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OFF-RESONANCE TRANSFORMER CHARGING FOR 250-kV WATER BLUMLEIN*

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SUMMARY

An off-resonance transformer for charging a 250-kV Blumlein system provides a viable alternative to other charging schemes by permitting the use of conventional thyratrons. Such a transformer must have reliability, a reasonable voltage step-up, and a non-reversing primary current. This paper presents the analysis, design, and performance data for such a transformer. The strong interrelationship between transformer design and Blumlein requirements necessitates that Blumlein description and design criterion be briefly presented prior to transformer design such that transformer load requirements be defined.

INTRODUCTION

The ETA, Experimental Test Accelerator, being built at Lawrence Livermore Laboratory is a 5-MeV, 10-kA machine. Being a linear induction machine, the accelerating potential is generated by separate modules, each capable of producing a 250-kV accelerating pulse of 50-ns duration to a 10-kA electron beam. Each module is a complete system which consists of a variety of pulse conditioning components as shown in Fig. 1. Since there are numerous modules, high reliability and long life are required of components comprising the module.

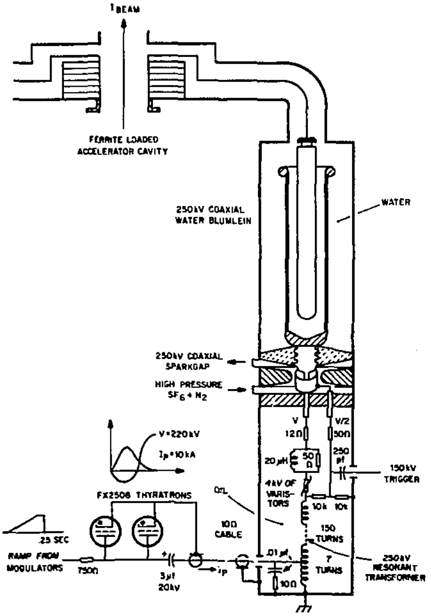

FIG. 1 ACCELERATING MODULE

The Blumlein and its charging system are considered to be an independent module subsystem. The design of either component is dependent upon the characteristics of the other, so both designs are presented. As needed, other details which influence design are described.

Blumlein Design

The Blumlein is a 10-Ω water line. The low impedance geometry is necessary as the Blumlein delivers approximately 50% of stored energy to waveshaping and compensating networks. At the cost of heavy Blumlein loading, these networks ensure that the electron beam has the desired accelerating potential. The choice of water as the dielectric permits the construction of high energy density Blumleins. This is due to water's high permittivity (∿80) as opposed to permittivities of 2-3 for most oils. Water has the advantage of being able to recover from a breakdown without having formed conducting by-products (carbon, acids, etc.). However, water does require a circulation system and conditioning to remove dissolved gasses and conducting ions.

Blumlein dimensions are determined by line impedances and the degree of safety desired. The breakdown strength of water is a function of the time water has to hold off voltage. Based on a minimum charge time of 10-μs, water breakdown occurs at approximately 200-kV/cm. By limiting the maximum voltage gradients to 100-kV/cm, a reasonable safety factor is provided. Using this design criterion, the Blumlein dimensions are shown in Fig. 2.

Details of mechanical construction are important if electrical parameters are to be attained. To this end, the metal electrodes are, of course, radiused to minimize or eliminate gradient magnification. In addition a 1-1/2" diameter corona ring is placed at the open circuit end of the middle conductor. Since surface preparation is so crucial, all surfaces which are in the vicinity of the higher voltage gradients are electropolished to remove whiskers and protrusions. All Blumlein components are constructed of stainless steel, which unlike aluminum, does not oxidize in very pure water and is less likely to suffer from surface damage in the event of a breakdown.

For short duration charging cycles (μs), the water Blumlein appears to the charging system as a parallel resistor, capacitor combination. Calculations based on Blumlein geometry and the dimensions of Fig. 2 show the

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capacitance to be 10-nF. Using the maximum realizable value for water resistivity, 18-MΩ-cm, the shunt resistance is approximately 10-kΩ. These values represent the complete load seen by the charging system. The capacitance is the dominating element as the energy dissipated into the resistor is small provided the charging time is not excessive.

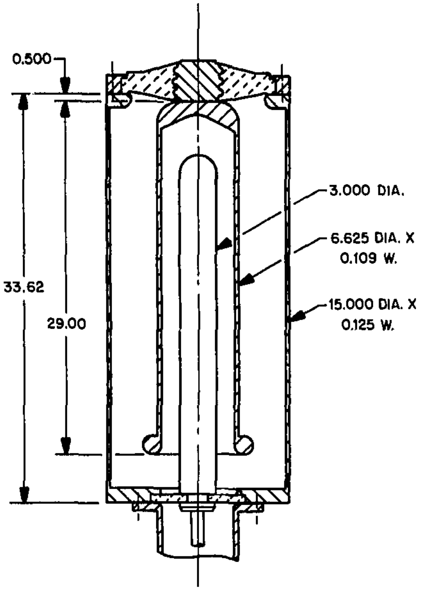


FIG. 2 BLUMLEIN DIMENSIONS

Transformer Analysis

The design of a charging transformer is influenced by many parameters; the drive, the load, step-up ratio, charge time, etc. The Blumlein load is known. The primary drive circuit is determined by the switch and its capabilities and limitations. The primary switch for this transformer is the English Electric thyratron FX 2508 (a modified CX 1159). This thyratron is used because 400 are available from the dismantled Astron accelerator.

The use of this thyratron imposes voltage and current constraints upon transformer design. The FX 2508 was designed to be pulse charged to 32-kV which cannot be done with ETA due to dc power supply limitations. In consideration of the slow (250-ms) charging rate, the tubes are derated to 20-25-kV. The FX 2508 is also specified at 2-kA peak current, however, lab tests show that at low repetition rates (5 pps) they can handle 6-kA peak current for millions of shots. A limitation of any single anode thyratron is its inability to conduct current bilaterally without internal damage. To properly handle negative current, auxiliary circuits such as diodes or perhaps double-ended thyratrons would be required. Circuit protection for the number of thyratrons to be used is not an economically feasible solution.

Based upon thyratron capabilities and limitations, the transformer is required to have a minimum voltage step-up of 10:1 and a non-reversing primary current not to exceed 10-kA. The 10-kA maximum is predicated upon using two parallel thyratrons operating at 5-kA each.

Since the load is essentially capacitive, a resonant charging transformer is logical. To determine which of several possible resonant charging modes would be best suited, a careful analysis of the transformer circuit is appropriate. Using the circuit of Fig. 3, the Laplace loop equations may be written for the primary and secondary currents. These are:

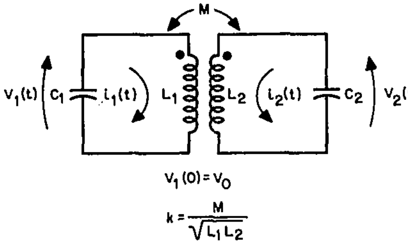


FIG. 3 RESONANT TRANSFORMER CIRCUIT

$$\frac{V_o}{s} = I_1(s)\left[\frac{1}{C_1 s} + L_1 s\right] + I_2(s)Ms \qquad (1)$$

and

$$0 = I_2(s)\left[\frac{1}{C_2 s} + L_2 s\right] + I_1(s)Ms \qquad (2)$$

where V_o is the initial voltage on the primary capacitor C_1, M is the mutual inductance between the primary and secondary windings and the subscripts 1 and 2 denote the primary and secondary terms respectively. Using the relationship $M=k\sqrt{L_1L_2}$ (k is the coefficient of coupling) and rearranging the current equations yields:

$$I_1(s) = \frac{V_o}{L_1}\;\frac{w_2^2 + s^2}{s^4\left(1-k^2\right)+s^2\left(w_1^2+w_2^2\right)+w_1^2w_2^2} \qquad (3)$$

and

$$I_2(s) = \frac{-V_o k}{\sqrt{L_1L_2}}\;\frac{s^2}{s^4\left(1-k^2\right)+s^2\left(w_1^2+w_2^2\right)+w_1^2w_2^2} \qquad (4)$$

where $w_1^2 = I/L_1C_1$ and $w_2^2 = 1/L_2C_2$.

The case where the primary and secondary resonant frequencies are equal is worth considering since the equations are considerably simplified and are more easily solved. The time domain solutions for primary and secondary voltages and currents are:

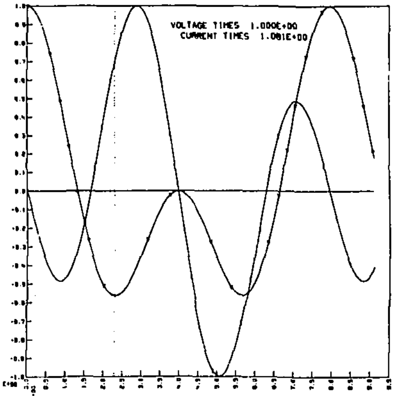
$$i_1(t) = \frac{V_o}{2wL_1}\left[\frac{1}{\sqrt{1-k}}\sin\frac{wt}{\sqrt{1-k}} + \frac{1}{\sqrt{1+k}}\sin\frac{wt}{\sqrt{1+k}}\right] \qquad (5)$$

$$i_2(t) = \frac{-V_o}{2w\sqrt{L_1L_2}}\left[\frac{1}{\sqrt{1-k}}\sin\frac{wt}{\sqrt{1-k}} - \frac{1}{\sqrt{1+k}}\sin\frac{wt}{\sqrt{1+k}}\right] \qquad (6)$$

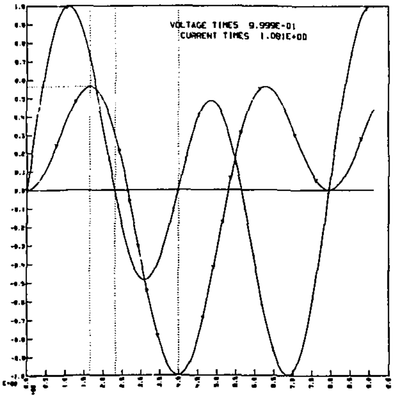
$$v_1(t) = \frac{V_o}{2}\left[\cos\frac{wt}{\sqrt{1-k}} + \cos\frac{wt}{\sqrt{1+k}}\right] \tag{7}$$

$$v_2(t) = \frac{V_o}{2}\sqrt{\frac{L_2}{L_1}}\left[\cos\frac{wt}{\sqrt{1-k}} - \cos\frac{wt}{\sqrt{1+k}}\right] \tag{8}$$

The most commonly used transformer of this type has a coefficient of coupling $k = .6$.[2,3] The current and voltage relationships for the primary and secondary windings are repeated here for comparison purposes (Fig. 4). The largest value of secondary voltage occurs when the maximum of the low and high frequency terms peak simultaneously. At this instant in time the primary and secondary currents are zero, and the primary voltage is zero. Theoretically, this is a condition for 100% energy transfer; in practice, because of transformer and switch losses, a 90-95% efficiency has been achieved. Unfortunately, the primary current of the transformer does reverse and the transformer cannot be used because of the decision to use existing thyratrons.



PRIMARY VOLTAGE AND SECONDARY CURRENT VS.TIME
K= 0.600 ; WP/WS=1.000



SECONDARY VOLTAGE AND PRIMARY CURRENT VS. TIME
K= 0.600 ; WP/WS=1.000

FIG. 4 PRIMARY AND SECONDARY VOLTAGES AND CURRENT FOR A TRANSFORMER HAVING $k = .6$ and $w_1 = w_2$

Although a thorough analysis of the primary current and secondary voltage as a function of coupling coefficient is arduous, an examination of the time domain solution indicates that for any value of coupling, the primary current does not reverse before the first secondary voltage peak. However, it is not until $k > .8$ that the first voltage peak begins to exceed the second voltage peak. For $k = .8$ (Fig. 5) the current in the primary at the voltage peak is a considerable percentage of its maximum value and even though this is an acceptable mode of operation in that it satisfies the design criterion, it is not desirable because of the low efficiency and because the unused energy in the transformer primary continues to drive the secondary thereby inhibiting sparkgap recovery. To dampen this energy, in a high rep-rate system, it becomes necessary to include lossy devices which further reduce the energy transfer efficiency. One good feature of this mode of operation is that the voltage peak occurs on the first cycle and therefore the charge time is shorter.

Having found no desirable mode of transformer operation for equal primary and secondary resonant frequencies, equations (3) and (4) must be solved for the general case where $w_1 \neq w_2$. The solutions are:

$$i_1(t) = \frac{V_o}{L_1\sqrt{\;}}\left[\frac{w_2^2 - s_1^2}{s_1}\sin s_1 t - \frac{w_2^2 - s_2^2}{s_2}\sin s_2 t\right] \tag{9}$$

$$i_2(t) = \frac{-V_o k}{\sqrt{L_1 L_2}\sqrt{\;}}\left[s_2 \sin s_2 t - s_1 \sin s_1 t\right] \tag{10}$$

where

$$s_1^2,\ s_2^2 = \frac{\left(w_1^2 + w_2^2\right) \mp \sqrt{w_1^4 + w_2^4 - 2\left(1-2k^2\right)w_1^2 w_2^2}}{2\left(1-k^2\right)} \tag{11}$$

and

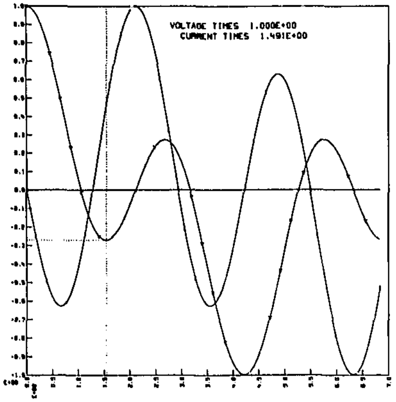
$$\sqrt{\;} = \sqrt{w_1^4 + w_2^4 - 2\left(1-2k^2\right)w_1^2 w_2^2} \tag{12}$$

The corresponding voltages are:

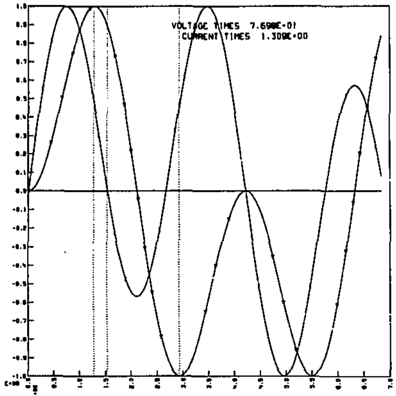
$$v_1(t) = \frac{V_o w_1^2}{\sqrt{\;}}\sqrt{\frac{L_2}{L_1}}\left[\frac{w_2^2 - s_1^2}{s_1^2}\cos s_1 t - \frac{w_2^2 - s_2^2}{s_2^2}\cos s_2 t\right] \tag{13}$$

$$v_2(t) = \frac{V_o k w_2^2}{\sqrt{\;}}\sqrt{\frac{L_2}{L_1}}\left[\cos s_2 t - \cos s_1 t\right] \tag{14}$$

Examination of equations (9 through 14) reveals that by factoring out w_1, the equations may be interpreted as functions of k and the ratio of the two frequencies. On this basis solutions for these equations are generated by computer. To add versatility to the output results, the transformer simulated has the input voltage, primary and secondary inductors, and secondary resonant frequency equal to one. Only the coefficient of coupling and ratio of primary to secondary frequencies are varied. This results in a family of voltage and current waveforms where for each value of k, a set of curves - each curve representing a different resonant frequency ratio - is generated.



PRIMARY VOLTAGE AND SECONDARY CURRENT VS.TIME
K= 0.800 ; HP/HS=1.000

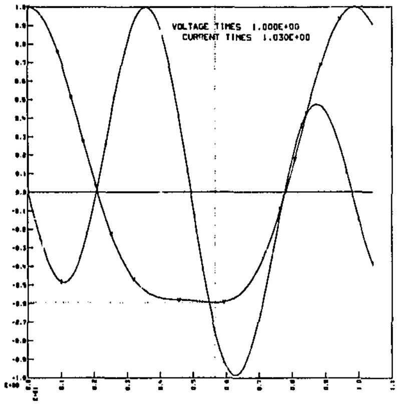


SECONDARY VOLTAGE AND PRIMARY CURRENT VS. TIME
K= 0.800 ; HP/HS=1.000

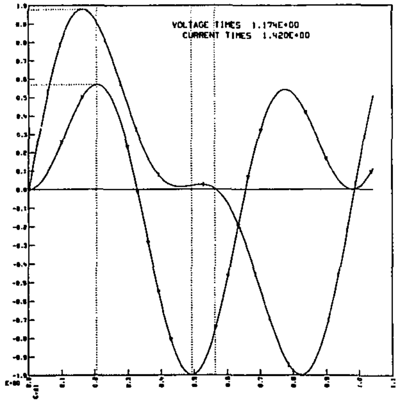
FIG. 5 PRIMARY AND SECONDARY VOLTAGES AND CURRENT FOR A TRANSFORMER HAVING k = .8 and $w_1 = w_2$

An examination of all computer generated curves reveals that a particular set of transformer parameters does indeed satisfy all the requirements. The voltage and current waveforms shown in Fig. 6 correspond to a value of coupling equal to .525 and a frequency ratio equal to .69. It should be understood that these numbers do not represent a unique solution-slight variations about either of these parameters have only slight effects on the waveforms. In fact, all values of w_p/w_s less than .69 satisfy the thyratron current requirements of non-reversal for k = .525. Furthermore, any transformer, regardless of k, has at some point a w_p/w_s at which current reversal does not occur before the secondary voltage peaks. At this point other factors become important; primary energy storage, voltage step-up, and energy distribution at the time of maximum secondary voltage. The goal now is to maintain the highest efficiency while having a minimum of energy stored in the transformer when the sparkgap is triggered.

Fig. 6 shows that the current in the primary is non-reversing and near zero at the secondary voltage peak. The primary voltage has actually reversed by 60% at this time but this energy remains in the capacitor because the thyratron opens at the zero current point. Although this case is not optimum from an energy transfer standpoint, the remaining energy has no adverse effect upon the sparkgap recovery time and does satisfy the step-up and primary current requirements.



PRIMARY VOLTAGE AND SECONDARY CURRENT VS.TIME
K= 0.525 ; HP/HS=0.690



SECONDARY VOLTAGE AND PRIMARY CURRENT VS. TIME
K= 0.525 ; HP/HS=0.690

FIG. 6 PRIMARY AND SECONDARY VOLTAGES AND CURRENTS FOR A TRANSFORMER HAVING k = .525 and w_1/w_2 = .69

Transformer Design

At this point, transformer design in terms of inductances, capacitances, current limits and voltage gains is ready to begin. The known values are Eqs. 9-14, the secondary capacitance (10-nF), k (.525), and w_1w_2 (.69). Also known are the maximum primary current (10-kA), minimum voltage gain (10:1), and the range for charging time ($t \sim 10$-μs). There is enough information that the other transformer values - primary inductance and capacitance and secondary inductance may be determined.

As there are several transformers which can be designed to operate under the specified limits, tradeoffs in terms of reliability and efficiency are made. For the former of these reasons, a realizable voltage step-up of 13:1 is reasonable. The higher transformer gain reduces the thyratron dc operating voltage from 25 to about 20-kV at the cost of lengthening the charging time. To offset anticipated 5-10% losses in the secondary damping circuitry and the 10% losses in the primary drive due to tube drop and cable inductance, a design voltage gain of 15:1 is required. Substituting the values of k and w_1/w_2 into the secondary voltage equation (Eq. 14) yields:

$$\frac{v_2(t)}{V_o} = .59 \sqrt{\frac{L_2}{L_1}} \left[\cos .92\, w_1 t - \cos 1.85\, w_1 t\right] \qquad (15)$$

$v_2(t)$ attains its peak value at time $t \sim \pi/(.92w_1)$. Substituting this value of time into the above equation and using the design value of 15:1 for the voltage gain yields:

$$L_2 = 162L_1 \qquad (16)$$

Similarly the primary current equation becomes:

$$i_1(t) = \frac{V_o}{L_1 w_1 (1.88)} \left[1.37\sin .92w_1 t + .72\sin 1.85w_1 t\right] \qquad (17)$$

The current peaks at $t \sim 2.07/1.85w_1$, and for a design peak current value of 10-kA and an anticipated primary drive voltage of 20-kV, the current equation reduces to:

$$L_1 w_1 = \sqrt{\frac{L_1}{C_1}} = 1.93 \qquad (18)$$

or

$$C_1 = .270L_1 \qquad (19)$$

Knowing the resonant frequency ratio

$$\frac{w_1}{w_2} = .69 = \frac{\sqrt{L_2C_2}}{\sqrt{L_1C_1}} \qquad (20)$$

and values of C_2, L_2, and C_1 in terms of L_1, the value of the primary inductance is easily found to be $L_1 = 12.6$-μH. Other transformer values are then found to be $L_2 = 2.04$-mH and $C_1 = 3.4$-μF. These values allow the determination of the secondary charging time which is 22-μs after switch closure. However, examination of Fig. 6 shows that the peak-to-peak voltage swing occurs in slightly more than half the time required to attain maximum secondary voltage. This time is slightly less than 13-μs which reasonably approaches the design value.

Transformer Construction and Testing

The transformer is a spiral wound auto-transformer as this type of construction lends itself to fast and simple manufacture. Transformer dimensions and number of turns are determined by the coefficient of coupling, the inductance values, and the container. The number of turns for the primary and secondary and the relative spacing of those windings were initially determined from standard formulae for inductance and coupling coefficient. These values were modified to account for the shielding affect of the container walls and several low voltage transformer models were constructed to insure proper performance. The low value of coupling requires a thick transformer winding and thus permits the use of relatively thick foils and insulations. The foil is capacitor grade 2-inch wide, 7 mil aluminum and the insulation consists of 6-inch wide, 7 mil mylar between two 6-inch wide, .5 mil kraft paper (for oil wicking). The thick foil minimizes corona problems and the insulation width and thickness provide a long creepage path and an insulation voltage breakdown strength far in excess of anticipated potentials-all necessary requirements for long life and reliability. As shown in the transformer cross section, Fig. 7, the transformer has non-shorting curved conducting surfaces as the output (250-kV) and drive (20-kV) terminals to shape the electric fields and eliminate gradient magnification.

The final transformer winding consists of a 7-1/2 turn primary wound onto the outside of a 150 turn secondary separated by an approximate 3/16" spacer; foil and insulation dimensioned as previously described. The drive point is the junction of the primary and secondary windings. The transformer is 4 inches I.D. and 9-1/2 inches O.D.

The averaged measured values for the primary and secondary inductances and coupling for the 34 transformers constructed are approximately $L_p = 11.5$-μH, $L_s = 2.0$-mH, and $k = .525$. Low level operational tests using a SCR switch are shown in Fig. 8. These waveforms compare favorably with the computer generated waveforms of Fig. 6. Secondary voltage and primary current oscillograms for output voltage of 130-kV are shown in Fig. 9. The first prototype has over 100,000 shots without failure at voltages in excess of 200-kV.

The other circuitry in the transformer container (which is oil filled) provides the sparkgap midplane potential, damping, and decoupling. Referring to the schematic in Fig. 1 and to Fig. 7, these components are identifiable. The varistor in series with the high voltage output provide damping after sparkgap breakdown by becoming a large impedance at low current levels. The 20-μH, 50-Ω parallel combination decouple the sparkgap and transformer at high frequencies. The series 12-Ω resistor supplies additional damping and aids sparkgap recovery. The 20-kΩ resistor string provides the sparkgap trigger electrode with its required V/2 potential. The 250-pF capacitor is a coaxial parallel plate structure which couples the sparkgap trigger voltage to the sparkgap trigger electrode.

CONCLUSION

Using a thyratron as a primary switch imposes current restrictions with which a conventional charging transformer cannot comply. A .525 coupled transformer operating in an off-resonance mode satisfied the current requirements, but at the expense of a non-optimum energy transfer. A .6 coupled transformer can be used to overcome the energy transfer problem, but only if a bilateral switch such as a spark gap or, preferably, an inexpensive double-ended thyratron is used.

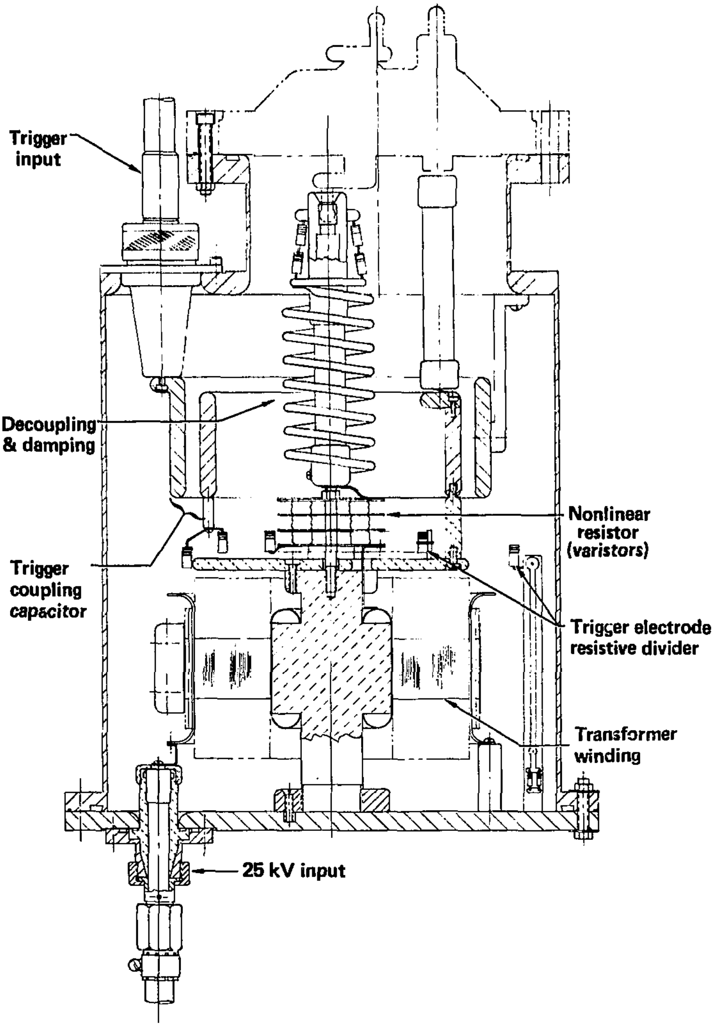


FIG. 7 TRANSFORMER CROSS-SECTION

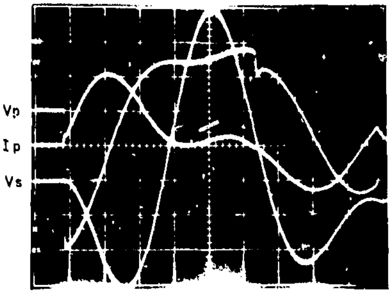


FIG. 8 LOW LEVEL MEASUREMENTS OF PRIMARY CURRENT, PRIMARY VOLTAGE AND SECONDARY VOLTAGE FOR TRANSFORMER HAVING k = .525 and w_p/w_s = .69

V_p @ 5 V/DIV, I_p @ 5 A/DIV,
V_s @ 50 V/DIV, t @ 5μs/DIV.

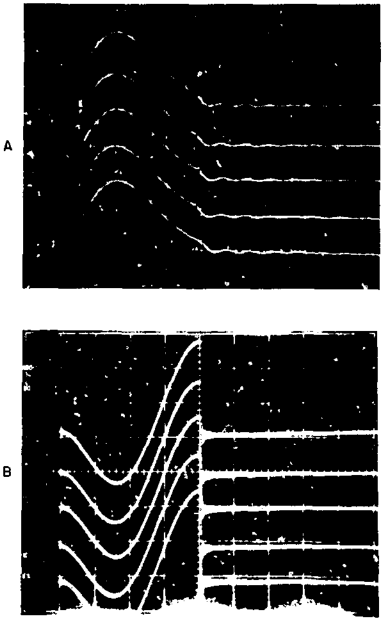


FIG. 9 SECONDARY VOLTAGE AND PRIMARY CURRENT FOR TRANSFORMER (k = .525 and w_p/w_s = .69) OPERATING AT 130-kV.

9(a) I_p @ 2.6 kA/DIV, t @ 5μs/DIV.
9(b) V_s @ 50 kV/DIV, t @ 5μs/DIV.

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