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TITLE ENERGY STORAGE TRANSFORMER POWER CONDITIONING SYSTEMS FOR MEGAJOULE CLASS FLUX COMPRESSION GENERATORS

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ENERGY STORAGE TRANSFORMER POWER CONDITIONING SYSTEMS FOR MEGAJOULE CLASS FLUX COMPRESSION GENERATORS

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ABSTRACT

Circuit and energy storage transformer configurations are developed to match high impedance loads to low impedance sources. With the secondary open, a large di/dt is produced in the primary circuit by inserting a resistance, characteristic of an opening switch, and the load circuit is connected using a preset spark gap. Transformer design concepts using a foil-MYLAR "sandwich" for the secondary winding are described, permitting close primary-secondary coupling. Transformer experiments driven by a 0.25 MJ capacitor bank support the overall system concepts. A compact flux compression generator-transformer system is described.

INTRODUCTION

Flux compression generators represent reliable, convenient and economical sources of large amounts of electrical energy. Flux compressors are usually low impedance sources, and are well suited to drive a wide variety of low impedance experimental loads. On the other hand, an interesting family of high impedance, high voltage loads, such as the high voltage electron diode, could take advantage of the positive features of flux compression generators if suitable energy storage/power conditioning systems were available to match the high impedance loads to low impedance sources.

While intermediate energy storage in the form of capacitors or high voltage pulse lines represents a straightforward approach to power conditioning and impedance matching, the need to store energy in the electric field of a dielectric at an energy density 2-3 orders of magnitude below the magnetic energy density of the flux compression generator negates many of the benefits of the flux compressor as a primary energy source.

A transformer is a conceptually simple concept for matching a high impedance load to a low impedance source. For high speed, high energy systems, an air core approach to transformer design is virtually required despite its inherent inefficiencies, and high voltage operation places stringent demands on insulation techniques in a closely packaged system. The addition of a current interrupting switch allows the design of a relatively "nominal" power conditioner for use with a variety of current sources -- or more precisely, to make the power and energy delivered to the load less dependent upon the exact performance of the current source. In this mode of operation, the transformer acts first as an energy storage inductor, accepting energy from the source over a relatively long period of time. This is followed by discharge of the stored energy into a load. The use of coupled inductors instead of a single inductor provides added flexibility.

CIRCUIT CONSIDERATIONS

High impedance loads (typically larger than one ohm) driven by low impedance sources require a power conditioning system to provide impedance matching between the source and the load. The elementary transformer system, shown in Figure 1, has a time varying current source driving the primary of the transformer, and the load resistance, RLD, is connected directly to the secondary. Impedance matching is achieved by adjusting the primary to secondary turns ratio, N, in the transformer. The current and power waveforms which the circuit applies to the load are closely related to the current and di/dt delivered by the primary-side energy source. This approach is simple but allows little opportunity for shaping the waveform applied to the load.

In contrast, the transformer-switch approach, shown in Figure 2, stores energy from the current source in the primary inductance, LPRI, of the transformer. The interruption of the primary current by the operation of the opening switch, "A," is accompanied by the closing of the load isolating switch "B" in the transformer secondary, and by the delivery of current to the load resistance, RLD. Considerable flexibility in the shaping of the output pulse is achieved at the cost of additional complexity.

The energy storage transformer approach is particularly useful when the timescale which characterizes the primary current source is long compared to the timescale required by the load. This approach can increase the peak power to the load, shorten its risetime, and decrease its width, while the transformer provides the required impedance matching. Flux compression generators are an example of primary energy sources which take advantage of this feature. While some very fast flux compression generators are available, a family of simple, high gain generators, based on helical geometry, naturally operate on timescales of tens of microseconds, and pulse compression is required in order to drive loads which require microsecond or shorter power pulses. For these cases, the "charging" time, during which flux and energy are stored in the inductance of the transformer primary, can be treated separately from the "power conditioning" time during which energy is applied to the load.

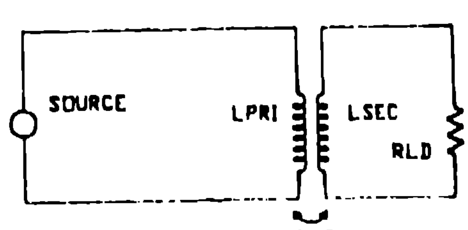

Fig.1. Elementary transformer circuit.

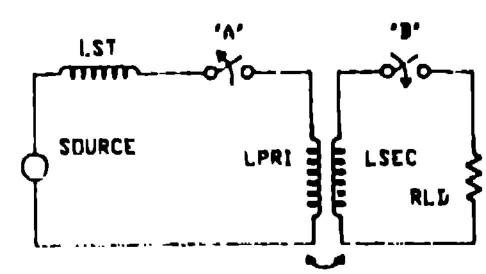

Fig.2. Transformer circuit with switches.

An approximate equivalent circuit is shown in Figure 3. This circuit includes primary-side and secondary-side inherent circuit inductances, LST and LLD. At the instant of switching, the opening of switch "A" is modeled by an instantaneous excursion to a finite resistance, RFUS. The initial current flowing in the primary loop is ζ, and the initial current in the secondary loop is zero.

The Laplace Transform [1] equations describing this circuit are:

$$0 = RFUS*IPRI + (LST + LPRI)*(s*IPRI - \zeta) - LMUT*s*ILD \quad (1)$$

$$0 = RLD*ILD + (LSEC + LLD)*s*ILD - LMUT*(s*IPRI - \zeta) \quad (2)$$

The general time-dependent solution for the current in the secondary loop, ild(t), is:

$$ild(t) = Imax\,[\varepsilon^{-at} - \varepsilon^{-bt}] \quad (3)$$

where 1/a and 1/b are positive real time constants.

Identifying some convenient parameters, the transformer windings have a physical coupling coefficient, "K", which is given by:

$$K = LMUT/\sqrt{LPRI*LSEC} \quad (4)$$

which has a maximum value of 1.0 for "perfect" coupling. The inductances LST and LLD, external to the transformer, may be included by identifying an "equivalent coupling coefficient", K_x, given by:

$$K_x = K/\sqrt{(1 + p)(1 + q)} \quad (5)$$

$$\text{where } p = LST/LPRI \quad (6)$$

$$\text{and } q = LLD/LSEC \quad (7)$$

Note that K_x is always less than, or equal to, K. Another useful concept is an "equivalent turns ratio", defined as:

$$N_x = \sqrt{LSEC(1 + q)} \,/\, \sqrt{LPRI(1 + p)} \quad (8)$$

Following the concept of reflected impedances for ideal transformers, the switch resistance reflected into the secondary circuit is:

$$RFUS_x = N_x^2 * RFUS \quad (9)$$

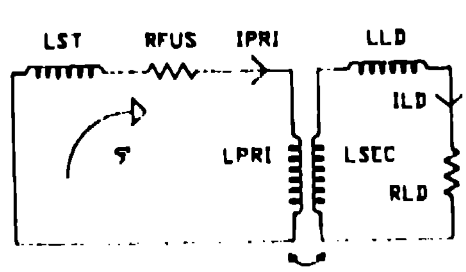

Fig. 3. Equivalent circuit at instant of switching.

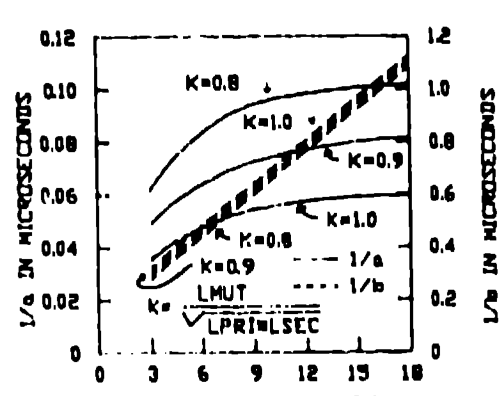

Fig. 4. Time constants as a function of LSEC.

A time constant characteristic of the circuit can then be identified which has the form of a one-loop series circuit time constant:

$$T = 2*LSEC*(1 + q)/(RFUS_x + RLD) \quad (10)$$

Finally, a dimensionless parameter is introduced which is the ratio of the load and reflected switch resistances:

$$G = RLD/RFUS_x \quad (11)$$

The parameters of the general solution (Equation 3) can now be written in compact form as:

$$Imax = \zeta*K_x/(N_x*(1 + G)*Q) \quad (12)$$

$$1/a,\ 1/b = T*(1 - K_x^2)/(1 \pm Q) \quad (13)$$

$$\text{where } Q = \sqrt{1 - 4*G*(1 - K_x^2)/(1 + G)^2} \quad (14)$$

To show the effect of parameter variations on Imax, 1/a, and 1/b, circuit element values were assumed as follows: p = 0.4, q = 0.1, LPRI = 0.175μH, RLD = 20 ohms, and RFUS = 1.3 ohms. The transformer coupling coefficient and the secondary inductance were chosen as variables.

The two time constants, 1/a and 1/b, which essentially control the rise and fall times of the current pulse when they differ appreciably, are plotted in Figure 4 as a function of the transformer secondary inductance with the transformer coupling coefficient as a parameter. The rising (shorter) time constant, 1/a, (corresponding to the 1 + Q root in Equation 13) increases slightly with larger secondary inductance, but becomes much lower as the coupling increases. The falling (longer) time constant, 1/b, (corresponding to the 1 - Q root) is more sensitive to changes in LSEC but is relatively unaffected by changes in K. For a closely coupled transformer, the fall time is 10 to 20 times longer than the rise time, producing a steeply rising pulse with a relatively long period of near constant power.

The normalized amplitude factor, Imax/ζ, is shown in Figure 5 as a function of the transformer secondary inductance with the coupling coefficient as a parameter. As the secondary inductance increases, the amplitude decreases and also shows a wider variation with changes in the coupling coefficient, K.

The transformer secondary inductance is determined by geometry and the number of secondary turns. Increasing the number of turns results in

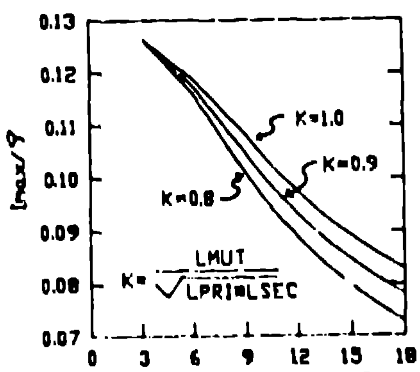

Fig.5. Current amplitude as a function of LSEC.

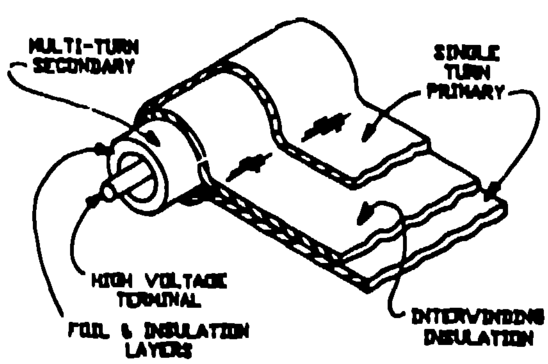

Fig.6. Foil transformer design.

increased secondary inductance. As the number of turns is increased, Figures 4 and 5 indicate that the current pulse decreases in amplitude, the rise time is relatively unaffected, and the tail of the pulse is lengthened.

TRANSFORMER DESIGN CONCEPTS

The preceding circuit analysis of energy storage transformer concepts shows that the coupling coefficient is a significant parameter in determining circuit performance. Both foil wound and wire wound transformers have been employed in direct-coupled applications to match flux compression generators to higher impedance loads [2,3,4]. Detailed development of long lifetime transformers for repetitive applications based on foil construction and elaborate field shaping structures has been reported [5].

A conceptual approach to the design of a heavy duty, air core energy storage transformer is shown in Figure 6. The device consists of a relatively heavy, single turn primary winding located outside of a multiple-turn secondary winding. The primary turn is insulated from itself and from the secondary winding by interwinding insulation which is an extension of the insulation in the main transmission line which connects the transformer to the primary current source through the primary loop opening switch. The thickness of the interwinding insulation is a critical factor in determining the coupling coefficient of the transformer since it represents an unavoidable volume of primary flux which is not coupled by secondary turns. The voltage holdoff demanded of the interwinding insulation may be minimized by specifically designating the outermost turn of the foil secondary to be the low voltage reference of the secondary circuit and holding that reference close to the primary potential. The secondary winding is composed of a continuous strip of foil (which can be relatively thin because secondary currents are of extremely short time duration) encased in plastic film insulation and wound spirally on a cylindrical form which becomes the high voltage terminal of the transformer.

Controlling interturn breakdowns, both by bulk insulation puncture and by tracking around the end of the (secondary) interturn insulation, represents the most demanding design feature of spiral, closely coupled foil-wound transformers. For multiple pulse operations, elaborate field shaping structures which force the electric field to be predominatly radial have been successfully operated for millions of shots in the direct drive mode [5]. Open, film wound structures graded with resistive solutions have been demonstrated successfully [2] for single pulse operation. Recently a composite material consisting of high electrical integrity MYLAR (of almost any convenient thickness) bonded to a thin (two to four mil) layer of

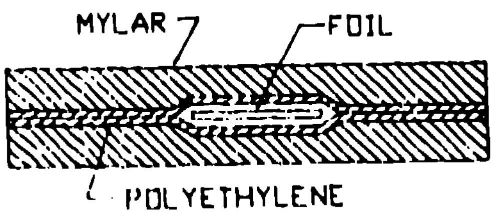

Fig. 7. MYLAR-polyethylene foil "sandwich".

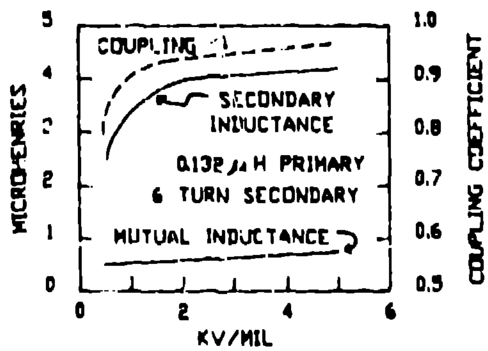

Fig.8. Transformer parameters vs insulation stress.

polyethylene has become commercially available. By thermally bonding adjacent polyethylene layers together with a foil conductor in between, a continuous flat, "ribbon-like" structure can be produced as shown in Figure 7. When interleaved with additional conventional MYLAR sheets and wound on the output terminal, a coil is produced in which the turn to turn voltage appears across high quality MYLAR, and edge tracking is inhibited by the bonded polyethylene. These windings have been successfully tested at turn-to-turn voltages in excess of 200 kV using 100 mils of MYLAR insulation, for an average insulation stress of 2.0 kV/mil.

Calculations of the self inductance of a single turn primary, a multiple turn secondary, and the mutual inductance of the coupled windings were carried out following the methods described in Grover [6]. The effects of changes in insulation stress and number of turns were calculated. For this study the width of both primary and secondary windings was fixed at 38.1 cm (15 in), and the inner diameter of the primary was fixed at 24.5 cm (10 in). The primary conductor was 0.3175 cm (1/8 in) thick and has a calculated inductance of 132 nanohenries. The secondary conductor was 0.0051 cm (2 mil) thick foil and, with its outer diameter constrained by the fixed inner diameter of the primary minus the thickness of the interwinding insulation, its inner diameter is a function of the interturn insulation thickness. A peak voltage of 1.0 MV was assumed across the secondary for all cases, implying that the current and di/dt in the primary might change significantly from case to case. The interwinding insulation was stressed to approximately the same level as the secondary interturn insulation by setting the interwinding insulation thickness for all cases to:

$$TPS = 1.0*10^6/(N*S) \quad \text{mils} \qquad (15)$$

where N is the number of secondary turns and S is the secondary insulation stress in volts/mil.

Figure 8 shows the variation in the parameters of a 1:6 ratio transformer as the average insulation stress is increased from 500 v/mil (conventional DC breakdown stress for many plastics) to 5 kV/mil (an optimistic upper limit for impregnated capacitor-like windings). As the insulation stress is increased, the secondary self-inductance increases slightly as a result of more complete coupling of the inner turns to the flux produced by the outer turns. The mutual inductance also increases as the inner turns are coupled more closely to the primary turn. The coupling coefficient reaches 0.96 for 5 kV/mil configurations.

A variety of transformer impedance (turns) ratios are required to match differing loads to specific sources and opening switches. Figure 9 shows the

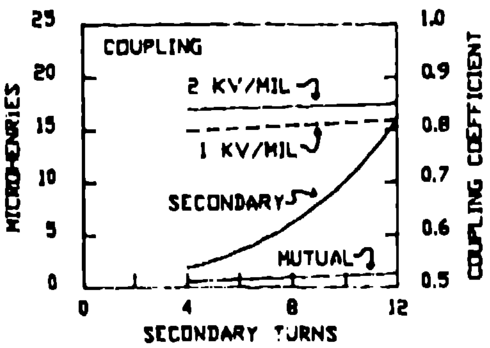

Fig.9. Transformer parameters vs secondary turns.

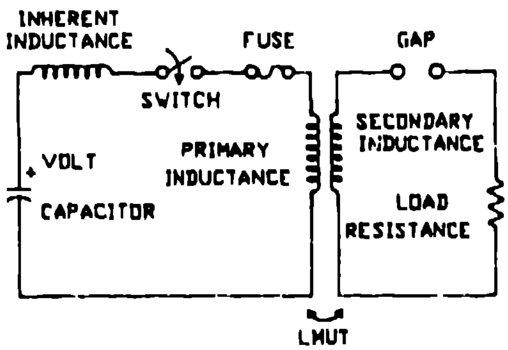

Fig.10. Laboratory test circuit.

effect of turns ratio upon transformer parameters. An insulation stress of 2.0 kV/mil, comparable to that already demonstrated, is assumed. Coupling coefficients in the range of 0.90 to 0.95 can be expected for a relatively wide range of transformer ratios. For practical windings it is observed that radial dimensions are of the order of 20 percent greater than the sum of the layer thicknesses, and a "packing factor" can be introduced to account for the unavoidable extra space in the windings. This results in a slight decrease in coupling between the windings. If the interwinding insulation stress is reduced to 1.0 kV/mil, the coupling coefficient is lowered to the 0.875 - 0.90 range.

EXPERIMENTAL RESULTS and PROJECTED PERFORMANCE

To confirm the design predictions, a model transformer was tested on a 36.6 μF laboratory capacitor bank charged to 40 kV. The circuit is shown in Figure 10, where the load resistance is 30 ohms, the inductance of the single turn primary is 175 nH, the six-turn secondary is 9.03 μH, and the mutual inductance between the windings is 1.03 μH. The physical transformer coupling coefficient is 0.82. The opening switch in the primary circuit is a 1.0 mil thick aluminum foil fuse of 35 cm length and 6.1 cm width surrounded by 100-micron glass beads. The bank and the fuse add 105 nH of uncoupled inductance to the primary loop, and the uncoupled inductance of the secondary loop is estimated as 20 nH. When the uncoupled inductances are added to the inductance of the actual transformer winding, an "effective" coupling, Kx, of 0.796 is obtained. An SF-6 filled spark gap, set to close at 500 kV, isolates the load from the transformer during energy storage. Figure 11 shows the primary current and the voltage across the secondary load resistor.

A differential equation-based computer code was written to simulate the experimental circuit. Included in the simulation is a specific energy fuse model. The computer-simulated load voltage is compared to the experimental load voltage in Figure 12. The computer simulation is in good agreement with the experimental results, indicating that the simulation can be used to predict system performance and to provide design information for the power conditioning transformer.

Using elementary models of a flux compression generator, the performance of a transformer energy storage power conditioning system was calculated. For a compact configuration, the transformer and fuse opening switch can be integrated into a single package by replacing the single-turn primary of the transformer with a thin foil conductor, which vaporizes under heavy current and serves also as the fuse opening switch. For generator applications, this

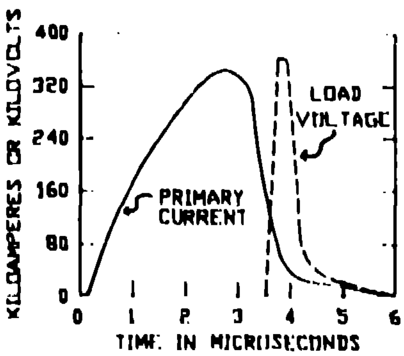

Fig.11. Measured primary current and load voltage.

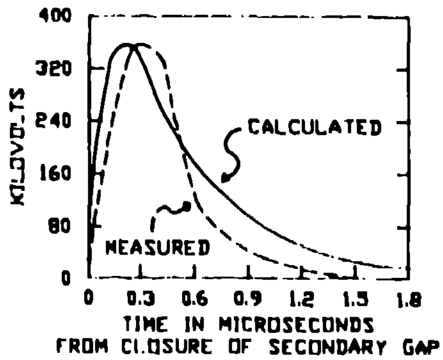

Fig.12. Simulated and measured load voltage.

approach has the added advantage of minimizing the external (uncoupled) inductance in the primary circuit loop, therefore improving the efficiency. Figure 13 shows the the current delivered by a 4.0 μH, 50 microsecond helical generator to the primary of a 1:6 transformer. The primary of the transformer is a foil fuse 120 cm long, 60 cm wide, and 2 mils thick. The secondary current delivered to a 10 ohm resistive load is also shown. In Figure 14, the power delivered to the load by the energy storage power conditioning system is plotted as a function of time.

CONCLUSIONS

The energy storage transformer can be used as a combined impedance matching and power conditioning system. The technique allows the operation of high impedance loads from low impedance sources, and produces an output waveform that is conceptually independent of the timescale of the primary energy source. Close coupling between the primary and secondary windings leads to best performance, producing an output waveform consisting of a double decaying exponential. The risetime is dominated by coupling, the turns ratio, and primary inductance, and the fall time by secondary inductance and load resistance. Physical coupling coefficients of 0.85 are feasible using fused MYLAR/polyethylene insulation techniques at average stresses of 2 kV/mil, and better coupling is possible at higher stress. An integrated fuse-transformer configuration in which the fuse is also the primary winding conductor makes for an extremely compact power conditioning concept.

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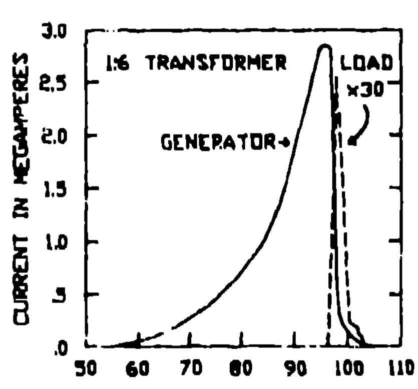

Fig.13. Primary and secondary currents from MCG.

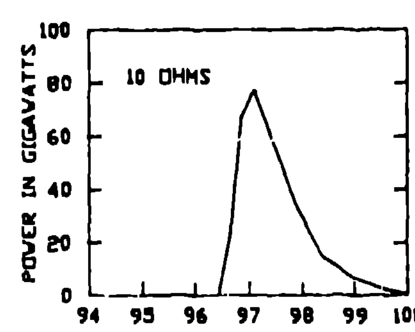

Fig. 14. Power delivered to the load from MCG.