A COMPACT BATTERY-POWERED 500kV PULSE GENERATOR FOR UWB RADIATION *

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Abstract

Many applications involving compact and portable systems for generating high power electromagnetic fields depend on the enabling pulsed high voltage technology. This paper describes a system that is able to produce nanosecond rise time pulses with voltage exceeding 500kV. It is based on a pulsed resonant Tesla transformer, and requires also a pulse forming line, a fast spark–gap output switch, and an antenna. After dealing with the system design and various measurement results, the paper suggests means by which improvements to the existing system could be made.

I. INTRODUCTION

Electrical pulse generators capable of producing very high voltage outputs (>100kV) are a key element in a range of research activities, particularly in the areas of particle and plasma physics [1]. There are two established techniques by which fast rising pulses can be produced, one using pulse transformers and the other based on Marx generator type circuits. Pulse transformers have a number of significant advantages e.g. design simplicity, compactness and cost effectiveness, and although the output voltage has a slower rise time this can be improved by the use of a pulse forming line (PFL) in conjunction with a fast spark gap switch (FSG). High voltage transformers however require considerable insulation between the primary and secondary windings, which inevitably reduces the magnetic coupling and lowers the total energy transfer efficiency. In order to overcome this problem, the transformer can be designed as an oscillating LC circuit operating in a pulsed resonant mode [2,3]. By this means maximum energy is transferred to the load only after a number of resonant half cycles following closure of the primary circuit. Transformers operating in this mode are often referred to as Tesla transformers.

This paper presents a simple, compact and portable pulsed generator in which a Tesla transformer is the key element. The work was undertaken by the Plasma and Pulsed Power Group (P^3G) at Loughborough University in conjunction with Dstl, UK, for the production of UWB radiation [4,5]. Results of various measurements are presented and discussed, and possible improvements to the overall system are proposed.

II. SYSTEM DESCRIPTION

Fig.1 shows a schematic of the system, with the key elements highlighted.

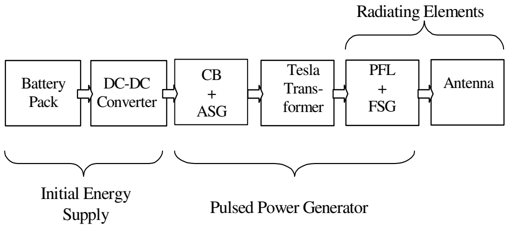

Figure 1. Main elements of the generator system.

The initial energy supply for the system consists of a battery pack for which commercially available and rechargeable sealed lead-acid batteries (12V, 4Ah) are used. A 60W DC–DC converter amplifies the battery voltage up to about 30kV, to charge a 24nF capacitor bank (CB) consisting of twelve 2nF, 30kV capacitors. The single turn primary winding of an air-cored pulse transformer is fed from the bank through a 2-electrode pressurized air spark gap (ASG) switch and a short flat transmission line. The breakdown voltage of the spark gap is 15kV when operated at atmospheric pressure, but this can be raised to 32kV by pressurizing to 150kPa.

The total inductance L_p of the transformer primary circuit is about 220nH. To ensure good insulation and coupling with the primary winding, while avoiding electrical breakdown the multi-turn secondary is wound on a

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conical polyethylene mandrel immersed in transformer oil. The total inductance L_s of the secondary circuit is 75μH and the primary/secondary mutual inductance, M is about 2.1μH, giving an overall transformer coupling coefficient of ~0.52. Design of the Tesla transformer involved the use of an accurate filamentary model developed at Loughborough University [6], which predicted inductance values reasonably close to those actually measured.

The pulse transformer is operated as a Tesla transformer, having two inductively coupled damped resonant circuits as shown in Fig. 2 [1], where R_p the primary resistance is about 90mΩ and R_s the secondary resistance is about 10Ω. The total capacitance of the secondary circuit C_s, including the oil filled PFL, is about 60pF.

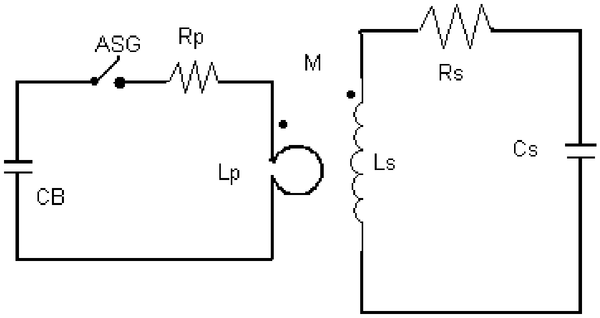

Figure 2. Circuit diagram for pulse generator.

Fig. 3 presents a schematic of the experimental system. A coaxial PFL is integrated in the secondary circuit of the transformer, in such a way that the inner conductor of the PFL is at the top of the secondary winding. Transformer oil is used as both a dielectric and an insulating medium for the PFL.

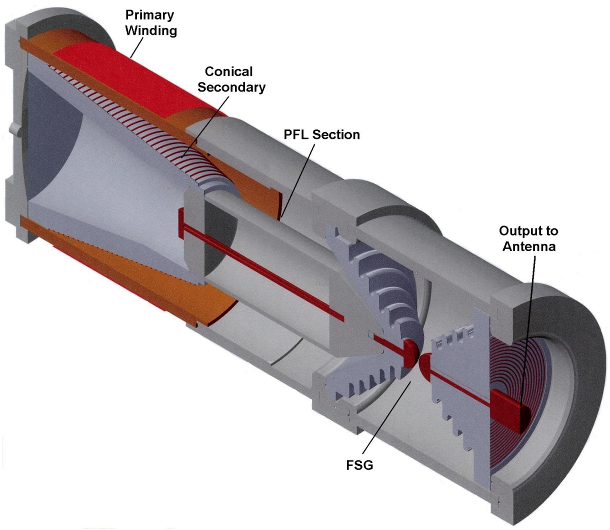

Figure 3. Schematic of the system (excluding initial energy supply, CB and antenna).

Figure 4. Overall view of the system.

Closure of the 2-electrode SF_6 pressurized FSG switch on the output side of the PFL enables electromagnetic power to be delivered to an antenna. The inter electrode gap of the FSG is 6mm, with the hold-off voltage controlled by gas pressure. To minimize the volume of the system, an omni-directional half wavelength dipole-type structure is used as a transmitting antenna, since this is both compact and radiation efficient. The length to diameter ratio of a dipole affects its bandwidth [7], and for wideband operation a ratio of about 10 was chosen. An overall view of the experimental system is shown in Fig. 4.

III. MEASUREMENTS

A. *Voltage Measurements*

The voltage across CB was measured during experiments by means of a commercially available 100kV probe. A capacitive divider, calibrated in situ using a commercially available 1MV probe, monitored the open-circuit secondary voltage across the PFL capacitance. Recordings of the CB voltage and the corresponding secondary voltage are shown in Fig. 5 for single-shot firing of the generator.

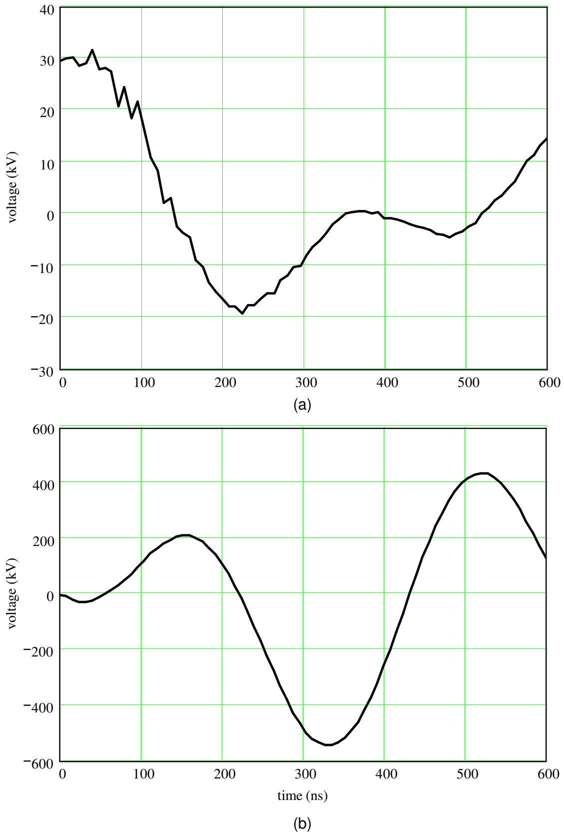

Figure 5. (a) CB voltage and (b) open secondary voltage waveforms during single-shot testing of the pulse generator.

It can be seen from the results in Fig. 5 that, with a primary charging voltage of 29.8kV, the open secondary voltage is 542kV, giving a voltage gain for the pulse transformer of approximately 18. The primary/secondary energy transfer efficiency of the transformer [2] is about 83%, although a higher coupling coefficient between the transformer windings will clearly raise this figure. Fig. 6 presents results for the pulse generator when tested in a repetitive mode with a pulse repetition frequency (PRF) of 200Hz. For these tests the CB charging voltage was reduced to prevent the secondary voltage from exceeding 350kV, and the battery pack and DC – DC converter were replaced by a more robust 3kW mains operated power supply. Even at this high PRF no insulation breakdown occurred in either the Tesla transformer or the PFL. The waveform measurements in the single-shot mode were obtained using a 300MHz digitizing oscilloscope, and in repetitive mode by using a 4GHz, 20GS/s digitising oscilloscope with 1 million points per sweep.

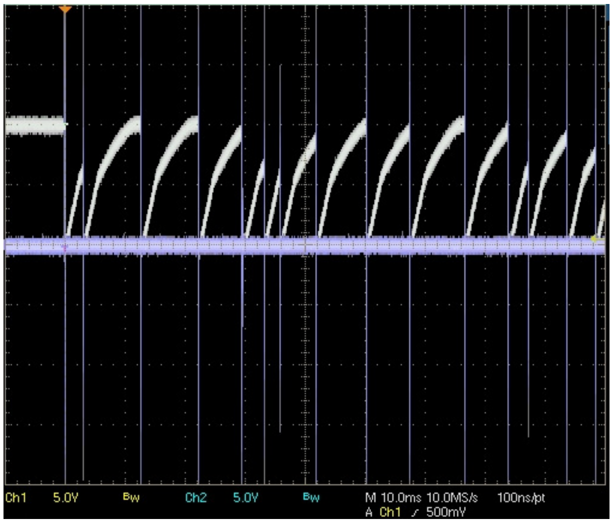

Figure 6. Voltage measurements (as in Fig. 5) in repetitive mode (PRF 200Hz, CB charging voltage of 20kV). For each cycle, the primary voltage is shown as a thick short trace while the secondary voltage is shown as a thin trace.

B. *Radiated Field*

The system was mounted on a mobile platform and radiation measurements obtained in open space far from potentially reflective objects. Time domain field waveforms were obtained using a biconic antenna as a field probe [8], since the resulting output signal $v(\tau)$ from this antenna into a 50Ω termination is related to the time variation of the incident electric field $E(t)$ using

$$E(t) = \frac{1}{n}\int_0^t v(\tau)d\tau \qquad (1)$$

where $n = \frac{3}{2}r^2\frac{\cos\theta}{c}$ in which r is the radius of the sensor, θ is the half angle of the antenna cone and c is the speed of light in vacuum. As shown in Fig. 7, the sensor is mounted on the top plate of a Faraday cage and is insulated from the metal plate which serves as the ground plane. Inside the Faraday cage a 50Ω high frequency coaxial cable connects the sensor to a battery powered digitizing oscilloscope. Fig. 8 shows the measured electric field 3m from the source in single-shot mode, when the pressure inside the FSG is set to 375kPa to give a breakdown voltage of about 250kV. The whole system was also tested in a repetitive mode with a PRF of 5Hz.

A figure of merit (FOM) that serves as a useful measure of the system's performance as an UWB radiator is that given by the ratio of the range normalized electric field to the operating voltage of the pulse generator driving the antenna i.e. RE_{rad}/V_{op}. The FOM for the system presented above is 0.24, a value similar to those reported elsewhere for omnidirectional UWB transmitters [5,7,9,10].

Figure 7. View of the Faraday cage with the biconical antenna mounted.

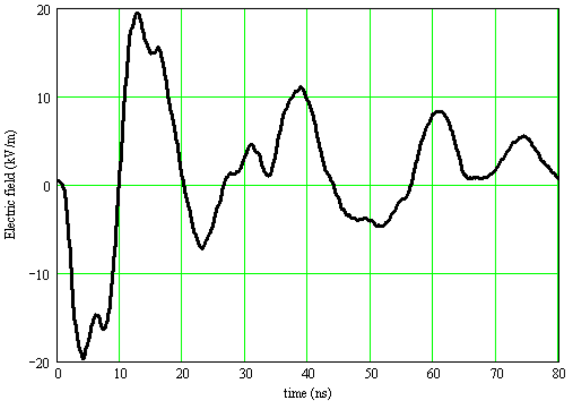

Figure 8. Radiated field waveform measured 3m from the antenna (single shot mode).

IV. CONCLUSION

The paper has presented the development of a pulse generator for UWB radiation, with the key element of the system being a high voltage Tesla transformer. It has been demonstrated that more than 0.5MV has been generated in single-shot mode and over 350kV at a PRF up to 200Hz. A transmission FOM of 0.24 has been achieved, which is quite reasonable for a dipole type antenna structure. Overall the device is simple, portable and robust. Future development will include increasing the coupling coefficient of the transformer to increase its efficiency, together with various design changes to reduce substantially the total weight and volume while increasing the emitted energy. A theoretical model to include the transient response of the antenna is also under development.

V. REFERENCES

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