Design and temporal control study of multi-LC network medical Intense Pulsed Light (IPL) system

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Dr. Walid K. Hamoudi
Laser Physics Division, Applied Sciences Department, University of Technology/Baghdad.
Email: wjuaini2007@ yahoo.com
Dr. Raid A. Ismail
Laser Physics Division, Applied Sciences Department, University of Technology/Baghdad
Hussein A. Shakir
Laser Physics Division, Applied Sciences Department, University of Technology/Baghdad

Abstract

Intense Pulsed Light systems employ flash lamps as optical sources to provide the required light intensity with certain temporal profile for use in a large number of medical applications; namely, the aesthetic ones. Driving a flash lamp requires high voltage DC power supply, capacitive energy storage, and flash lamp triggering unit. Single and double-mesh discharge and triggering circuits were designed and built to provide intense light pulses of variable time durations. Variable energy and duration intense light pulses needed in aesthetic medical applications were obtained. The system was treated as RLC circuit with a light pulse profile follows the temporal behavior of the exciting current pulse. Distributing the energy delivered to one lamp on to a number of LC meshes permitted longer current pulses, and consequently, increased the light pulse length and shortened its current rise time.

Keywords: flash lamp, light pulse length, current pulse, single-mesh, double-mesh, trigger.

تصميم و دراسة السلوك الزماني لمنظومة النبضة الضوئية الطبية عالية الشدة المكونة من شبكة (المحاثة-السعة) متعددة المراحل

الخلاصة

توظف منظومات النبضة الضوئية عالية الشدة مصابيح وميضية، كمصادر ضوئية، لتجهيز الشدة الضوئية المطلوبة عند أمد زمني معين لاستخدامها في العديد من التطبيقات الطبية، وبالخصوص عمليات التجميل. يتطلب تشغيل المصباح الوميضي مجهز قدرة مستمر ومتسعة خزن ووحدة قدح. تم تصميم وبناء مجهزات قدرة تعمل بشبكة (محاثة - سعة) مفردة ومزدوجة من أجل توليد نبضات ضوئية ذوات امد زمني مختلف. أوضحت النتائج المستحصلة توليد نبضات ضوئية مختلفة الطاقة والامد الزمني والتي تتطلبها التطبيقات الطبية في التجميل. تم معاملة المنظومة على انها دائرة (مقاومة - محاثة - سعة) تجهز نبضات ضوئية تتبع السلوك الزمني لنبضة تيار الضخ. أن توزيع الطاقة المجهزة لمصباح منفرد على مراحل (محاثة – سعة) قد سمح في الحصول على نبضات تيار طويلة وبالنتيجة على نبضات ضوئية طويلة الامد بزمن نهوض قصير.

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

INTRODUCTION

Intense light pulses are used to pump solid and liquid lasers [1] and also directly in the dermatological applications. Different light pulse lengths are required to treat different biological tissues. Laser and intense pulsed light (IPL) devices are used routinely by healthcare professionals for aesthetic applications [2]. The temporal pulse length has a decisive role in efficacy of the response biological tissue [3]. For optimum conditions, the light pulse duration has to be equal or slightly shorter than the thermal relaxation time of the targeted tissue. Flash lamp is a gas-discharge device that behaves firstly as an initial infinite resistance and then a negative dynamic resistance during the electrical discharge phase [4]. The lamp usually used as a pumping source for solid state lasers is linear xenon flash lamp which is capable of emitting a large amount of spectral energy in short duration times [5]. Xe flash lamp is a relatively efficient device as it converts 40 to 60% of the electrical input energy into radiation [6]. Flash lamps are usually operated from a single - or multiple-mesh *LC* network. The network stores the discharge energy and delivers it to the lamp in the desired current pulse shape [7]. So, the power supply accumulates the electrical energy in a capacitor bank. When a high voltage pulse is produced by the flash lamp triggering circuit and delivered to the external envelope of the lamp, the lamp becomes ionized and conductive. The stored energy is released and dissipated through the lamp immediately. It produces highly excited Xe plasma within the flash lamp and it is flashing. After that the lamp extinguishes and returns to its non-conductive state [8]. The emitted pulsed light covers a wide spectral range from ultraviolet (UV) to infrared (IR) [9]. High voltage power supply, based on a modular HV converter, was designed for millisecond long-pulse applications. It was phase shifted (low ripple) and running at 95% full load efficiency with less than 10 J of stored energy at the maximum voltage [10]. A variable (0.1-3 kV) voltage supply with variable pulse duration (0.1-2 ms) was developed using a high voltage (MOSFET) switch. The variable pulse duration was achieved by varying the turn off delay time while the pulse amplitude was controlled by adjusting the biasing supply of switch [12]. A high-frequency 25 kHz, high-voltage 35 kV (HFHV) pulse power supply, which adopts series-parallel resonant converter topology, was reported. Switching frequency and duty cycle were utilized to deal with the high output voltage [13]. Flat-top high-voltage (HV) pulsed power converters system was reported. 1% stability was experimentally achieved with a simple Proportional-Integral-Derivative regulation [14]. To confirm profile correlation between light and its corresponding electrical current pulses, time resolved spectral data of IPL outputs was employed to characterize the emitted light pulses [15]. In the present work, a single and double-mesh pulse forming networks were constructed. The current discharge profile through the Xe lamp was measured and compared with its pulsed light. The measurements were recorded and stored on a digital storage oscilloscope.

Experimental Work:

A linear Xe flash lamp with an arc length of 11 cm and a bore diameter of 1 cm was employed. A variable high voltage DC power supply up to 1 KV was designed to charge the energy-storage capacitor bank. The amount of electrical energy delivered to the lamp was 260 J. The triggering was done externally by a 10 KV high voltage pulse circuit. The current flowing through the lamp during flashing was found by measuring the voltage drop across 70 mΩ resistor; connected in series with the lamp. AT-C403, 10:1 ratio probe was coupled to 200 MHz, UNI-T/UT2202C digital storage oscilloscope to measure the voltage. The light pulses from the lamp were captured and observed by using a reversed biased (400 – 1100 nm), Hamamatsu (S875-16R 4F) Si-photodiode connected to the oscilloscope. Fig (1) shows the designed single-mesh electrical discharge circuit. The pulse forming network was constructed from a single capacitor $(C = 680\ \mu F)$ and a single inductor $(L = 489\ \mu H)$. Here; the bank capacitor was charged to a voltage of 900V.The trigger capacitor voltage was 180 V. The voltage from an AC transformer was doubled, rectified by a full-wave voltage doubling circuit and then controlled by incorporating an AC voltage controller. The resistors (R3 – R7) have two important roles: to provide the trigger capacitor C3 with sufficient amount of voltage, and to behave as bleeding resistors when the switch S1 is opened. After charging the capacitor bank to a specified voltage, the trigger capacitor is also charged through the potential divider to a specified voltage. The high voltage pulse in the secondary winding of the trigger coil is supplied to the external envelop of the flash lamp. At this time, the Xe gas becomes ionized and conductive. This would make the capacitor bank to discharge through the lamp and produce flash light.

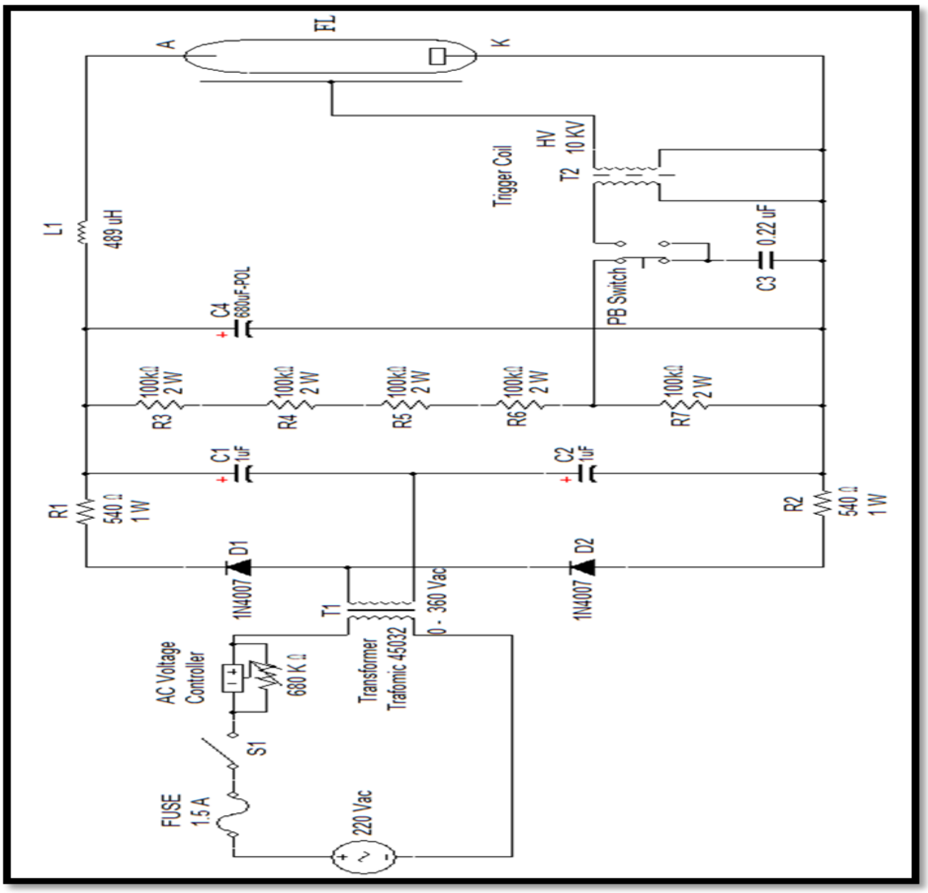

Figure (1): Single-mesh discharge circuit

The same power supply of Fig (1) was used in the double-mesh circuit; but with two LC networks connected in series. The capacitance per mesh was $680\ \mu F$ while the values of the inductances where
$(L_1 = 489\ \mu H\ and\ L_2 = 470\ \mu H)$ Fig (2) illustrates the circuit diagram of the double-mesh discharge circuit.

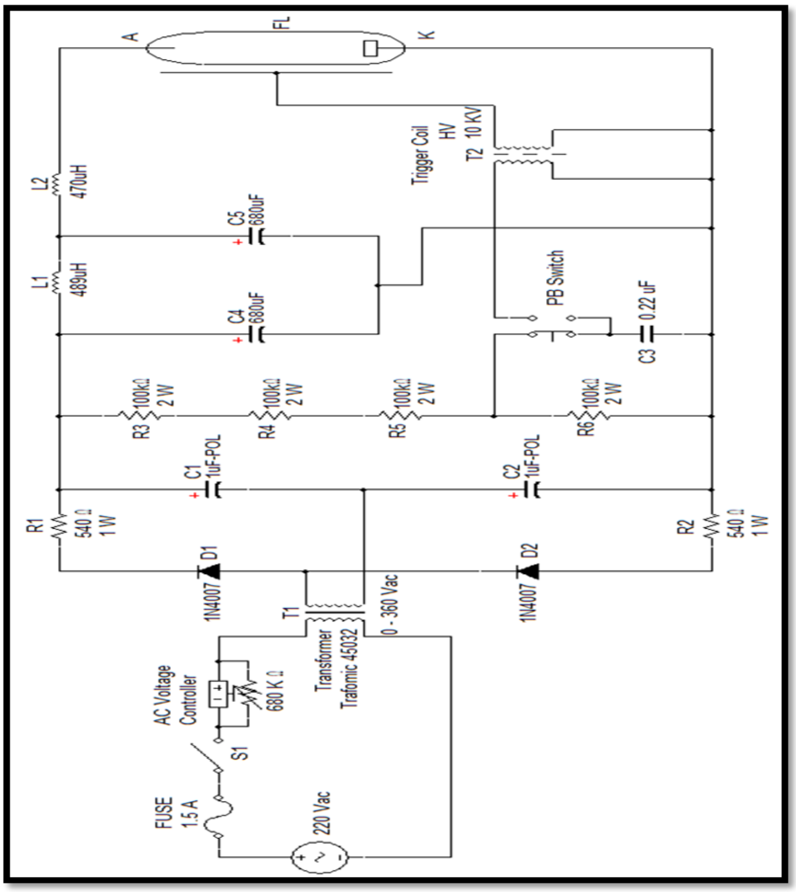

Figure (2): Double-mesh discharge circuit

Results and Discussions:

To maintain the same amount of energy delivered to the lamp in the single LC circuit, the bank capacitors of the double mesh circuit were charged to a voltage of 636V. The lamp used in this work was within the criteria $\left(10 \le \frac{l}{d} \le 20\right)$ where l and d are the arc length and the bore diameter of the lamp used respectively. This means that this lamp is characterized with high internal impedance and long discharge duration [15], a choice that goes well with the objectives of this work. The lamp was filled with Xenon as a gas-fill with pressure at 450 Torr. The final selection of the discharge circuit parameters depends on the commercially available components rather than on the exact calculated values. Favorable characteristics of IPL devices are a large capacitor bank to allow a constant current delivered to the flash lamp and thus; the emission of a nearly square-shaped pulse [7]. Despite their large tolerances, all capacitors used in the discharge circuits were electrolytic capacitors because of their good insulating characteristics and larger capacitance values and voltages durability. Fig (3) shows in a block diagram the complete design of the electrical circuits for the flash lamp operation in which the trigger unit is dependent upon the DC power supply.

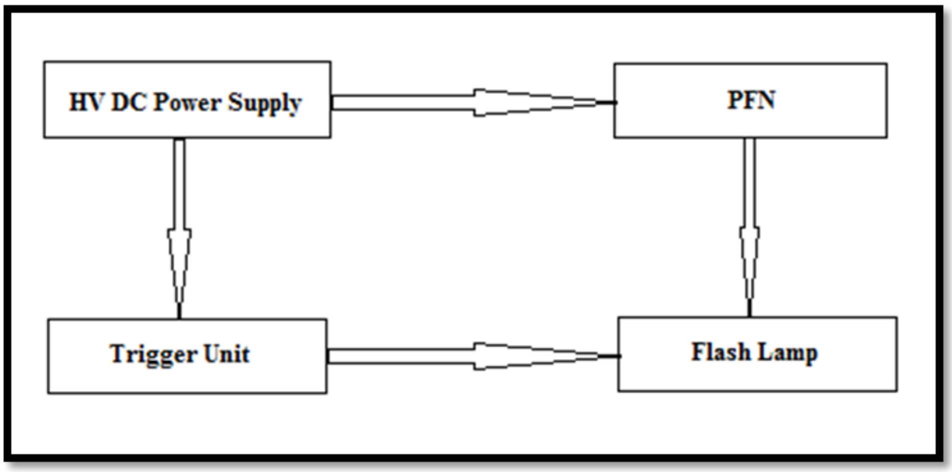

Figure (3): Block diagram of the flash lamp driving electrical circuit.

Fig (4) shows two pulses; the light pulse emitted from the flash lamp (upper) and the voltage waveform (lower) from a single-mesh discharge circuit across a 70 mΩ resistor connected in series with the flash lamp.

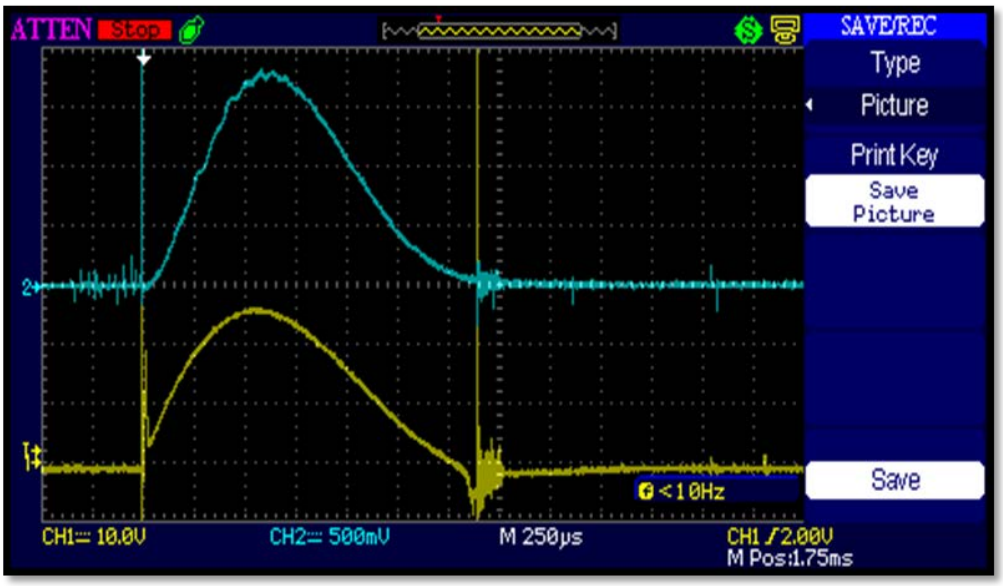

Figure (4): The voltage waveform across the 70 mΩ resistor (lower trace) and the light waveform of the single-mesh discharge circuit (upper trace), (*horizontal*) 250 µs/div; (*vertical*) 10, 0.5 V/div respectively.

In Fig (4), the voltage (or current) pulse duration t_p and the light pulse length $t_p{}'$ were measured at 10% points of the peak amplitude. It was found that $t_p = 1.425\ ms\ and\ t_p{}' = 1.325\ ms$. The peak discharged current can be measured simply by applying ohm's law [16], and it was found that $i_p = 370\ A$. The measurements associated with the double-mesh discharge circuit are presented

in Fig (5). For the double-mesh discharge circuit, the current pulse duration $t_p$was measured at 70% points of the peak amplitude while the effective light pulse length $t_p{}'$ was measured at 50% points. So, it was found that $t_p = 1.5\ ms, t_p{}' = 1.4\ ms$ and $i_p = 257\ A$. Here; the lamp was pumped with the same amount of energy delivered to the single-mesh discharge circuit (260 J), but at lower charging voltage (636 V). The lowering of the voltage was compensated by doubling the value of capacitance. Wherein the amount of electrical energy delivered to the lamp is $\left(E = \frac{1}{2}CV^2\right)$ [17]. For this reason, i_p of the double-mesh was lower than that of the single-mesh and this gave rise to the lamp resistance.

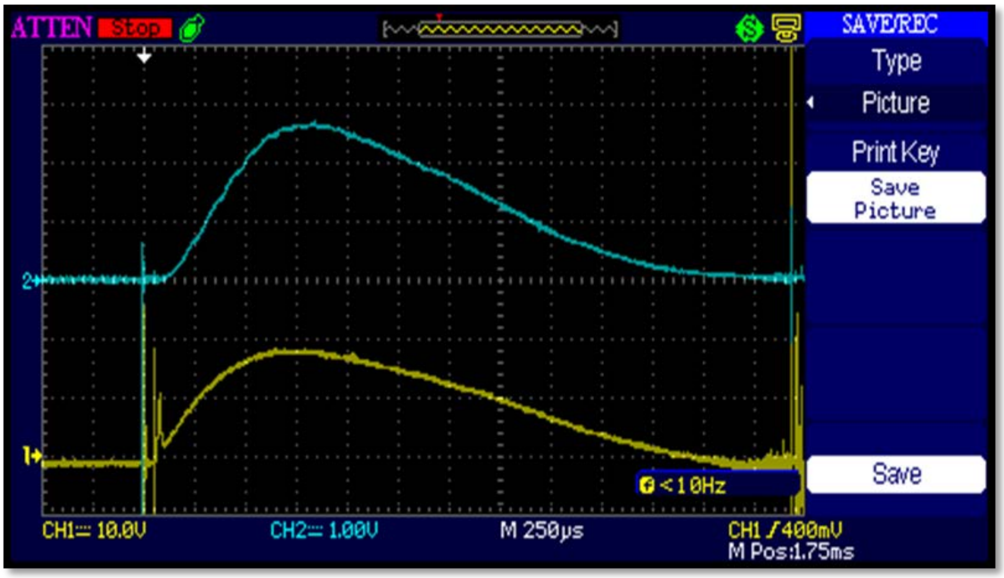

Figure (5): Voltage waveform across 70 mΩ (lower trace) and light waveform of double-mesh discharge (upper trace), (*horizontal*) 250 µs/div; (*vertical*) 10, 1 V/div respectively.

Conclusions:

In the present work, maximum power transfer from a pulse forming network (PFN) to a load (flash lamp) was optimum when impedances were matched. The emitted pulsed light from a lamp followed the profile of its pulsed current. The optical pulse duration emitted from a lamp was equal or slightly shorter than the current. An increase in the number of meshes, with the same amount of energy delivered to a lamp has increased the current pulse duration; consequently, it increased the light pulse length.

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