Conclusion

This paper has described a new resonance transformer that has characteristics similar to those of a two-winding inductively coupled transformer. The resonance circuit can be designed to provide either current or voltage transformation, and can combine its transformer duty with power factor correction.

The circuit is a viable competitor to a conventional transformer, and is likely to prove to be superior to a conventional system in many applications.

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Design of Coaxial-Cable Pulse Transformers

RICHARD E. DOLLINGER, MEMBER, IEEE, DOUGLAS A. MOLL, STUDENT MEMBER, IEEE, AND DAVID L. SMITH, MEMBER, IEEE

Abstract—**Coaxial-cable pulse transformers with good high-frequency response (30-ns rise time) and excellent high-voltage interwinding insulation ($\gtrsim$300 kV primary to secondary) were designed, built, and tested. They have the advantage that the open-circuit transformation ratio is unaffected by the thickness of the interwinding insulation, and good coupling is maintained with step-up designs. An equivalent circuit was developed, involving two coupling coefficients, which predicted the measured results with reasonable accuracy. Values of primary, secondary, and leakage inductances were 1.4, 2.2, and 0.8 μH, respectively.**

I. Introduction

COAXIAL CABLES used as isolation pulse transformers (such as for triggering spark gaps) have been in use for some time [1]-[5]. These transformers have inherent advantages over wire-wound transformers (as in a conventional power transformer), such as tight magnetic coupling and good insulation between the primary and secondary.

To insure efficient voltage transfer, the transformer's primary magnetizing impedance should be much larger than the source impedance. The use of magnetic cores is advantageous if this criterion is to be met at low frequencies. Air-core coils of several turns (such as wire-wound or strip-wound) can meet this criterion at higher frequencies but their response is limited by turn-to-turn capacitance at higher frequencies. When very high frequencies are encountered, a one-turn, air-core coaxial transformer is effective (see Fig. 1). When air-core transformers of this type are used, it is important that the input be applied to the outer conductor so that good coupling is attained [6]. This paper presents a model which is useful in designing the one-turn, air-core transformer described previously [6].

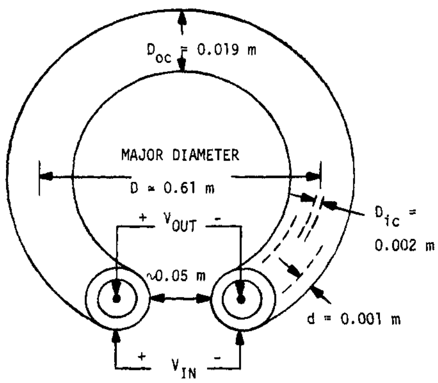

Fig. 1. Coaxial pulse transformer.

II. Transformer Modeling and Characteristics

Fig. 2 shows a model which has shown improved accuracy in describing the transformer of Fig. 1. The magnetic coupling coefficient k_p is the fraction of flux generated by current in the primary that links the secondary. Similarly, k_s is the fraction of flux generated by current in the secondary that links the primary. Two coupling coefficients (k_p and k_s) are used instead of the single coefficient normally used in transformer models, because the magnetic geometry of a coaxial transformer differs from that of a normal transformer with separate windings (k_1 in the figure should be k_s).

When the outer conductor of the transformer is pulsed as the primary, it can intuitively be seen from Fig. 1 that virtually all of the generated flux is external to the secondary, or

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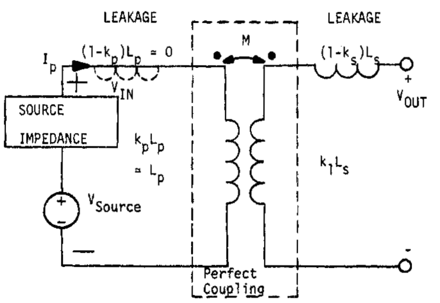

Fig. 2. Coaxial transformer model.

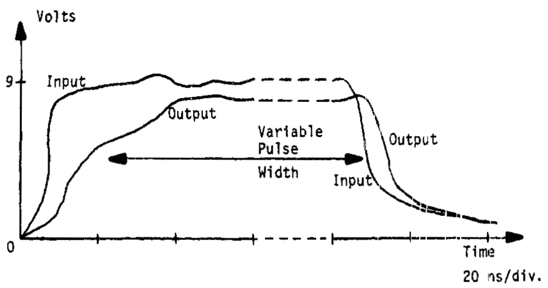

Fig. 3. Typical pulses.

TABLE I

D_{oc}/D_{ic}	D_{oc} (cm)	MEASURED ± 5% L_p (μH)	L_s (μH)	k_s	M (μH)	CALCULATED L_p (μH)	L_s (μH)	k_s	M (μH)
1.33	2.14	2.10	2.25	0.93	2.07	1.85	2.00	0.93	1.85
3.50	1.46	2.35	3.27	0.72	2.44	2.05	2.68	0.77	2.05
6.35	1.46	2.34	3.59	0.65	2.45	2.05	2.98	0.69	2.05
11.4	4.90	1.62	3.10	0.52	1.62	1.44	2.66	0.54	1.44
21.3	4.90	1.65	3.50	0.47	1.65	1.44	2.98	0.48	1.44

inner conductor. The converse, however, does not follow because flux generated by current in the secondary is not entirely external to the outer conductor. Thus a certain proportion of the flux is contained in the space between the inner and outer conductors. As a result, k_p is essentially one and k_s is less than one. This was experimentally verified as the leakage inductance of the primary was found to be negligible, and the leakage inductance of the secondary was relatively large. Numerically, the values in the model of the coaxial transformer are calculated as follows from the basic inductance equations for a single turn loop [7]:

primary inductance:

$$L_p = (0.6279)\, D \left(2.303 \log \frac{8D}{D_{oc}} - 2\right) \mu\text{H}$$

secondary inductance:

$$L_s = (0.6279)\, D \left(2.303 \log \frac{8D}{D_{ic}} - 2\right) \mu\text{H}$$

secondary leakage inductance:

$$(1 - k_s) L_s = L_s - L_p$$

mutual inductance:

$$M = \sqrt{(k_p L_p)(k_s L_s)}, \qquad k_p = 1.$$

Transmission-line effects become apparent when frequencies become high enough to make the largest physical dimension of the transformer D comparable in size to one-half wavelength. At this particular frequency, the impedance viewed from the input terminals is that of a transmission line a half wavelength long terminated in a short circuit (i.e., zero input impedance). Thus all of the input voltage is dropped across the source impedance. Therefore, there is no applied primary voltage, and there can be no output at the secondary.

In order to maintain good coupling ($k_p \simeq 1$), it is necessary to prevent flux originating from primary current at one point on the loop from penetrating the outer conductor at other locations around the loop. The desired magnetic shielding is provided by eddy currents induced in the outer conductor. These decrease following the initial application of the pulse with an approximate diffusion time constant, $T_e = \mu dD/4\rho$, where ρ is the resistivity of the outer conductor and μ is the magnetic permeability [8]. The time constant T_e for the transformer having the dimensions given in Fig. 1, is approximately 11 ms. Thus for pulses shorter than this, excellent sheilding is provided and $k_p \simeq 1$.

III. Test Data

A number of transformers were constructed with varying ratios of outer conductor diameter to inner conductor diameter, in order to test the accuracy of the model presented. The results are given in Table I, where the primary is the outer conductor. It can be seen in all cases that measured inductances correspond with the values calculated using the given formulas.

Fig. 3 shows typical input and output pulses. The input pulse was generated using a low-impedance (1-Ω), parallel-plate transmission-line pulser [9]. The output was taken across a load resistor R_L of 50 Ω. The rise time of the output pulse is due to a combination of the time constant $[(1 - k_s)L_s]/R_L$ and also the transmission-line effects discussed previously in the paper. The reduced magnitude of the output pulse is due to the voltage drop across the secondary leakage inductance. (The magnitudes of the input and output pulse are the same if the load impedance is high.) The transformer used is the one shown in Fig. 1, for which the values $L_p = 1.4$ μH, $L_s = 2.2$ μH, $M = 1.4$ μH, $k_p = 1$, and $k_s = 0.64$ are calculated.

This type of transformer with a 1:2 voltage step-up ratio ($D \simeq 0.40$ m and $D_{oc} \simeq 0.03$ m) has been used to provide a 300-kV, 30-ns rise-time trigger to a rail gap for the TeePee 1B Theta Pinch from a 150-kV, 13-stage Marx bank [6]. The two-turn secondary was made of the inner insulation and center conductor of RG-8/U coaxial cable with extra insulation added. This additional insulation was needed to prevent arcing and to reduce the effect of capacitive coupling of the signal (which also allows for a reduction in common-mode noise). The fact that the voltage step-up ratio equals the turns ratio is a result of $k_p \simeq 1$ when the outer conductor is the primary. This has also been tested for a turns ratio of 1:3.

IV. Conclusions

By treating the transformer magnetic coupling coefficient $k = \sqrt{k_p k_s}$ as two separate parts, the simple model has been formed which satisfactorily explains the experimental results of coaxial pulse transformers. The performance of coaxial transformers with the outer conductor driven as the primary is not degraded when these are insulated for very high voltages. Finally, they are quite practical for short-pulse applications due to self-magnetic shielding and good coupling.

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Improvements on Transmission-Line Pulsers

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Abstract—**A series of pulsers operating up to 100 kW with efficiencies up to 80 percent have been built. The voltage levels, rise times, durations, and repetition rates have been investigated for pulsers operating into different loads. The difficulties of mechanical and solid-state switching (e.g., contact erosion, sticking, and bouncing contacts), have been eliminated by using a stream of mercury droplets to bridge the gap between two switch electrodes in order to discharge a transmission line into a load or by discharging charged mercury droplets into the load.**

I. Introduction

A COMMON SOLUTION to the problem of generating pulses with nanosecond rise times has been to discharge a transmission line into its characteristic impedance. This is done by discharging a length (L) of coaxial cable into its characteristic impedance, resulting in a pulse of duration $2L$ divided by the propagation velocity [1]. Improved operation at higher voltages into lower resistance loads at high repetition rates with little contact erosion has been obtained by using mercury droplets as the switching medium, rather than common mechanical switches or avalanche transistor stacks [2]-[4].

In the past, subnanosecond pulses have been obtained by making the initially charged line very short [5]-[8]. The first pulser referenced used a hydrogen spark to discharge a stray capacitance of 2 pF to produce 20- to 400-V pulses with rise times of 1 ns from a supply of 0.5 to 2 kV at repetition rates up to 80 kHz. The next two pulsers referenced use a small metal ball or cylinder as the initially charged line. The ball is charged and then electrostatically repelled toward another lead which is attached to the load, where it discharges. Using this type of pulser with pressurized nitrogen can produce ~2-kV pulses of ~200-ps duration and 0.5-ns rise time into 50-Ω loads with repetition rates of several hundred hertz. The last pulser [8] uses a metal ball that is alternately rotated past the charging and discharging lead by an insulated paddle. The advantages of the rotating-ball generator include variable pulsewidth (proportional to ball diameter) and variable repetition rate (i.e., rate of impinging droplets). Improved results which have been obtained using charged mercury droplets

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