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A High-Voltage Pulse Transformer for Explosive Pulsed-Power Devices

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Abstract

It is often necessary to use a high-voltage pulse transformer for impedance matching an explosive generator to a higher impedance load. Also, a particular application may require high-voltage rather than the high current which flux compressor generators (FCGs) normally deliver when driving suitable low impedance loads. We have designed and built transformers for use with FCGs. They are air-core transformers with measured coupling coefficients in the range of 0.88 to 0.94. The turns ratio for these transformers vary from 10 to 40. We have used these transformers in FCG shots and have measured 250 kV and 250 kA on the secondary, simultaneously and without breakdown. So far the FCG and not the transformer have limited the voltage. Experiments to determine a voltage limit are ongoing. Our design and results are presented.

Introduction

Because explosively driven flux compressors work best into low-impedance loads a step-up transformer is necessary to drive high-impedance loads, such as an electron-beam diode. Transformers designed and tested for such an application have been previously reported [1-4]. These transformers have all been of the tape-wound type. They are cylindrical in shape where primary and secondary are wound azimuthally around the cylinder-axis, creating mostly a B_z field. A sketch of such a transformer is shown in figure 1.

Figure 1—A tape-wound transformer with a solenoid geometry, from Ref. [1].

We report on another type of transformer that is also cylindrical in shape but where the primary and secondary windings are coaxial, that is the currents are primarily in the z -direction, creating mostly a B_ϕ field. A simplified sketch is shown in figure 2.

Figure 2—A cut-away view of a coaxial transformer with a single turn primary. Primary and secondary are offset for clarity.

The primary is a single turn coax made of aluminum. The multi-turn secondary is wound on a polyethylene core, which slips inside the primary. The secondary is comprised of 2 parallel windings, each wound 180° around the transformer circumference. Therefore, the high-voltage secondary output-terminals are separated by about 80% of the transformer outer diameter. In practice, each of the secondary windings are comprised of several individual insulated wires and are brought out through insulated holes in the primary. We use the maximum number of parallel wires that will fit around the ID of the secondary, without overlapping the wires.

We believe the coaxial design has some important advantages over the tape-wound design. First, it inherently has a higher coupling constant. The spacing between primary and secondary is the same for every secondary turn and does not progressively increase with the number of secondary turns as in the tape-wound design. Second, the windings do not have edges that enhance the electric field and increase the possibility of breakdown. Therefore, there is no need to employ any voltage-grading techniques [1,5]. Third, it is our experience that the wire-wound coaxial transformer is easier to fabricate and is more robust than the tape-wound transformer [6].

Calculation of Inductance and Coupling

The calculation of primary and secondary inductance is approximate but very simple. End effects are not accounted for. The primary and secondary are treated as ideal coaxes. This is not an approximation for the primary because it is constructed with metal pipe, but the secondary is made up of many parallel wires. By using the maximum number of wires possible the coax assumption is better justified. Given these assumptions the primary, secondary, mutual inductance, and coupling coefficient are,

$$\begin{aligned} L_p &= \frac{\mu_o}{2\pi} \left(\ln \frac{c}{a} + \mu_r \ln \frac{d}{c} + \ln \frac{b}{d} \right) \Delta z & L_s &= \frac{\mu_o}{2\pi} N^2 \left(\mu_r \ln \frac{d}{c} \right) \Delta z \\ M &= \frac{\mu_o}{2\pi} N \left(\mu_r \ln \frac{d}{c} \right) \Delta z & k &= \frac{M}{\sqrt{L_p L_s}} \end{aligned} \quad (1)$$

where a , b , c , d , and Δz are the primary inner and outer radii and the secondary inner and outer radii, and the transformer length, respectively. In these equations we allow for a secondary magnetic-core with relative permeability μ_r , but for our air core transformers μ_r equals 1. Note that in the limit $\mu_r \gg 1$, these equations yield $L_s/L_p = N^2$, the usual result.

Design and Test of a Transformer

The insulation thickness is given by $(c-a)$ and $(b-d)$ on the inner and outer radii, respectively. A minimal amount of insulation is used to maximize coupling. To wind the secondary we use the inner conductor of Reynolds type-C coax cable, which has an insulation thickness of 0.03". In addition we add 20 layers of .002" thick kapton sheet around the OD and ID of the secondary.

When designing any transformer it is important to have the secondary impedance much greater than the load impedance. If ω is a characteristic frequency for the pulse then we require,

$$L_s \gg L_{load} \quad \text{and} \quad \omega L_s \gg R_{load} \quad (2)$$

When transformed to the primary this condition is equivalent to

$$\omega L_p \gg X(Z_{load}) \approx \frac{Z_{load}}{N^2} \quad (3)$$

Another design consideration arises if there is a closing switch in the secondary circuit. Under that condition for the generator to run efficiently (i.e. drive a low-impedance when the switch is open) we require that,

$$L_p \ll L_{generator} \quad (4)$$

It can be (and often is) the case that equations (3) and (4) cannot be simultaneously satisfied. In that situation the designer should use a FCG code that includes a transformer model [7] to optimize performance under these less than ideal conditions.

We have designed 2 types of coaxial transformers as described above. We have built and tested 3 transformers of the first type. We have finished design of the second type and will assemble and test it in the near future. For the first type, which with we have more experience, the secondary has 11 turns and an inductance of 5.4 μ H. It is desirable to have a larger secondary inductance but physical constraints on the size of the transformer limit the secondary inductance. We measured the coupling coefficient to be 0.94. The coupling coefficient is measured by discharging a HV, 55 μ F capacitor bank into the transformer primary with the secondary shorted. Under these conditions we measure both the primary and secondary currents and calculate the coupling coefficient.

The primary inductance for this transformer is about 52 nH, and leakage inductance is given by,

$$L_{\text{leakage}} = (1 - k^2) L_P = 6 \text{ nH} \quad (5)$$

To maximize transformer performance it is important to keep any stray inductance between the FCG and the transformer primary to a value much smaller than the transformer leakage inductance. We do this by keeping connections to a minimum length and using the usual low-inductance design principals.

Experimental Results

The first test used an explosive plate-generator driving the transformer with a secondary load of a few microhenries. Data from this shot is shown in figures 3 and 4. Note that there is an offset in the time scales for the two figures. The plate generator was driven with a capacitor bank.

Figure 3 – Primary and secondary current. Peak primary current is 3.7 MA.

Figure 4 – Primary and secondary voltage. Peak secondary voltage is 263 kV.

In this test the transformer delivered about 100 kJ to the load. Similar data has been obtained on 3 other transformers. We are presently building a new transformer that will be driven with up to 8 MA of primary current and will be tested up to 500 kV on the secondary. This transformer will be tested using a large capacitor bank and is designed for multiple-pulse operation.

Summary

We have successfully tested air-core pulse transformers for use with FCGs. These transformers are coaxial, have a high coupling coefficient, and have delivered about 100 kJ to a load. We are continuing to test these transformers to explore their voltage and energy limits.

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