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# A THREE MEGAVOLT TRANSFORMER FOR PFL PULSE CHARGING*

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## Abstract

High voltage pulse transformer powered by low voltage capacitor banks have proven to be simple reliable systems for charging pulse forming transmission lines (PFL) up to the one megavolt range.[1,2] A new transformer has been developed which will operate up to three megavolts in a PFL charging application. This transformer establishes the feasibility of multimegavolt operation and retains the features of compactness and high energy transfer efficiency that has been characteristic of lower voltage systems. This report includes a description of the physical features of the transformer, its electrical characteristics and a discussion of the operational results.


## Introduction

Air core pulse transformers are an attractive alternative to Marx generators for charging high voltage pulse forming transmission lines such as those used with high power electron or ion beam accelerators. In general, transformer systems are more compact than Marx generators because the low-voltage, primary capacitor bank is inherently a more dense assembly and is ordinarily not operated in a tank of insulating oil. The resulting system requires substantially less floor space and does not require separate oil storage and handling facilities. These simplifications yield a system that costs less to build and operate than a Marx system.

The transformer that was built for the present experiments is an air core spiral strip design. It incorporates ring cage shielding to shape the electric field in the margins of the transformer (Fig. 1). Shaping the electric field in this manner is essential to preventing dielectric breakdown along the edges of the secondary winding. This type of transformer is particularly well suited to PFL service because it is less vulnerable to breakdown between the final turns of the secondary winding from nanosecond voltage transients generated by PFL discharges than helical wire wound transformers. The reason for this is the high inter-turn capacitance of strip transformers. Since the turns directly overlay each other, the capacitance components are directly in series to ground making the total capacitance comparatively low. This characteristic produces uniform voltage grading through the thickness of the secondary winding and avoids the problem of wave transit time isolation between turns.

At Sandia Laboratories shielded spiral strip transformers were originally developed for a number of systems which operated with output voltages up to 1 MV.[1,3,4] The new transformer was tested to 2.2 MV in an off resonance single swing charging mode and to 3 MV in a dual resonance charging mode.

## System Description

A 4.6 kJ, ± 50 kV capacitor bank was designed and built to provide primary pulsed power for the system. The load section consisted of a coaxial water capacitor, a gas dielectric spark gap switch and a water load resistor. Photographs of the system are shown in Fig. 2a and 2b and a cross sectional diagram in Fig. 3. Figure 4 is an electrical schematic of the system.

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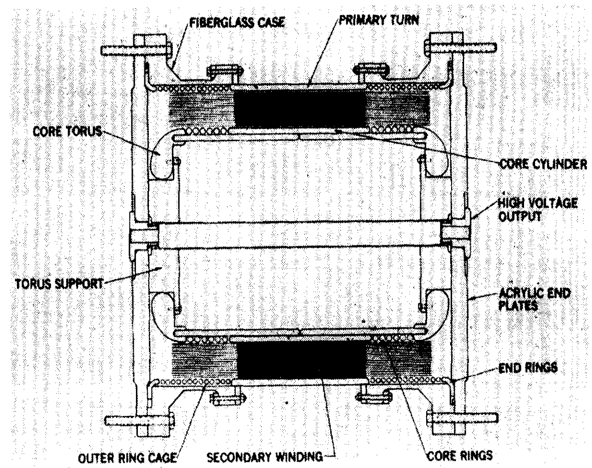
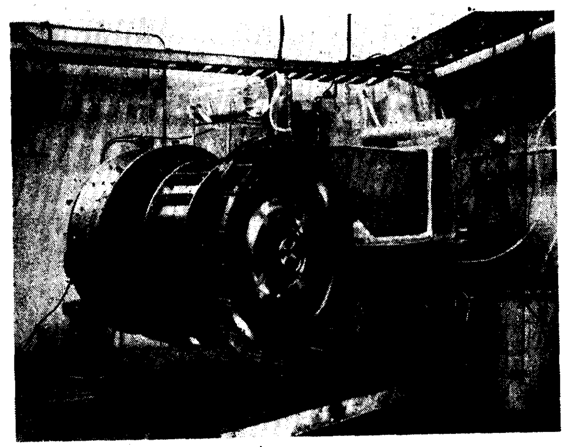
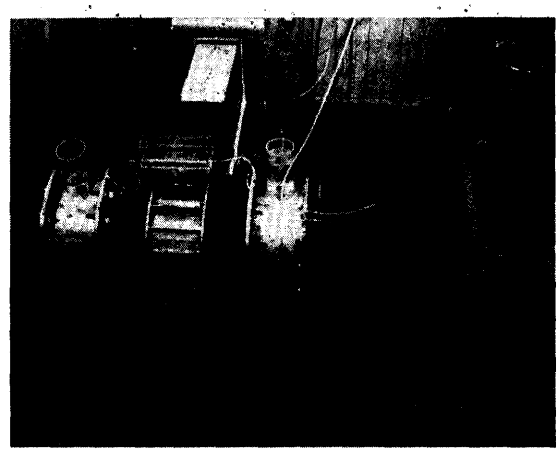



Fig. 1. Cross section of 3 MV transformer.



(a)



(b)

Fig. 2. a. Transformer and capacitor bank.
b. Complete transformer test system.



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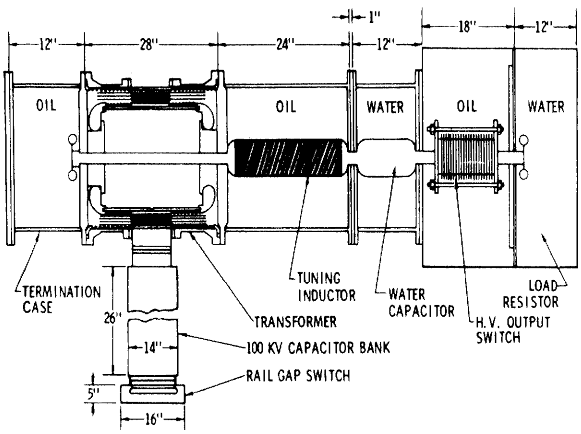


Fig. 3. Cross section of test assembly.

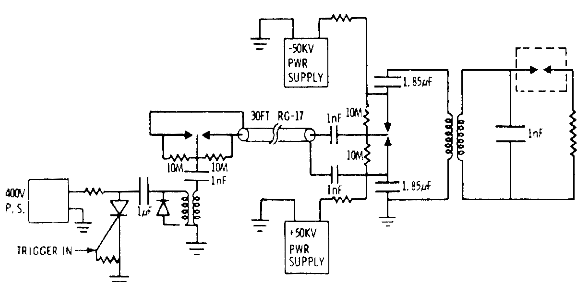


Fig. 4. Electrical schematic of test system.

The capacitor bank was electrically connected to the transformer primary through a parallel plate transmission line to minimize hookup inductance. The bank was switched with a commercially available rail gap switch which operated repeatably in a multichannel mode when filled with a gas mixture of 14.5 percent $SF_6$ and 85.5 percent Argon.

The secondary load section was connected in-line with the axis of the transformer. For single swing charge tests, the water capacitor was connected directly to the output of the transformer. For the dual resonance tests, an oil immersed tuning inductor was added between the transformer and load capacitor. The housings for both the capacitor and inductor were 60 cm diameter tubes with acrylic interfaces between the oil and water sections. The switch and load resistor were housed in open top box sections which permitted access to the interiors without uncoupling the exterior assembly.

The output switch[5] was a two-electrode self-breaking gas ($SF_6$) dielectric spark gap. The self-break level was varied over a range of 1 to 3 MV by controlling the gas pressure in the switch.

## Transformer

The transformer has a single turn primary surrounding a 42-turn secondary winding. The active width of both windings is 30 cm. Eight layers of 0.019 cm thick polyester film provide the turn to turn insulation between the 0.025 cm thick copper turns. The total winding thickness for 42 turns is 7.6 cm and at 3 MV operates at a mean dielectric stress of approximately 450 kV/cm.

The width of the polyester insulation is 60 cm which leaves a 15 cm margin on both sides of the copper winding. These margins are enclosed inside a concentric ring cage built into the core and case of the transformer. The function of the ring cages is to maintain a coaxial field distribution across the margins which is nearly parallel to the uniform field through the thickness of the winding. The equipotential lines outside the winding are thereby prevented from bending sharply around the edges of the thin winding conductor and creating highly enhanced electric fields which could cause insulation breakdown.

To allow free passage of the magnetic field through the ring cage and prevent induced currents from flowing in the rings, the rings are arranged with a longitudinal separation of 0.32 cm and are individually split to form one or more gaps in the hoop direction. The two ring sets in the case have one gap per ring and the two sets on the core have four gaps. The gaps in the case rings are aligned with the slot in the primary turn. They are connected together electrically and to the primary turn along a single line opposite the slot. On the core, each of the four groups of ring segments in the two sets is connected to the slotted core cylinder along a single line through its mid section. The purpose of making line connections opposite the gaps in the ring cages is to prevent breakdown across the gaps from high voltage transients which have rise or fall times shorter than the wave transit time around the rings. With mid point connections, a fast voltage pulse sweeps symmetrically around the rings in opposite directions. When the two wave fronts meet at a gap, the voltage difference across it is essentially zero.

For structural reasons the transformer case was made of two 60 cm diameter filament wound fiberglass reinforced polyester tube sections with integral flanges. These flanges support the acrylic end plates of the transformer and provide a rigid connection to the external load system. The primary turn, located between the fiberglass case sections, is also part of the structural assembly. It is attached to the fiberglass sections through shallow flanges around each edge of the turn. When fully assembled, the transformer was sealed so that the interior volume was liquid tight. It was then filled with oil and vacuum impregnated for a period of approximately three weeks before electrical tests began.

The inductance parameters of the transformer were initially calculated and later confirmed by measurements. They are given in Table I.

TABLE I

Transformer Inductance

| | |
|---|---|
| Primary inductance | 0.590 μH |
| Secondary inductance | 488 μH |
| Mutual inductance | 14 μH |
| Coupling coefficient | 0.83 |

## Operational Results

The transformer system was first operated in an off resonance single swing charging mode. For these tests, the capacitor bank was directly coupled to the transformer primary in a minimum inductance configuration and the transfomer output fed directly to the 1.1 nF load capacitor. The charge transfer time was 1 μs as shown by the waveform in Fig. 5. The system was tested at successively higher voltages to a maximum of 2.2 MV.

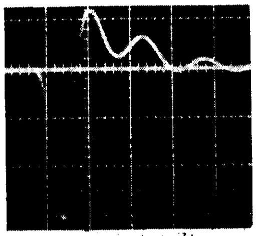

Fig. 5. Secondary capacitor voltage in single swing charge mode. Voltage = 0.5 MV/div. Sweep = 1 μs/div.

This level corresponded to ± 50 kV charge on the primary capacitor bank and an energy transfer efficiency of 58 percent.

For the second series of tests the system was converted to a dual resonance charging mode[7,8] where the maximum voltage on the load capacitor was reached on the second or reverse voltage excursion. Converting the system to this mode of operation involved changing the load capacitor to 0.76 nF and adding additional inductance to both the primary and secondary sections of the circuit to match the open circuit frequencies and simultaneously reduce the effective coupling coefficient to 0.6. The tuning inductors added were 0.07 μH on the primary side and 328 μH on the secondary side.

With the system converted to a dual resonance mode, the total charge transfer time was 3.0 μs. A typical output voltage waveform in shown in Fig. 6. The system was tested at progressively higher voltages up to and including the 3 MV level. At 3 MV, the primary capacitor bank was charged to ± 45 kV which corresponded to an energy transfer efficiency of 91 percent.

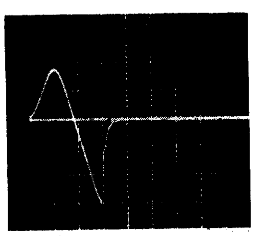

Fig. 6. Secondary capacitor voltage in dual resonance charge mode. Voltage = 1.0 MV/div. Sweep = 1 μs/div.

Throughout the testing no serious difficulties were encountered. At approximately 2.2 MV a minor flashover occurred along an acrylic winding support in the transformer. Removal of these supports prevented reoccurrence of this problem up to the full design voltage. Between 2.5 and 3 MV, periodic breakdowns occurred in the water capacitor which precluded the possibility of taking the system to a higher voltage.

## Conclusions

The experiments with the 3 MV transformer clearly demonstrate the feasibility of multi-megavolt transformer operation for pulse charging applications. The key to obtaining reliable performance with a spiral strip transformer lies in proper electric field shaping in the margins of the transformer without disrupting the magnetic field. This can be achieved by utilizing concentric ring cages in the transformer margins which are designed to avoid eddy current loops in the assembly. The transformer operates with high energy transfer efficiency in the multi-megavolt range with its physical and electrical characteristics scaled from design procedures developed for lower voltage systems.

## Acknowledgments

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