LA-UR-79-3102

MASTER

TITLE: LOW-LEAKAGE, HIGH-CURRENT POWER CROWBAR TRANSFORMER

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SUBMITTED TO: 8th Symposium on "Engineering Problems of Fusion Research," San Francisco, CA, November 13-16, 1979.

University of California

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UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

LOW-LEAKAGE, HIGH-CURRENT POWER CROWBAR TRANSFORMER

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Abstract

The design, fabrication, and testing of two sizes of power crowbar transformers for the ZT-40 Toroidal Z-Pinch experiment at the Los Alamos Scientific Laboratory are described. Low-leakage transformers in series with the poloidal and the toroidal field coils are used to sustain magnetic field currents initially produced by 50-kV capacitor banks. The transformer primaries are driven by cost-effective, ignitron-switched, 10-kV high-density capacitor banks. The transformer secondaries, in series with the field coils, provide from 1,000 to 1,500 V to cancel the resistive voltage drop in the coil circuits.

Prototype transformers, with a total leakage inductance measured in the secondary of 5 nH, have been tested with peak secondary currents in excess of 600 kA resulting from a 10-kV primary charge voltage. The test procedures and results and the mechanical construction details are presented.

Introduction

The LASL ZT-40 Reverse Field Pinch (RFP) experiment is designed to provide large, time-varying poloidal and toroidal magnetic fields for formation, maintenance, and confinement of the reverse field plasma configuration. The experiment is designed to permit varying the time in which the reversed field configuration is formed from 2.5 μs to 800 μs by changing the number of poloidal field transformer feeds, the number of toroidal field windings, and by changing capacitor banks (50 kV to 10 kV). The initial peak magnetic fields are initially established by capacitor banks. Then the crowbarred currents producing the poloidal and the toroidal fields are sustained by a voltage source in series wih the circulating currents provided by the low-leakage, step-down transformers described in this paper.

Electrical Design

The basic circuit diagram for the ZT-40 experiment, shown in Fig. 1, illustrates the location of the power crowbar transformers in the overall system. The requirements of the transformers vary with the desired time in which the currents producing the fields rise to peak value. The worst case is the 2.5 μs field risetime mode, in which the total current passing through the transformer secondaries is approximately 10^7 A, and the load inductance for both the toroidal and the poloidal field windings is on the order of 10 nH. The total transformer leakage inductance (or insertion impedance) must be small compared to the field windings to insure good energy transfer efficiency. The ZT-40 experiment was thus designed to have 12 parallel transformers in both the poloidal and the toroidal field systems. The required series voltage provided by the transformer secondary is on the order of 1000 V.

The low-leakage transformer design is based on earlier work by Hirhano[1] in Japan. The LASL design permits easy assembly and disassembly for

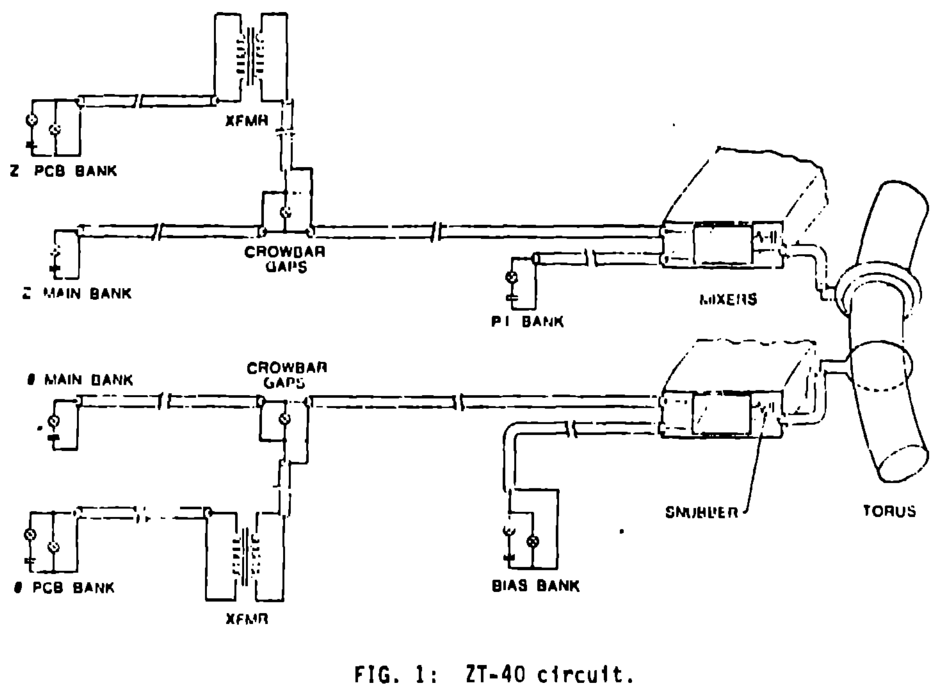

FIG. 1: ZT-40 circuit.

modification of the turns ratio and maintenance without changing parts and coaxial cable header input and output.

The low-leakage inductance is obtained by closely coupling the primary and secondary windings and designing a low-leakage flux path. The numbers of primary and secondary windings (fabricated from flat plates) are identical. The windings are stacked on the core so that primary and secondary windings alternate as shown in Fig. 2. The windings are then interconnected to provide the desired turns ratio (i.e., one 10-turn primary winding and 5 secondary windings of 2 turns each in parallel gives a 10:2 turns ratio as in Fig. 3). Several of these modules are then placed in parallel on the same core to produce one of the twelve transformers required for each circuit. The leakage inductance associated with each turn, L_{LT} consists of two major portions, the turn leakage inductance and the interconnection leakage inductance, both of which can be approximated by a strip line inductance. The associated turn leakage inductance is then

$$L_{LT} = \mu_0 \left[\frac{d_T}{w_T} \cdot l_T + \frac{d_I}{w_I} \cdot l_I \right] , \qquad (1)$$

where d_T is the turn separation, w_T is the turn width, l_T is the mean turn circumference, d_I is the interconnection separation, w_I is the interconnection width, and l_I is the length of the interconnection. The total leakage inductance of the transformer in the secondary, L_{LTS}, can be expressed as

$$L_{LTS} = \frac{N_{ST}}{N_M} \frac{L_{LT}}{N_{SM}} + \frac{N_{PT}}{N_M} \frac{L_{LT}}{N^2} , \qquad (2)$$

where N_{ST} = Number of secondary turns per secondary winding,
N_M = Number of modules per core,
N_{SM} = Number of secondary windings per module,

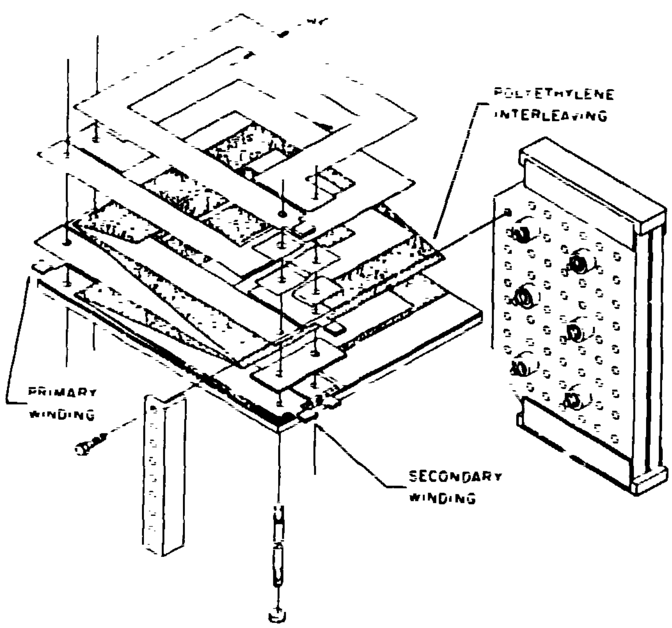

FIG. 2: Exploded winding module.

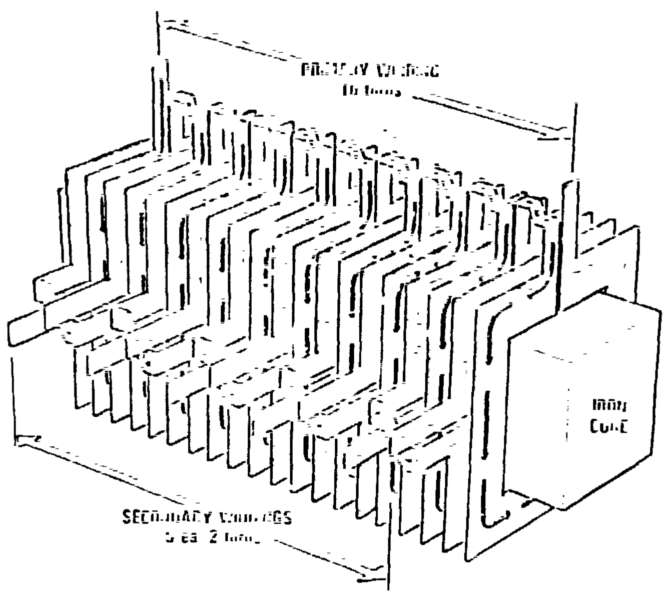

FIG. 3: ZT-40 power crowbar transformer winding schematic - 10:2.

N_{PT} = Number of primary turns per primary winding, and
N = Turns ratio = N_P/N_S.

The core cross section and the number of secondary turns (or volt seconds) were determined using computer simulation of the ZT-40 circuit, including the plasma-dominated inductive loads. The primaries of the transformers are driven with 10-kV ignitron-switched, high-density capacitor banks, and the turns ratio desired depends on the plasma losses, the transformer secondary current, and the operating mode of ZT-40.

Mechanical Design

The main thrust of the mechanical design of the power crowbar transformer was to minimize the leakage inductance, to permit turns ratio changes without redesign, and to provide flexible, low-inductance, high-current input and output coaxial cable connections.

To minimize current path length and to permit the winding turns ratio to be changed, a compression joint, as shown in Fig. 4, was selected as the method for effecting the current connections. A tab was brazed to the end of each winding connection to increase the contact area and to minimize contact burning problems. This configuration permits the winding modules to be disassembled and then reassembled with a different turns ratio, because the connection tabs can be clamped to any point along the length of the cable header of Fig. 2.

Current is conducted to and from the transformer by RG 17-14 coaxial cable. The cables are terminated in parallel plate cable headers (Fig. 5). The headers are insulated from each other using 0.8-mm-thick sheets of low-density polyethylene (Fig. 2), which also insulate between the winding end of the header and the winding ends that are not connected to the header. Polyethylene hats are used to extend the creep distances at the cable outer termination. The inner conductor of the cable is terminated with a crimped-on, stud-type connector. The outer conductor

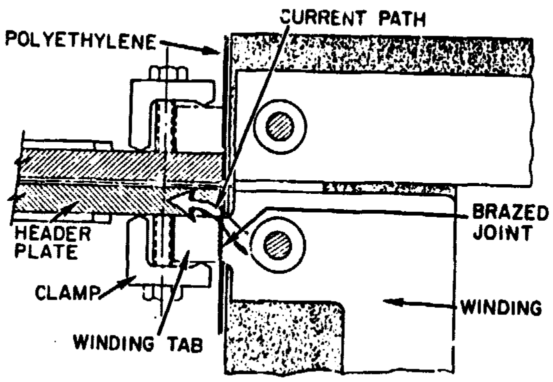

FIG. 4: Winding/header cross section

is terminated by clamping it to a wrought copper coupling, which is shrunk fit into the aluminum header. The header plates are held together and repulsive forces resisted using Grade 8 through bolts with phenolic standoffs. The primary and secondary headers are similar.

The means of connecting between adjacent windings is a simple compression joint (Fig. 6). The windings are aluminum, as are the buss strips and small strips of 1.57-mm-thick polyethylene that are used between windings and buss strips as required. A G-10 fiber-glass-reinforced threaded rod through the buss connection area provides the needed compressive force.

To minimize inductance, clearances between secondary and primary, conductors were reduced as much as possible without resorting to oil, potting compounds, or SF_6. This was effected by using several layers of polyethylene, with a total thickness of 7.6 mm, interleaved in a serpentine fashion (Fig. 2) between the primary windings (for example, to closely

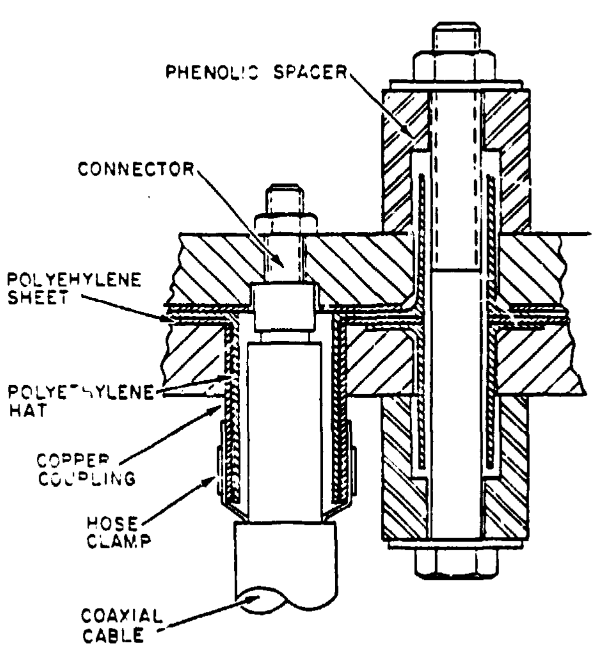

FIG. 5: Cable header cross section.

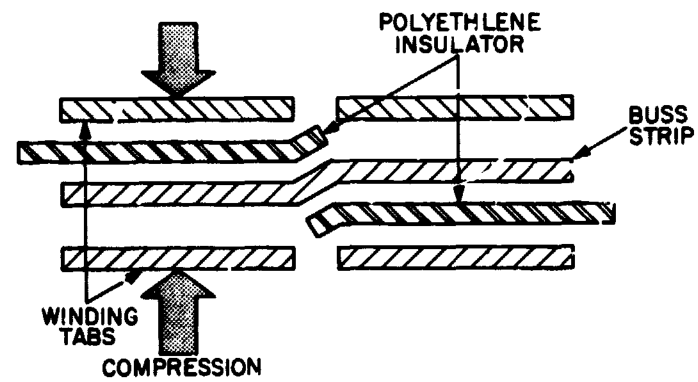

FIG. 6: Winding interconnect.

approach the bussing area of the secondary windings). The use of multiple layers of insulation overcomes pinhole problems associated with individual layers of polyethylene. The polyethylene was replaced by Mylar in the production units because the vendor found it was easier to assemble the winding modules.

The polyethylene interleaving between the primary and secondary windings does not insulate the windings from the transformer core. Consequently, an air gap of 12.7 mm is used in conjunction with Mylar tape to provide voltage holdoff. A window-frame-shaped piece of 1.57-mm-thick polyethylene (Fig. 7) is used in this gap to force winding alignment relative to the transformer core. This piece of polyethylene also helps to prevent arcing as a result of corona in this area, as well as excludes contamination.

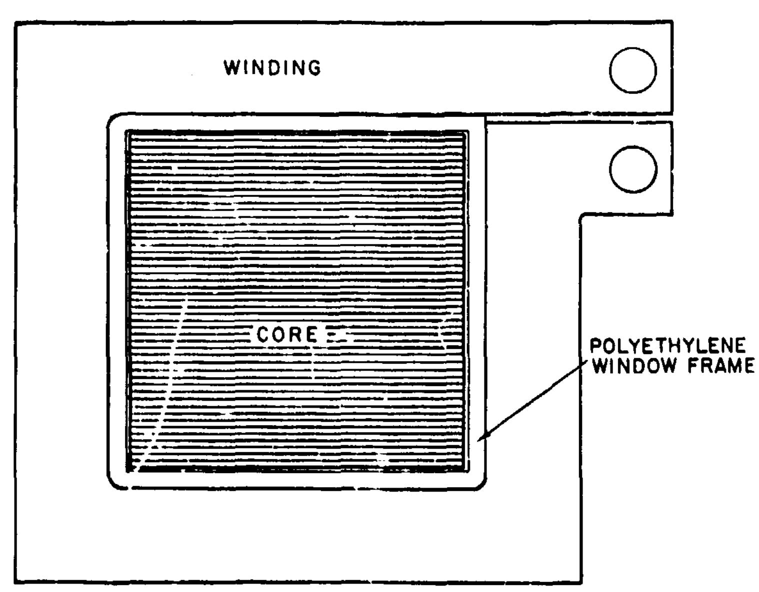

FIG. 7: Core cross section.

The original transformer design permits turns ratio changes without the fabrication of new parts. However, the change is a time-consuming process when all 24 power crowbar transformers must be changed. A design modification is now being instituted that will permit changes between ratios of 10:1, 20:1, 30:1, or 60:1 with a time investment of 1 hour per transformer.

Testing

Experimental Transformer

The experimental transformer consisted of two transformer modules with 20:2 turns ratios on the same core. This arrangement was to be one-third the number of windings of the final transformer.

The capacitance measurement for the experimental transformer was 0.22 microfarads, which meant that a full-size transformer would have a capacitance of 0.66 microfarads. The leakage inductance was 10.92 nH, which translates to 10.92 ÷ 3, or 3.64 nH for a full-sized transformer.

This transformer was hi-potted to 17.5 kVdc from primary to secondary and pulse hi-potted to 10 kV across the primaries. A 10-kV, high-density capacitor bank was discharged through the transformer into a dummy load, with a resultant peak secondary current of 272 kA.

A saturated core test was performed by removing the dummy load and pulsing the transformer with the secondary open. Monitoring the primary current indicated that the transformer core was saturating late in the pulse, but without excessive primary currents. The dummy load was reconnected and observations of the load current verified no damage had occurred as a result of the saturated core test.

Prototype Transformer

The prototype transformer consisted of six transformer modules, each module having 20:2 turns ratios.

A leakage inductance measurement of 4.35 nH was obtained for this transformer. (At a later date a better coupling between turns was accomplished and, although a new leakage inductance measurement was not made, it is expected that a lower value was obtained.

Again a 10-kV capacitor bank was discharged through the transformer into a dummy load, producing a peak secondary current of 660 kA. A similar saturated core test was performed as with the experimental transformer, without negative effects.

A 1,000-shot life test at full voltage (10 kV) and full current (660 kA into a dummy load) has been performed with no indication of difficulty. The primary and secondary currents are the same shape and amplitude for shot #1,000 as for shot #1. (Further testing is planned.)

Production Transformer

Both the theta and zeta production transformers are being fabricated by Stangenes Industries of Mountain View, CA. Each of these transformers consists of four transformer modules, each having a 30:3 turns ratio.

Factory testing is performed in the following areas:

Leakage Inductance - $\leq$ 9 nH
Hi-potting - 21 kVdc primary to secondary
15 kV pulse across the primaries.

LASL is testing these transformers at full voltage (10 kV) and full current (350 kA for the Theta transformer and 500 kA for the Zeta transformer) into a dummy load. The first production Theta transformer was life tested for 1,000 shots at full voltage and full current into a dummy load with no problems.

Summary

Two sizes of low-leakage, high-current transformers have been designed and tested for the ZT-40 RFP experiment. The total leakage inductance in the secondary has been measured for the two-turn secondary transformer as less than 4 nH and less than 9 nH for the three-turn secondary transformer. These transformers operate with a primary voltage of 10 kV and secondary voltages from 1000-1500 V with peak secondary currents of 660 kA.

This type of low-leakage transformer is ideal for inserting a current-sustaining voltage in series with the magnetic field windings of the ZT-40 and other similar experiments. A typical transformer is illustrated in Fig. 8.

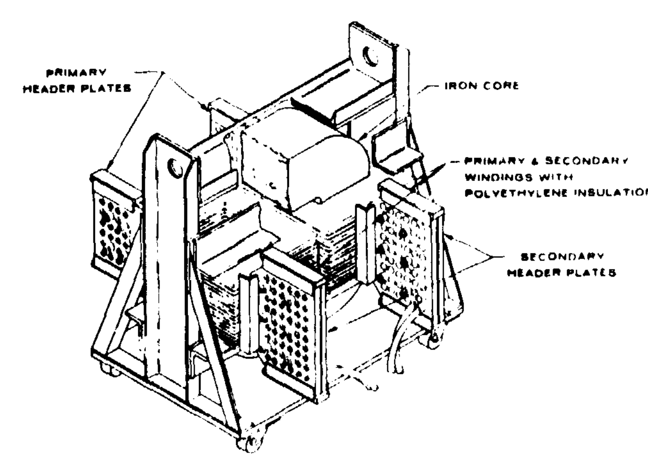

FIG. 8: ZT-40 power crowbar transformer.

References

1. "Fast Power 'Crowbar' System Using a Current Transformer with Extremely Low Leakage Inductance," S. Kitagawa and K. Nirano, Rev. Sci. Instrum., Vol. 45, No. 7, p 962, July 1974.