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TRANSFORMERS FOR EXPLOSIVE PULSED POWER COUPLING TO VARIOUS LOADS*

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ABSTRACT

Tape-wound step-up transformers have been fabricated and used with magnetic flux compression generators in the past with effective coupling coefficients of ~0.76. We have attempted to design some units with coefficients in the range of 0.85-0.92 by taking advantage of newer dielectrics. The intent is to raise the voltage stress from <0.39 MV/cm to the range of 0.98-1.97 MV/cm. This has the effect of making the secondary thinner and permitting a higher coupling efficiency. Several designs for coupling the 13.2-cm-wide by 52.8-cm-long plate generator to loads in the range of 10 to 30 Ω with an output of ~1 MV have been studied. These designs must take into account that the primary of the transformer is switched into the circuit as a load in parallel with the generator's ballast inductor. Thus, the load impedance must be transformed to be comparable to $\dot{I}L_B/I_B = Z_B$ to transfer a significant fraction of the power from the generator to the load. A final design examines the constraints imposed by attempting to transform the output of a plate generator up to 10 MV into a high impedance load, ~377 Ω. A voltage stress of 3.9 MV/cm is required in this particular design for 140 kV per turn in the secondary winding.

INTRODUCTION

The plate-type FCG (flux compression generator) is a low impedance source of pulsed power. To power a relatively high impedance load with one of these generators, some method of impedance matching must be used to couple the load with the power supply. The 13.2 cm × 52.8 cm plate generator achieves an output impedance of 30-40 mΩ near the completion of its burn. However, an electron beam diode, for example, may represent a load impedance of 1-50 Ω, depending on the exact configuration. To effect the necessary match between the FCG and the load, we have designed several air-core pulse transformers with differing characteristics to illustrate the compromises that one may make in adapting transformer technology for this application. An important aspect of this study is to show how the construction can be tailored to achieve coupling coefficients >~0.9, with associated energy efficiencies. Our primary interest has been to provide <1 MV to load impedances of 10, 20, and 30 Ω from the

* Work supported by the US Department of Energy.

plate generator. However, we also studied the case of a 5-10 MV system in which the load impedance was 377 Ω.

Historically, air-core transformers have been used to produce high voltage from explosive generators by using a solenoid-wound secondary with a one-turn primary by Fowler, et al.[1] Then, Erickson, et al.[2] demonstrated that a plate-generator output could be transformed to ~1 MV by using a 10.2-cm-diameter, foil-wound secondary transformer that was a direct descendent of J. C. Martin's[3] pulsed transformer development. Our goal has been to extend the achievements of Erickson by taking advantage of newer dielectrics that permit higher voltage stresses in the secondary winding and by using better winding techniques. In this manner, one expects to significantly improve on the previously reported coupling coefficient, k, of ~0.76 by making a thinner secondary winding or pack. Such an improvement leads to an improvement in the efficiency of transferring energy from the generator to the load which can be seen by observing that for an inductive load, L_L, the load current, i_2, is maximized when L_L is minimized by

$$L_2 = L_L \left(1 - k^2\left(\frac{L_1}{l_0 + L_1}\right)\right) \qquad (1)$$

where L_1 = the transformer primary inductance, L_2 = the transformer secondary inductance, k = the coupling coefficient, and l_0 = the stray inductance between the generator and transformer.[4] An additional benefit of the newer materials and tighter secondary windings should be an improvement in reliability which is crucial for single-shot explosive FCG experiments.

CIRCUIT MODEL

To provide a basis for discussion, we start by considering the transformer circuit that was modeled. In Fig. 1, the generator power supply is shown coupled through a closing switch to the transformer primary. In this circuit, the quantities of interest in the model are L_G = generator inductance, $\mathcal{L}_G$ = generator impedance, L_B = ballast inductor, τ_s = time when closing switch completes circuit to the transformer primary, L_1 = transformer primary inductance, L_2 = transformer secondary inductance, M = mutual inductance between the primary and secondary, n = turn ratio of the transformer, R_L = load resistance or impedance, V_L = voltage developed across R_L, i_1 = primary current, and i_2 = secondary current. Now, if all quantities are referred to the primary side of the transformer, we have Fig. 2 where the quantities i_2, L_2, M, V_L, and R_L are transformed to $i_2' = ni_2$, $L_2' = L_2/n^2$, $M' = M/n$, $R_L' = R_L/n^2$, and $V_L' = V_L/n$.

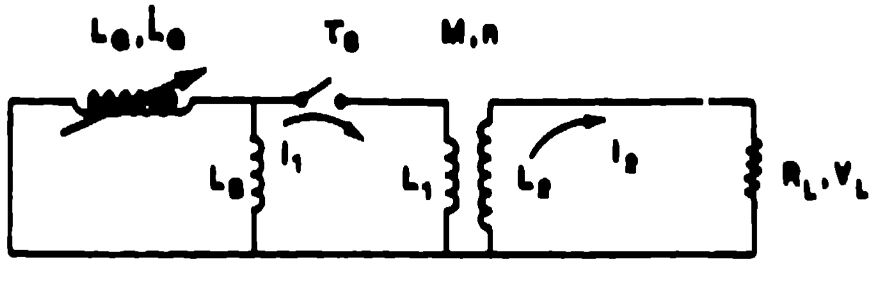


Figure 1.

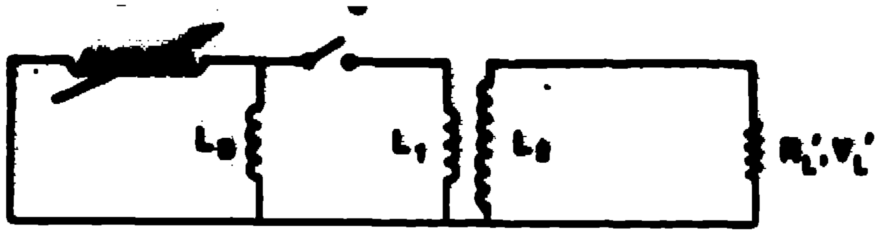


Figure 2

To obtain some other useful quantities, we may use the equivalent circuit, Fig. 3, to examine the "T" equivalent of our transformer. The L_L (leakage inductance) is defined as $L_L = (L_1 - M') + (L_2' - M')$, but when coils L_1 and L_2 are telescoped over each other, are the same length, and are spaced close to each other, then we see that the leakage inductance becomes $L_L = 2(L_1 - M')$. Also, M' is now recognized as the shunt inductance for the transformer. The coupling coefficient is defined as

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad , \tag{2}$$

and the leakage and shunt inductances can be represented as simple functions of k;

$$L_L = 2\, L_1\, (1-k) \tag{3}$$

$$L_S \equiv M' = L_1 k \quad . \tag{4}$$

However, the assumptions necessary to simplify L_L and the physical constraints required to make an efficient air-core step-up transformer result in a non-trivial C_D (distributed capacitance) which is primarily due to the secondary coil. Thus, we modify our circuit schematic to include this capacitance in Fig. 4, where C_D' is referred to the primary. The relationship with C_D is $C_D' = n^2 C_D$.

Throughout the circuit development, we have shown the closing switch such that when it closes at τ_S, the ballast inductor and the transformer are parallel circuit elements. Thus, we must not only transform the output of the FCG up to the desired load voltage, but the load impedance must be transformed down such that $R_L/n^2 = R_L' \sim Z_B = \dot{I}_B L_B / I_B$, where I_B = the current flowing in the ballast inductor, $\dot{I}_B$ = the time derivative of the ballast current, and Z_B = the effective impedance of the ballast loop. From an intuitive viewpoint, one can see that this is a very dynamic situation since an increase in $\dot{I}$ to the transformer will lead to a decrease in $\dot{I}_B$.

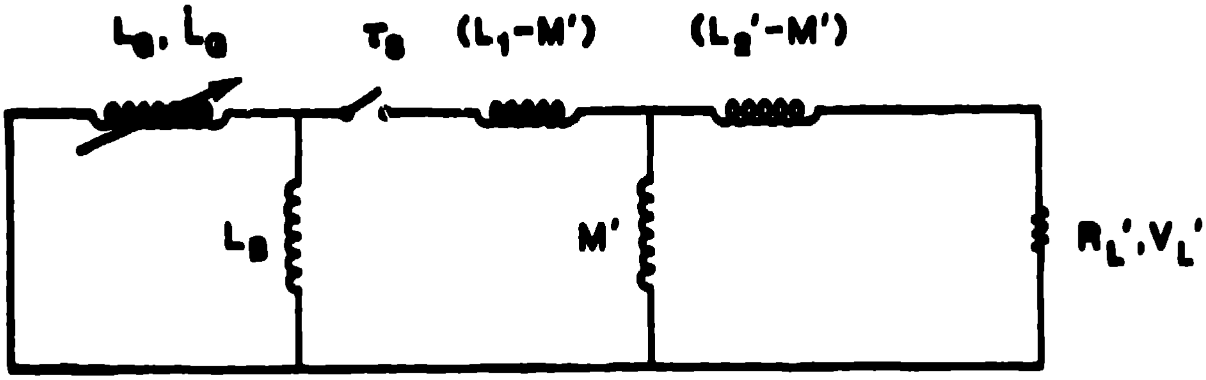


Figure 3.

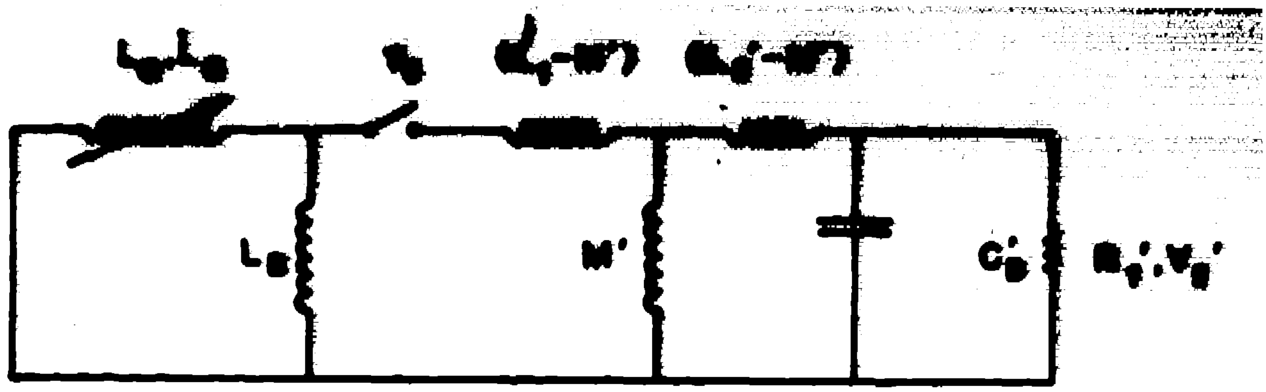
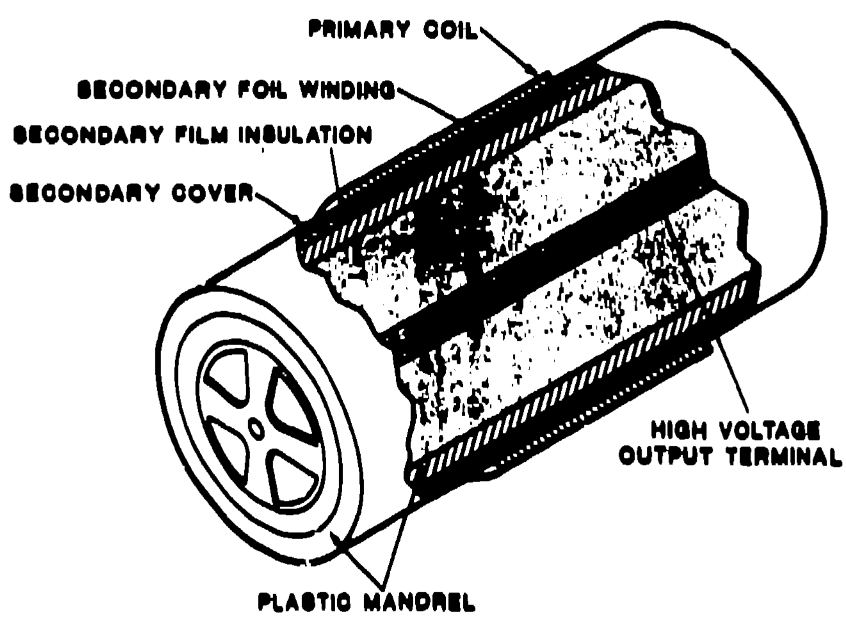


Figure 4.

This, in turn, lowers the effective Z_B which acts to counter the match being sought. Given this situation, it was necessary to use both the quantities that have been derived here and a circuit code, written by R. S. Caird, to analyze the specific transformer designs and load impedances considered for the explosive power supplies.

SPECIFIC DESIGNS

Specific transformer designs have been obtained by using a "build-out" approach. A winding mandrel size is selected, and with this outer diameter as a starting point, the remaining components are added in successive layers, Fig. 5. In this manner, the relative cross section of the secondary winding within the primary coil is minimized, with an associated increase in the coupling coefficient. An important consideration in these designs is that they can be used only once, so the expense of an individual unit can be reduced while still preserving enough reliability to ensure adequate performance for its one pulse. For example, the mandrel could be an elaborate, graded metal system with a very high reliability, appropriate for rep-rate applications, but the expense of this approach would also be prohibitive for single-shot use. Alternatively, PVC, polyvinyl chloride, pipe is very inexpensive and has very desirable fabrication characteristics.



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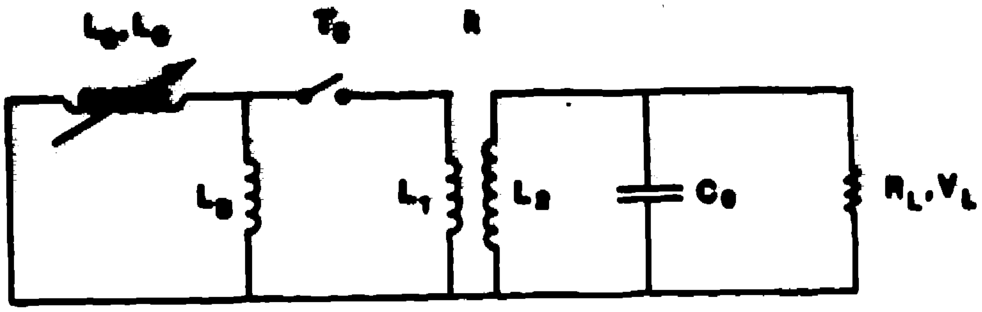

Figure 6.

The calculations for the 377 Ω load were performed on the same circuit as for the smaller impedances, except initial generator currents of 1 and 2 MA were used, Table V. For an initial current of 1 MA, the currents flowing in the generator, ballast, and primary were very similar to the typical case shown in Fig. 7. In Fig. 9, the voltage across the load as a function of time is plotted for both the impedance matched, 137 turn design and the significantly mismatched, 80 turn transformer. The initial generator current for these plots was 2.0 MA. One should note that the unmatched wave form is significantly different from the matched case.

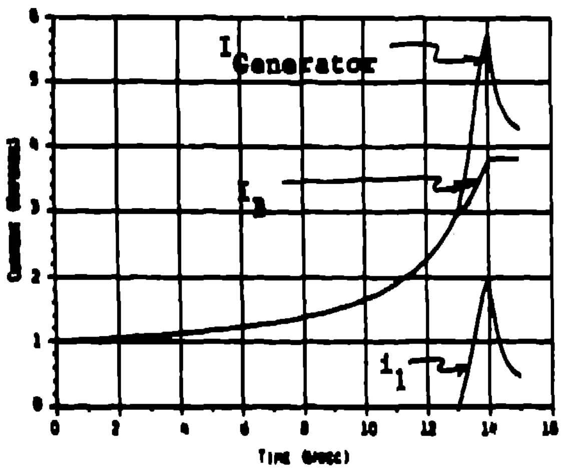

Figure 7.

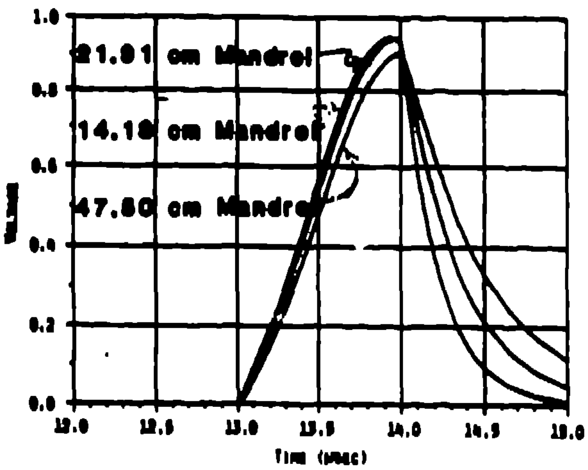

Figure 8.

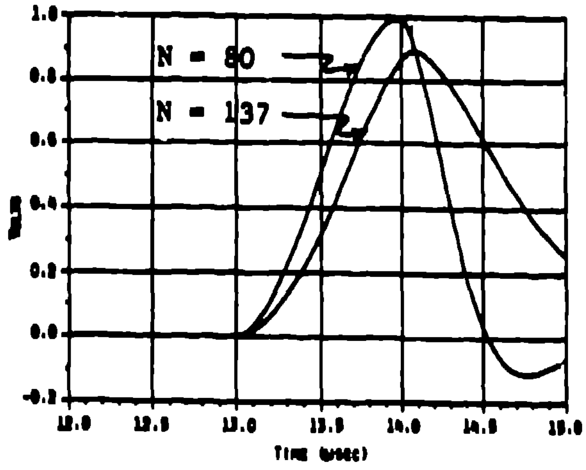

Figure 9.

Table I. [illegible]

Impedance (Ω)	Number of Turns	Voltage Stress (MV/cm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	18	1.97	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	18	0.98	[illegible]	[illegible]	[illegible]	[illegible]	10.5	[illegible]
20	27	1.97	65.7	[illegible]	1,360	0.940	7.10	99.1
20	27	0.98	69.0	40,200	1,500	0.925	10.5	66.6
30	33	1.97	63.5	[illegible]	[illegible]	0.944	7.49	95.0
30	33	0.98	71.0	[illegible]	1,970	0.923	10.9	66.5

Table II. Mandrel Size = 21.91 cm

Impedance (Ω)	Number of Turns	Voltage Stress (MV/cm)	Primary Inductance (nH)	Secondary Inductance (nH)	Mutual Inductance (nH)	Coupling Coefficient	Leakage Inductance (nH)	Shunt Inductance (nH)
10	18	1.97	130	30,000	2,140	0.939	10.3	123
10	18	0.98	135	39,000	2,220	0.960	10.8	130
20	27	1.97	128	87,000	3,220	0.938	10.8	123
20	27	0.98	138	89,500	3,310	0.944	15.3	130
30	33	1.97	129	131,000	3,950	0.937	11.9	124
30	33	0.98	139	134,000	4,070	0.941	16.4	131

Table III. Mandrel Size = 47.50 cm

Impedance (Ω)	Number of Turns	Voltage Stress (MV/cm)	Primary Inductance (nH)	Secondary Inductance (nH)	Mutual Inductance (nH)	Coupling Coefficient	Leakage Inductance (nH)	Shunt Inductance (nH)
10	18	1.97	343	108,000	5,960	0.978	13.1	336
10	18	0.98	334	109,000	6,030	0.969	22.0	343
20	27	1.97	343	244,000	8,940	0.978	13.1	336
20	27	0.98	334	245,000	9,040	0.969	22.0	343
30	33	1.97	344	364,000	10,900	0.977	13.8	336
30	33	0.98	334	367,000	11,100	0.968	22.8	343

Table IV.

Mandrel (cm)	Impedance (Ω)	Generator Current (MA)	Primary Current (MA)	Secondary Current (kA)	Load Voltage (kV)	Load Energy (kJ)	Load Power (GW)
14.13	10	5.80	2.00	87.5	875	43	75
	20	5.85	2.10	62.0	1230	45	78
	30	5.83	2.08	50.0	1500	44	75
21.91	10	5.75	1.90	92.5	925	32	80
	20	5.65	1.80	60.0	1200	36	70
	30	5.62	1.80	47.5	1420	46	70
47.5	10	5.40	1.50	79.0	790	43	62
	20	5.30	1.58	55.0	1100	45	60
	30	5.40	1.51	44.0	1320	44.5	58

Table V. Load Impedance = 377 Ω, Voltage Stress = 3.9 MV/cm

Number of Turns	Initial Current (MA)	Primary Inductance (nH)	Secondary Inductance (nH)	Coupling Coefficient	Leakage Inductance (nH)	Shunt Inductance (nH)	Secondary Current (kA)	Load Voltage (MV)	Load Power (GW)
137	1	107	1,470,000	0.906	20.1	97.1	12.0	4.53	54.6
137	2	107	1,470,000	0.906	20.1	97.1	24.0	9.20	221
80	1	103	493,000	0.912	18.2	93.9	13.2	4.95	65.3
80	2	103	493,000	0.912	18.2	93.9	26.5	9.90	262

Thus, we chose three PVC pipe sizes with outer diameters of 14.13 cm, 21.91 cm, and 47.5 cm for design mandrel sizes. Given these mandrel sizes, the insulation film/metal foil winding is wound into place, a thin plastic cover is applied to allow impregnation, and the secondary assembly is placed within a one-turn primary coil that is sized for the actual secondary diameter.

To arrive at specific parameters for the purposes of this study, a numerical calculation was used to compute the inductances of interest. Three more details are required before these calculations are possible. First, for the smaller two mandrel sizes, a 30.4-cm-wide secondary foil is planned with the primary coil extending beyond the secondary by 0.64 cm on each end. The 47.5 cm mandrel is designed for a 45.7 cm secondary length with a similar primary extension as in the other two units. A similar primary extension as for the other two units is used for this mandrel. Finally, in all cases the cover over the secondary winding is 0.159-cm-thick. The results of these calculations are presented in Tables I, II, and III, for the 14.13 cm, 21.91 cm, and 47.5 cm mandrels, respectively. The number of turns was determined by the requirement to transform the load impedance to the 30 mΩ of the generator. The effective per-turn capacitance, C_D^T, of the secondary winding can be approximated by $C_D^T \cong \epsilon\epsilon_o A/\delta$ where ϵ_o = free space permittivity = 8.85 × 10^{-12} H/m, ϵ = relative permittivity, A = area of one turn, and δ = insulation thickness between turns. For the 21.91 cm mandrel, this will give C_D^T's for the 1.97 MV/cm and 0.98 MV/cm stresses of about 12.3 nF and 6.21 nF, respectively. The net capacitance, C_D, is then $C_D = C_D^T/n$, so for example, the high-stress, 20 Ω version of the transformer with this mandrel will have an approximate capacitance of 456 pF.

A final pair of designs addresses the extreme condition of transforming the output of the plate FCG to power a 377 Ω load. In both of these cases, the mandrel diameter is 21.91 cm, and its length is 61 cm. The insulation stress used is a very large 3.9 MV/cm, which may be just possible with the latest dielectric materials on a one-shot basis. The difference in the two designs is that one has a n of 137, which impedance matches the 377 Ω load to 20 mΩ, while the other has a somewhat arbitrary n of 80. This second value transforms the load impedance down only to 59 mΩ, or about a factor of two above the nominal generator burnout impedance of 30 mΩ. The other quantities of interest are listed in Table V.

CIRCUIT CALCULATIONS

Circuit calculations have been performed using the circuit in Fig. 1 and R. S. Caird's circuit code for the transformer designs in Tables I, II, and III. The one modification to this circuit was to add C_D into the secondary side of the transformer. Thus, the actual circuit that was calculated is shown in Fig. 6. The generator modeled is the 13.2 cm × 52.8 cm plate flux compression generator. The initial current in the generator and ballast inductor is 1.0 MA, and the ballast inductance is 60 nH. The closing switch was actuated at 13 μs, relative to first generator action, where the total flux compression time is 14 μs. From the calculations, a typical example of the currents flowing in the generator, ballast inductor, and transformer primary as a function of time is shown in Fig. 7. A summary of the circuit calculations for the transformer designs using a stress of 1.97 MV/cm is given in Table IV. In Fig. 8, the 10 Ω load voltage as a function of time is plotted for each of the three mandrel sizes.

RESULTS

The design calculations demonstrate that, at least [illegible] coupling coefficients significantly better than 0.9 can be [illegible]. Also, the leakage inductance over the range of mandrel [illegible] relatively weak function with a variation of only ~7 to [illegible]. Of course, this range would have been much greater if the length of the 47.5-cm-diameter mandrel had been maintained at the 30.4-cm-length of the other two systems. Nevertheless, as demonstrated by the results of the 10 Ω calculations, the coupling coefficient, while important, is not the complete answer to questions of efficiency. In this instance, the combination of a k = 0.959 and a leakage inductance of 10.5 nH was sufficient to allow the 21.91 cm mandrel transformer to pass the highest voltage and power to its load. One should note that the difference from this mandrel size to the 47.5 cm system in leakage inductance is only 4.6 nH, and the large transformer had a clearly superior coupling coefficient of 0.978, almost that of a ferrite cored unit. The reason for the sensitivity lies in the remaining inductance of the plate FCG at the time the switch is closed, only 48 nH. Thus, the largest mandrel, with its larger values of leakage inductance, never results in superior performance, even with its large values of k. In fact, for the 30 Ω load impedance, the smallest mandrel with its similarly smaller k value of 0.941 performs better than either of the other two transformers. This is true primarily because both the 21.91 cm and the 47.5 cm mandrel units now have leakage inductances that are a reasonable fraction of the remaining generator inductance. To improve the performance of the largest mandrel in principle one could lengthen the 47.5 cm mandrel until the relative inductances were lowered sufficiently to result in low leakage inductance while maintaining these rather impressive coupling coefficients. However, as a practical matter the inductance between the generator and the primary coil will increase with the very large difference between the width of the generator output and the width of the transformer primary coil. From Eq. (1), the increase in this l_o can significantly reduce the system performance, and one will probably find that these designs are probably near or slightly beyond the practical width to couple with the 13.2 cm-wide generator.

In the extreme transformer designs a very significant feature is revealed. While the narrowest, fastest rising pulse is obtained with the transformer designed to match the FCG output impedance with the load, the overall best performance, in terms of voltage, current, and power, is achieved with the unmatched unit. The voltage improvement is 700 kV in the later case. The reason for this is that the combination of a slightly improved coupling coefficient and a lower leakage inductance outweigh the significance of source-load impedance matching. Since the choice of the turn ratio for the unmatched transformer was arbitrary, it is quite possible that a yet lower number of turns would yield even better performance in spite of an ever worsening impedance matching condition.

SUMMARY

From these calculations we can draw three conclusions. First, if one can find and use dielectric systems that are reliable at voltage stresses of 0.98-1.97 MV/cm, then it should be possible to construct pulse transformers with coupling coefficients of at least 0.9 or better. For example, one might consider using a combination of polypropylene and castor oil or polypropylene and fluorinat as two potential dielectric systems to achieve hold-off of these voltage stresses. Another issue concerns the sensitivity of the transformer performance to its leakage inductance when a plate generator is the power supply. The requirement to balance both the coupling coefficient and the transformer's effective leakage inductance in order to optimize system performance has been common practice in transformer design for decades. What is different in this instance is that the transformer is being switched into the generator circuit at a time when there is only <50 nH of inductance remaining in the FCG. Thus, the relative tuning of the transformer for this power supply is a somewhat more delicate matter than is usually the situation. Finally, we have seen, by using the calculations for the 377 Ω load, that the leakage inductance sensitivity in system performance with this power supply can even outweigh the importance of impedance matching the load with the power supply. In the specific example given, this mismatch was a factor of two while the net output was significantly improved.

There are several aspects of air-core transformer design that were not addressed. The most important aspect that was omitted is the importance and application of grading structures within the winding structures to control and, where necessary, lower the field stresses acting on the insulation system. The omission here is only due to an effort to draw the emphasis to the rather unique challenges of coupling a FCG through a transformer to a load. To build an experimental transformer, this aspect of the design is a critical concern. Also, we did not attempt to address the general issue of what differentiates a capacitor from a transformer in terms of the ultimate voltage stresses that can be applied in the two devices. Finally, no effort was made to determine what the ultimate constraints for energy flow through an air-core transformer could be. This is partly due to insufficient work on this subject and partly due to technological improvement which will change the results derived from current capability. Nevertheless, we anticipate addressing these questions in the relatively near future within our experimental program.

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