United States Patent [11] **3,599,074**

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[21] Appl. No. **356**
[22] Filed **Jan. 2, 1970**
[45] Patented **Aug. 10, 1971**
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[54] HIGH-POWER DIRECT-CURRENT TO SQUARE-WAVE CONVERTER UTILIZING AN INDUCTIVELY COUPLED GAS DISCHARGE TUBE

4 Claims, 11 Drawing Figs.

[52] **U.S. Cl.** **321/2,**
321/9 A, 321/35, 336/222
[51] **Int. Cl.** **H02m 1/06,**
H02m 3/30, H01f 27/28
[50] **Field of Search** 323/44;
321/2, 8, 9 A, 32, 34—36, 45 C, 45; 336/222;
315/57; 219/6.5

[56] **References Cited**

UNITED STATES PATENTS

1,813,580	7/1931	Morrison	315/57
1,961,057	5/1934	Livingston	321/45CUX
1,981,066	11/1934	Osnos	336/222
2,521,955	9/1950	Vang	219/6.5 X
3,290,550	12/1966	Senkewich	323/44 X
3,409,817	11/1968	Gillett	321/9 A UX
3,518,526	6/1970	Genuit	321/45 X

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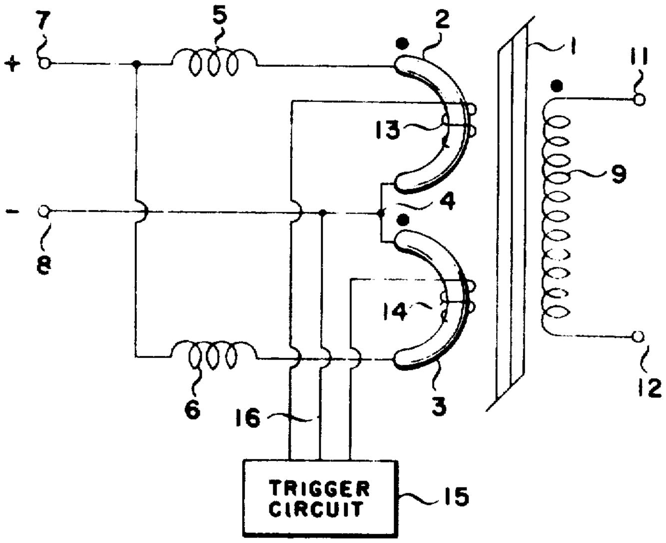
ABSTRACT: A high-power square wave generator employing a transformer, the core of which has a rectangular hysteresis loop and the center-tapped primary winding of which comprises a pair of triggered gas discharge tubes. Alternate firing of the discharge tubes induces a square wave in the transformer's secondary winding. The device may be utilized as the power carrier source for very-high-power carrier amplifiers of the silicon controlled rectifier, thyratron, or magnetic amplifier type. An alternate embodiment employs a nonsaturating ferrite core in lieu of a rectangular loop core, and an auxiliary gas discharge tube shunted across the secondary winding for switching control.



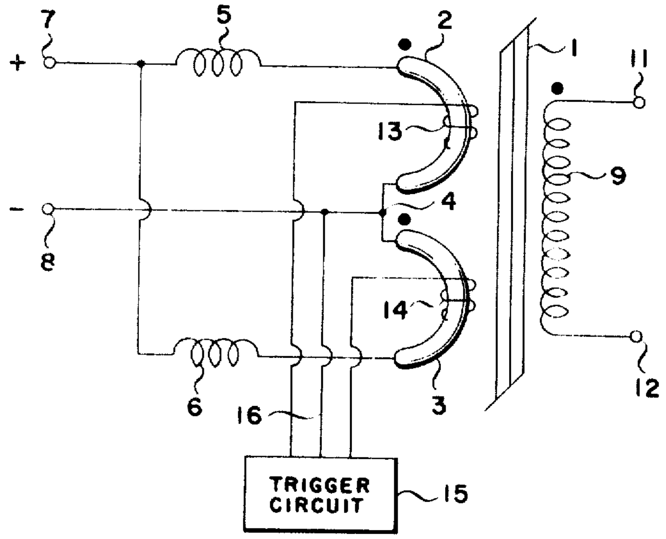


FIG. 1

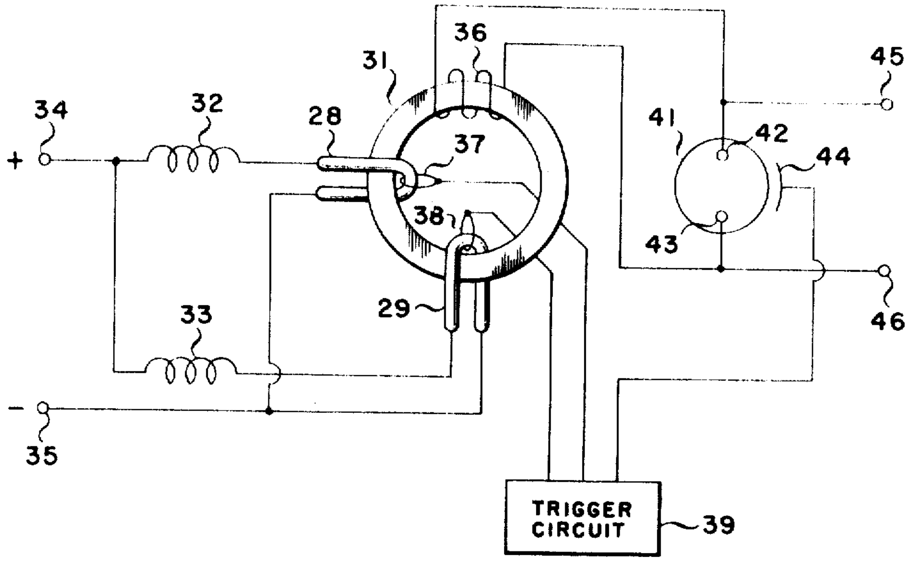


FIG. 3

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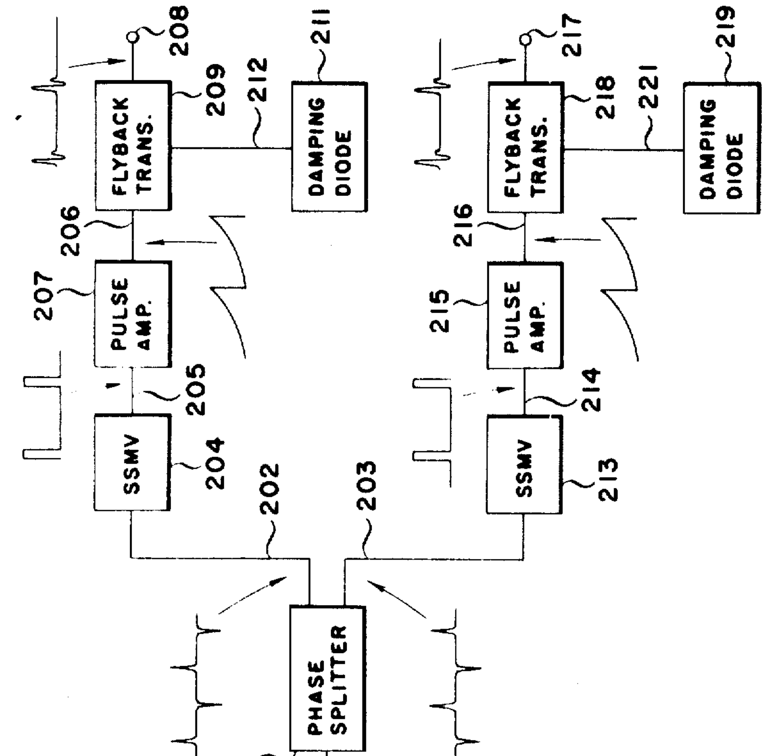

FIG. 11 CONTD.

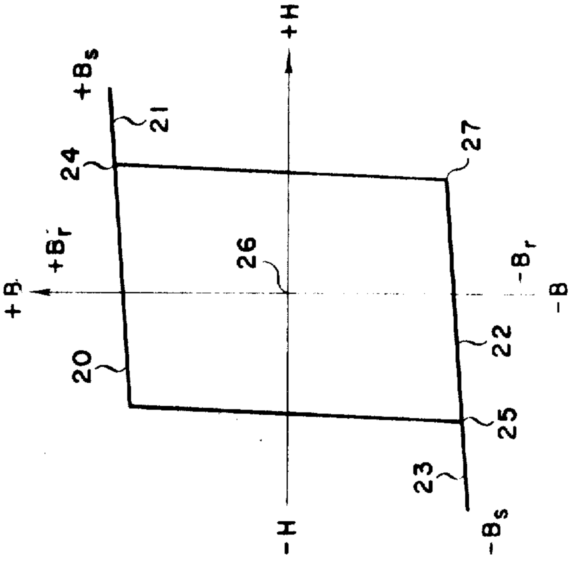

FIG. 2

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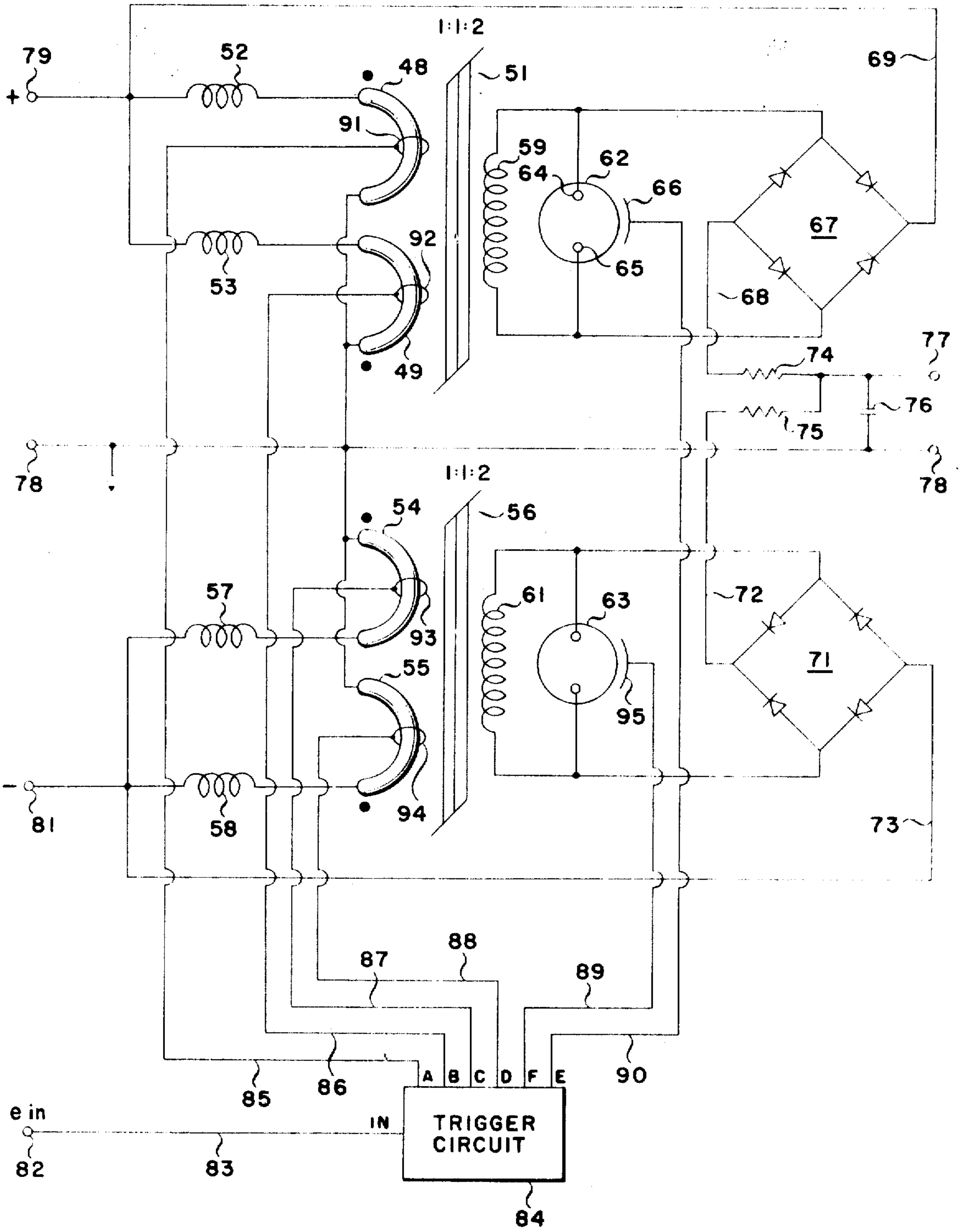

FIG. 4

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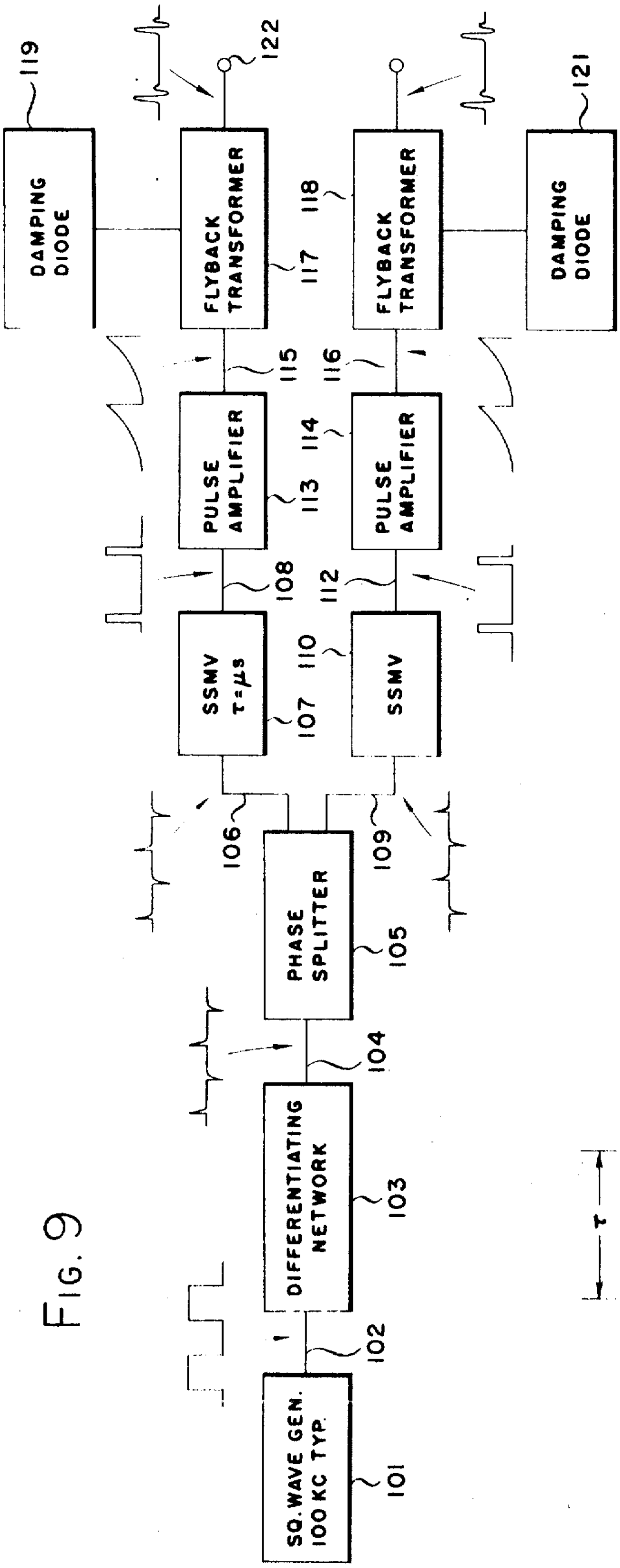

FIG. 9

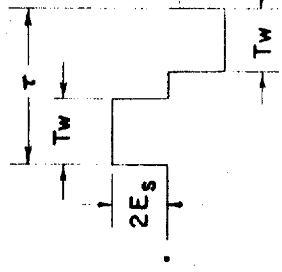

FIG. 5

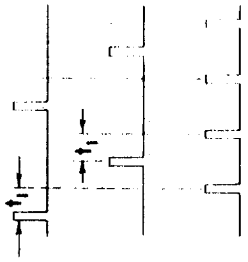

FIG. 6

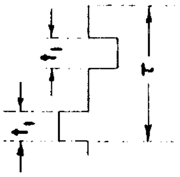

FIG. 7

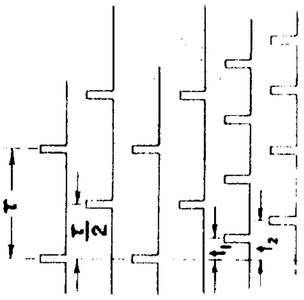

FIG. 8

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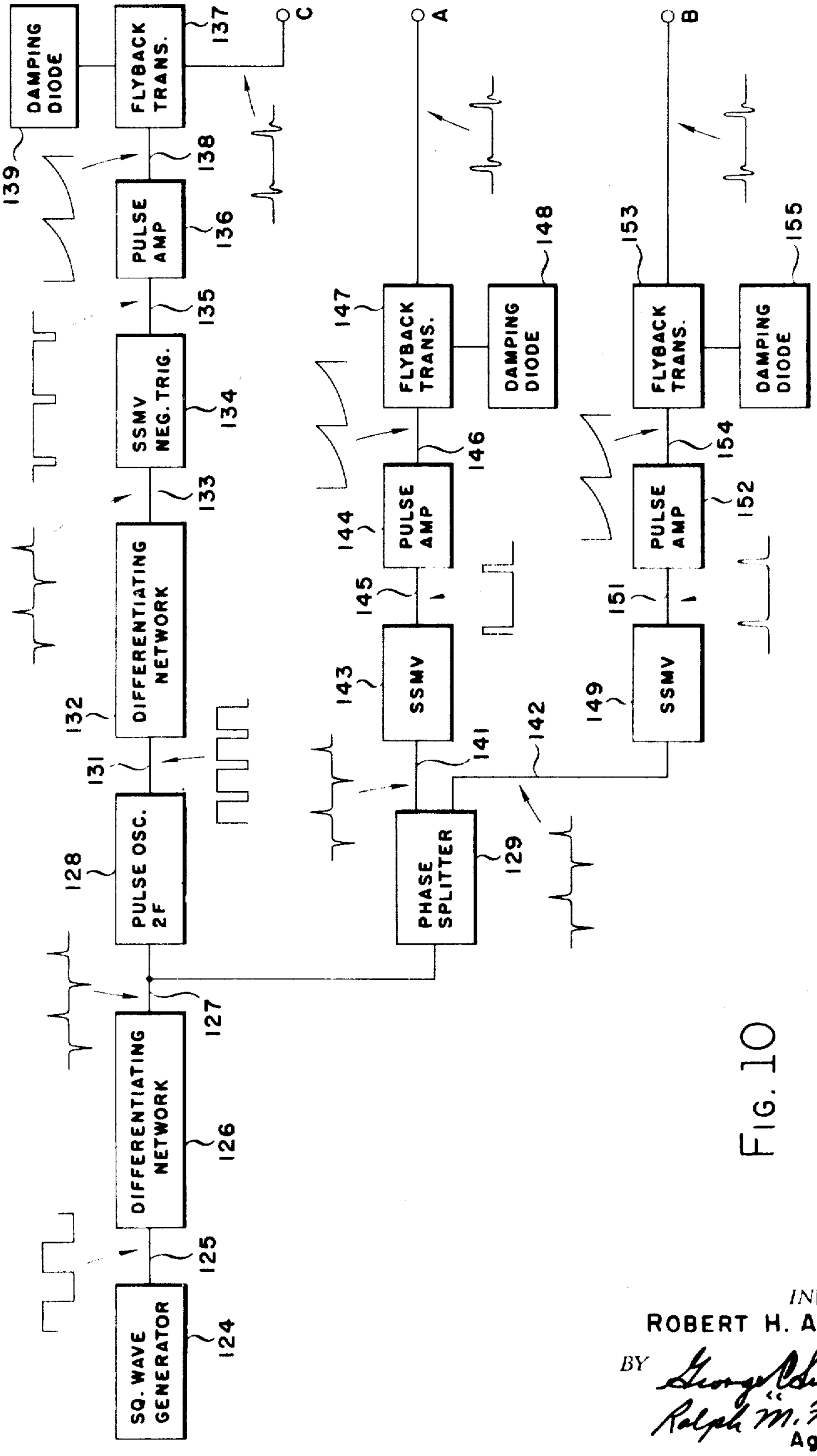

FIG. 10

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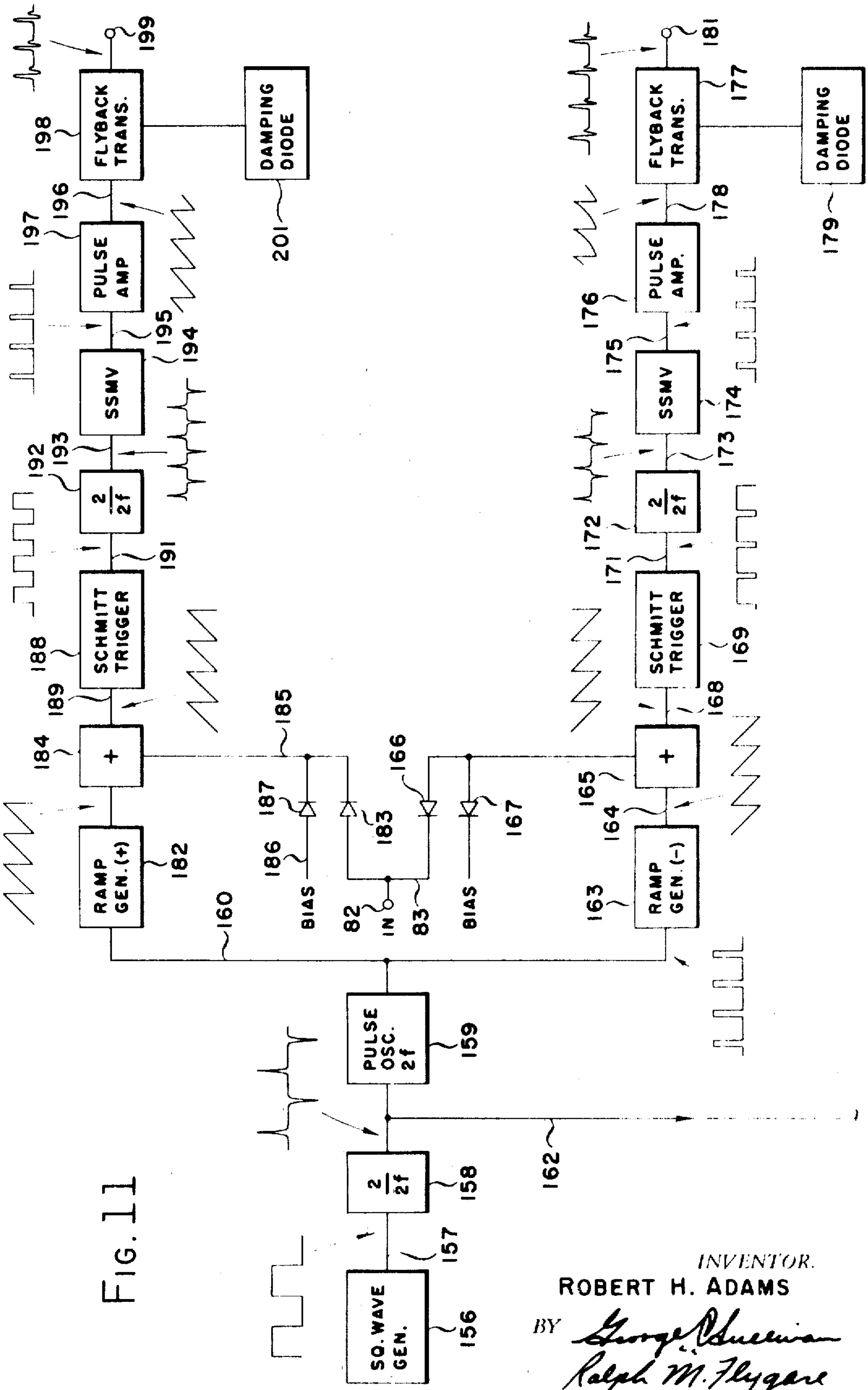

FIG. 11

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HIGH-POWER DIRECT-CURRENT TO SQUARE-WAVE CONVERTER UTILIZING AN INDUCTIVELY COUPLED GAS DISCHARGE TUBE

BACKGROUND OF THE INVENTION

Power amplifiers operating from an AC carrier source have a very favorable reliability/cost compromise as compared with other types of power amplifiers, and also exhibit especially favorable flexibility in operating conditions. Heretofore, a practical limitation on the output power of carrier type amplifiers has been the source of high-frequency carrier power. Also, the speed of response of such amplifiers is often severely limited by the frequency of the AC carrier power source, because the speed depends upon the period of the AC carrier. Vacuum tube and transistor amplifiers have been found impractical in certain very-high-power applications (e.g., hundreds of kilowatts of output power) and conventional magnetic amplifiers have generally failed to overcome like shortcomings due to the aforementioned limitations.

There is provided by the present invention a novel and improved square wave generator suitable for use as a source of very-high-power carrier power, or AC operating power, for magnetic amplifiers and the like. Typically, carrier powers in the range of 100 kilowatts and frequencies up to about 100 kilohertz can be readily obtained. Carrier-type amplifiers incorporating the novel carrier generator of the present invention may be used as modulators, as very-low-frequency radio transmitters, as exciters for large sonar arrays, and as exciters for shaker motors. The novel power source of the present invention comprises a transformer having a core of square-loop hysteresis material and a pair of triggered gas discharge tubes, of opposite polarities, inductively coupled to the core to serve as a centertapped primary winding. Each gas discharge tube functions as a section of the primary winding of the transformer only when it is ionized. An inductor is placed in series with each discharge tube and the supply voltage appears across the inductor instead of the tube, thereby extinguishing the tube, once the core goes into saturation. Hence, a square wave is produced when the two tubes are alternately fired by an associated trigger circuit. The cyclical energization of the two primary windings causes the core to be cycled around its hysteresis loop. The output power is in the form of a square wave which is obtained from a secondary winding inductively coupled to the core.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified schematic circuit diagram of a square wave generator constructed in accordance with the invention.

FIG. 2 is a graphic representation of the induced flux density (B) versus the magnetizing force (H) characteristics of the core material employed in the transformer of FIG. 1.

FIG. 3 is a simplified schematic diagram of an alternate embodiment of a square wave generator in accordance with the invention, employing a nonsaturating ferrite core in lieu of a rectangular-loop core, and which employs an additional gas discharge tube across the output.

FIG. 4 is a schematic circuit diagram of a carrier amplifier constructed in accordance with the invention, and which employs a pair of square wave generators of the kind shown in FIG. 3.

FIGS. 5—8 illustrate various waveforms related to the functioning of the circuit of FIG. 4.

FIG. 9 is a block diagram of a trigger circuit suitable for use in amplifier systems constructed in accordance with the invention.

FIG. 10 is a block diagram of an alternate trigger circuit.

FIG. 11 is a block diagram of a second alternative trigger circuit.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The square wave generator shown in FIG. 1 comprises a transformer, the core 1 of which is made of a material having a rectangular hysteresis loop. Two gas discharge tubes 2 and 3 are inductively coupled to core 1 and serve as primary transformer windings. Each of the primary windings (2 and 3) are connected in series via junction 4. Ignition extinguishing inductors 5 and 6 are connected in series between respective ones of tubes 2 and 3, and a constant voltage DC power supply. Terminal 7 connects to the positive DC supply and terminal 8 connects to the negative DC supply. Secondary winding 9 is inductively coupled to core 1 of the transformer. The output square wave power is obtained via terminals 11 and 12 which connect to secondary winding 9.

Since the present invention is dependent in part upon the properties of gas discharge tubes, the following description of their characteristics will be useful in comprehending the invention. It is characteristic of cold cathode gas filled discharge tubes that the voltage required to initiate a discharge between two electrodes depends upon the nature and pressure of the gas, its state of ionization, the shape and material of the discharge electrodes and the distance between them—the gap length. Hereinafter, this voltage is referred to as the "ignition" voltage. At low interelectrode voltages, negligible current will flow if the gas is initially deionized. As the voltage is increased slowly the molecules of the gas become ionized, until eventually a discharge is set up with a rapid increase in current flow which may typically rise from microamperes to milliamperes at a critical voltage which is the static ignition voltage for the discharge gap. The discharge is characterized by a glow which appears at the cathode and may extend towards the anode and beyond the immediate neighborhood of the gap, depending upon the degree of ionization, and is associated with the migration of ions, which term is taken to include all ionization products. When once a discharge has been established, a much lower voltage in general is required to maintain it. The critical voltage below which the discharge decays, neglecting a slight rise just before extinguishing is called the "maintaining" voltage. If the discharge current be limited so that the whole cathode surface is not covered with glow, the interelectrode voltage tends to remain constant, and independent of the discharge current, at a value approximately the same as the maintaining voltage. When once the discharge current is increased beyond the value at which the whole of the cathode surface is covered with glow, the interelectrode voltage rises again.

As mentioned above, ions tend to diffuse from the immediate neighborhood of the discharge. This phenomenon has been extensively used to lower the static ignition potential of another discharge gap in the same tube envelope. In one known device there is provided a main discharge gap between a main anode and a trigger gap between an auxiliary anode and the said cathode. The auxiliary anode is much closer to the cathode than the main anode so that the ignition voltage of the trigger gap is considerably below that of the main gap. The trigger gap is used to lower the ignition voltage of, or to "prime" the main gap by ionization coupling. Alternatively, the triggering effect may be obtained by an electrode disposed externally of the envelope at a location between the main electrodes. Either triggering method may be employed in the practice of the present invention.

Referring again to FIG. 1, tubes 2 and 3 are each provided with a trigger electrode, (13 and 14) for initiating ignition in response to an applied trigger pulse from trigger circuit 15. The trigger circuit, which is returned to junction 4 via line 16, will be described more fully in a subsequent part of this specification.

The basic principal of operation of the circuit of FIG. 1 is that the pair of gas discharge tubes 2 and 3 function as the primary winding of the transformer only when they are ionized. At the beginning of the first half-cycle of operation, one of the tubes (2 or 3) is ionized by the application of a trigger pulse to its trigger electrode (13 or 14). This tube, as a winding of the transformer, carries the supply voltage and thereby causes the core 1 to be driven to a saturation. When the core 1 reaches saturation, the current through the tube 2 tends to rapidly increase. However, the DC supply voltage (7, 8) will now appear across the inductor 5 instead of the tube 2, thereby reducing the voltage across the tube 2 to a level below its ionization potential, and thereby cause the tube 2 to be extinguished. A similar process is repeated with the other tube (3) for the other half cycle of operation.

In a typical construction the gas discharge tubes 2 and 3 may comprise an hermetic container filled with xenon gas and having a cathode, an anode, and an external trigger electrode.

The core material (1) may comprise Square Permalloy 80, manufactured by Magnetics Inc., in a tape-wound configuration. The Square Permalloy material, in the form of a 0.001-inch thick tape, and operating at a frequency of 70 kHz., will require a magnetizing force of 0.30 oersteds. Other well-known materials exhibiting a substantially rectangular hysteresis loop may also be used. For example, there are various types of ferrites and other kinds of magnetic tapes, including Orthonik and 4–79 Moly-Permalloy which exhibit the required characteristics. These materials may be given different heat treatments to effect different desired properties. In addition to the wide variety of materials applicable, the core 1 may be constructed in a number of different geometries. For example, strips of material, or toroidal cores are possible as long as both tubes are substantially surrounded by the core. It must be emphasized that the present invention is not limited to any specific geometries of the transformer core nor to any specific materials therefor, and the examples given are illustrative only.

The gas tube discharge, in a typical construction, will produce 0.385 oersteds of magnetizing force, thereby insuring saturation of the core 1. The output appearing across the secondary winding 9 of the transformer provides the high-power square wave pulse strain which may be utilized as the carrier for amplifiers of the previously mentioned type. The DC supply voltage, comprising the main power source, applied to the discharge tubes 2 and 3 via terminals 7 and 8 may be relatively low voltage, e.g., 150—350 volts. Typically the output pulse repetition rate may be of the order to 100 kHz., although it is possible to operate up to 1 megahertz with presently available core material.

The DC supply voltage (7–8) must be lower than the self-ionization potential of the discharge tubes 2 and 3, and must be higher than the extinguishing potential or ionization threshold of the discharge tubes. The trigger circuit 15 alternately triggers the discharge tubes 2 and 3 in a period which satisfies the following criteria:

$$T>4AB/E$$

where:

A = cross-sectional area of core
B = flux density at which core saturates
E = supply potential
T = period of trigger pulses.

Referring to the hysteresis loop shown in FIG. 2, it will be noted that a number of significant points of operation of the loop have been identified; namely, point 20 (positive B*r*) which represents a point of positive remanence; the point 21 (positive B*s*) which represents positive saturation; the point 22 (—B*r*) which represents negative remanence; the point 23 (—B*s*) which represents negative saturation; and the points 24 and 25 which represent, respectively, the beginnings of the positive saturation region and of the negative saturation region. Discussing for the moment the operation of a transformer device utilizing a core exhibiting a hysteresis loop such as is shown in FIG. 2, and a coil wound thereon, initially assume that the core is at the operating point 20 (positive remanence). If a voltage is applied to the coil tending to pass a current through the coil on the core in a direction tending to cause a magnetizing force of positive H, that is in a direction tending to increase the flux in the said core in the same direction, the core will tend to be driven from point 20 (positive B*r*) to point 21 (positive B*s*). During this state of operation there is relatively little flux change in the core, and the coil therefore presents a relatively low impedance whereby energy fed to the coil during this state of operation will pass readily therethrough and may be utilized to effect a usable output. On the other hand, if the core should initially be at the point 22 (—B*r*) prior to the application of a positive H input pulse, upon application of such a pulse the core will tend to be driven in a counterclockwise direction around the hysteresis loop from point 22 (—B*r*) to the region of point 21 (positive saturation). The voltage level of the input pulse for such a state of operation is preferably so chosen that the core is actually driven only to approximately point 24, that is to the beginning of the positive saturation region rather than to point 21 which represents full saturation. During this latter state of operation, there is a very large flux change through the core and the coil therefore exhibits a relatively high impedance to the applied pulse. As a result, substantially all of the energy applied to the coil when the core is initially at —B*r* will be expended in flipping the core from point 22 to point 24 and to the load, and thence to point 20, positive B*r*. Thus, depending upon whether the core is initially at point 20 (positive B*r*) or at point 22 (—B*r*), an applied pulse producing a magnetizing force in the positive H direction will be presented respectively with either a low impedance or a high impedance and will effect either a relatively small output or a relatively large output. These characteristics of the transformer are significant in the construction of the square wave generator of the present invention.

Referring again to FIGS. 1 and 2, assume that the discharge tubes 2 and 3 are not ionized and the core 1 magnetization is at point 22 or 26. Then a trigger pulse is impressed on the trigger electrode 13; this pulse is of sufficient amplitude and duration to ionize the discharge tube 2 and drive the core 1 in a region between points 27 and 14. After a time duration given by the expression $4AB/E$, the core 1 will saturate, as indicated at point 21, resulting in a large change in current in the discharge tube 2. The DC supply voltage will now be impressed across series inductor 5, resulting in a potential which is much less than the ionization threshold or extinguishing potential being developed across discharge tube 2. Since no trigger pulse is now being impressed on discharge tube 2, it will become extinguished. Magnetization of the core 1 is now at point 20 and is returned to point 22 by repeating the above process with respect to discharge tube 3.

The apparatus schematically illustrated in FIG. 3 closely resembles that of FIG. 1 except that it employs a ferrite core in lieu of the rectangular hysteresis loop core of the apparatus of FIG. 1, and also utilizes an additional gas discharge tube. This circuit comprises gas discharge tubes 28 and 29 which are inductively coupled to ferrite ring core 31. Inductance coils 32 and 33 are connected in series with tubes 28 and 29, respectively. The DC supply voltage is applied across terminals 34 and 35. Core 31 is provided with secondary winding 36. External trigger electrodes 37 and 38 control the ignition of tubes 28 and 29, respectively, in response to trigger pulses received from trigger circuit 39.

Gas discharge tube 41 comprises a pair of internal electrodes 42 and 43, and an external trigger electrode 44. Tube 41 has its internal electrodes 42 and 43 connected across secondary winding 36. The external electrode 44 is connected to trigger circuit 39. In this embodiment of the invention, ignition of discharge tube 41 will cause a large and rapid change in the current flow through the ionized primary discharge tube 28 (or 29). The core 31 is not driven into saturation. This embodiment allows the operating (viz, switching) frequency to be increased several orders of magnitude over that of the embodiment of FIG. 1. This accrues to the use of ferrites instead of square loop materials for the core 31. The square wave output is obtained via terminals 45 and 46.

The apparatus of FIGS. 1 or 2 may be employed as a high-power carrier source for a power amplifier. Using two such carrier sources, the outputs of each being modulated by a third gas discharge tube, and using appropriate rectifiers and filters, a high-power amplifier can be constructed in accordance with the previously mentioned objectives of the invention. Such an arrangement is shown in FIG. 4. This embodiment comprises gas discharge tubes **48** and **49** which are inductively coupled to core **51**. Inductors **52** and **53** are placed in series with tubes **48** and **49**, respectively. Similarly, tubes **54** and **55** are coupled to core **56**, and are in series with inductors **57** and **58**, respectively. The transformers (**51**, **56**) are provided with secondary windings **59** and **61**, respectively. Gas discharge tubes **62** and **63** are alike and each comprises a pair of internal electrodes (e.g., **64** and **65**) and an external trigger electrode (e.g., **66**). Tube **62** has its internal electrodes connected across secondary winding **59**. When these tubes (**62** and **63**) ionize and conduct, they will effectively short circuit the secondary windings of their respective transformers (**59**, **61**).

Bridge rectifier **67** has its AC input connected across secondary winding **59**; the rectified output appears on lines **68** and **69**. Similarly, bridge rectifier **71** is connected across winding **61** and provides a rectified output on lines **72** and **73**. The rectified outputs from bridges **67** and **71** are combined via resistors **74** and **75**, smoothed by shunt capacitor **76** and appear at output terminal **77**. The output at terminal **77** is referenced to ground terminal **78**.

A positive operating or supply voltage is applied to terminal **79**, and a negative supply voltage is applied to terminal **81**. An input signal which is to be amplified by the amplifier apparatus of FIG. 4 is applied to input terminal **82**. This input signal is supplied via line **83** to trigger circuit **84** which in turn provides pulse-width modulation control signals in the form of a plurality of trigger pulses on multiple output lines. The trigger pulses appearing on lines **85**—**90** are supplied to respective ones of trigger electrodes **91**—**95** and **66**. A more detailed description of the trigger circuit **84** will be provided hereinafter.

Operation of the apparatus of FIG. 4 will be described commencing with a condition in which none of the gas discharge tubes (**48**, **49**, **54**, **55**, **62** and **63**) are ionized. Also, assume that cores **51** and **56** are at a magnetization condition corresponding to either point **20** or point **21** (as seen in FIG. 2). A trigger pulse on line **85**, having a duration and an amplitude sufficient to result in ionization of tube **48**, will drive core **51** into the region between points **23** and **24** (refer again to FIG. 2). After an interval which corresponds to the expression:

$$2aB_m/E_s$$

where

a = cross-sectional area of core in square meters

B_m = flux density of core at saturation in webers per square meter

E_s = supply potential in volts,

the core **51** will saturate; thereby reaching point **24**. This will result in a large change in the current through tube **48**. The supply voltage across terminals **79** and **78** will now appear across inductor **52**, thus causing the potential across tube **48** to fall below the level needed to maintain ionization therein. Since the trigger pulse on line **85** will now have terminated, tube **48** will become extinguished. The core **51**, which is now at point **24**, may be returned to point **20** by triggering tube **49**. This will be accomplished by a pulse arriving on line **86**.

The operation of tubes **54**, **55**, and core **56**, follows a similar sequence and is responsive to trigger pulses on lines **87** and **88**.

Whenever the current in tubes **48** or **49** (or, **54** or **55**) begins to increase rapidly, the supply voltage will appear across the corresponding series inductor and the related tube will be extinguished. This effect permits the width of the pulse generated by the discharge tube to be controlled. This, as has been previously mentioned, occurs when the core goes into saturation; but, will also occur when the transformer secondary winding is short circuited. Tubes **62** and **63** are used to accomplish this short-circuiting function.

Assuming that tubes **48** and **49** are being alternately ionized in the manner described above, and discharge tube **62** is extinguished, then a pulse train as shown in FIG. 5 will appear across secondary winding **59**. The rectified potential appearing on lines **68** and **69** will correspond to the following expression:

$$e_{rect.} = -(4TEs)/\tau$$

where τ is the period of the pulse in seconds.

Assuming now that a trigger pulse, on line **90**, is applied to tube **62**, which is related to the trigger pulses on lines **85** and **86** in the manner shown in FIG. 6, then a pulse train as shown in FIG. 7 will appear across secondary winding **59**. As a consequence the average DC potential on lines **68** and **69** will correspond to the following expression:

$$e_{rect.} = -(4t_1E_s)/\tau$$

As can be seen, by causing t_1 to range from 0 to $2Bma/E_s$ the average potential at the output of the bridge rectifier **67** can be made to range from 0 to $-8aBm/\tau$. The foregoing functional description applies to the circuit comprising tubes **54**, **55** and **63**, with the exception that the bridge rectifier **71** gives a positive output potential on line **72** through resistor **75**. The time sequence of the pulses produced by the trigger circuit **64** are shown in FIG. 8.

From the foregoing, it can be seen that one of the square wave generators functions on the negative half-cycle of operation and the other functions on the positive half-cycle. Amplification is accomplished by modulating the pulse width of the transformer's output pulse by means of discharge tubes **62** and **63** which shunt the outputs. The ionization of these tubes (**62** and **63**) produces the same effect as the saturation of the cores in the first-described embodiment, namely, a rapid increase in current. This action terminates the pulse.

In a typical construction such a direct-coupled amplifier may have a half-power point for frequencies up to approximately 100 kHz. The amplifier may be designed to match its load rather than designing the load around the amplifier. Furthermore, the degree of phase shift is substantially less than that of prior art amplifiers of comparable power. This permits a greater amount of feedback to be employed around the amplifier without the instabilities frequently encountered in conventional amplifiers.

There is shown in FIG. 9 a block diagram of a trigger circuit suitable for performing the function of trigger circuit **15** as shown in FIG. 1. This portion of the system comprises square wave generator **101**, the output of which is supplied via line **102** to differentiating network **103**. In a typical construction, the repetition rate of the square wave pulse train on line **102** is 100 kHz. The differentiated pulses appearing on line **104** are applied to a phase splitter **105**. The output appearing on line **106** is supplied to a single-shot multivibrator **107** which provides a pulse output on line **108** having a timed duration (t) of approximately 1 microsecond. The pulse train appearing on line **109** is phase displaced from that appearing on line **106** by 180°. This signal (**109**) is applied to single-shot multivibrator **110** to provide 1-microsecond pulse on line **112**.

The pulses on lines **108** and **112** are amplified via pulse amplifiers **113** and **114**, respectively. The current pulses appearing on lines **115** and **116**, respectively, are supplied to flyback transformers **117** and **118**, respectively. Damper diodes **119** and **121** suppress the negative-going portion of the current pulse obtained from transformers **117** and **118**, respectively.

As employed in the circuit of FIG. 1, terminal **122** will supply the current pulse to trigger electrode **13** and terminal **123** will supply the current pulse to trigger electrode **14**.

There is shown in FIG. 10 a block diagram of a trigger circuit suitable for performing the function of trigger circuit **39**, as shown in FIG. 3. This trigger circuit closely resembles the above-described circuit of FIG. 9, with the exception it provides the required extra trigger pulse for switching the auxiliary gas discharge tube which is shunted across the secondary of the transformer.

Referring to FIG. 10, free-running square wave generator 124 provides a train of square wave pulses on line 125. These square wave pulses are differentiated by means of network 126. The differentiated pulses on line 127 are provided directly to pulse oscillator 128 and phase splitter 129. Oscillator 128 comprises a free-running-type oscillator which is synchronized by means of the input pulses appearing on line 127. The output appearing on line 131 will have a pulse repetition frequency which is twice the frequency of the square wave pulse train on line 127. These 2F pulses (131) are differentiated via network 132 and supplied via line 133 to single-shot multivibrator 134. Multivibrator 134 is designed to trigger on the negative portion of the incoming pulse and provide a train of negative output pulses on line 135.

The pulse train on line 135 is amplified by pulse amplifier 136 to provide current pulses to flyback transformer 137, via line 138. The current pulses from the secondary of transformer 137 appear at terminal C which may be used to energize electrode 44 (as seen in FIG. 3). Damper diode 139 suppresses the negative-going portion of the output current pulse appearing at terminal C.

Phase splitter 129 provides two phase-displaced pulse trains on lines 141 and 142, respectively, which are shifted with respect to each other by 180°. The first pulse train (141) is supplied to single-shot multivibrator 143 which provides a train of positive-going pulses to pulse amplifier 144 via line 145. The amplified current pulses on line 146 are supplied to transformer 147 and thence to output terminal A. The negative-going portion of the output current pulse at terminal A is suppressed by damper diode 148. The current pulse at terminal A may be used to supply the trigger pulse to electrode 37 of the circuit shown in FIG. 3.

The phase-displaced pulse train on line 142 is supplied to single-shot multivibrator 149. The output pulse train on line 151 is amplified via pulse amplifier 152 and supplied as a current pulse train to transformer 153 via line 154. The current output on transformer 153 comprises positive-going current pulses which are phased displaced from those obtained from transformer 147. As in the previous instance, the negative-going portion of the output is suppressed by damper diode (155).

The phase relationship of the several pulses appearing at terminals A, B, and C establish the required sequence of ignition of the respective gas discharge tubes 38, 37, and 41. Specifically, tube 29 will initially be ignited, after which tube 41 will ignite. This will cause tube 29 to be extinguished. Thereafter tube 28 will ignite, followed by ignition of tube 41. The ignition of tube 41 will result in tube 28 being extinguished and the foregoing cycle will be repeated.

There is shown in FIG. 11 yet another trigger circuit suitable for functioning in the manner required by trigger circuit 84 as shown in FIG. 4. In this instance, the master clock pulse train is generated by free-running square wave generator 156. The square wave output on line 157 is differentiated by network 158 and supplied to pulse oscillator 159 and phase splitter 161 via line 162. The output from oscillator 159 is supplied to negative ramp generator 163 via line 160. The output on line 164 comprises a negative-slope ramp signal which is supplied to summing junction 165. The input signal (e_{in}), which appears on line 83 of FIG. 4, is supplied to input terminal 82. This input signal is supplied via checking diode 166 to the second input of summing junction 165. A bias potential is also supplied to this summing junction input (165) via diode 167. The bias thus provided avoids crossover distortion in the Class-B operation of the amplifier system. The summed output on line 168 is applied to Schmitt trigger 169. A square wave train on line 171 is differentiated via network 172 to provide a train of positive- and negative-going pulses on line 173. Single-shot multivibrator 174 provides a train of positive-going pulses on line 175, in response to the input pulses on line 173. Pulse amplifier 176 generates positive current pulses which are supplied to transformer 177 via line 178. The negative portion of the output current pulse from transformer 177 is suppressed by damper diode 179. The voltage pulses on terminal 181 are to be supplied to line 89 of FIG. 4.

The pulse train obtained from oscillator 159 is also supplied via line 160 to positive ramp generator 182. The remainder of this circuit generally resembles the previously described portion of the circuit which followed the negative ramp generator 163. In this instance, however, the input signal on line 83 is supplied via diode 183 to summing junction 184 on line 185. A bias potential on line 186 is impressed on line 185 via diode 187. The output of the summing junction 184 is supplied to Schmitt trigger 188 via line 189. The resulting square wave train on line 191 is differentiated by network 192 to provide positive and negative pulses on line 193. Single-shot multivibrator 194 provides pulses on line 195 which are amplified to current pulses on line 196 via amplifier 197. The current pulses are supplied from line 196 to the primary winding of flyback transformer 198 and results in voltage pulses at terminal 199. The negative-going portion of the current pulses are suppressed by diode 201.

The current pulses at terminal 199 are supplied to line 90 as seen in FIG. 4.

The positive and negative pulses on line 162 are divided into two phase-displaced signals on lines 202 and 203, respectively. The pulses on line 202 are phase displaced from those on line 203 by 180°, and are supplied to multivibrator 204. The pulses on line 205 are amplified and supplied as current pulses to line 206 via amplifier 207. The current pulses appearing at 208 are derived via transformer 209 and are supplied to lines 86 and 88 of FIG. 4. Damper diode 211 is connected to transformer 209 via line 212 for the purpose of suppressing the negative-going portion of the output pulse.

The phase displaced pulses on line 203 are supplied to single-shot multivibrator 213. The pulses on line 214 are amplified via pulse amplifier 215 to provide current pulses on line 216. The current pulses at terminal 217 are obtained through transformer 218. Damper diode 219 is connected to transformer 218 via line 221. The voltage pulses appearing at terminal 217 are supplied to line 89 of FIG. 4.

The above-described circuit of FIG. 11 provides four separate output trains of current pulses having a time-sequence relationship corresponding to that shown in FIG. 8, and which appropriately controls the sequential ignition of gas discharge tubes 48, 49, 54, 55, 62 and 63.

From the foregoing it will be seen that amplifiers employing the square wave generator of the present invention provide highly reliable means for amplifying low-level signals with very low phase shift and at very high output power levels. The reliability of the invention is due in part to the fact that the gas discharge tubes and other components employed in the practice of the invention are substantially immune to damage by high instantaneous transient peak currents. In practice, amplifiers may be constructed in accordance of the invention with supply voltages above approximately 130 volts DC. Therefore, the reliability may be optimized by appropriate selection of the supply voltage. The simple configuration of the circuit of the invention for a given power rating is superior to amplifiers using transistors vacuum tubes in the output stage. Phase shift is primarily centered around the capacitor which corresponds to capacitor 76 of FIG. 4, and with either inductive or resistance loads will not exceed plus or minus 90°. No appreciable power is required for the trigger control pulses. Hence, stability is readily obtained in the feedback loop.

Having described various embodiments, it will be apparent to those versed in the art that further modifications and variations in the invention may be readily accomplished. For example, the magnetic cores such as those interposed between the gas discharge tube primary and the wire-wound secondary of the transformers of FIGS. 1, 3 and 4 may be omitted in certain instances. That is, the primary and secondary windings may be inductively coupled without the benefit of a core in the magnetic circuit. Also, the ratios between the primary and the secondary windings may be changed from the 1:1:2 ratios shown in connection with the preferred embodiments. Other design modifications will be apparent to those versed in the art.

What I claim is:

1. Apparatus for converting direct-current in a first circuit to square wave power in a second circuit comprising:
  - primary transformer-winding means comprising a gas discharge tube operatively connected to said first circuit for receiving direct-current electrical energy therefrom and responsive to energization thereof to produce a magnetic field;
  - second transformer-winding means operatively connected to said second circuit and inductively coupled to said tube for converting changes in said magnetic field to electrical energy;
  - trigger means connected to said gas discharge tube for cyclically initiating conduction therein;
  - an inductor connected in series with said gas discharge tube;
  - a source of direct-current for supplying power to the series-connected inductor and gas discharge tube; and
  - a core of magnetic material having a substantially rectangular hysteresis loop inductively coupled to both said tube and said secondary transformer-winding means.

2. Apparatus as defined in claim 1 including: rectifier means connected to said secondary transformer-winding means; and
  - pulse width modulator means connected to said trigger means for controlling the duration of conduction of said gas discharge tube in accordance with a variable input signal.

3. Apparatus for transferring electrical energy from one circuit to another, comprising:
  - a transformer core having substantially rectangular hysteresis loop properties;
  - a gas discharge tube inductively coupled to said core;
  - a wire winding inductively coupled to said core;
  - an inductor connected in series with said gas discharge tube;
  - a source of direct-current for supplying power to the series-connected inductor and gas discharge tube;
  - trigger means connected to said gas discharge tube for cyclically initiating conduction therein;
  - pulse-width modulator means connected to said trigger means for controlling the duration of conduction of said gas discharge tube in response to an analog input signal; and
  - demodulator means connected to said winding for converting the output therefrom, from an alternating-current to a direct-current.

4. Apparatus for transferring electrical energy from a first circuit to a second circuit comprising:
  - primary transformer-winding means comprising a gas discharge tube operatively connected to said first circuit for receiving electrical energy therefrom and responsive to energization thereof to produce a magnetic field;
  - second transformer-winding means operatively connected to said circuit and inductively coupled to said tube for converting changes in said magnetic field to electrical energy;
  - a core of magnetic material inductively coupled to both said tube and said secondary transformer-winding means; and
  - means connected to said secondary transformer-winding means for cyclically placing a short circuit thereacross.