A COMPACT, HIGH REPETITION-RATE TRIGGER GENERATOR

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Abstract

This paper describes an innovative design for a compact, high repetition-rate trigger generator. The basic circuit and its operation are discussed. Solid state switching and magnetic pulse compression enable the design to operate at rep-rates in the tens of kHz and to be fabricated in a small, compact volume. A breadboard model has been designed and fabricated which can produce an open circuit voltage of up to 40 kV. Two stages of magnetic pulse compression are used along with two pulse transformers to step up the voltage from the primary energy storage elements (at ~ 400 V) to the final output voltage of 40 kV. In addition, an energy recovery circuit is used to absorb and recover reflected energy from the typical collapsing impedance load, which would otherwise be dissipated as heat in the other components as well as interfere with the repetitive operation of the pulser. Finally, test results from this breadboard trigger generator are presented, including demonstrated operation at rep-rates of up to 20 kHz.

Introduction and Design Approach

The primary goal of this project was to design and develop a compact repetitive trigger generator which could produce a burst of output pulses with open circuit amplitudes of 40 kV. The initial design requirements for this trigger generator are listed below in Table 1.

Table 1
Compact Trigger Generator Requirements

Output Voltage:	40 kV (open circuit)
Pulselength:	~1 µsec
Current Pulse Risetime:	< 500 nsec
Pulse Energy:	~40-50 mJ
Rep Rate:	2-20 kHz (adjustable) for a burst of 10 pulses 100 Bursts per second average

In addition to the requirements listed in the table, several other factors were taken into consideration during the initial design phase. It was desirable to make the trigger generator as compact as possible. Reliability and lifetime were also important issues. With the high repetition rate, a lifetime of $>10^{11}$ discharge cycles is necessary.

The specification for a 20 kHz repetition rate, given with the requirements of long lifetime and compactness, suggests the use of solid state switching devices, such as Bipolar Power Transistors, Power MOSFETs, Insulated Gate Bipolar Transistors (IGBTs), or possibly MOS-Controlled Thyristors (MCTs) [1]. Because the MCT technology is still in its infancy and devices were not yet readily available, MCTs were rejected as switching candidates. Bipolar Power Transistors typically require larger switch trigger circuitry than the other two options because of their drive current requirements and were therefore also eliminated. Previous experience with Power MOSFETs had proven their capability to operate reliably at these high switching frequencies and high average power levels far exceeding the requirements for this particular application [2,3]. Power MOSFETs were therefore chosen as the switching technology for the compact trigger generator.

Because single MOSFET devices are limited in voltage to approximately 1000 V, a large quantity of devices must be grouped in a series array in order to satisfy the output voltage requirement or else some voltage multiplication is needed in order to amplify a lower voltage to the 40 kV pulsed output. Since constructing such an array of solid state devices which could handle 40 kV would not lend itself to a small physical package, it was decided to use pulse transformers to step up the voltage from an initial value of 400 V. This number was selected in order to allow the use of 500-600 V rated, low on-state resistance power MOSFETs.

Direct discharge of a capacitor with power MOSFETs and a step-up pulse transformer would require devices with high peak current specifications (>250 A) and pulse transformers with very low leakage inductances. To get around these difficulties, a 2 stage magnetic pulse compression circuit was used to sharpen the risetime of the initial pulse and to narrow the pulsewidth from an initial duration of ~10 µsec to the desired output pulselength of 1 µsec. This general technique has been well documented [4,5,6,7,8] and will therefore not be discussed in detail in this paper. However, difficulties arise with this technique when energy is reflected from the load. A solution to this problem will be discussed in a later section.

The leakage inductance requirements of a fast risetime, 400 V to 40 kV step-up transformer precludes pulse compression at the 400 V level. On the other hand, if the pulse compression were to be performed at the 40 kV output voltage, insulation requirements, low switch currents, and the high volt-second values associated with this voltage level would imply the need for a large number of turns for the windings of the two magnetic switches. This would cause excessive and unnecessary complications in the design process. The approach that we have adopted was to perform this process at the intermediate voltage of 5 kV, where component voltage ratings are still reasonable and readily available. The voltage transformation then occurs in two separate stages, each providing a voltage step-up of approximately 1:10.

The overall system, as depicted in the block diagram of Figure 1, consists of a primary energy storage element (capacitor) operating at a voltage of 400 V. This is then discharged into the primary of the first 1:8 step-up pulse transformer by a single Power MOSFET switch, producing a pulse of approximately 10 µsec duration. The secondary of the pulse transformer charges the first stage of the magnetic pulse compression section of the trigger generator. After approximately 4 µsec, the magnetic switch in the first stage saturates and voltage is applied to the capacitor in the second stage. The second stage magnetic switch then saturates after another 1 µsec and the pulse is transferred to the primary of the second 1:9 step-up pulse transformer, producing an output pulse of 40 kV on the secondary.

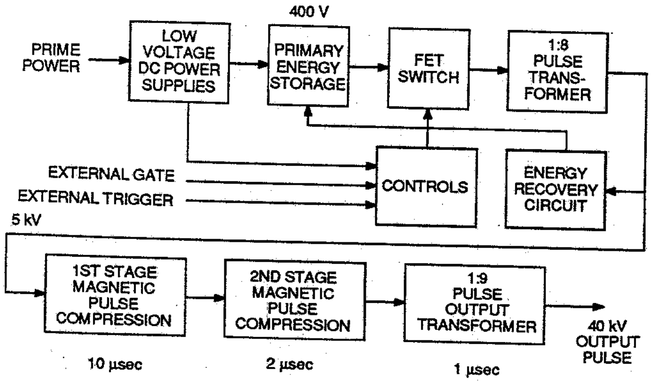

Figure 1: Block Diagram of Compact Trigger Generator Assembly.

In addition, a controls unit adjusts the repetition rate and also the burst length of the output pulses by varying the gate drive timing circuitry for the Power MOSFET driver. Finally, an energy recovery circuit is used to couple reflected energy from the load back into the primary energy storage capacitor, reducing the energy losses in the system and minimizing problems which might be associated with the additional heat dissipation and voltage transients resulting from the reflected energy.

Design Considerations

Control Logic

The control logic of the compact trigger generator was designed such that the unit could operate in one of two modes. The first of these two modes is known as the trigger mode. In this case, an external signal starts the generation of output trigger pulses. The repetition rate and the pulse burst duration are both determined by the adjustment of a pair of potentiometers. An external monitor output is also implemented for observation of the generated pulse train.

In the second mode of operation, an input gate signal initiates the pulse train which then continues as long as the gate pulse signal is applied. As in the other mode of operation, the repetition rate is determined by the front panel potentiometer adjustment.

Shown in Figure 2 is a block diagram of the control logic implemented in the compact trigger generator. Optical isolators are used to provide isolation between the control logic and the incoming control signals. Filtering, a careful control of the physical layout and logic design, and several other techniques were also implemented to reduce the possibility of EMI related problems which might affect operation of the trigger generator.

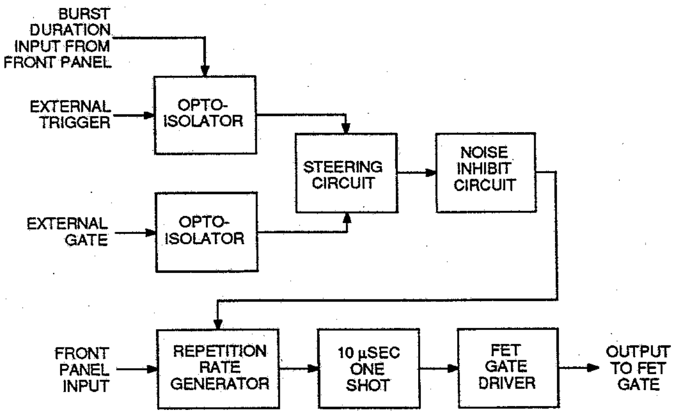

Figure 2: Block Diagram of Control Logic for the Compact Trigger Generator.

The control logic circuits, low voltage power supplies, primary energy store, power MOSFET, and the first pulse transformer are all housed in a small electronics chassis which is 9" wide x 4" tall x 8" deep.

Pulse Generation

Shown in Figure 3 is a simplified schematic of the pulse generation, compression, and amplification sections of the compact trigger generator. A low voltage power supply rectifies the incoming 120 V ac power and charges the 50 µF primary energy storage (filter) capacitor up to a voltage of 400 V dc. When triggered by the control logic circuitry, the power MOSFET switch (a single International Rectifier IRFPC50, rated at 600 V, 42 A peak, and 180 W dissipation) discharges the capacitor into the primary winding of the first pulse transformer. This transformer has a 1:8 turns ratio and is wound on a 4 mil tape wound C core (Arnold AH-9). As it only operates from 400 V to 5 kV, the transformer was not encapsulated. The output pulse from the first pulse transformer is then transmitted to the pulse compression and final amplification stages through a small length of coaxial cable.

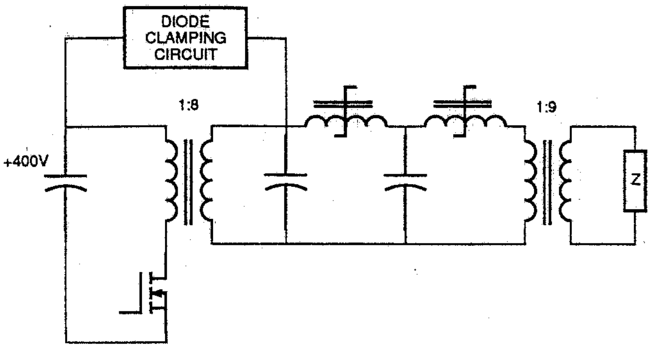

Figure 3: Simplified Schematic Diagram of the Pulse Generation, Compression, and Amplification Stages in the Compact Trigger Generator.

As pointed out previously, there are two series-switching, magnetic pulse compression stages. Each of the two saturable inductor switches is fabricated using a pair of ferrite cores (Ferroxcube 3C8 material). The first switch is wound with 250 turns for a saturation time of approximately 4 µsec. The second switch has a 70 turn winding around the ferrite core, such that it closes 1 µsec after voltage is applied to the switch. The energy storage elements in both stages of the magnetic pulse compression section are a pair of 6 kV, 2.2 nF ceramic capacitors.

The output pulse transformer has a 1:9 turns ratio. In this case, it is wound on a similar, but slightly different core (Arnold AH-15). The single layer primary winding is wound directly on top of a fabricated G-10 insulator bobbin. Insulation material is then applied and the first of the secondary winding layers is laid down. Insulation material is again applied between the secondary layers and each successive layer is wound with fewer turns such that the overall winding becomes "pyramid" shaped.

As with the control logic circuitry and low voltage electronics, it was highly desirable to minimize the size associated with the high voltage components, especially since it was desirable to locate these as close as possible to the output load. The pulse compression and output pulse transformer stages of the compact trigger generator were therefore assembled and potted inside a metal cylinder, which is 2.75 inches in diameter and 10 inches in length. A short length of coaxial cable was then used to transmit the pulse to the output load. This coaxial arrangement of all of the high voltage components (those which handle voltages $\geq$ 4 kV) assisted in shielding and helped to minimize any EMI effects which might have disturbed other sensitive electronics located near the load.

Energy Recovery Circuit

A typical application for the compact trigger generator would be to supply the high voltage trigger pulse required to cause the initial breakdown phase in a spark gap switch. In this type of operation, the load seen by the trigger generator varies from an open circuit during the initial stage of the output pulse to a "short circuit" during the remainder of the pulse. With this type of collapsing impedance load, energy is inevitably reflected back from the load towards the source.

This reflected energy can cause a number of potential problems for the trigger generator. The majority of the energy will be dissipated as heat in the components of the trigger generator. In a high rep-rate application, this energy can result in substantial dissipated power, complicating the thermal management and overall design of the unit. In addition, this reflected energy can also cause large voltage transients to occur which can possibly damage components in the unit. Finally, and most importantly, the energy can still be travelling through the system at the time the next pulse is initiated, resulting in large shot to shot variations in the output pulse amplitude.

In order to minimize these effects, one can insert relatively low value shunting resistors across each pulse compression capacitor to attenuate the reflected energy. However, this method will also strongly affect the efficiency of the trigger generator since the original pulse will also be attenuated. For these reasons, we have designed and incorporated an energy recovery circuit to absorb the reflected energy and direct it back into the primary energy storage capacitor, where it can be stored and "re-cycled" for further use during the next pulse discharge cycle. The clamping diode in this circuit also serves to minimize the voltage across the power MOSFET as the reflected reverse polarity voltage pulse hits the secondary of the first pulse transformer.

Operational Data and Results

Several breadboard prototype trigger generators have been fabricated, assembled, and tested. Shown in Figure 4 is a sample output waveform from one of the prototype units operating at a frequency of 20 kHz during the burst of 5 pulses. An expanded view of a single pulse from this burst is displayed in Figure 5. As can be seen from these two waveforms, the output voltage pulses reach a maximum peak voltage of 20 kV. In this case, the load seen by the trigger generator was primarily capacitive, with a value of approximately 50 pF. This particular value of capacitance represents an essentially "matched" load to the ~4.5 nF capacitor in the second pulse compression stage, resulting in an output voltage which is roughly one half of the normal open circuit voltage and a slightly increased output pulse risetime. Although this "loaded" condition did modify the performance of the trigger generators, the achievable parameters were quite acceptable for the primary design application of the units.

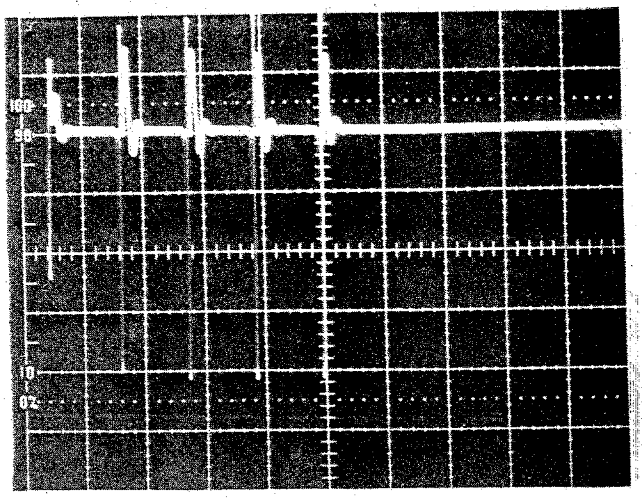

Figure 4: Output Voltage Waveform Showing 20 kHz Burst (5 kV/div and 50 μsec/div).

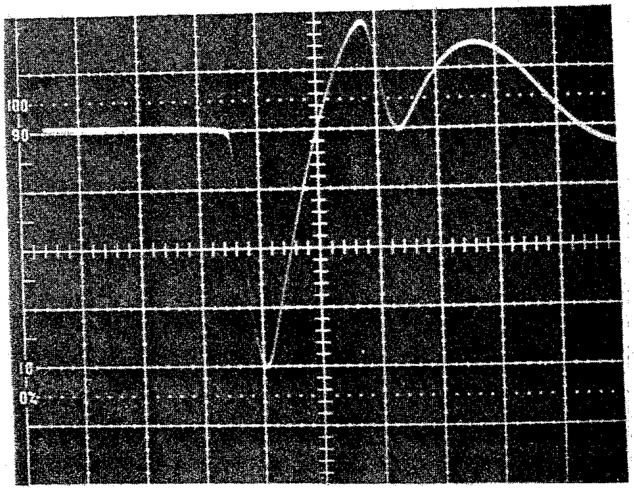

Figure 5: Expanded View of Output Voltage Waveform Single Pulse (5 kV/div and 2 μsec/div).

Summary and Conclusion

A set of compact, high repetition-rate trigger generators have been designed, fabricated, and assembled which can produce a burst of 20 kHz output pulses with open circuit voltages of up to 40 kV. All of the original design goals for this unit have been achieved with these series of prototypes. Given that this design concept has now been proven, the approach may now be scaled up relatively easily to units which could provide both higher output voltages and/or more energy per pulse.

Acknowledgements

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