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A MINIATURE HIGH-POWER POS DRIVEN BY A 300 kV TESLA-CHARGED PFL GENERATOR

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Abstract

A pulsed power generator based on a high-voltage Tesla transformer charging a 3.8 Ω/53 ns water-filled pulse forming line (PFL) to 300 kV has been developed at Loughborough University as a training tool for pulsed-power students. The generator uses all forms of insulation specific to pulsed power technology – liquid (oil and water), gas (SF₆) and vacuum, a series of fast voltage and current sensors, and is able to produce multi-GW pulses on a simple x-ray diode load.

Recently, a miniature (cm-size) plasma opening switch (POS) using protons (H⁺ ions) has been coupled to the output of the Tesla-charged PFL generator, with the overall system constituting the first phase of a programme aimed at the development of a novel repetitive, table-top generator capable of producing 15 GW pulses for high power microwave loads.

Experimental results demonstrating the performance of the POS in reducing the rise time of the input current while increasing the load power are presented, together with constructional details and diagnostic techniques. Future plans are outlined.

I. INTRODUCTION

A broad range of modern industrial applications, from intense microwave and UWB sources used in defense to the generators used for food sterilization, all require compact and repetitive pulsed power systems able to provide an output power in excess of 10 GW. Although a Marx generator provides a straightforward solution, it is certainly not the simplest and most compact source at this level of power. Loughborough has a long tradition in building and implementing compact Tesla-based generators for various applications and has demonstrated in practice that under certain conditions the Tesla transformer provides a better solution than a Marx generator. In most situations the transformer is used to charge a pulse forming line (PFL) which in turn is

discharged to a load via a high-voltage closing switch, thus conditioning the output pulse and increasing the power delivered.

However, as the demand in the level of power is further increased, another element, the plasma opening switch (POS), becomes very useful. The POS operates in vacuum, requires a small cold plasma source and relies on magnetic insulation to withstand high output voltages of up to a few MVs. The POS two-electrode geometry is usually coaxial-cylindrical, with the load at one end and the input power generator at the other. Once a critical operating current is reached, the switch opens in a time much shorter than the rise time of the input current, and a much increased power is transferred to the load. The POS was developed initially for very high-current applications (hundreds of kA up to a few MA) and considerable effort was expended in developing large units capable of fast opening under input currents having a rise time ranging from hundreds of ns to 1 μs. However, as the first reported experiments [1] established, the POS is able to open currents having much shorter rise times (i.e., tens of ns) and, under optimum conditions, to generate a load current with a rise time about ten times shorter than the input current. It is the aim of the present experiments to demonstrate that a POS can be miniaturized down to a cm size and used at a current level of a few tens of kA.

Although it is anticipated that eventually semiconductor based opening switches will be capable of handling tens of GW of power, and this is in principle already possible, it will be both extremely voluminous and very heavy, and also prohibitively expensive. For very high power generation at the present level of technology, the only practical solution for a very compact opening switch is the POS, even if it does require an auxiliary energy source for the production of plasma. It is a long-term goal of the Loughborough Pulsed Power Group to develop a table-top repetitive POS-based generator capable of producing powers well in excess of 10 GW. Once this is achieved, the same approach can be adopted in much larger and more powerful systems, by the use of a multi-modular approach.

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This paper firstly presents a fully developed Tesla transformer-based PFL generator together with the required diagnostic equipment. Secondly, a miniature POS is described, together with its own auxiliary plasma gun source. Plasma diagnostic experiments are mentioned, using dedicated Faraday cup sensors and an ultrahigh-speed camera. Results obtained from the complete Tesla-PFL-POS system coupled to a dynamic load represented by an X-ray diode are then presented and briefly commented on. Finally, future plans related to the development of a table-top system are outlined.

II. 300 kV TESLA TRANSFORMER-BASED PFL GENERATOR

A. Tesla transformer

Figure 1 shows the electrical arrangement comprising the Tesla transformer-based PFL generator. The capacitor bank C_b consists of three parallel-connected 30 kV capacitors with a combined capacitance of 1.8 μF and, together with a parallel-plate short transmission line, forms the power source for the system. To keep within the safe working current of the capacitors (i.e., 25 kA), the charging voltage is necessarily restricted to 25 kV.

A low-inductance trigatron S1 operated under compressed air and triggered by a 60 kV voltage impulse produced by a TG-70 trigger generator, closes the primary winding circuit of the Tesla transformer, with the equivalent resistance and inductance of this circuit being $R_b = 30 \text{ m}\Omega$ and $L_b = 125 \text{ nH}$. The primary winding comprises a single-turn of copper sheet, sandwiched between layers of Mylar-polyethylene and having a self-inductance L_p of 164 nH. The secondary winding of enameled round copper wire is wound on a conical dielectric former and has a self-inductance L_s of 64.5 μH with a relatively high resistance of 2 Ω introduced during operation by significant skin and proximity effects. Because of the high secondary voltage, the transformer operating at a resonant frequency of about 220 kHz, is immersed in oil with the primary/secondary mutual inductance M being 2.1 μH . The corresponding coupling coefficient k of 0.64 is very close to the ideal 0.6 value required for the design of a dual-resonant Tesla transformer. No further treatment of the high-voltage transformer oil was required during its two-years of successful operation, after the initial filtering using an oil pump.

The two main components of the Tesla transformer are shown in Figure 2. The detailed design of the transformer required the use of a 2D numerical model [2], which accounts for magnetic diffusion, skin and proximity effects and even for the influence of metallic components located in the immediate vicinity, such as the PFL.

B. Pulse forming line

During operation, the Tesla transformer charges a 3.8 Ω / 50 ns water filled pulse forming line (PFL), with an equivalent capacitance of about 6 nF. Using a pump and a two-stage filter, the resistivity of the circulated water was quickly brought back after each shot to somewhere in excess of 15 $\text{M}\Omega\text{cm}$, under which conditions the maximum PFL charging voltage attained was 400 kV. Although the line is charged by a bi-polar pulse over a time exceeding 2 μs , no breakdown has been observed. However, during its two-years of operation, probably due to the central electrode being of aluminum and the outer one of stainless steel, electro-chemical reactions have contributed to a slow degradation of the performance. Eventually a long period of time was required after each shot, for the filter system to produce the conditions required for high-voltage operation. Figure 3 shows the individual components of the PFL and Figure 4 the complete generator.

C. High-voltage fast spark gap

The output of the PFL is connected directly to the load (or, in the final phase of programme, to a POS) via the switch S2 of Figure 1. This is a self-breaking high-voltage fast spark gap made from a pair of 60 mm diameter bead-blasted brass hemispheres, securely mounted on polythene supports with 5 mm separation (Figure 5a). The switch operates under high-pressure SF_6 and has an excellent closing voltage reproducibility.

D. Diagnostic equipment

The time variation of the current and voltage during operation is monitored by a number of appropriately located sensors. The voltage of the Tesla transformer capacitor bank voltage is measured with a commercially available probe and the primary circuit current with a calibrated *in-situ* B-dot probe, located in a tunnel in the ground plate of the short transmission line connecting the bank to the primary single-turn winding of the transformer. To remove any possible capacitive coupling, the probe is shielded using a thin slotted tube made from copper sheet and connected to the ground plate of the transmission line. The Tesla transformer output voltage is monitored by a V-dot sensor [3], installed in the thick stainless steel metal wall of the PFL, very close to its output (Figure 5). The pair of Rogowski coils used to monitor the output current of the PFL (i.e., the input current to POS) and the output from POS (i.e., load current) in the vacuum chamber (Figure 6a) have rise and droop times of 1 ns and 2 μs respectively, and the design and manufacturing technique are described elsewhere [4]. The most challenging part of the sensor is the very low inductance of the matching current viewing resistor which is required to be at most some hundreds of pH. As the arrangement suggested in [5] was difficult to be implemented, a novel solution was adopted that uses at

Figure 1 Equivalent electrical circuit for the generator including a load (in the final phase of the programme a POS was implemented, shown as a variable resistance attached by dotted lines). Subscripts *b* for capacitor bank, *p* and *s* for the Tesla transformer primary and secondary circuits, *L* for load. S1 and S2 are closing switches, C_{PFL} is PFL capacitance

(a)

(b)

Figure 2 Tesla transformer: (a) primary winding (b) secondary winding

least eight micro-resistors coupled in parallel (see Figure 6b).

Results

Figure 7 shows the output voltage of the PFL during charging and the voltage delivered to a fixed inductive load following closure of switch S2. The load power pulse reaches 6 GW with the line charged to 300 kV and even higher values were obtained in one-off shots during the experimental programme.

III. TESLA-PFL-POS GENERATOR

A. Plasma Opening Switch

In recent experiments, a POS has been attached to the PFL output to provide a second output conditioning stage. The POS has cylindrical geometry with four equally spaced plasma gun injectors. The design of the plasma gun to emit H^+ , C^+ and C^{++} ions was presented elsewhere [6] and the plasma emitted was investigated using both Faraday cups and an ultrahigh-speed camera [6]. It was demonstrated that the proton plasma density and velocity

Figure 3 PFL components

Figure 4 Complete generator schematic

(a)

(b)

Figure 5 (a) PFL V-dot sensor and high-voltage spark-gap (b) real V-dot sensor mounted on PFL

(a)

(b)

Figure 6 (a) One of the two Rogowski coils mounted inside the vacuum chamber wall (note the plasma gun cables, part of the POS)
(b) very low inductance current viewing resistor mounted on a BNC panel connector

Figure 7 PFL output voltage during charging by Tesla transformer and following closure of s2 at 300 kV

Figure 8 Plasma guns circuit

obtained from Faraday cup measurements correspond to a threshold opening current of only a few tens of kA, matching the conditions obtained when the PFL starts to discharge. The POS is shown in Figure 4 mounted on top of the generator and the equivalent electrical circuit for the four guns attached in parallel at the output of a 1 μF capacitor bank is presented in Figure 8. The plasma gun circuit is closed by a trigatron similar to S1 with the two TG-70 generators used to trigger the two trigatrons synchronized by a multi output time-delay unit. No particular problems were encountered during the experimental programme, apart from maintaining the vacuum in the POS chamber at close to 10^{-4} Torr and reconditioning the insulator surface of the plasma guns after about 100 shots.

B. Results

The time history of the currents and voltages of the generator is presented in Figure 9a which also shows the required time synchronization between the Tesla

transformer and plasma gun circuits. The results in Figure 9b are obtained on a short circuit and those in Figure 9c with an X-ray diode. These data are both for unoptimised systems and it is believed the rise time can be further improved when the system is optimized with a dynamic load such as a vircator attached. However, the load power delivered to the X-ray load is already in excess of 10 GW, clearly showing the potential of the system.

IV. CONCLUSIONS

The *first stage* of a major Loughborough programme, with the aim of demonstrating a table-top repetitive system with an output greater than 10 GW, has been successfully completed, with a powerful 300 kV Tesla-charged PFL pulsed power generator operating with a high reproducibility. Studies performed with Faraday cups show that both protons and carbon ions are emitted and ultrahigh-speed camera studies helped to provide an understanding of the plasma dynamics. Tests using the

miniature POS demonstrated that a power well in excess of 10 GW can be produced on dynamic loads such as an X-ray diode, and the way is open for design of a table-top, repetitive, 15 GW machine based on a miniature POS.

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(a)

(b)

(c)

Figure 9 Results with POS attached to the generator (a) variation of system voltages and currents; (b) result obtained with a short circuit load (c) result obtained with a dynamic load (X-ray diode): POS input current, load current and voltage are all presented