COMPACT PULSED TRANSFORMER POWER CONDITIONING SYSTEM FOR GENERATING HIGH VOLTAGE, HIGH ENERGY, RAPID RISETIME PULSES

P.M. Renon, D.J. Hall, K.E. Hackett, J.L. Holmes
Air Force Weapons Laboratory, Kirtland AFB, NM 87117

M.C. Scott, E.A. Lopez, J.D. Graham
Maxwell Laboratories, Inc., Albuquerque, NM 87117

G.F. Kiuttu
Mission Research Corporation, Albuquerque, NM 87105

ABSTRACT

Compact, lightweight air-core pulse transformers in open air have been developed at the Air Force Weapons Laboratory (AFWL). A SHIVA Star capacitor bank module (36 μF, 120 kV, 260 kJ) was used to drive a transformer for generating high voltage (HV) pulses into resistive loads. Voltages reaching 400 kV were delivered to a 6 Ω load at a total energy delivery of 50 kJ to the load. In order to achieve single high energy pulses to the load, several fused primary concepts were investigated and developed. These concepts along with transformer construction and 1st order models of the system are presented.

INTRODUCTION

Power conditioning systems are necessary to adapt the electrical parameters of a prime power source to those necessary for the load. In many instances, we used simplifying approximations for various circuit parameters which were extremely useful in output pulse predictions. In one instance in particular, the extremely complicated transient electromagnetic diffusion was simplified by static approximations. We show later (in Phase II experiments of the Results section), that this static approximation (without the complicated physics) was able to predict the actual results with a fair degree of accuracy.

Pulse Amplitude

From network theory, it follows that voltage attains a maximum across an open circuit, while peak current is achieved through a short circuit. Consider the simplified transformer model of Fig. 1. The circuit equations describing the circuits are

\[ V_1 = L_1 (\frac{dI_1}{dt}) - M \left( \frac{dI_2}{dt} \right) \]  

\[ V_2 = -M \left( \frac{dI_1}{dt} \right) + L_2 \left( \frac{dI_2}{dt} \right) \]

Here, the voltage amplification ratio can be expressed as

\[ \frac{V_2}{V_1} = \frac{L_2 (\frac{dI_2}{dt})}{[L_1 (\frac{dI_1}{dt}) - M(\frac{dI_2}{dt})]} \]

Since \( V_2 \) is maximum across an open circuit \( (I_2 = 0) \), the maximum ratio can be defined as

\[ \frac{V_2}{V_1}_{\text{MAX}} = \frac{M}{L_1} \]

Also because \( M = k(L_2/L_1)^{1/2} \), we must maximize the ratio \( k(L_2/L_1)^{1/2} \) to maximize the output voltage. Unfortunately, the size of \( L_2 \) limits the risetime of the current to the load resistor R. If a fast risetime is desired, then the number of turns allowed on the secondary must be limited to satisfy the requirements.

![Figure 1. Simplified Transformer Model.](image-url)
Risetime

If the primary voltage remains fairly constant during the time that the current is rising on the secondary, the current, as a function of time, across the secondary may be approximated by the following convolution (equivalent circuit shown in Fig. 2),

$$i_2(t) = \frac{V_1(0) M}{L_1 L_2 - M^2} \times [u(t) \exp\left(-\frac{RL_1}{L_1 L_2 - M^2}t\right)] \cdot (5)$$

Solving the convolution integral, $i_2(t)$ simplifies to

$$i_2(t) = \frac{V_1(0) M}{RL_1} [1 - \exp(-\delta t)] u(t), \quad (6)$$

where

$$\delta = \frac{RL_1}{(L_1 L_2 - M^2)}. \quad (7)$$

Eq. 6 can then be solved to yield the risetime

$$T_{rise} = 2.2 \left(\frac{L_2}{R}\right) (1 - \delta^2). \quad (8)$$

It can be seen from the above, that the risetime is aided by the $(1 - \delta^2)$ term, which implies that the more closely coupled the transformer, the faster the risetime.

Pulse Width

Consider the circuit shown in Fig. 3. If a unipolar pulse is to be utilized as an output pulse from a pulsed transformer, one can use the cosine, quarter cycle approximation. This results in a pulse width, $\tau$, the duration of which can be expressed as

$$\tau = \frac{(\pi/2)}{C_1 (L_1 + L_{1\text{stray}})^{1/2}} \quad (9)$$

Again, for $L_1 > L_{1\text{stray}}$, Eq. 9 may be simplified to

$$\tau = \frac{(\pi/2)}{C_1 L_1}^{1/2} \quad (10)$$

**DESIGN**

Our pulsed transformer system, was required to meet specified parameters dictated by a designated load (see Table 1).

**Table 1.**

<table>
<thead>
<tr>
<th>AFWL Pulse Transformer Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Load</td>
</tr>
<tr>
<td>Risetime</td>
</tr>
<tr>
<td>Pulse Width</td>
</tr>
<tr>
<td>Energy</td>
</tr>
</tbody>
</table>

Figure 3. Capacitor Driven Transformer Circuit.

Long adaptor plates from previous fuse experiments were used to connect the capacitor bank to the transformer [1]. The minimum feed inductance (minimum line separation) of this configuration was determined to be 80 nH. The total stray inductance, including the capacitor module, was calculated to be 100 nH. With an existing primary winding inductance of 210 nH, the maximum voltage seen at the primary, for a 120 kV charge, is $V_1(t=0) = 81$ kV. The constraint that the load voltage be > 250 kV, requires that the turns ratio $N_2$ be greater than or equal to 4 (if integral values assumed). The required output risetime places a limit on the allowable secondary inductance, which in turn limits the number of turns allowed on the secondary side. The possible range of $R$ was determined and is plotted as $L_2$ versus $k$, for resistance values between 5 to 10 Ω, in Figure 4.

The AFWL transformer is a 1:6 turn, spring wound transformer, shown in Fig. 5, having the parameters listed in Table 2.
Table 2
AFWL Pulse Transformer Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Self Inductance</td>
<td>210 nH</td>
</tr>
<tr>
<td>Secondary Self Inductance</td>
<td>9.0 μH</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>1:6</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>1.2 μH</td>
</tr>
<tr>
<td>Coupling Coefficient</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Results

Phase I (Fuseless Experiments)

To characterize the transformer system, it was necessary to run "parameter search" shots. Data from these shots showed that enough energy could be extracted during the first quarter cycle of the pulse to satisfy the requirements listed in Table 1. Output voltage from a typical Phase I shot is shown in Fig. 6.

\[
\begin{align*}
V_1 &= L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \\
V_2 &= -M \frac{di_1}{dt} + L_2 \frac{di_2}{dt}
\end{align*}
\]

where

\[
\begin{align*}
V_1 &= \int_0^1 i_1 dt - V_0, \quad \text{and} \\
V_2 &= -I_2 R
\end{align*}
\]

If

\[
i_1(t) = I_0 e^{-a t} \sin(\omega_0 t)[u(t)-u(t-x/2v_0)]
\]

(i.e., if the current is perfectly interrupted at \( t = x/2v_0 \)), then the secondary current can be calculated by solving Eq. (2). The convolution

\[
I_2(t) = \frac{M/L_2}{(d/dt)/[d/dt + (R/L_2)]} I_1
\]

when solved, yields a term corresponding to the unit step on the secondary side as well. Unfortunately, these two unit step functions would generate a voltage proportional to their derivative (i.e., a dirac delta function). The voltage on the primary side is across the fuse used to interrupt the current, while the voltage spike on the secondary side shows up across the load. Fortunately, current cannot be interrupted in an infinitesimal time. The fuses utilized were able to interrupt the current in approximately 200 ns, which still generated a huge voltage spike across the load. A computer program was written to predict the performance of the system with a variable fuse geometry and the computer generated data is overlayed with an actual shot in Fig. 7. Refovsky et al. [1], showed good agreement between experimental and computer generated data, when the bottom transmission line was the same width as the fuse. Unfortunately, this was not the case in our experiment. Our fuses were only a fraction of the width of the transmission line. This caused prominent edge effects [2,3] and upon physical examination of the fuses, it became evident, that the entire fuse cross sectional area could not be used in the fuse resistivity calculations. We therefore applied a correction factor, which was the width of the fuse divided by the thickness (i.e., a dimensionless parameter), taken to the "fractional power" (0.8 -- 0.9). This "fractional power correction" generated results which were in excellent agreement with the experimental results. The edge effect is a dynamic process (i.e., magnetic diffusion [2,3], current distribution based on potential theory [4], etc.), but the "fractional power correction" (i.e., a static correction) consistently modeled the experimental results very accurately and was used throughout all the computer simulations. It is possible to model the transient electromagnetic diffusion by finite element methods, as Pappas et al. [5] have shown. In our experiments, however, the fractional power coefficients (0.8 -- 0.9) indicate that only limited diffusion take place, and simplicity was favored over a more elaborate finite element method model of the transient electromagnetic diffusion. The equivalent circuit used in the computer program is shown in Fig. 8.

Phase II (Singly Fused Experiments)

In an attempt to eliminate current pulses after the first quarter cycle, thin aluminum foils, quenched with 200 μm diameter sand, were used to interrupt the current on the primary. Unfortunately, this technique did not cause the secondary voltage to diminish. Consider Eqs. 1 & 2.

\[
\begin{align*}
V_1 &= L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \\
V_2 &= -M \frac{di_1}{dt} + L_2 \frac{di_2}{dt}
\end{align*}
\]

where

\[
\begin{align*}
V_1 &= \int_0^1 i_1 dt - V_0, \quad \text{and} \\
V_2 &= -I_2 R
\end{align*}
\]

As shown in Fig. 7, the backswing on the voltage due to the interrupted primary current, generated a voltage spike greatly exceeding the magnitude of the desired pulse. This proved to be a particularly annoying problem. The extremely fast dv/dt on the secondary caused surface breakdowns to form across approx. 8 feet (linear distance) of insulator. This is not surprising since "Surface Discharge Switches" are very fast closing switches [6,7,8,9]. Fig. 9 shows a circuit including the technique we employed to reduce the voltage backswing. Fig. 10 shows the system configuration. Here a
"voltage spike suppressor" inductor is placed in parallel with the fuse. The parallel inductor is a plate of steel (high resistivity, high inductance due to the geometry) that is negligible in the circuit when the fuse is "cold." When the fuse is heated, it becomes highly resistive, and the inductor is "switched in." This "new" current path decreases the high di/dt, normally characterized by forcing the current through a higher inductance path. The increased series inductance in the primary circuit shows up as change in frequency as well as reduced amplitude. This is evident in Fig. II, which is a plot of actual and computer generated Phase III data.

Figure 8. Equivalent Circuit Model for Phase II.

Figure 9. Circuit Model of Phase III.

Figure 10. Experimental Setup of Phase III.

Figure 11. Typical Phase III Shot.

Phase IV (Double Fuse with Parallel Inductor)

In Phase III the decay constant was reduced to a point where ringing continued on for an unacceptable time. The next approach was to place a fuse of high resistivity (shim stock stainless) in parallel with the aluminum fuse. The rationale being a slow opening switch (i.e. microsecond time-scale), in parallel with the inductor to suppress any inductive spikes. The equivalent circuit of this set-up is shown in Fig. 12. Unfortunately, no resistivity versus specific heat data was available for stainless steel, which prohibited the modeling of the parallel fuse. This configuration gave us the best results. A plot of this is shown in Figure 13. A summary of experimental data is provided in Table 3.

Figure 12. Circuit Model of Phase IV.

CONCLUSIONS

We have demonstrated that pulse transformers can be used to match the low impedance of capacitor modules (a SHIVA module where \(L/C\frac{1}{2}= 19\) m), to high impedance loads of 6 to 12 G's. The current interruption schemes employed were very effective in controlling the output pulses, but resulted in poor voltage transfer due to added stray inductance on the primary. Voltage transfer can be improved by minimizing the distance between the capacitor modules and the pulse transformer, but that results in an inability to interrupt the current on the primary. Fortunately, the interruption of the current on the primary is not necessary, since the output feed of the pulse transformer can be made coaxial having one end connected to a load and the
Table 3
Representative Samples of AFWL Pulse Transformer Experiment Data

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Phase (I – IV)</th>
<th>Charging Voltage(V)</th>
<th>Peak Load Voltage(V)</th>
<th>Load Resistance(Ω)</th>
<th>Energy Delivered(J)</th>
<th>Risetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>030687T2</td>
<td>I</td>
<td>60,000</td>
<td>159,000</td>
<td>11</td>
<td>5,700</td>
<td>0.75</td>
</tr>
<tr>
<td>031087T1</td>
<td>I</td>
<td>80,000</td>
<td>194,000</td>
<td>10</td>
<td>9,100</td>
<td>0.75</td>
</tr>
<tr>
<td>032487T5</td>
<td>I</td>
<td>80,000</td>
<td>247,000</td>
<td>12</td>
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<td>12</td>
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<td>400,000</td>
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<td>50,000</td>
<td>1.00</td>
</tr>
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REFERENCES


