A NOVEL SUPER LOW INDUCTANCE PRIMARY RING UTILIZED IN A PULSED DUAL RESONANT TUNED TRANSFORMER

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Abstract

The Air Force Research Laboratory (AFRL) has developed a Super Low Inductance Primary (SLIP), dual resonant tuned transformer for Ultra Wide Band impulse radiation applications. The design criteria and the theoretical formulation for such a device are presented. Transformers with sub-microHenry (μH) inductance in the primary are achievable. The inductive loop of the primary incorporates the capacitive energy store and pulse power switch. Correspondingly, low inductance in the secondary winding is plausible, thus decreasing loss due to stray capacitance. Implementation of dual resonant tuning is more easily attained with this technique, permitting the pulse power system to occupy a smaller volume.

I. INTRODUCTION

Dual resonant tuned transformers have been used for years as intermediate frequency transformers. More recently, they have also been employed to provide high voltage transformation at high repetition rates. The principal benefits of this technology are high efficiency, as well as low volume and weight.

The initiative for this work is an upgrade of the Hindenburg series (H-series) pulsers developed at the Air Force Research Laboratory. A specific requirement for each of the pulsers is portability. Several problems have been evident with the most recent device, H-5, and the supporting pulse power system. The most prominent of these is the large volume of the pulse power system.

In an attempt to minimize this volume, the SLIP ring has been developed. This transformer design not only results in a more compact pulse power section, but also allows minimization of the primary by incorporating the capacitance and pulse power switch in the primary turn. The voltage gain for this device is driven, not by the ratio of turns, but instead by the largest achievable ratio of primary to secondary inductance, or

$$\frac{V_2}{V_1} = \sqrt{L_2/L_1}\,. \qquad (1)$$

II. CONSTRUCTION OF THE PRIMARY

A SLIP ring is composed of not less than two conductive loops in one of several forms. The first of these consists of two cylinders with differing diameters, which can be positioned concentrically. The capacitors are sandwiched between the conducting plates (Figures 1 and 2.).

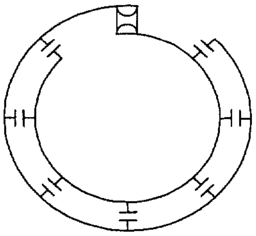

Figure 1. SLIP ring schematic. Capacitors are placed between the two concentric cylinders and the circuit is completed by the pulse power switch.

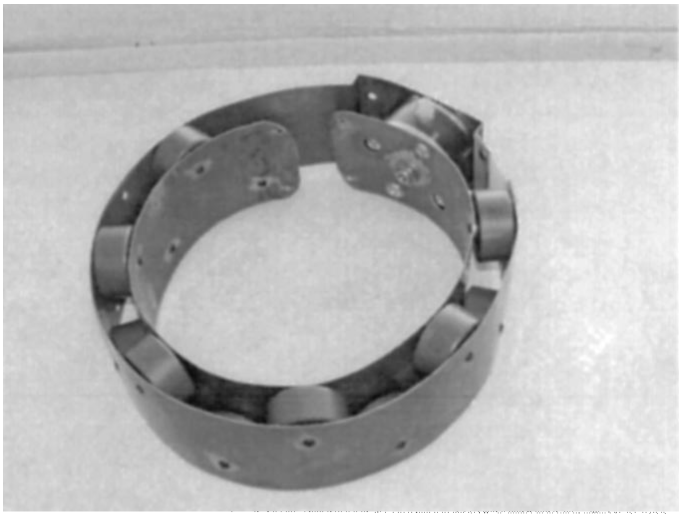

Figure 2. Assembled concentric cylinders with switch and capacitors.

The second configuration (Figure 3) consists of two sheets of copper curved into two split cylindrical shells of

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0-7803-5498-2/99/$10.00©1999 IEEE.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1999**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **A Novel Super Low Inductance Primary Ring Utilized In A Pulsed Dual Resonant Tuned Transformer**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory, Directed Energy Directorate Kirtland Air Force Base, NM**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

The Air Force Research Laboratory (AFRL) has developed a Super Low Inductance Primary (SLIP), dual resonant tuned transformer for Ultra Wide Band impulse radiation applications. The design criteria and the theoretical formulation for such a device are presented. Transformers with sub-microHenry (pII) inductance in the primary are achievable. The inductive loop of the primary incorporates the capacitive energy store and pulse power switch. Correspondingly, low inductance in the secondary winding is plausible, thus decreasing loss due to stray capacitance. Implementation of dual resonant tuning is more easily attained with this technique, permitting the pulse power system to occupy a smaller volume.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

equal diameter. They are placed side by side, coaxially, with sufficient separation between them to allow for the hold-off of the charging voltage, and also facilitate the connection of the requisite number of capacitors between the cylinder edges.

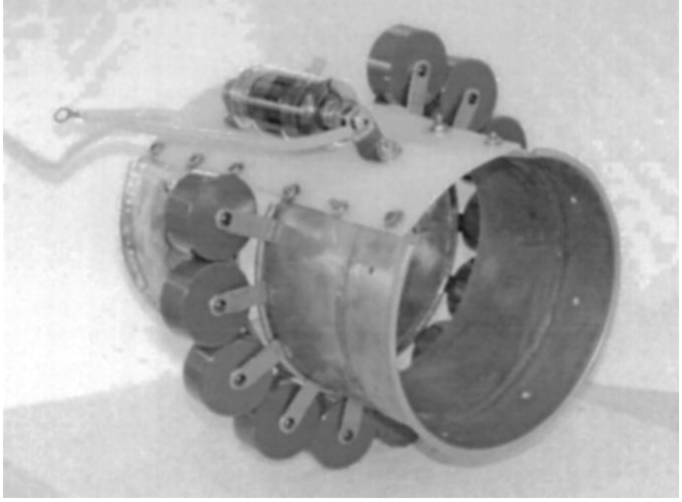

Figure 3. Assembled coaxial cylinders with switch and capacitors.

As with the first configuration, the third configuration investigated also utilizes a conductor/capacitor layering system (Figure 4). However, it is constructed using two or more flat copper discs, which are placed in a stack and alternately shorted together.

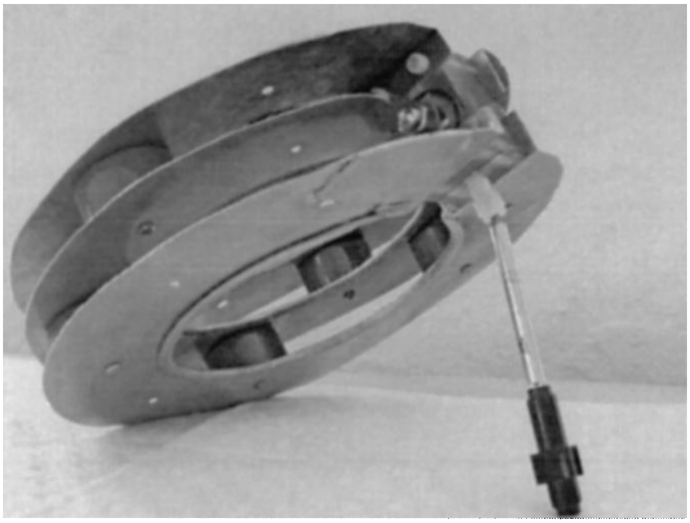

Figure 4. Assembled stacked discs with switch and capacitors.

In every configuration, 2-nF doorknob capacitors and a gas switch are used to complete the circuit for the primary of the transformer. The ultimate connection between conductors is made by positioning the pulse power switch between the slit in the conductive rings. In doing so, a single-switched, multi-ringed, single-turn current-loop equivalent is established.

However, the chief, non-traditional characteristic of the discharge current is that no capacitor discharges via one physical loop. The ratio of the current in a given loop is a function of the actual location of the capacitor on the loop. Therefore, if a capacitor is directly opposite the switch, as in the first configuration, the current in that switch flows through half of one loop and half of the other.

III. EXPERIMENTAL SETUP

The desired output voltage from the secondary typically drives the size of the secondary winding. The size of the secondary, in turn, influences the requirements for the fabrication of the primary because the capacitance of the secondary is the main consideration for the primary's energy store.

Thus, the existing secondary of H-2 was used for the experimental proof of principle. The secondary consists of 30 turns of 0.125-inch diameter wire wound in a 6.75-inch diameter cylinder. The spacing between the turns is 0.375 inches, yielding a measured inductance for the solenoid of 80 μH. When incorporated in the system, the total capacitance of the secondary is 78 pF, which results in the secondary's self-resonant frequency of 2.01 MHz.

According to the rules of energy conservation, the capacitance of the primary, driven by that of the secondary, is equal to

$$C_p = C_s\left(\frac{V_s^2}{V_p^2}\right). \qquad (2)$$

Based on this and the physical limitations imposed by the actual capacitors, a capacitance of 24 nF was chosen for the primary. Given this value and the stipulation that the self-resonant frequency of the primary equal that of the secondary, the inductance of the primary must therefore theoretically be 260 nH.

In addition to minimized inductance, each of the SLIP ring configurations also had to fit into an existing oil containment vessel. While all three configurations have this capability, only the coaxial design will be discussed because its operation parameters were best suited for this series of experiments. This particular primary required a coaxial cylinder separation of at least ½ inch between the constituent ground and high voltage cylinders in order to achieve proper voltage hold-off. A diameter of 8 inches was chosen so that the SLIP ring could be placed around the secondary winding.

The inductance for a two cylinder inductor can be theoretically determined using the appropriate equations in the text by Grover [1]. However, based on the equation [2,3] for an 8-inch diameter cylinder with inductance of

200 nH, it was found that a cylinder with a length of 5.5 inches would be required. Allowing for the inductance of the switch, it was, therefore, decided to construct two 6-inch long cylinders. The resulting coaxially configured primary had an experimentally determined self-resonant frequency of 2.15 MHz.

IV. DETERMINATION OF COUPLING COEFFICIENT

A diagnostic problem becomes readily apparent when the system is assembled. It is neither possible to short out the primary, nor consider it an open circuit. Consequently, the typical measurements for the dual resonant tuned transformer circuit can not be made. The coupling coefficient, however, may be determined experimentally by ringing-over the secondary and examining the acquired scope trace, such as the one shown in Figure 5.

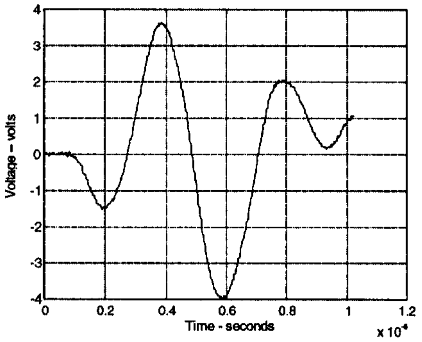

Figure 5. A typical plot of the output voltage pulse of the H-2 device with a SLIP ring installed in the transformer.

Because the SLIP ring transformer is based on the concepts of air coil pulse transformers and dual resonant tuned transformers, it is useful to recall the underlying theory of these devices. In a work by G.J. Rohwein [4], it is shown that the voltage from the secondary, V_2, as a function of time is given by

$$V_2(t) = \frac{V_0}{2}\sqrt{\frac{L_2}{L_1}}\, e^{-t/T}\left(\cos\frac{\omega t}{\sqrt{1-K}} - \cos\frac{\omega t}{\sqrt{1+K}}\right), \qquad (3)$$

where T is the damping constant, V_0 is the charge on the primary capacitor, L_1 and L_2 are the inductance of the primary and secondary, respectively. The radian frequency of the primary and secondary circuits is given by ω, and K represents the coupling coefficient. For this equation, the second voltage peak exceeds the first for all coupling coefficients less than 0.8. Moreover, the energy transfer efficiency is maximized if the coupling coefficient is equal to 0.6 for dual resonant tuned transformers.

As mentioned above, the SLIP ring-based transformer does not adhere to the commonly accepted tenants of previously constructed dual resonant tuned transformers. Figure 6 presents a schematic of this new design in which the coupling coefficient of the primary's inductive loop, K_p, is also shown. This variable is required for a more accurate calculation of the coupling coefficient of the system, the proof of which follows.

Equation 4 gives the output voltage as a function of time for the secondary of a SLIP ring transformer with N capacitors.

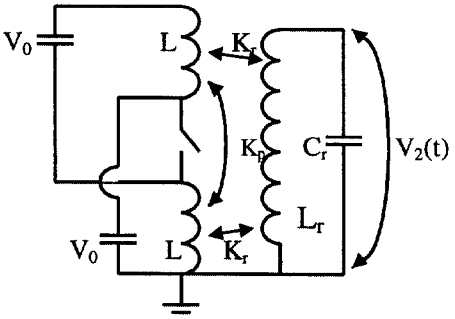

Figure 6. Equivalent circuit for a two capacitor SLIP ring-based transformer.

$$V_r(t) = \frac{V_o}{\sqrt{2}\,\omega_o^{4}}\sqrt{\frac{L_r}{L}}\,\frac{1+K_p-2K_r^{2}}{\left(1+K_p\right)^{1.5}} \cdot \left\{\cos\left[\frac{\omega_o t}{\sqrt{1+\sqrt{\frac{2K_r^{2}}{1+K_p}}}}\right] - \cos\left[\frac{\omega_o t}{\sqrt{1-\sqrt{\frac{2K_r^{2}}{1+K_p}}}}\right]\right\} \qquad (4)$$

The ratio formed by Equation 4 for the second and the third voltage maxima can then used to solve for the primary-to-secondary coupling coefficient, K_r. This can be accomplished by taking the appropriate voltage and time values from Figure 5, as well as the system resonant frequency, $\omega_o/2\pi$, and the primary-to-primary coupling coefficient, K_p, making the respective substitutions into the equation of ratios, and finally solving the system for K_r. Using this method, a primary-to-secondary coupling coefficient of 0.55 was calculated for the SLIP ring in the coaxial configuration.

Further, the first maximum amplitude for $V_r(t)$ occurs when

$$\cos\left[\frac{\omega_o t}{\sqrt{1+\sqrt{\frac{2K_r^{2}}{1+K_p}}}}\right] = -1 \quad \text{and} \quad \cos\left[\frac{\omega_o t}{\sqrt{1-\sqrt{\frac{2K_r^{2}}{1+K_p}}}}\right] = 1 \qquad (5)$$

which requires that

$$\frac{\omega_0 t}{\sqrt{1+\sqrt{\frac{2K_r^2}{1+K_p}}}} = \pi \quad \text{and} \quad \frac{\omega_0 t}{\sqrt{1-\sqrt{\frac{2K_r^2}{1+K_p}}}} = 2\pi \tag{6}$$

The ratio of the two prior equations allows for the calculation of that coupling coefficient which yields maximum output voltage, $V_r(t)$.

$$\frac{\dfrac{\omega_0 t}{\sqrt{1-\sqrt{\frac{2K_r^2}{1+K_p}}}}}{\dfrac{\omega_0 t}{\sqrt{1+\sqrt{\frac{2K_r^2}{1+K_p}}}}} = \frac{2\pi}{\pi}. \tag{7}$$

Solving for K_r in terms of K_p yields

$$K_r = \frac{3}{5}\sqrt{\frac{1+K_p}{2}}. \tag{8}$$

Thus, knowledge of the primary-to-primary coupling coefficient is required for the calculation of the value of the primary-to-secondary coupling coefficient that corresponds to the maximum output voltage.

V. SUMMARY

The transformer has been successfully operated at 450 kV peak output voltage. This corresponds to a charge of 60% of the maximum rating of the capacitors. Present experimentation has limited the output repetition rate to 500 Hz, but there is no reason to believe that the system will not operate in excess of 1 kHz.

VI. REFERENCES

[1] Frederick W. Grover, *Inductance Calculations: Working Formulas and Tables,* Dover (1962).

[2] K. S. H. Lee, *Inductance and Current Density of a Cylindrical Shell,* Sensor and Simulation Notes Note 130, Northrop Corp Labs, Pasadena, CA. (1971).

[3] James P. O'Loughlin, numerous Internal Notes and Correspondence, Air Force Research Laboratory, Kirtland AFB, NM.

[4] G. J. Rohwein, *High Voltage Air Core Pulse Transformers,* Sandia National Laboratory Report SAND80-0451.