A Compact High Voltage Switch-Mode Power Supply for XRF

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Abstract: This paper describes a high voltage design using Switch Mode Power Supply technique. Silicon-Controlled Rectifier (SCR) was employed as a switching unit. The main improvement consists in stable performance and fine applicability. Less weight, easy to produce install and remove, easy to get the productive material, the simplicities of the power converter and the minimum industrial cost are the main features of the Power supply.

Keywords: High voltage; SCR; transformer; voltage multiplier

1 Introduction

The use of high voltage in scientific and industrial applications is commonplace. Custom designed high voltage power supplies can found in instruments for spectroscopy, medical, capillary electrophoresis, mass spectrometry, electrostatic spraying, lasers, spectrometers, X-ray diffraction, and many other analytical imaging and process applications [1-2]. In the past few years, the method of switch-mode power supply has been chosen to design a high voltage power supply. Higher switch frequencies should be more efficient than conventional linear power supplies, and have yielded small, light, more compact and less expensive power supplies. However, the factors of stability over long period of time, the simplicities of the power converter must be taken into account seriously in designing the high voltage switch-mode power supply [3].

This paper describes the design and testing of a high-voltage switch-mode power supply which operates at a frequency up to 12.5 kHz. SCR was employed as a switching unit. A set-up transformer and the voltage multiplier were used to produce a high voltage DC which is employed in the X-ray fluorescence (XRF) device.

2 Circuit Design

The basic building block of the high voltage power supply is shown in Figure 1. The inverter circuit can be represented by induction L, SCR, fast recovery diode VD1, capacitor C1 and high-frequency set-up transformer T. The SCR was controlled by a pulse-width modulator integrated circuit TL494, where both the duty cycle and the switching frequency can be adjusted.

A Voltage multiplier design consisting of capacitors (C2—C14) and diode (VD2—VD14) was used to generate high voltage DC. The output voltage is detected with the assistance of measuring meter G1 and resistance R1. For the load testing, G2, R2 is used as the ammeter and the load resistance, respectively.

The power supply circuit operates by rapidly switching mode in normal state. A signal from TL494 is sent to drive the switching unit SCR into switching. During the operation of switching, C1 plays an important role in charging and discharging, which induce the critical part of the transforming the DC signal into an AC signal in the transformer primary N1. The details of principle of the converter can be found in Ref. [4]. The AC signal is then passed into the voltage multiplier circuit. By means of combining diodes and capacitors, the circuit converts AC electric power delivered by the
transformer to higher DC voltage with the act of rectifying and smoothing. It is well known that the output of high voltage should increase with respect to the development of stages number of voltage multiplier. On the other hand, as the number of stages is increased, some losses are expected. In the present work, 6 stages of voltage multiplier were selected, and the values of nonpolarity capacitors C2-C14 were chosen to be 2000 pF, corresponding to the voltage drop of 20 kV. The fast recovery high voltage diodes, IN 4007 are used in the voltage multiplier for proper rectifying.

3 Measuring Results

3.1 The waveforms of the SCR

Figure 2 shows the voltage and input pulse waveforms observed at the anode and the gate of SCR under the condition of a switching frequency of 12.5 kHz. These waveforms are typical for the inverter circuit under different operating frequency and DC voltage. One can see from figure 2 that a cycle of oscillation generated by switching SCR, which indicate a proper converting state.

3.2 C-V Curve (R2=100 MΩ)

The measuring results of C-V curve for the power supply are listed in Table 1. The output voltage will increase with respect to the rises of the input voltage. As can be observed in the table, the maximum of efficiency reaches to 87.22% with the frequency of 12.5 kHz. Special attentions were paid to the changing of the efficiency. With the increasing of the input DC voltage, the efficiency of the inverter circuit improved. This result shows that the SCR, whose normal running current is 50 A, will work better under the high voltage and strong current conditions.

Thus, from the results presented in Table 1, the C-V Curve is presented in Figure 3.

C-V Curve is a powerful tool for the analyzing of voltage characterization. The linear relation between the electric current and voltage, shown in Figure 3, indicated the stable performance and fine applicability of the power supply.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Input Voltage (V)</th>
<th>Input Current (A)</th>
<th>Output Voltage (kV)</th>
<th>Output Current (mA)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5</td>
<td>53.70</td>
<td>1.02</td>
<td>68.80</td>
<td>0.6944</td>
</tr>
<tr>
<td>2</td>
<td>12.5</td>
<td>49.61</td>
<td>0.95</td>
<td>63.60</td>
<td>0.6416</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>43.85</td>
<td>0.84</td>
<td>56.00</td>
<td>0.5680</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>39.35</td>
<td>0.76</td>
<td>50.00</td>
<td>0.5050</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
<td>31.75</td>
<td>0.61</td>
<td>40.00</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>12.5</td>
<td>27.34</td>
<td>0.52</td>
<td>34.20</td>
<td>0.3171</td>
</tr>
</tbody>
</table>

3.3 The testing of heavy-duty load (R2=50 MΩ)

To test the load capacity of the power supply, the measurement of heavy-duty load was carried out in one selected point. A value for the input voltage of 48.96 V was selected, which resulted in the output voltage of 56 kV, and the corresponding value of output current was 1.098 mA. The efficiency reaches to 87.82% with the converting frequency of 12.5 kHz. Compared with the light-load condition, one can see that the designed compact high-voltage power supply have strong capability of converting under heavy-duty load condition.

3.4 The relationship between the fall of potential and the load current

The inherent resistance of the voltage multiplier has
considerable influence on the performance of the high voltage supply. For the multilevel voltage multiplier, the relationship between the output high voltage and the electric power from the transformer is given by the formula:

\[ U_{\text{max}} = (2n-1)U_0 \]  

(1)

Where 
- \( U_0 \) is the secondary voltage of transformer T 
- \( n \) is the stage number of voltage-multiplier

And the fall of potential within the voltage multiplier can be calculated from the following equation:

\[ \Delta U = \left[ I / (6FC) \right] (4n^3 + 3n^2 + 2n) \]  

(2)

Where 
- \( I \) is the load current 
- \( F \) is the frequency of operation 
- \( C \) is the value of capacitor

Therefore, theoretical value of potential fall induced by the voltage multiplier was obtained from the equation (2):

\[ \Delta U_{p} = 6.56I(kV) \]  

(3)

This calculated value is in good agreement with our experimental results (not shown here).

4. Conclusions

This paper has dealt with design and construction of a compact high-voltage power supply. The complete supply is packaged in the oil insulator, whose volume is 173×75×240 mm³. The main improvement consists in stable performance and fine applicability. Less weight, easy to produce install and remove, easy to get the productive material are the main features of the Power supply. Based on the long time experience of the experimental testing and in-situ application in the XRF device, the designed high voltage power supply shows the stable and reliable characters, which implies its potential application in many areas.

The design specifications are as follows:
- Output Voltage: 50kV
- Output Current: 0–1mA
- Efficiency: >85%
- Frequency: 12.5kHz

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References