Simulation and Analysis of Pulse Power Supply for Mercury-free Plasma UV-lamp

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***Abstract* - This paper describes about the efficient design of pulse power supply for mercury-free plasma UV-lamp based applications. The single phase AC-DC Unity Power Factor (UPF) converter along with flyback converter is employed to design efficient and high voltage pulse power supply. The system has fixed Pulse Repetition Frequency (PRF), Pulse Duration (T_{on}) and pulse amplitude. Design and analysis of pulse power supply with output voltage of -5kV and output current of 2.5A with PRF (25 kHz) and T_{on} (2 μs), fed from single phase AC voltage is presented. To verify the proposed design, the topology is simulated in MATLAB and simulation results on resistive load are presented in the paper.**

***Keywords* – High voltage supply, Mercury-free plasma UV-lamp, Pulse repetition frequency, Unity power factor.**

I. INTRODUCTION

The mercury-free plasma (MFP) UV-lamp is an emerging technology for sterilization of water, fruits, medical equipment, air-conditioners, air fresheners etc. The design of pulse power supply for MFP UV-lamp based technology is critical as it requires fast rising time, ripple-free output pulsed voltage, intelligent control and high efficiency. The metamorphic development in power electronics technologies and semiconductor devices enhanced the performance of high voltage pulse power supply specially its pulse shape, pulse repetition rate and stability.

The commonly used topology for pulse power generation is based on pulse forming approach. The drawback of this approach are its low impedance matching range, poor output pulse shape, load dependency of output shape, and less durability [1-2]. Treatment of air pollution and ozone generation through bidirectional high voltage pulse plasma power supply using semiconductor switch is proposed in literature [3]. In this type, H-bridge converter followed by high voltage transformer is used. It has low efficiency due to hard switching of semiconductor switches and high output voltage drop. High voltage pulse output generation using solid state devices are presented for high power applications [4-6]. It has advantages of high efficiency, flat output pulse voltage shape and long lifetime. But due to complexity in control algorithm design and requirement of voltage balancing across solid state devices, uses are limited for plasma applications.

A high voltage, high power pulsed power supply for airborne radar tube application utilizing IGBT transistors in a series resonant topology to achieve high power density with variable output voltage operation is demonstrated [7]. Pulse power supply for electrosurgical applications using plasma generator is presented [8]. It uses push-pull topology in combination with resonant network to generate the pulsed output voltage. The advantages of this topology are high operating frequency and the capability to work with reactive as well as non-linear loads. A DC-pulse power supply is demonstrated for reactive sputtering plasma control applications [9]. It uses H-bridge topology and regulated DC sources for various type of output pulse train based on the specific requirements of the plasma processes. A high voltage pulsed power supply based on push-pull topology is investigated for analysing the behaviour of Dielectric Barrier Discharge (DBD) plasma lamp with respect to intensity and power consumption [10]. It has advantages of controlling the output pulsed voltage level and operating frequency.

Controlled high voltage pulsed power supply having flexibility of load current measurement during treatment process for plasma nitriding application is presented [11]. It uses microcontroller based feedback system to prevent over current caused by arc discharge in the system. Power supply for plasma DBD system using multilevel converter topology is reported [12]. It uses modular DC-DC boost and DC-AC converter and has flexibility of changing the output voltage and operating frequency. A highly efficient and portable high voltage pulsed power supply using switch mode power converters is demonstrated for driving plasma focus devices [13]. It has the flexibility of operating in repetitive discharge mode at specified operating frequency. The charging process of capacitor bank is independently controlled through graphical user interface for safety purpose.

In this paper, simulation and analysis of a robust and efficient pulse power supply for MFP-UP-lamp technology is presented. Continuous pulse output voltage of -5kV with Pulse Repetition Frequency (PRF) of 25kHz and Pulse Duration (T_{on}) of 2μs has been achieved. It has the advantages of flat output voltage shape, low harmonic content in the line current, unity power factor, high efficiency and long lifetime.

II. SYSTEM DESCRIPTION

The schematic diagram of high voltage pulse power supply for MFP-UP-lamp technology is shown in figure 1. It consists of single phase AC-DC UPF converter, pulse generation unit, high voltage pulse switching network and high frequency step-up transformer.

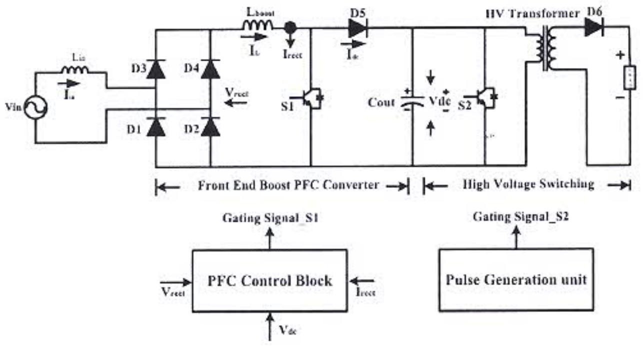

Fig. 1. Schematic diagram of plasma pulse power supply

The basic function of AC-to-DC boost converter stage is to convert the single-phase AC input voltage to a regulated DC voltage and Power Factor Correction (PFC) control block maintains the input current drawn from system sinusoidal and in-phase with the input voltage. The pulse generation unit is used to generate gating signal with Pulse Repetition Frequency (PRF) of 25kHz and Pulse Duration (T_{on}) of 2µs for high voltage switching module. High voltage switching module switches the regulated DC voltage to generate pulse of required width and repetition rate. High-voltage and high-frequency transformer is used to step-up the voltage at required level and to provide isolation.

III. DESIGN AND CONTROL CONFIGURATION

The required system specifications of high voltage pulse power supply for MFP-UP-lamp technology are listed in the table I.

TABLE I

SPECIFICATIONS OF THE PULSE POWER SUPPLY

Parameters	Ratings
Input AC voltage (V_{RMS})	(180-260)VAC
Rated output power (P_{out})	625W
Targeted Power factor (pf)	0.99
Single phase output voltage (V_{dc})	500VDC
Targeted THD	≤ 5%
Pulse output voltage (V_{pulse})	-5kVp-p
Pulse output current (I_{pulse})	2.5Ap-p
Pulse repetition frequency (PRF)	25kHz
Pulse width (T_{on})	2µs
Duty ratio	5%

A. Front-End Boost PFC Converter

Single-phase diode bridge rectifier is a PWM based continuous conduction mode (CCM) AC-to-DC UPF converter. It consists of line inductor (L_{in}), diode bridge (D1-D4), boost inductor (L_{Boost}), semiconductor switch (S1), diode (D5) and dc filter capacitor (C_{out}). The control configuration of AC-DC UPF boost converter is shown in figure 2.

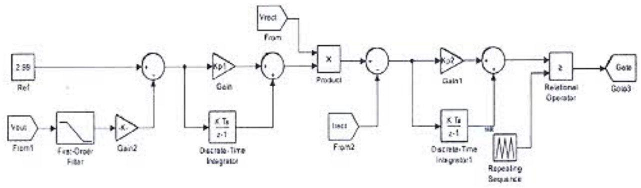

Fig. 2. Schematic diagram of control configuration

Average current mode control (ACMC) is one of the standard method used in AC-DC boost UPF converter. It is a two-loop control technique viz. inner and outer control loop. Inner control loop is used for correctly tracking the semi-sinusoidal waveform at twice the input frequency. Outer control loop is used to regulate the rectified DC output voltage irrespective of variations in input supply. The bandwidth of inner control loop is higher and runs at faster rate as compared to voltage loop.

B. High Voltage Switching

The high voltage switching unit consists of semiconductor switch (S2), high-voltage and high-frequency transformer (HVHF) and diode (D6). It switches DC voltage to generate pulse of required width and repetition rate. The high-voltage and high-frequency transformer is used to step-up the voltage at required output level and to provide isolation in the system. The schematic diagram of high-voltage and high-frequency transformer is shown in figure 3.

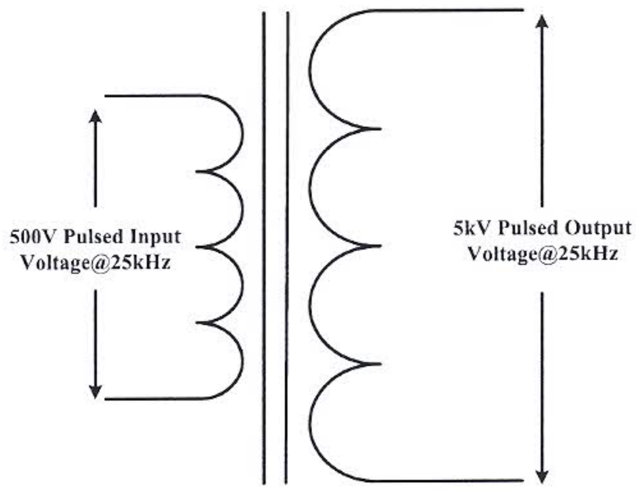

Fig. 3. High voltage and high frequency transformer

C. *Pulse Generation Unit*

The PWM pulses for high voltage switching network at specified PRF and pulse width is provided through pulse generation unit. The schematic diagram of pulse generation unit is shown in figure 4.

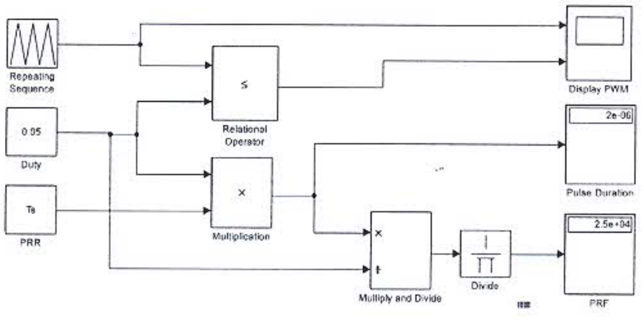

Fig. 4. Schematic diagram of pulse generation unit

IV. SIMULATION MODEL AND RESULTS

The high voltage pulse power supply for MFP-UP-lamp technology is simulated in MATLAB-Simulink-based environment for validation of the design. The designed component values used in simulation are presented in table II.

TABLE II

COMPONENTS USED IN THE SIMULATION

Components	Value
Boost Inductor (L_{Boost})	2.5mH
DC filter capacitor (C_{out})	600μF
Input filter inductor (L_{input})	10μH
HV transformer turns ration ($N_1 : N_2$)	19:200

The simulation model consisting AC-DC front-end UPF converter, control algorithm and high voltage switching unit to achieve -5kV, 2.5A pulse output system is shown in figure 5.

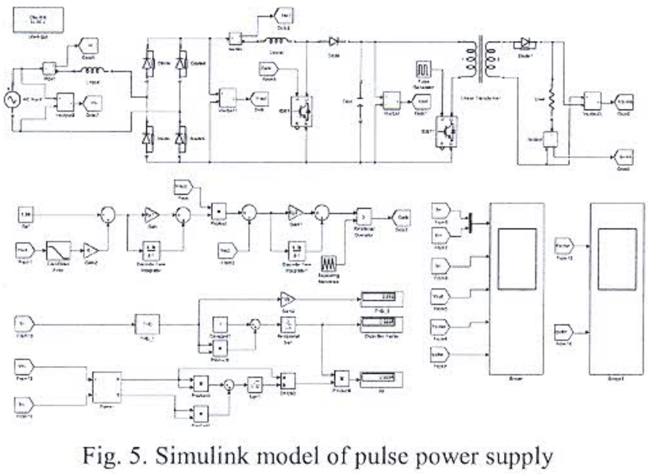

Fig. 5. Simulink model of pulse power supply

The harmonic spectrum of grid current is shown in figure 6 and the observed THD is 3.15%, which is well below the specified limit in IEEE-519 standard.

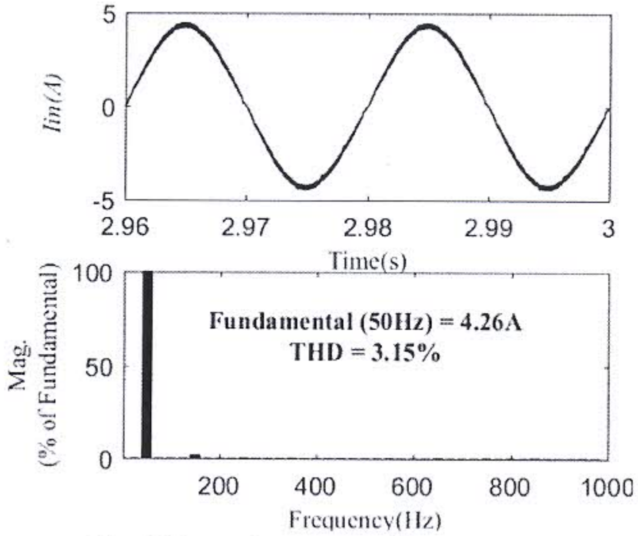

Fig. 6. Harmonic spectrum of input current

The steady-state response of pulse power supply for MFP-UP-lamp technology at resistive load is presented in figure 7 and it shows the input voltage, input line current with PFC operation and regulated DC voltage waveforms.

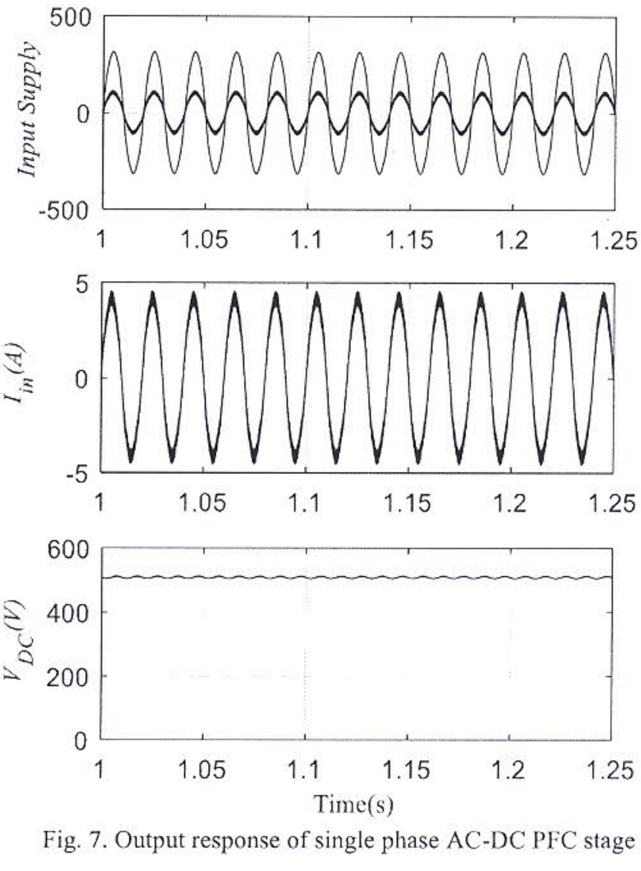

Fig. 7. Output response of single phase AC-DC PFC stage

The power factor has been analyzed with variation in output power. It is observed that over the wide range of output power, the power factor varies from 0.9770 to 0.9994 for 10-100% of full-load. The graph between percentage load and power factor is shown in figure 8.

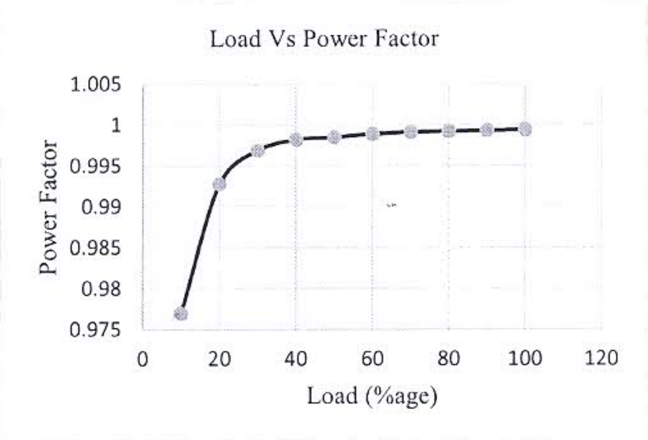

Fig. 8. Variation of power factor with respect to load

The input voltage of the high-voltage and high-frequency transformer is shown in figure 9. The pulse output voltage and current at rated power level having pulse repetition frequency of 25kHz and pulse duration of 2μs is shown in figure 10. The observed pulsed output voltage and current are -5kV, 2.5A peak respectively.

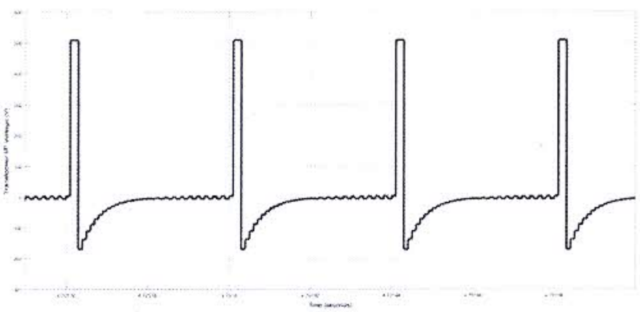

Fig. 9. Input voltage of high-voltage transformer

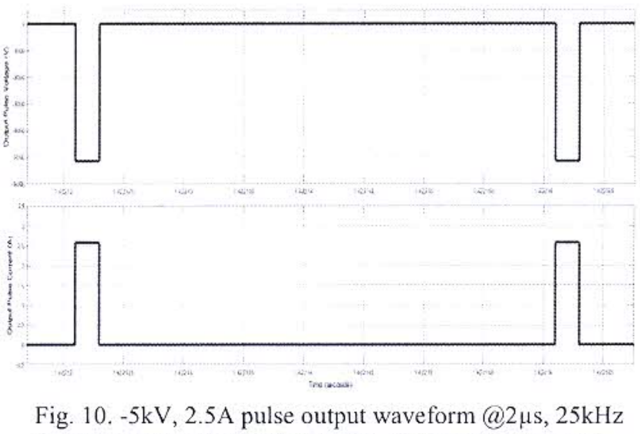

Fig. 10. -5kV, 2.5A pulse output waveform @2μs, 25kHz
Scale: X axis 1 unit=10μs; Y axis 1 unit=1kV and 0.5A

CONCLUSION

A comprehensive analysis and simulation of high voltage pulse power supply for MFP-UP-lamp technology with applications in sterilization of water, fruits, medical equipment, air-conditioners, air fresheners agricultural is presented. ACMC technique operating in continuous conduction mode is used for PFC converter stage. The output DC voltage (V_{dc}), power factor and harmonic contents produced in PFC converter are evaluated and analysed. The power factor varies in a narrow range from 0.9770 to 0.9994 with wider load power variation (10-100% of load power). The measured pulse output voltage and current having pulse repetition frequency of 25kHz and pulse duration of 2μs current are -5kV, 2.5A peak respectively. The system control performance in steady-state operation has been evaluated on a resistive load and it has been observed that system is stable for wider load range.

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