of the cycle D1 is reverse biased and D2 for-
ward biased charging C2 to \( V_{\text{out}} = 2V_{\text{in}} \). In a similar fash-
on all the capacitors are charged to \( 2V_{\text{in}} \) through the respective diodes. \( V_{\text{out}} \) is obtained as the sum of the voltage across
the odd capacitors and the ground. Thus we can get the de-
sired dc output across the load. A 3rd order filter circuit con-
sisting of 3 resistor-capacitor units is used to remove the output
voltage ripple and provide a smooth dc [7].

2) Design Equations:
\[
\begin{align*}
E_{\text{out}} &= 2n \times E_{\text{pk}} \\
I_{\text{load}} &= E_{\text{out}} / R \\
C_1 &= C_2 = nC \\
C_3 &= C_4 = (n-1)C \\
V_{\text{drop}} &= n^2 I_{\text{load}} / fC \\
V_{\text{ripple}} &= n I_{\text{load}} / fC
\end{align*}
\]

Where,
\( n \) = number of stages (2 capacitors and 2 diodes form 1 stage)
\( E_{\text{out}} \) = output voltage
\( E_{\text{pk}} \) = peak input voltage
\( I_{\text{load}} \) = load current
\( C \) = capacitance value
\( C_1, C_2, C_3, C_4 \) are the stage capacitances
\( R \) = load resistance
\( f \) = input frequency
\( V_{\text{drop}} \) = drop in output voltage
\( V_{\text{ripple}} \) = output voltage ripple

b) HV Transformer:
Fig. 3 shows a transformer (step up). The transformer used
here has a saturable core with the primary, secondary and
feedback windings wound on it. The primary and feedback
windings are bifilar. The primary input is provided by a pair
of transistors called Royer oscillator. The turns-ratio is de-
signed such that it can provide the required input to the volt-
age multiplier for further multiplication.
1) Working:
A dc supply is connected to the transformer primary center tap (PCT). Another smaller dc voltage is given to the center tap of the feedback winding. The starting and ending of the feedback winding is connected to one of the bases of the 2 transistors through an appropriate resistance value. Practically no two transistors are alike also there will be some inherent noise in the circuit. Due to these reasons one of the transistors will be driven to saturation causing the other to go to cut-off. Say Q1 goes to saturation first. This allows current to flow in the 1st half of the primary winding through P2 to Q2 to ground. During the next moment Q1 goes to cutoff causing Q2 to go to saturation. So now the power flow is through the 2nd half of the primary winding. Thus the transistors undergo a push pull action causing the voltage at the 2 halves of the primary winding to oscillate. Now by the transformer action the secondary voltage is generated. Here in simulation the transistors are identical and no noise is present therefore an external pulse is used to provide the initial trigger to 1 of the transistors. [4]

2) Major Transformer Equations:

\[
\begin{align*}
 n &= \frac{N_s}{N_p} = \frac{V_{out}}{V_{in}} \quad (7) \\
 N_p &= \frac{V_{in} \times 10^8}{2 \times B \times f \times A_c} \quad (8) \\
 N_s &= \frac{V_{out} \times 10^8}{2 \times B \times f \times A_c} \quad (9) \\
 R &= \rho \times \frac{l}{A_w} \quad (10) \\
 A_c &= H \times (OD-ID) \times SF/2 \quad \text{for toroidal core} \quad (11)
\end{align*}
\]

Where,
- \(N_p\) = number of turns of primary winding
- \(N_s\) = number of turns of secondary winding
- \(n\) = turns ratio
- \(V_{in}\) = input voltage
- \(V_{out}\) = output voltage
- \(B\) = flux density
- \(f\) = frequency
- \(A_c\) = core area
- \(R\) = Resistance of winding
- \(A_w\) = area of wire
- \(l\) = path length
- \(\rho\) = resistivity
- \(H\) = height of core
- \(OD\) = outer diameter
- \(ID\) = inner diameter
- \(SF\) = stacking factor

\[c) \text{Generation and Control:} \]
Fig. 4 shows the generation circuit consisting of voltage multiplier, transformer, oscillator and filter. The control part consisting of voltage divider, differential amplifier, and series pass regulator is also shown. The transistor base is connected to the feedback winding. The input dc appears as square pulse which is out of phase at the base of the 2 transistors. Hence the push-pull action starts, giving square pulses to transformer primary. By transformer action voltage is stepped up at the secondary. The output of transformer secondary acts as input to the voltage multiplier. The voltage multiplier multiplies and rectifies the input giving a pulsating dc at its output. This dc is then filtered to give the HV bias. A part of this HV is fed back as one of the inputs to the error amplifier. A reference signal is given as the 2nd input. This reference can be given through a multiplexer if the reference needs to be varied. The error amplifier detects the difference in voltage between its 2 inputs and gives a corresponding voltage to the base of the series pass regulator. As the base bias of this Darlington pair varies the corresponding emitter voltage also varies. The emitter of the pair is connected to the transformer PCT. Thus by the regulator action a voltage corresponding to the reference is given as transformer input. Thus the control action is performed.

V. SIMULATION RESULTS
Fig. 5 is the result obtained while simulating a 2.5 stage voltage multiplier (fig. 2). In figure pink graph shows the input ac signal. Its value is 250V (rms). The green line shows pulsating output dc. The red line shows dc after filtering. Its value is around 1250V dc. Thus voltage multiplication has taken place.

\[V_{out}=2 \times 2.5 \times V_{in} \text{ i.e. } 5 \times 250=1250 \quad (12)\]

The simulation of the whole circuit is shown in fig. 6 and fig. 7. A 5V dc (yellow) is converted into 230V dc. The voltages at the base of the transistors are around 1V and are out of phase. The transformer input is 5V (rms) (blue and green). The numbers of turns of primary and secondary windings are 100 and 1000 thus giving a turns ratio of 10. Hence we get a voltage of around 48V (rms) at the transformer secondary. The voltage multiplier gives a voltage 5 times its input (approx. 230V HV), as shown by the red line.

\[\text{Transformer output}=10 \times 5=50V \text{ (rms)} \quad (13)\]
\[\text{Voltage multiplier output}=50 \times 2.5=250V \quad (14)\]
VI. CONCLUSION

X-ray study is carried out with the help of detectors. There are various types of detectors, each having its own advantages and disadvantage. Many of the detectors need a high voltage bias for their working. In a spacecraft the main source of power is the solar panel or battery. The magnitude of voltage from these sources lies in the lower range; say between 28V to 43 V. Hence it is essential to convert this value to the required HV value (for biasing the x-ray detectors referred earlier) using dc-dc converters. The high voltage unit must work at a low power, must be compact and light in weight. It must also be space qualified to withstand the variations in temperature, pressure and radiation conditions of the outer space. A dc-dc converter satisfying the above criteria has been designed. In the circuit transformer serves as an isolator in addition to stepping up the voltage. The number of stages in the voltage multiplier can be adjusted according to the required voltage. All the components used in the circuit are designed for high reliability and compactness. Thus this design can deliver a high voltage for space applications.

ACKNOWLEDGMENT

The author would like to thank Ramakrishna Sharma, Ravi Kulkarni and Vidya S. Rao for their sincere guidance and support.

REFERENCE