PULSE FORMING CIRCUIT

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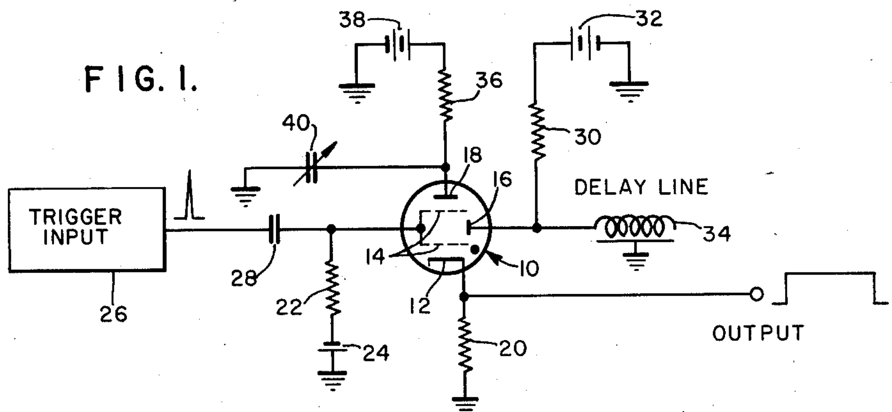

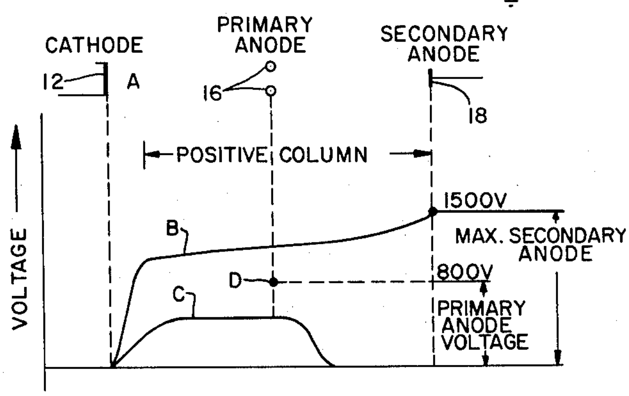

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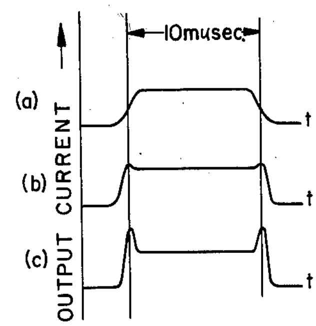

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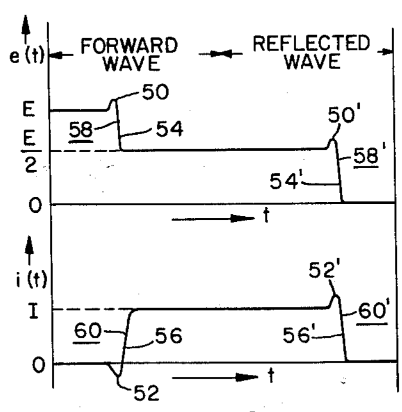

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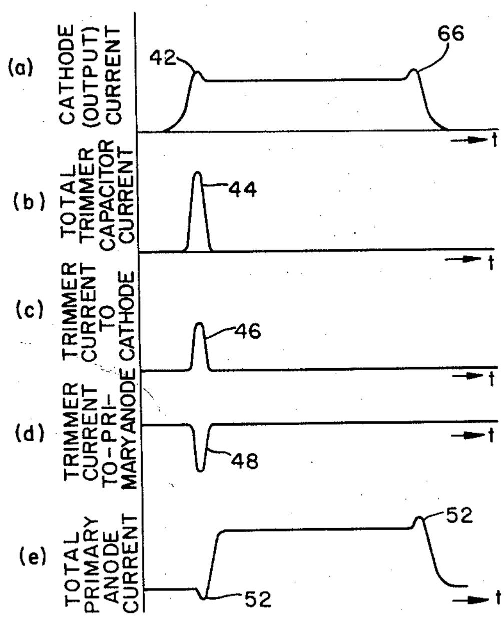

F I G. 3.

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PULSE FORMING CIRCUIT

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This invention relates generally to pulse forming circuits and particularly to circuits of the kind employing thyratron switching tubes for generating rectangular pulses.

Thyratron tubes have been found useful in pulse forming circuits because of their high current capabilities and high switching speeds. In certain kinds of electronic cameras, which are used to record high speed transient phenomena such as plasma shock waves, thyratron switching circuits are used to generate high voltage rectangular gating pulses requiring extremely fast rise and decay times of the order of nanoseconds (1 nanosecond$=1\times10^{-9}$ second). Prior attempts to reduce the rise time by decreasing the ionization time of the tubes have proceeded to the point of reaching the voltage and current limits of available tubes. Other approaches to the problem have resulted in reducing the rise time at the expense of increasing the decay time.

Accordingly, a principal object of this invention is to reduce both the rise and decay times of rectangular pulses.

A further object is to provide a pulse forming circuit capable of generating rectangular voltage pulses having magnitudes of several hundred volts and rise and decay times of less than 3 nanoseconds.

The foregoing and other objects are realized according to the invention in a pulse forming circuit that utilizes a thyratron switching tube for controlling the discharge of current from two energy storage devices. The electrodes of the thyratron are comprised of a cathode, a control grid, a primary anode, and a secondary anode. One of the energy storage devices comprises a capacitor connected to the secondary anode of the tube, while the other storage device comprises a delay line connected to the primary anode. The discharge current from both devices flows through an output load resistor connected in the cathode circuit.

In the quiescent state of the circuit, a negative bias voltage on the control grid maintains the tube nonconducting, such that the delay line is charged to a moderately high positive potential relative to the cathode and the capacitor is charged to a potential highly positive relative to both the primary anode and the cathode.

To initiate a rectangular pulse, the tube is rendered conducting by applying a positive trigger pulse to the control grid. The capacitor quickly discharges through the tube to produce a rapidly rising output pulse. While the secondary anode remains at a higher positive potential than the primary anode, some of the discharge current flows into the primary anode circuit in a sense to add further charge to the delay line. This charging current appears as a brief negative current pulse or wave that travels along the length of the delay line.

Shortly after the initiation of the traveling negative current wave, the potential of the secondary anode drops below that of the primary anode, because current flowing

through the tube discharges the capacitor. When this occurs, the delay line discharges through the primary anode cathode circuit of the tube, thereby reversing the direction of current flow in the delay line and sending a positive going traveling current wave down the delay line. Both current waves are reflected out of phase at the end of the delay line, and are now sent back to the primary anode as a brief positive pulse followed by a negative pulse.

During its discharge, the delay line delivers a constant amplitude current to the load resistance, which appears as the main portion of the rectangular output pulse. The output pulse terminates when both waves reach the primary anode, with the brief positive current wave reaching the primary anode slightly ahead of the negative current wave and serving to square up the trailing edge of the output pulse.

In the drawings, wherein like numerals indicate like parts or phenomena:

FIG. 1 is a schematic circuit of one embodiment of the pulse forming circuit according to the invention;

FIG. 2 is a graph showing certain voltage distributions in a thyratron tube; and

FIGS. 3, 4, and 5 are graphs of waveforms useful in explaining the operation of the pulse forming circuit.

FIG. 1 shows one embodiment of the pulse forming circuit according to the invention. The pulse forming circuit comprises a thyratron switching tube **10** which is preferably a tetrode, such as a type 2D21. The switching tube **10** includes a cathode **12**, a control electrode **14**, a primary anode **16** surrounded by the control electrode **14**, and a secondary anode **18** spaced from the control electrode **14**. As depicted herein, the switching tube **10** is connected and operated in a nonconventional manner. For example, the control electrode **14**, or the electrode which triggers the tube **10** into conduction, usually functions as a shield electrode in conventional circuits, and the primary anode **16** usually is used to trigger the tube **10** into conduction. As will become apparent, certain advantages result from the novel operation of the switching tube **10**.

A cathode load resistor **20** is connected between the cathode **12** and ground. The control electrode **14** is biased to a highly negative potential by connection through a grid bias resistor **22** to a negative voltage source **24**. The bias on the control electrode **14** is in excess of the cutoff bias of the switching tube **10**. The control electrode **14** is connected to a trigger pulse source **26** through a coupling capacitor **28**, the source **26** providing a voltage pulse of sufficient magnitude to overcome the bias on the control electrode **14** and thereby cause the tube **10** to switch into a conducting condition.

The primary anode **16** is maintained at a moderately high positive potential by connection through a first voltage dropping resistor **30** to a primary anode voltage source **32**. A delay line **34** is also connected between the primary anode **16** and ground, and forms one discharge circuit.

The secondary anode **18** is maintained at a relatively high positive potential by connection through a second voltage dropping resistor **36** to a secondary anode voltage source **38**. A trimmer capacitor **40** is connected between the secondary anode **18** and ground, and forms another discharge circuit. Typical operating potentials for the tube **10** are realized when the bias source **24** is −75 volts, the primary anode source **32** is +800 volts, and the secondary anode source **38** is +1500 volts.

The operation of the pulse forming circuit will now be described. In the absence of a positive trigger pulse on the control electrode **14** from the trigger pulse source **26**, the switching tube **10** is biased to a nonconducting condition. As a result, the trimmer capacitor **40** is charged to the full voltage of the secondary anode voltage source **38**, and the delay line **34** is charged to the full voltage of the primary anode voltage source **32**.

When a positive trigger pulse is applied to the control electrode **14** from the trigger pulse source **26**, the switching tube **10** is rendered conducting, such that current flows from the secondary anode **18** to the cathode **12**, to provide a low resistance discharge path for the trimmer capacitor **40**. When this occurs, the primary anode **16** is immersed in the positive column, a region of the switching tube **10** extending between the secondary anode **18** and an area A next adjacent to the cathode **12**, as shown in FIG. 2. For purposes of this discussion, it is not necessary to refer to the control electrode **14**, hence it is omitted from FIG. 2 for convenience.

Referring in more detail to FIG. 2, which is a diagrammatic view and graph showing the voltage distribution in the space between the cathode **12** and the secondary anode **18** of the switching tube **10**, curve B represents the voltage distribution at the moment the tube **10** reaches full ionization, and curve C represents the voltage a short time later. It is seen that at the time full ionization of the tube **10** is reached, the voltage rises sharply from zero voltage at the cathode **12** to a relatively high voltage approaching the maximum secondary anode voltage **18**, at the area A next adjacent to the cathode **12**. From the area A to the secondary anode **18**, the voltage rises rather gradually to a voltage just below the maximum secondary anode voltage **18** before it makes a short abrupt rise to the maximum voltage. The space between area A and the secondary anode **18** is known as the positive column referred to.

Assuming that the secondary anode **18** initially is at a potential of 1500 volts and the primary anode **16** is initially at a potential of 800 volts, it is seen from curve B that at the moment the switching tube **10** fires and conducts, the primary anode **16** is at a potential, indicated at point D, that is less than that of the positive column. Positive ions from the positive column bombard the primary anode **16** and cause secondary emission therefrom of electrons which flow to the secondary anode **18**. Current therefore flows in the conventional sense from the secondary anode **18** to the primary anode **16**.

Current also flows from the secondary anode **18** to the cathode **12**. Thus, the trimmer capacitor **40** quickly discharges through two paths, current flowing in one path in the primary anode circuit, and in another path from the secondary anode **18** to the cathode **12** and through the load resistor **20**. The current flow in the second path, through the load resistor **20** produces a sharply rising wavefront **42** in the output current, as shown in FIG. 3(*a*). In FIG. 3, the total trimmer capacitor discharge current is shown in FIG. 3(*b*) as a relatively large current pulse **44**. The cathode current is shown in FIG. 3(*c*) as a smaller magnitude current pulse **46** and the primary anode current is shown in FIG. 3(*d*) as a current pulse **48** of the same order of magnitude as the cathode current pulse **46**. The direction of the primary anode current pulse **48** is shown negative because it is a charging current and it is assumed herein that a discharging current is positive. The direction of flow of the initial primary anode current pulse **48** is such as to add further charge to the delay line **34**. Hence, during the initial flow of the tube currents, the delay line **34** does not discharge but rather is briefly charged to a higher potential.

The short pulse of primary anode current **48** flowing into the delay line **34** sends traveling current and voltage waves down the delay line **34**. FIG. 4 shows these waves as they would appear at a fixed point along the delay line as the waves go by. FIG. 4(*a*) shows the voltage $e(t)$ as a function of time and FIG. 4(*b*) shows the current $i(t)$ as a function of time. The voltage wave appears as a short positive going pulse **50** and the current wave appears as a short negative going pulse **52**. The current pulse **52** is negative because it is in a direction opposite that of the discharge current of the delay line **34**, which is considered as positive.

The duration of the pulse of current **52** lasts as long as the primary anode **16** remains at a potential below that of the positive column in the tube **10**. However, as the tube **10** draws current, the secondary anode **18** potential quickly falls by an amount determined by the discharge of capacitor **40**, bringing the potential of the positive column down with it and below the potential of the primary anode **16**, as shown in curve C of FIG. 2. When this occurs, the current flowing in the primary anode circuit reverses direction, thereby terminating the negative current pulse **52** (FIG. 4) and initiating a discharge of the voltage in the delay line **34** through the primary anode circuit. The discharge in the primary anode circuit path gives rise to a negative going voltage wave **54** and a positive going current wave **56** which travel down the delay line immediately behind the positive voltage wave **50** and the negative current wave **52** previously sent down the line **34**. Thus the combined voltage wave **58** traveling down the line away from the primary anode **16** is a positive pulse **50** followed by a negative step **54**, and the combined current wave **60** is a negative pulse **52** followed by a positive step **56**. The negative voltage step **54** drops the voltage on the delay line **34** to one half of its initial value E, or to $E/2$. The positive current step **56** raises the current in the delay line **34** to a value I.

While the waves **58** and **60** travel down the delay line **34**, the total primary anode current has the form shown in the left half of FIG. 3(*e*), and the output current, as well as the output voltage, has the form shown in the left half of FIG. 3(*a*).

When the traveling voltage and current waves **58** and **60** reach the end of the delay line **34** the voltage wave **58** is reflected in phase and the current wave **60** is reflected out of the phase with the incident waves. Thus the reflected voltage wave **58′** appears as a positive pulse **50′** leading a negative step **54′**, and the reflected current wave **60′** appears as a positive pulse **52′** leading a negative step **56′**.

When the reflected waves **58′** and **60′** reach the primary anode **16** again, the traveling waves terminate, the delay line **34** is fully discharged, and the output current and voltage waves terminate. However, the effect of the initial traveling current pulse **52**, upon termination, is to add a positive component **66** to the output current pulse which tends to square up the trailing edge of the output pulse, as shown in FIG. 3(*a*). The traveling current pulse **52** is shown in FIG. 3(*e*) as a negative pulse in the leading edge of the total primary anode current waveform and as a positive pulse in the trailing edge thereof.

As a result of this positive component **66** the decay times of rectangular pulses having magnitudes of several hundred volts can be reduced to less than 3 nanoseconds.

Moreover, by first providing a fast discharge of the trimmer capacitor **40** through the tube **10**, the rise time can likewise be reduced to less than 3 nanoseconds. The fast discharge is enhanced by utilizing as the control electrode **14** which controls the ionization, the electrode that is conventionally used as a shield electrode. The close proximity of one portion of the control electrode **14** to the cathode **12** permits greater control over the ionization and results in shorter ionization times with consequent fast discharge of the trimmer capacitor **40**.

Typical operating values for the circuit of FIG. 1 are as follows:

Resistor 20	ohms	50
Resistor 36	megohms	10
Capacitor 40	micromicrofarads	4–30
Resistor 30	megohms	10
Source 32	volts	800
Source 38	do	1500
Capacitor 28	micromicrofarads	100
Resistor 22	kilohms	10
Source 24	volts	−75
Delay line 34	2 feet of RG–58/U cable	

In one operative embodiment constructed with the above circuit values, rectangular pulses of 350 volts in magnitude were generated having rise and decay times less than 3 nanoseconds.

The value of the trimmer capacitor **40** can be varied to produce a desired waveform. The larger the value of capacitance the greater will be the spikes appearing at the beginning of the pulse and the faster the rise time. Depending upon design considerations, the capacitance may be made relatively large to produce a steep rise at the expense of overshoot in the pulse, or it may be made relatively small to produce a substantially flat waveform at the expense of longer rise time. FIG. 5 shows variations in the shape of the output waveform with variations in the value of the trimmer capacitor **40**. Typically, the output waveform may have a duration of 10 nanoseconds. FIG. 5(*a*) shows a typical uncompensated waveform, that is, one resulting from zero trimmer capacitance. FIG. 5(*b*) shows a typical properly compensated waveform resulting from the proper value of trimmer capacitance. FIG. 5(*c*) shows an overcompensated waveform resulting from too high a value of trimmer capacitance.

It is now apparent that by means of the circuit arrangement of the invention it is possible to generate high voltage rectangular pulses with short rise and decay times.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A pulse forming circuit, comprising: a thyratron switching tube including a cathode, a control grid, a primary anode, and a secondary anode; a load resistor connected in series with said tube; a first charging circuit including a first energy storage device connected to said primary anode; a second charging circuit including a second energy storage device connected to said secondary anode; said charging circuits including means for simultaneously charging said second energy storage device to an initial voltage greater than the voltage on said first energy storage device; means for maintaining said tube normally nonconducting whereby both of said energy storage devices are fully charged to their initial voltages, and means for switching said tube into a conducting condition to provide a common discharge path for both of said energy storage devices through said load resistor.

2. A pulse forming circuit according to claim 1 wherein said first energy storage device comprises a delay line and said second energy storage device comprises a capacitor.

3. A pulse forming circuit according to claim 1 wherein said first charging circuit includes a first voltage source of given magnitude, and said second charging circuit includes a voltage source that is greater in magnitude than said first voltage source.

4. A pulse forming circuit, comprising: a thyratron switching tube including a cathode, a control grid, a primary anode, and a secondary anode; a load resistor connected in series with said tube; a first charging circuit including a first energy storage device connected to said primary anode; a second charging circuit including a second energy storage device connected to said secondary anode, said load resistor being out of both of said charging circuits; said charging circuits including means for simultaneously charging said second energy storage device to an initial voltage greater than the voltage on said first energy storage device; means for applying a negative bias on said control grid that is greater than the negative cutoff potential thereof to maintain said tube normally nonconducting, whereby both of said energy storage devices are fully charged to their initial voltages; and means for switching said tube into a conducting condition to provide a common discharge path for both of said energy storage devices through said load resistor.

5. A pulse forming circuit, comprising: a thyratron switching tube including a cathode, a control grid, a primary anode, and a secondary anode; a load resistor connected in series with said tube; a first charging circuit including a delay line, a first resistor, and a first voltage source connected in series, with said primary anode connected to the junction between said first resistor and said delay line; a second charging circuit including a capacitor, a second resistor and a second voltage source connected in series, with said second anode connected to the junction between said second resistor and said capacitor; said charging circuits including means for simultaneously charging said capacitor to an initial voltage greater than the voltage on said delay line; means for maintaining said tube normally nonconducting, whereby said capacitor and said delay line are fully charged to their intial voltages and means for switching said tube into a conducting condition to provide a common discharge path for said capacitor and said delay line through said load resistor.

6. A pulse forming circuit, comprising:

a thyratron switching tube including a cathode, a control grid, a primary anode, and a secondary anode mounted in that order in a common electron path;

a capacitor connected in the secondary anode circuit of said tube;

a delay line connected in the primary anode circuit of said tube;

means for simultaneously charging said capacitor and said delay line to initial voltages such that the voltage on said capacitor is substantially greater than the voltage on said delay line;

means for biasing said control grid to maintain said tube normally nonconducting, whereby said capacitor and said delay line are fully charged to their initial voltages;

a load resistor connected in the cathode circuit of said tube and out of the charging paths of said capacitor and said delay line; and

means for applying a trigger pulse to said control grid to render said tube conducting to form a common discharge path for said capacitor and said delay line through said load resistor.

7. A pulse forming circuit, comprising:

a thyratron tube including, a cathode, a control grid, a primary anode and a secondary anode mounted in that order in a common electron stream path,

first source means for applying a positive potential on said primary anode,

second source means for applying to said secondary anode a positive potential that is substantially larger than potential on said primary anode,

means for biasing said control grid to maintain said tube initially nonconducting,

a capacitor connected to said primary anode,

a delay line connected to said secondary anode,

said capacitor and delay line being initially charged to the potentials of said first and second sources respectively, when said tube is nonconducting, a load resistor connected in series with said tube and out of the charging paths of said capacitor and said delay line,

and means for applying a triggering pulse to said control grid to render said tube conducting, whereupon said capacitor quickly discharges through said tube to produce a fast rising current pulse through said load resistor and a charging current pulse through said delay line during an interval when said primary anode is negative in potential relative to the secondary anode,

said delay line discharging through said tube when

the potential of said secondary anode falls below the primary anode voltage to produce through said load resistor a flat topped current pulse that terminates when said delay line is completely discharged,

the charging current pulse through the delay line being reflected to produce a positive pulse component which sharpens the trailing edge of the load current waveform.

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