

TRACE I, A TRANSFORMER-CHARGED ELECTRON BEAM GENERATOR*

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Summary

A transformer-charged electron beam generator has been developed. The system is designed to operate with up to 500 kV on a water-dielectric pulse-forming line (PFL) and to generate a 100 kA, 50 ns electron beam. The transformer charging supply replaces a 12-stage Marx generator and reduces the size, weight, and complexity of the system. It also eliminates the need for a large insulating-oil supply.

A description of the physical features of the machine is included along with a discussion of the electrical characteristics of the system.

Introduction

Using a transformer instead of a Marx generator for a pulse charging application can offer a number of benefits, which derive principally from two features: 1) the primary storage capacitors are not required to operate at the ultra-high output voltage and 2) the complicated switching and dc charging components of the Marx circuit are not required. Operation at lower voltages means that the primary capacitor bank and transformer need not be housed in an oversized tank of insulating oil. Since there is no need for separate oil storage and handling equipment, the resulting system is compact, requires substantially less floor space, and is thus more readily accommodated in a laboratory than is an equivalent Marx-charged system. Also, with fewer components, the possibilities for failure are reduced and maintenance is minimized. Finally, these simplifications yield a system that costs appreciably less than its Marx counterpart to build and operate.

TRACE I is a readily portable electron beam generator which incorporates the advantages of transformer charging in a physically integrated design. The system employs a single, low-voltage energy storage capacitor in combination with a spiral-wound pulse transformer to charge a Nereus¹ pulse-forming line. In the TRACE I transformer, high-voltage breakdown has been avoided by controlling the electric field shape in the border regions for charge cycle conditions and by using the high turn-to-turn capacitance of the spiral winding to grade the nanosecond transients produced by the discharge of the PFL.

The TRACE I transformer charges the PFL in a ringing dual-resonance mode, which reaches maximum operating voltage during the reverse voltage swing on the PFL. In preliminary tests, the system has reached a maximum voltage of 565 kV on the PFL without breakdown of the water in the line or damage to the transformer from PFL discharge transients. At peak voltage, the PFL is switched onto the diode by the self-breakdown of a polyethylene switch.

The complete TRACE I system consists of a control panel and dc power supply, a 20 kV primary energy storage capacitor, a high-voltage pulse transformer, a vacuum system, and the Nereus PFL with switch and diode. A complete description of the physical and

electrical characteristics of the Nereus transmission line and diode may be found in Reference 1.

Description

The TRACE I system (Figure 1) is approximately 1.5 m long, 0.6 m wide, and 1.2 m high and includes all system components mounted on a roll-around platform except for the control panel and vacuum roughing pump. The charging transformer is mounted in-line with the coaxial PFL and connects to the primary storage capacitor located below the transformer. The vacuum diffusion pump and water-processing equipment are mounted immediately below the PFL.

The primary storage capacitor is a 14.5 μ F, 20 kV capacitor charged with 10 mA dc power supply. The capacitor is fitted with a low-inductance (5 nH) in-plane spark gap switch designed for this application. A short flat-plate connection is made between the switch and transformer primary.

The Nereus PFL is a 8.3 nF, 1.9 Ω coaxial water capacitor, which at 500 kV stresses the water dielectric to 160 kV/cm. The PFL is connected to the transformer output through a compression coupling between the transformer core and the center electrode of the coaxial line. The transformer-PFL interface is a double-diaphragm arrangement with a 1.27 cm oil-filled space between. Because the transformer case is also the primary turn, it is electrically isolated from the outer case of the coaxial line. The ground connection to the line is made through the primary capacitor ground plate. Figure 2 shows a cross section of the TRACE I assembly.

Transformer

The charging transformer has a 60-turn, spiral secondary winding and a 30.5 cm wide, single-turn primary, which also serves as the external case. The secondary conductor is a copper strip 10 cm wide and 0.0254 cm thick. It is wound on a 10-cm diameter core and is insulated turn-to-turn with multilayered polyester film, which has a total thickness of 0.076 cm. The open volume inside the case and secondary winding is filled with castor oil to exclude air and to provide electrical insulation in the border regions of the winding. The ends of the transformer case are covered by 1.27 cm polycarbonate plate to confine the oil to the interior and provide insulated mounting flanges for the external attachments.

A spiral-strip-wound transformer was selected for this application because the voltage gradient is inherently uniform through the thickness of the winding stack during the charging cycle. Also, with its comparatively high turn-to-turn capacitance and low total capacitance to ground, it is able to withstand the nanosecond high-voltage transients imposed on the secondary winding from the discharges of the PFL.² A third advantage of spiral-strip transformers is that the primary, secondary, and mutual inductance combination for a given coupling coefficient is typically lower than for an equivalent wire-wound helical transformer, a characteristic which results in a faster charging cycle.

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Pulse Charging

Charge transfer from the primary energy storage capacitor to the PFL occurs in a dual-resonance mode, where the maximum voltage on the PFL is reached at the peak of the second or reverse voltage excursion. The conditions for dual-resonance charging are well documented in the literature.^{2,4,5,6,7} Briefly, the requirements for maximum charge transfer on the second voltage swing are that the primary and secondary frequencies be equal ($L_p C_p = L_s C_s$) and that the coupling coefficient of the transformer be exactly 0.6, these relations being readily derivable from the general circuit equations.^{4,5,6} This operating condition is of theoretical interest because in a lossless system the energy transfer from the primary to the secondary capacitor is 100 percent. It is also of practical interest because high-voltage transformers can be constructed quite easily with appropriate inductance combinations to match the primary and secondary frequencies and coupling coefficients near 0.6.

In real systems, however, there are always ohmic losses as well as small deviations from ideal combinations of inductance and capacitance; and these effects detune the circuit. Both effects also contribute to lower energy transfer. Special care must be taken, therefore, to minimize the primary circuit resistance and maximize the water resistivity in the secondary capacitor. Careful attention must also be given to matching primary and secondary frequencies. In practical cases, this means that with the primary and secondary capacitors specified, the transformer characteristics must be designed to provide a match between the primary and secondary sections of the circuit.

Performance

The TRACE I circuit (shown schematically in Figure 3) is approximately frequency-matched in the primary and secondary sections. The primary and secondary frequencies are 121 kHz and 108 kHz, respectively, and the coupling coefficient of the transformer is 0.55. With these characteristics and ohmic losses, the system typically operates with 46 percent energy transfer. A 20 kV initial charge on the primary capacitor will charge the PFL capacitor to 565 kV, a value which compares well with 595 kV calculated. This condition is illustrated in Figure 4, which is a plot of the calculated and measured charging wave forms on the PFL. Circuit response calculations were performed with the SCEPTRE⁸ transient analysis computer code. A calculated energy balance at the time of maximum secondary voltage indicates that approximately 10 percent of the initial stored energy remains in the primary circuit and is divided between the capacitor and the inductance, with about 44 percent apparently going to ohmic losses during the charge cycle. From these results, it is obvious that controlling the circuit resistance is essential to satisfactory system performance. The water resistivity in the PFL was maintained for these tests at around 2 MΩ-cm which corresponds to a total resistance of 1.7 kΩ. At least 1 MΩ-cm resistivity must be maintained for 500 kV operation. High-purity bubble-free water is also required to prevent premature breakdowns in the coaxial line. Because of the longer inherent charge time, the problems of resistive losses and water breakdown are of more concern than with the original Marx-charged system. However, conventional deionizing and filtering apparatus has proved to be satisfactory for maintaining adequate water quality.

References

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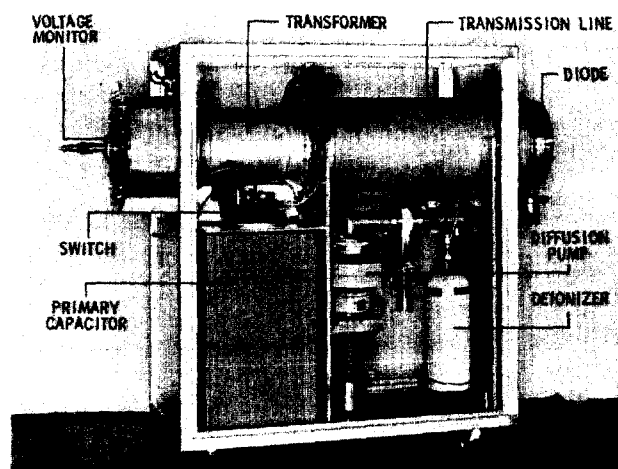


Figure 1. TRACE I Generator Assembly

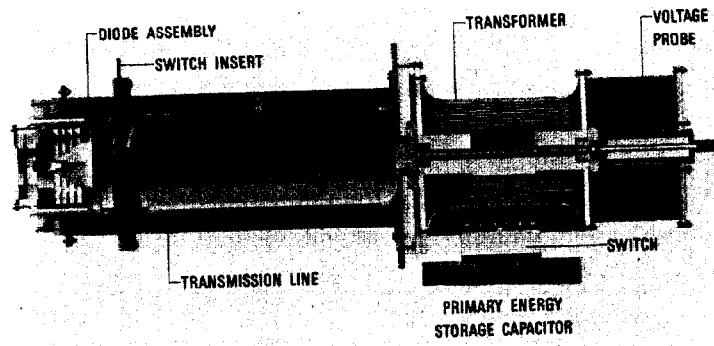
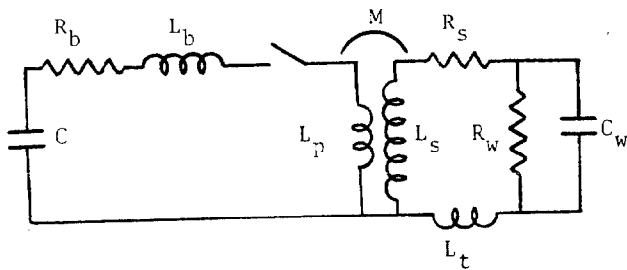


Figure 2. Cross Section of Pulse Train Assembly



$C_b = 14.5 \mu\text{F}$	Primary Storage Capacitor
$R_b = 8 \text{ m}\Omega$	Capacitor, Switch and Primary Resistance
$L_b = 30 \text{ nH}$	Capacitor and Switch Inductance
$L_p = 90 \text{ nH}$	Transformer Primary Inductance
$L_s = 260 \mu\text{H}$	Transformer Secondary Inductance
$M = 2.65 \mu\text{H}$	Transformer Mutual Inductance
$R_s = 16 \text{ m}\Omega$	Secondary Winding Resistance
$R_w = 1.7 \text{ K}\Omega$	PFL Water Resistance ($\rho = 2\text{M}\Omega\text{-cm}$)
$C_w = 8.3 \text{ nF}$	PFL Water Capacitor
$L_t = .5 \mu\text{H}$	Stray Connection Inductance

Figure 3. Charging Circuit Parameters and Schematic

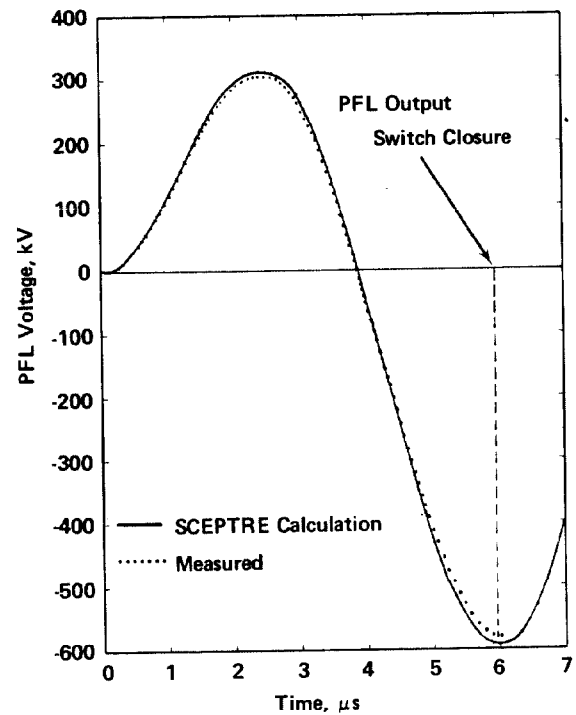


Figure 4. PFL Charging Voltage From 20 kV Primary Capacitor Discharge