Power Supply of X-Ray Tube to Dental Diagnosis.

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Abstract: **This works presents a design and implementation of a power supply-1kW for a dental X-ray equipment. Initially, some general aspects of the operation and parameters are discussed that have influence in the X-ray tube's efficiency.**

Two types of converters are described as solutions. A design methodology for each stage of the system is suggested.

The experimental results obtained from prototype implemented according to the suggested design procedures are presented, verifying the characteristics and analysis of the proposed structure.

I. INTRODUCTION

A particular application of a high-voltage DC power supply to drive an X ray tube used in an X ray power generator has attracted special interest in medical power electronics. The X ray power generator must have the particular capability to adjust its DC output voltage across an X ray tube in order to assure the best quality image for each specified pattern of body part. Higher output voltages are required so as to diagnose more dense body parts of all types of bones, and relatively lower high voltages may be adequately utilized for diagnosing soft tissues of the organs [1].

The power source of the x-ray tube permits selection of X ray energy (voltage), X-ray quantity (current) and exposure time. The filament circuit supplies the power needed to heat the cathode filament and boil off electrons. The high voltage circuit supplies high voltage needed to accelerate these electrons from the cathode to the anode for production of X ray.

With the evolution of the dental science the need of image equipments for dental diagnosis increased. Due to this fact, switch-mode power supplies have gained considerable attention in this application. Equipment with reduced size are researched and developed. This paper presents a switch-mode power supply of X ray tube equipment of dental diagnosis.

In Fig. 1 show the complete block diagram of power supply for X ray tube.

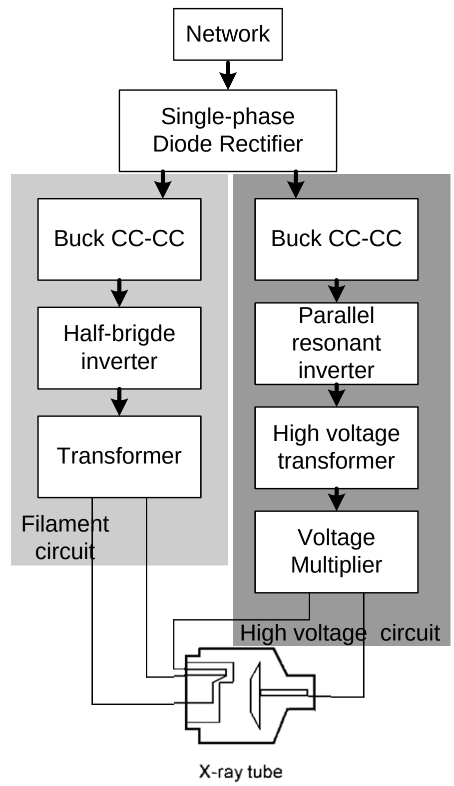

Fig. 1: Block diagram of power source for X ray.

The high voltage circuit is shown to Fig. 2. The capacitor C_r is a parasitic capacitance of high voltage transformer.

The X-ray supply using the parallel resonant inverter type DC-DC converter with voltage multiplier must have the short rising times for various load voltage and current settings. An overshoot of the output voltage may cause the damage of the X ray tube and exceeded exposure. Therefore, the characteristics listed below are essentially necessary for the medical use X ray power generator. [2]

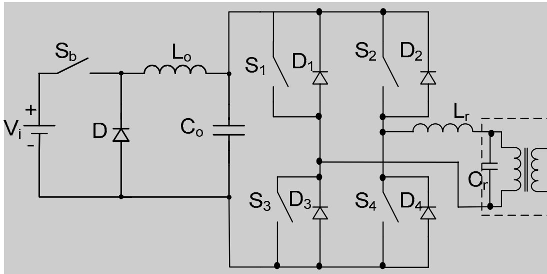

Fig. 2: High voltage circuit.

- The transient responses are as fast as possible in spite of wide variation ranges of load;
- The overshoot of output voltage must not absolutely generate;
- The ripple factor of the converter output voltage is as small as possible in the steady-state for each desired output voltage setting.

The high voltage transformer assembly also includes voltage multiplier for the high voltage circuit. Due to the high potential differences between the high voltage circuit and filament circuit, the transformers and voltage multiplier are usually immersed in oil which serves as an insulator and prevents sparking. The output voltage of voltage multiplier is between 60 kV to 86 kV, and the tube current is between 4 mA to 10 mA.

The filament temperature is proportional with the current though anode and cathode [3]. Thus the filament circuit improves the control of current though the X ray tube. The filament circuit is shown to Fig. 3.

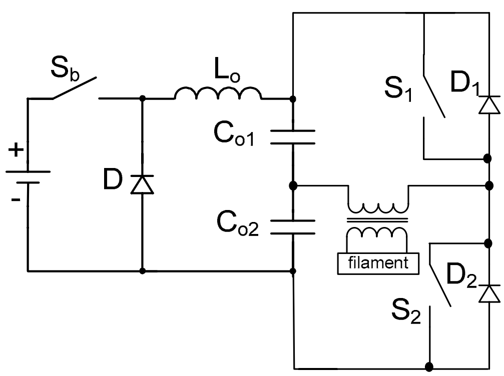

Fig. 3: Filament circuit.

II. HIGH VOLTAGE TRANSFORMER FOR HIGH FREQUENCY

The high voltage transformer for X ray tube has a large turn ratio. Besides, sufficient isolated distance between the primary and secondary windings is practically required to obtain the effective allowable insulation voltage. The electromagnetic coupling coefficient of the primary and secondary windings of the high voltage high frequency transformer is not so high and the parasitic elements are large.

The high voltage transformer model includes the leakage inductance L_d the stray-capacitance C_p and magnetization inductance L_m [4].

Fig. 4 illustrates the model of high voltage transformer for high frequency [5]. C_p is the stray-capacitance of transformer and parallel resonant capacitance of the parallel-resonant inverter.

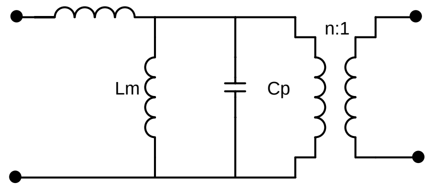

Fig. 4: High voltage transformer model.

Where:
L_d is the leakage inductance;
L_m is the magnetization inductance;
and C_p is the parallel capacitance.

The parasitic elements are determined for the methodology in 5. The transformer impedance was measured with impedance analysis. The results are visualized in the Fig. 5 e Fig. 6.

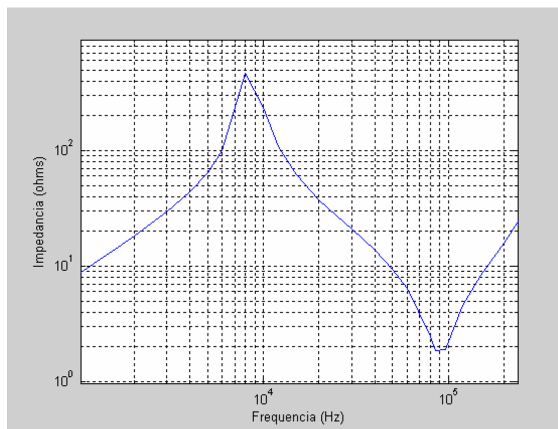

Fig. 5: Measurement of magnitude transformer impedance.

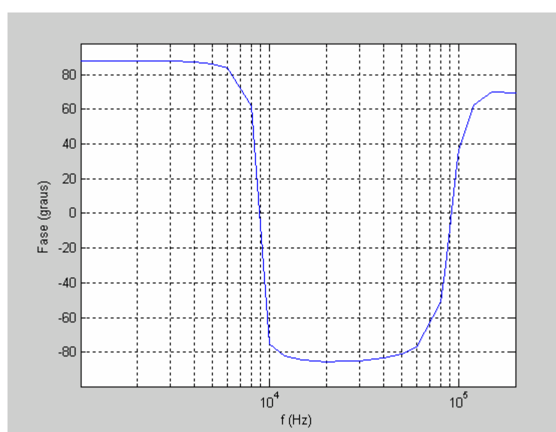

Fig. 6: Measurement of phase transformer impedance.

With the equations (1) and (2) obtained the C_p and L_d values.

$$C_p = \frac{1}{4.\pi^2.f_{op}^{\;2}.L_m} \quad (1)$$

$$L_d = \frac{1}{4.\pi^2.f_{os}^{\;2}.C_p} \quad (2)$$

Where:
f_{os} is series resonance frequency;
f_{op} is parallel resonance frequency.

III. CONTROL STRATEGY

The high voltage circuit has a control loop voltage and the filament circuit has a control loop current. they are used to regulate output voltage and current voltage in the X ray tube. (Fig. 7)

The parallel-resonant inverter and half-bridge inverter uses a fixed duty cycle (open-loop control). The PWM control is applied on the buck converters.

The X ray tube load can be electrically modeled as a variable load resistance circuitry which is determined according to the precise regulation of the filament heating current in the cathode of X ray tube. This filament current can be continuously regulated by filament circuit with a high frequency transformer isolated link [3].

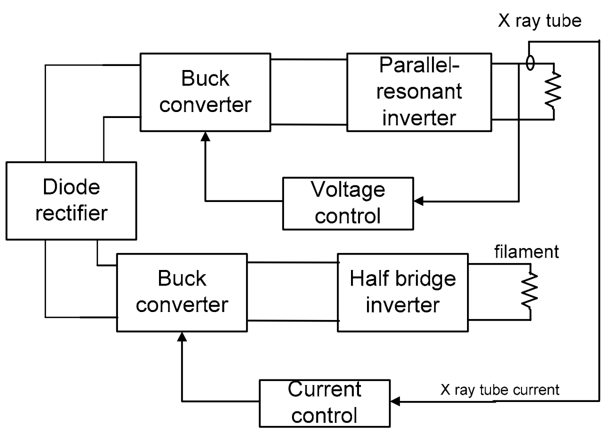

Fig. 7: Complete block diagram of the control loops.

The transfer function of the plant for the voltage loop was obtained using the switch PWM model [7] and can be seen in (3).

$$\frac{V_o(s)}{d(s)} = \frac{(sC_oR_{se}+1)R_oV_i}{a\cdot s^4 + b\cdot s^3 + c\cdot s^2 + d\cdot s + R_o} \quad (3)$$

Where:

$a = C_rR_oL_rC_oL_o;$

$b = C_oL_r(2C_rR_oR_{se} + L_o);$

$c = C_oL_o(R_o + R_{se}) + L_r(C_rR_o + C_oR_{se}) + L_oC_rR_o;$

$d = L_r + L_o + C_oR_{se}R_o$

IV EXPERIMENTAL RESULTS

A laboratory prototype of the power supply of X ray tube to dental diagnosis was implemented to prove the theoretical studies. The design specifications of the prototype can be seen in Table 1.

Table 1: Design specifications of high voltage circuit.

Parameters	Value
Line frequency (f_r)	60 Hz
RMS line voltage (V_{in})	220 V
Rated power (P_o)	1075 W
Minimum rated power (P_{omin})	280 W
Primary transformer voltage (RMS)	200 V
Switching frequency (f_s)	20 kHz
High voltage circuit efficiency (η)	85%
Filament circuit	
output voltage (V_o)	10 V
Rated power (P_o)	50 W
Switching frequency (f_s)	40 kHz

Fig. 8 presents a photograph of the high voltage converter prototype.

Fig. 8: Photograph of the high voltage circuit prototype.

Fig. 9, Fig. 10, Fig. 11 and Fig. 12 show the experimental results of the prototype. The THD of the output voltages were 6.5%. They are nearly sinusoidal in shape.

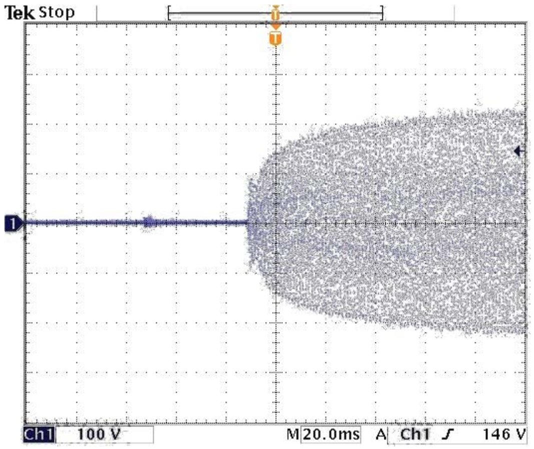

Fig. 9: Primary voltage.

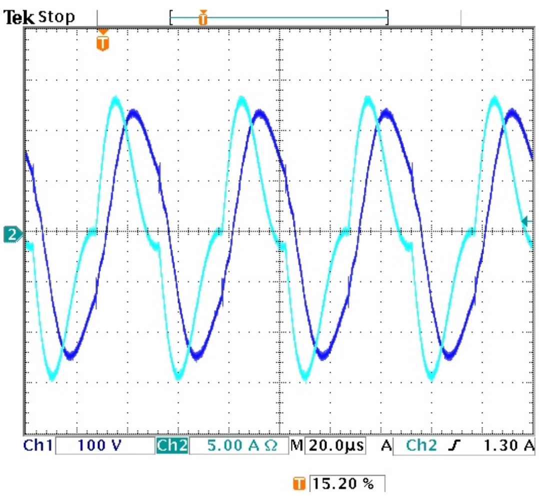

Fig. 10: Primary voltage and primary current.

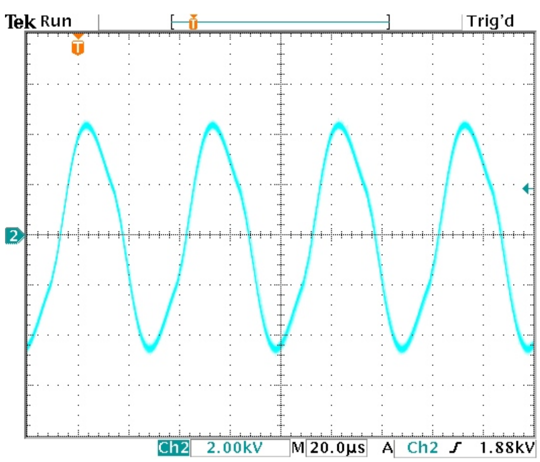

Fig. 11: Secundary voltage.

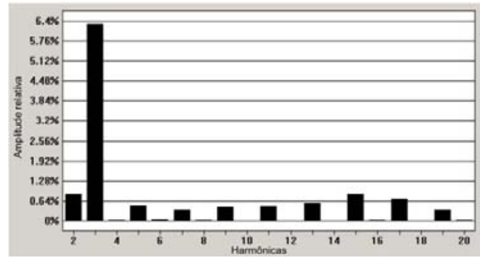

Fig. 12: Normalized output voltage harmonics.

Fig. 13 show the experimental result to verify the performance of the voltage control loop when the converter suffers load variations from 50% of the rated load to 100%.

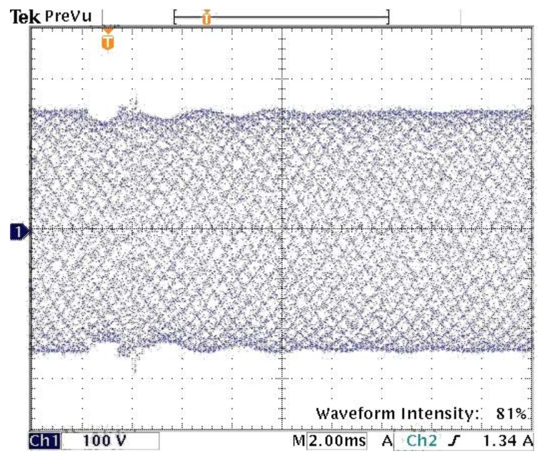

Fig. 13: Output voltage after a 50% increase in the load.

Fig. 14 shows the tested efficiency of the high voltage converter. The efficiency data were measured for an output power range of 25% to 100% of 1050 W. A peak efficiency of 90.0% was obtained at 1050 W.

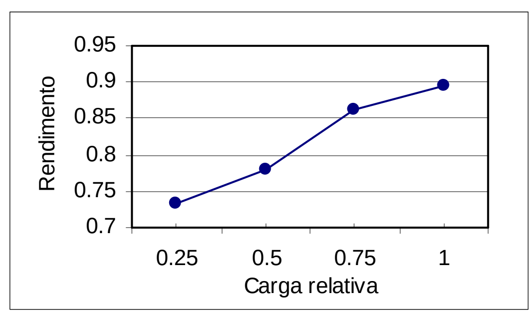

Fig. 14: High voltage converter efficiency.

Fig. 15 presents a photograph of the filament converter prototype.

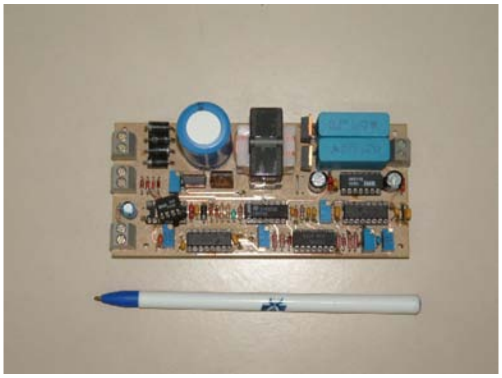

Fig. 15: Photograph of the filament converter prototype.

Fig. 16 and Fig. 17 show the experimental results of the filament converter prototype.

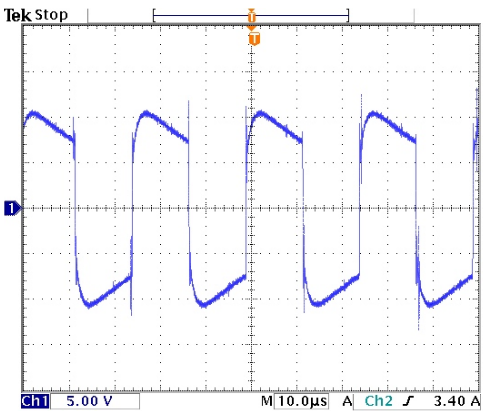

Fig. 16: Output current of filament circuit.

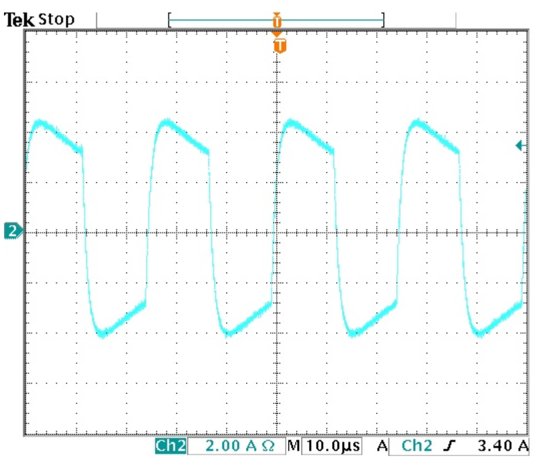

Fig. 17: Output voltage of filament circuit.

Fig. 18 show the experimental result to verify the performance of the filament voltage control loop when the converter suffers load variations from 50% of the rated load to 100%.

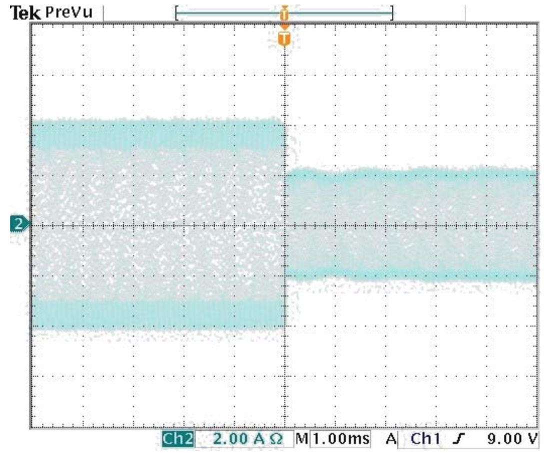

Fig. 18: Output voltage after a 50% decrease in the reference voltage.

Fig. 19 shows the tested efficiency of the filament circuit.

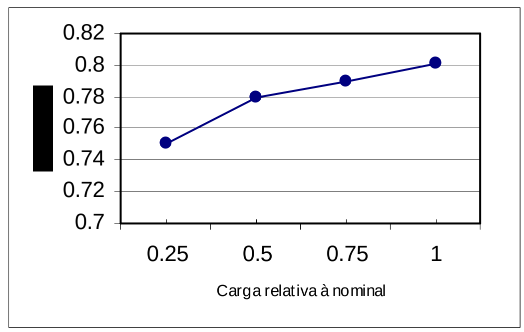

Fig. 19: Filament converter efficiency.

V. CONCLUSIONS

The parallel resonant converter can be easily controlled because of its simple transient characteristics in the open loop scheme. If stray capacitance in the secondary windings of the high-voltage transformers adequately designed, the influences of its harmful leakage inductance can be compensated without any additional resonant component. This converter could operate under zero current soft switching to minimize switching losses of power devices in spite of a wide load variation.

The results obtained with analysis and simulations have been compared. The theoretical and simulation results have been compared with the experimental results. The type of converter control discussed in this paper can be utilized in power supplies for X ray tube.

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