DESIGN AND OPERATION OF A 700kV, 700A MODULATOR [*]

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Abstract

A $700kV, 700A$ pulse modulator capable of repetitive operation is under development for use in our high power microwave program. The output pulse is designed to give a flat top of about $200ns$ at the rated voltage. The transformer consists of two sets of ferrite cores with their primaries driven in parallel and their secondaries connected in series. The primary on each core consists of 24 windings of 2 turns each, distributing the flux evenly throughout the core. The secondary winding has 20 turns which links both cores, giving a 20:1 step-up transformer for a $1k\Omega$ matched load. A novel pulser arrangement has been used to drive the transformer. Each core is driven by two 5Ω pulse lines plus/minus charged to $\sim 40kV$ with a switch connecting the two lines. In matched conditions this gives a $40kV$ voltage across the load. This configuration produces a fast rising pulse eliminating the pulse rise time degradation associated with the transfer function of a discrete element pulseline. The transformer has been tested at $100kV$ with a variety of dummy loads at low repetition rate. Preliminary results are also reported at high voltage with the modulator under oil.

I. INTRODUCTION

We present in this paper a summary of results obtained in the development of a $700kV$ modulator capable of driving a high power microwave source suitable for a linear collider. The development is on going and a further version of the modulator will be required for the final device. We have to date bench tested two versions of the modulator and will report key results from each phase of the investigation [1]. In the first transformer tested each set of cores was powered by two 5Ω artificial transmission lines and was expected to give an output voltage of up to $700kV$ at $350A$. Low voltage tests were encouraging but both low and high voltage tests under oil (albeit in a rather small tank) indicated that parasitic capacitance loaded the secondary and that the rise time was degraded. We have since doubled the number of lines driving the primary and have carried out testing at low ($\sim 100kV$) output voltage. Initial tests at high voltage are also reported. The module rise time performance is degraded over that found with the two 5Ω drivers, probably due to leakage inductance and/or non-uniform core excitation from the primary feed buss. Tests indicate that we should be able to produce a $200ns$ flat top pulse ($\pm 5\%$) into a $800 - 1700\Omega$ load in the current device, but that further modifications are required for optimal performance. In the following sections we detail the design of the transformer and present results on its performance. Indications of possible limitations in the performance of the present device are given and future modifications suggested.

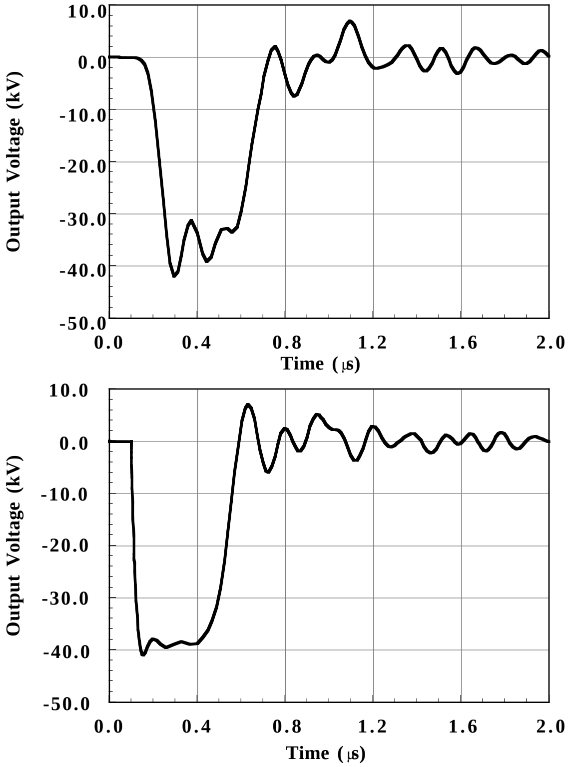

Figure. 1. SPICE code results showing voltage into a matched load for a conventional Blumlein configuration (upper frame) and the plus/minus configuration (lower frame).

II. TRANSFORMER DESIGN.

Before discussing the transformer performance we illustrate the improvement in rise time of the driving pulse in the plus/minus charge configuration over that in the conventional Blumlein configuration. This result has been confirmed experimentally. Fig. 1 shows SPICE simulation results obtained for the output voltage pulse into a matched resistive load in both configurations. It is clear that the former configuration is better than that obtained with the Blumlein. A decrease in the rise time for a six section line into a matched load from about $100ns$ for the Blumlein to $50ns$ for the plus/minus charge arrangement is observed. The rise time in the plus/minus charge configuration is not degraded by the response of the artificial pulse line, nor are the fluctuations in the output, which are clear in the Blumlein configuration, apparent. We use this configuration in the transformer and obtain a rise time of the primary pulse of less than $100ns$.

The pulse transformer is shown schematically in Fig. 2. It consists of two 10:1 step up transformers with their secondaries joined in series to give a 20:1 voltage gain for the transformer. Both of the transformer primaries are separately energized by

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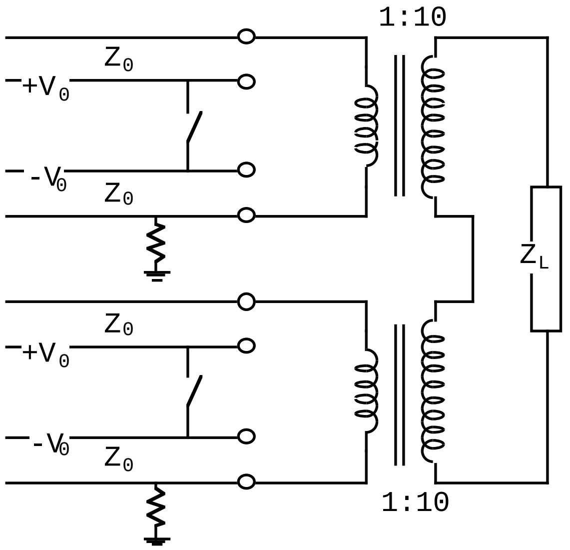

Figure. 2. Schematic of pulse transformer

two 5Ω pulse lines plus/minus charged to $40\ kV$. The transformer cores consist of two sets of 3 TDK-PE14 Ferrite cores, each of which has a flux swing of $7mVs$. In order to distribute and maintain flux uniformity throughout the core material the primary winding consists of 24 equally spaced, two turn windings connected in parallel. The secondaries have two counterwound twenty turn windings to provide efficient coupling, and to separate the high voltage output from the low voltage terminal. The 20 turn secondaries encircle both sets of cores giving a voltage step up of 20:1. As discussed at the start of this section the transmission lines are switched by a low inductance triggered gas switch located between the two lines as shown in the figure. In this location the rise time of the system is decreased compared to that obtained from a Blumlein driver.

The 24 parallel two turn windings are wound tightly around the cores and are distributed uniformly around the circumference of the cores. The windings are separated from each other at the mid-plane of the cores by about 1.5 inches so that there is a substantial mutual inductance coupling tending to keep the currents in each path constant. The secondary windings are on a tapered former giving a variable spacing between the winding and the cores of 0.5 in. at the low voltage end up to 3 in. at the high voltage end. There are two sets of 20 turn windings counterwound on opposite halves of the cores so that the low and high voltage ends of the transformer are 180^0 apart. The transformer is immersed in an oil filled tank with internal dimensions $48in.$ x $27in.$ x $46in.$ When used to drive an electron beam the output will be taken to an electron gun diode through a $20in.$ diameter port. In most of the results reported in this paper the transformer is operated at low voltage ($\sim$ 100-140 kV output) and is not immersed in the oil. Two sets of data are presented, one with the transformer fed by two 5Ω lines and, in the second case with the number of driving elements doubled giving a matched input impedance of 5Ω and pulse line impedances of 2.5Ω. The total energy stored in the capacitors in the primary transmission lines is 270 Joules.

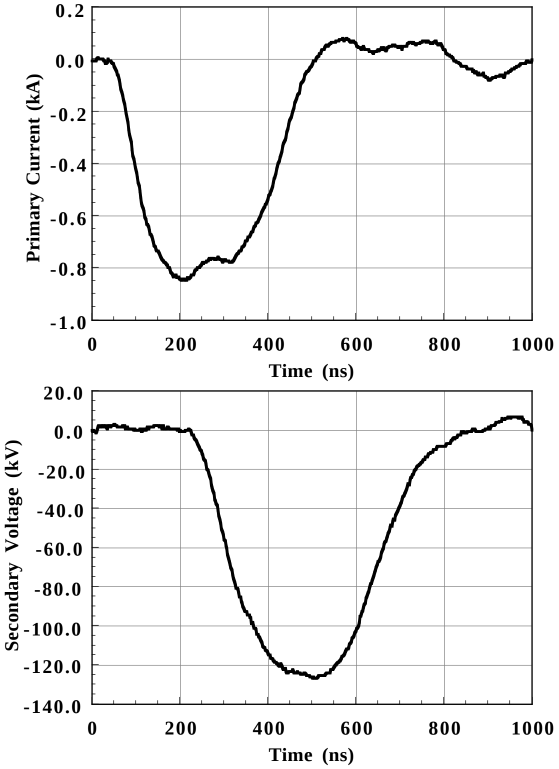

Figure. 3. Primary current and the secondary voltage for the 5Ω line driven transformer.

III. EXPERIMENTAL DATA

In figure 3 we show waveforms for the first case (with the system fed by two 5Ω lines). The data show the primary current through a single section of the transformer and the secondary voltage with a resistive dummy load of $2k\Omega$. The output voltage is about $125kV$ and the current $60A$. The primary current is about 800 A, slightly higher than the factor of ten increase over the secondary current expected. The core magnetization current is about 50 A. The secondary voltage waveforms have a duration of $340ns$ at half height and a duration of $190ns$ above 90% of peak value.

When the transformer was immersed under oil the system was taken up to an output voltage of about $450kV$ with an input voltage of approximately $23kV$. The output voltage waveform is shown in fig 4. The waveforms indicate adequate voltage insulation at the $400-500kV$ level, but show the loading of the transformer, when it is immersed in oil. The loading is believed to be a result of the parasitic capacitance due to the proximity of the tank, and to the increase in the stray capacitance between the primary and the secondary due to the presence of the oil. A rate of change of voltage at the secondary of $10^{12}V/s$ (corresponding to low voltage operation at $100kV$) requires a capacitance of about $20pF$ to account for the increase in the rise time of the output pulse. This is a 40% effect for the higher impedance drive line and 20% for the second case. In the latter case there is more current available than required and the effect is unimportant. Alternatively the use of a larger tank would alleviate the problem.

Similar data have been obtained for a variety of loads ranging from $700-1800\Omega$ with the input line impedance halved, but un-

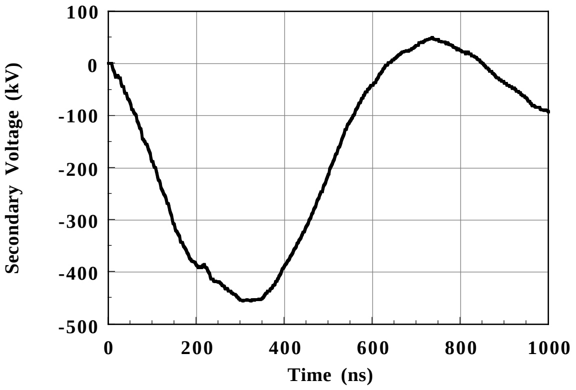

Figure. 4. Secondary voltage with transformer under oil.

der otherwise comparable conditions. In this case we have confirmed that the gain is as expected and the system will hold voltage up to at least $450kV$, the highest voltage tested to date. The primary and secondary waveforms follow each other well but the rise time, again with the transformer under oil, is degraded compared to that expected.

IV. DISCUSSION OF RESULTS

In the experiments reported above we have investigated the performance of a pulse transformer under two sets of operating conditions. In the first configuration the transformer was effectively driven by a 5Ω transmission line with a $200ns$ flat top. In this case the output voltage followed, in zero order, the input. However, when the transformer was immersed in oil the rise time was degraded to an unacceptable level. As a result the input drive impedance was halved by doubling the number of transmission lines feeding the transformer.

The rise time of the output pulse is controlled in part by the leakage inductance and the stray capacitance, and by the impedance of the driver pulse lines. In addition we have noted and measured a degradation in the rise time due to the time it takes the primary excitation wave to propagate around the cores. In the design used the primary turns are connected to a two wire buss which surrounds the cores. The buss is fed from both ends so that the propagation time is halved over that which would be obtained if the buss were fed from a single end. We have disconnected one of the two feeds and have observed an increase in the rise time of about $70ns$.

Unfortunately we cracked one of the cores in assembly and this caused breakdown in the low voltage tests in air. The crack became wider during the testing and the transformer performance deteriorated. The close coupling of the two sets of cores by the secondary winding causes the effect of the crack to affect both primaries and may be responsible in part for the slow rise time of the output signal.

V. CONCLUSIONS

The pulse transformer configuration tested has a number of novel features which lead to a the realization of a compact high gain transformer with a short rise time. These include a novel switching arrangement and the series summation of the output of two 10:1 transformers in order to achieve a 20:1 voltage gain device. The transformer is being disassembled to replace the cracked core and a number of improvements will be made in reassembly. These will include splitting the primary feeds into at least 4 sections instead of the two used in the present work. The number of parallel turns in the primary will be reduced to 12 to reduce the stray primary to secondary capacitance . We also plan to slightly reduce the leakage inductance between the primary and secondary since the present gap is overly conservative. This change and the reduction in the capacitance work in opposite directions and careful modeling is required to quantify these effects. With these, and other less important modifications, we expect to obtain an output pulse with a better rise time, a higher energy transfer efficiency and a flat top output of at least $200ns$ at the rated output conditions.

References

[1] *Pulse Generators*, edited by G. N. Glasoe & J. V. Lebacqz (McGraw-Hill, New York, 1948).