

1

2,941,125

DRIVER FOR INDUCTIVE LOADS

Donald K. Lippincott, Orinda, Calif., assignor, by mesne assignments, to Monogram Precision Industries, Inc., Culver City, Calif., a corporation of California

Filed May 7, 1957, Ser. No. 657,528

5 Claims. (Cl. 317—123)

This invention relates to drivers for developing currents of substantially rectangular waveform in inductive circuits. It is particularly adapted to the development of waveforms wherein the current flows during the greater portion of the cycle but is interrupted suddenly for short intervals, the decay and rise times of the interruption being equally short in comparison with the length of the interruption, although it can be used for developing pulses of inverse character; i.e., pulses of short duration interspersed by long intervening periods, or to the development of symmetrical waves. Because in practice the development of short interruptions in an otherwise constant current flow is the more difficult to achieve, the invention will be described in this connection, it being believed that the variations in operating parameters necessary to secure other waveforms in inductive circuits will be apparent to those skilled in the art.

The ability to produce waveforms of this character is one of the requirements in using the gyromagnetic effects of ferrites to switch microwave equipment, such as is employed in radar apparatus. While such use is by no means the only one for which the invention is adapted, it is illustrative of the problems the invention is able to meet and will be used for illustration throughout this specification.

Among the objects of the invention are to provide means for developing current waveforms having minimum rise and decay times, the rise times actually developed being limited primarily by the natural frequency of oscillation of the coils wherein the waveforms are produced; to provide a driver for producing such waveforms in primarily inductive circuits, wherein the rise and the decay of current constituting the waveforms are symmetrical; to provide a driver of the type referred to wherein the current-supply producing the waveform need be only very moderate voltage, far less than that necessary to produce similar waves in a load of the same inductance supplied directly across the circuit; to provide a driver that can interrupt the current flow for extremely short periods and reestablish the flow immediately at a desired maximum value and maintain the flow substantially at that value until the next interruption occurs; to provide a driver of extreme simplicity, using a minimum number of tubes and to provide a driver wherein the amplitude of the pulses constituting the waveforms developed is accurately under control.

One type of apparatus wherein rectangular current-waveforms must be produced in highly inductive circuits is that wherein the gyromagnetic effects of ferrites are employed to alter the transmission characteristics of waveguides. Illustrative of equipment of this class is a microwave attenuator employing the Faraday effect, wherein the ferrite element is included in a waveguide which is connected, for example, to a radio receiver. When the ferrite is in one magnetic state waves pass through the waveguide with minimum attenuation and reach the receiver. When in another magnetic state

2

the plane of polarization of the waves passing through the device is rotated by 90 degrees, with respect to waves transmitted in the first state, and reach an output waveguide so polarized that they are not transmitted but are either absorbed by a suitable dissipative element within the device itself or are reflected to be absorbed externally of the device; in either case they do not reach the receiver. Such devices may be designed so that the two magnetic states correspond to equal and opposite polarizations of the ferrite; it is more convenient, however, to design the equipment so that in one of the two critical states the ferrite is substantially completely demagnetized, while in the other state it is magnetized to a definite degree. With this arrangement only one value of magnetizing or polarizing current needs to be accurately controlled; the other critical state, corresponding to zero current, is effectively built into the device itself. It is a matter of engineering choice whether the equipment be designed so that maximum attenuation is produced by zero current or finite current, minimum insertion loss in either case corresponding to the opposite condition.

A characteristic use for a variable attenuator of this type is in connection with "T-R" apparatus in radar equipment. In such apparatus it is desired to isolate a radar receiver during the very brief interval when the transmitter is in operation to radiate the radar pulse. This corresponds to an interval of a few microseconds at most and as soon as the pulse is over the receiver is reactivated as rapidly as possible to receive the reflected waves. The interval between the transmitted pulses will be of the order of milliseconds while the duration of the pulse and inactivation of the receiver is microseconds. There is some latitude with regard to the time when the receiver is isolated, just before the radar pulse is transmitted, but once the transmission is over the sooner the receiver is again activated the smaller will be the "blind spot" immediately surrounding the radar equipment and this is a desideratum.

If the isolation of the receiver corresponds to the magnetized state of the ferrite it is relatively easy to secure reactivation of the receiver with the required speed; one need only interrupt the current that is flowing to achieve the required result. It is desirable, however, that the isolation be effective at all times when the apparatus is not in use, for radar equipments are very frequently closely grouped and if the receiver is effectively in circuit when the equipment is idle, pulses from nearby apparatus may be picked up at such amplitude as to injure the receiving apparatus. It is therefore preferable that the apparatus be so arranged that maximum attenuation is produced when there is no current in the polarizing coil.

Such an arrangement, however, requires that the rise-times of the current in the coil be very short. The inductance of the polarizing coils in characteristic apparatus may be anywhere between, say, 15 and 30 millihenrys; the polarizing currents required may be from 50 to 100 milliamperes. These are characteristic but not limiting values. It will be seen that to produce current waves of such amplitudes, in inductances of such values, and the current having rise times of the order of 0.5 microseconds, requires voltage pulses having an amplitude of several thousand volts to initiate the currents. The inherent resistance of the coils is, however, only a few ohms, and to maintain the currents, once they have been established, requires a few volts at most. Therefore during most of the cycle the power required is very small.

If a source of sufficient voltage to initiate waves is provided the greater part of the voltage developed must be absorbed externally of the apparatus, usually in vacuum tubes used for switching purposes. The power dissipated in the tubes may easily run into the hundreds of

watts, requiring large and expensive tubes, to say nothing of the power wasted. The present invention achieves the desired results using sources for supplying the currents necessary at a few hundred volts at most, and employing tubes having no higher rating than are required in the deflecting circuits of commercial television receivers.

In accordance with the present invention an auxiliary inductance, conveniently but not necessarily of equal value to that of the inductor comprising the load, is connected in a series circuit with the source, the load inductor, and switching means such as a tube which is preferably of the pentode type, including in this category the so-called "beam power" tubes. Bridged across this circuit, connected between the two inductors and one end of the source so as to short out the load inductor and its switching means, is a branch circuit comprising primarily a second switching means which may conveniently be of the same type as that used in the series circuit. Means are provided for actuating the switching means to connect, alternatively, the series circuit and the branch circuit. Most conveniently this is done by applying pulses in opposite polarity to the control grids of pentode tubes. The control pulses may be voltage pulses of substantially the waveforms desired for the current waves through the load coil; they may be developed, for example, through the two anode circuits of a multivibrator. The essential feature of the arrangement is that the branch circuit be opened at the instant that the series circuit is closed. Means are provided for controlling the currents in the series and branch circuits independently. The auxiliary coil carries at all times a minimum current equal to the requisite maximum current through the load. In addition to this minimum current through the auxiliary coil there is permitted to build up in it, through the branch circuit, an additional increment of current of a value such that at the instant prior to the closing of the circuit through the load coil the product of the incremental current times the inductance of the auxiliary coil is equal to, or somewhat greater than, the product of the load coil inductance times its normal load current; if the two inductances are equal the maximum current in the branch circuit, immediately before the circuit through the load is closed, will be double the normal load current, the incremental current and the load current being equal.

When the apparatus is in operation under the conditions described, with the desired current flowing in the load coil, a switching pulse is applied suddenly to interrupt the current through the load. As a result of this interruption there will be developed across the load coil an inductive "kick"; a pulse of voltage whose magnitude depends upon the product of the load current and the coil inductance, divided by the time required effectively to open the circuit. The tubes or other switching means used must be capable of withstanding this voltage pulse but it does not represent a material dissipation of energy. When current through the load coil is to be re-established, the series circuit is suddenly closed and the branch circuit is simultaneously opened at substantially the same rate. This reduces the current in the auxiliary coil to its former, minimum or load-current value and in so doing generates a voltage pulse equal to that developed when the current through the load coil was interrupted. This pulse is of just the right value to re-establish the load current through the inductance with a rise time substantially equal to the decay time when the load current was interrupted.

The above will be more readily understood from a description of a preferred form of the apparatus which follows, this description being illustrated by the accompanying drawings wherein:

Fig. 1 is a schematic diagram of one preferred embodiment of the invention; and

Fig. 2 shows the so-called "plate characteristic curves" of a type of tube employed in the apparatus illustrated in Fig. 1.

In the specific apparatus illustrated in Fig. 1, the load coil 1, shown in heavy lines, has an inductance of 15 millihenrys and is designed for operation with a load current of 85 milliamperes. Its conditions of operation require that the waveforms through it rise from 0 to peak value in one-half microsecond. For purposes of illustration it will be assumed that the waveform developed in it is trapezoidal; this will never be quite true but is convenient for purposes of illustration and the departure from the simple theory based on the assumption of a trapezoidal wave will be developed below.

The load coil is connected in series with an auxiliary inductor 3 of equal value to the load coil; i.e., 15 millihenrys. The series circuit including the two inductors is completed through a suitable current source 5 and the cathode-anode circuit of a tube 7, in this case a beam-power tube of the tube designated as "6BG6-G." A variable cathode resistor 9 is included in the series circuit, which is shown as completed through ground. The control-grid of the tube 7 is biased to ground potential through the customary grid resistor 11.

A branch circuit connects to the series circuit between the two inductors and includes a tube 13 of the same type as tube 7, and like it preferably provides an adjustable cathode resistor 15 connected to ground. Like tube 7, its control grid is biased to ground through the customary grid resistor 17. The screen grids of both tubes are supplied with their proper operating biases through resistors 19 and 19' respectively; under certain circumstances these may be omitted, depending upon the voltage of the source 5 and the mode of operation of the apparatus, as will later be described; optionally they may be made adjustable to control the tube currents instead of or in addition to the cathode resistors.

Actuating pulses for switching the tubes in the series and branch circuits are in this case provided by a multivibrator 21, connected to apply equal and opposite voltages to the grids of the respective tubes. The anodes of the two multivibrator tubes connect through blocking condensers 23 and 25 respectively to the two control grids of tubes 7 and 13. The time-constants of the circuits comprising condenser 23—resistor 11 and condenser 25—resistor 17 must be sufficiently long to hold the respective tubes below cut-off for the required periods. How long this should be will be discussed hereinafter. Because different modes of operation of the apparatus require different time-constants, an auxiliary condenser 25' is provided which may be paralleled with condenser 25 to give a long time-constant or cut out of circuit to give a short one. Preferably a clamp circuit comprising a rectifier diode 27 connects from the control grid circuit of tube 13 to a potentiometer 28, connected across a portion of the source 5 so that the clamp voltage may be adjusted over a range of perhaps 25–30 volts. This clamp circuit is not strictly necessary but is convenient in making preliminary adjustments. Also convenient for this purpose is a switch 29, whereby the diode 27 may be shorted out. A similar clamp 30 is preferably also included for the grid circuit of tube 7.

The device illustrated is intended for use with radar equipment, wherein the load current is cut off for a few microseconds out of a much longer cycle of pulse repetition. The interval between pulses is not particularly important, since the apparatus can be adjusted over a wide range, but for purposes of illustration the period of repetition will be taken as 1 millisecond. The pulser 21 is not, strictly speaking, a part of this invention. That shown is assumed to be a monostable multivibrator which is triggered through the line 31 immediately prior to the transmission of the radar pulse. In its stable state this multivibrator delivers a positive pulse through condenser 23 to the grid of tube 7, and, correspondingly, applies a negative potential to condenser 25. When the multivibrator receives a trigger pulse it is flipped to its

5

astable state, applying a positive pulse to tube 13 and a negative pulse to tube 7, maintaining this state for a fixed interval, which depends upon the parameters and adjustment of the multivibrator, and then returns to its stable state which it retains for nearly the 1 millisecond interval postulated, until the next triggering pulse arrives. Other pulsing methods can, of course, be used; a bistable multivibrator can be employed and be externally triggered in both directions. The pulses developed by the multivibrator or other pulsing source 21 must be of sufficient amplitude completely to cut off the tubes to which they are applied negatively, swinging the grids to cut-off from ground potential at the positive portion of the cycle; for the particular tubes here used this requires that the pulses exceed 40 volts in amplitude. Preferably their amplitudes will be somewhat greater than that barely required for cut-off, to give a margin of tolerance; say from 50-65 volts, peak-to-peak.

The apparatus as thus described can be operated in two somewhat different fashions, which may be designated, for convenience of reference, as "type I" and "type II" operation. Which type of operation is chosen depends on several factors, of which the most important is the length of the "off" time during which current through the load coil is interrupted. Also involved in the choice of type of operation is the maximum plate voltage that the tubes can carry continuously and the amount of power that they can dissipate safely. Type I operation is somewhat simpler to explain and will be described first; it is applicable, in the case of the here-described apparatus, when the period of interruption of the load-coil current is greater than 5 or 6 microseconds; for heavier currents, higher inductances or both still longer periods of interruption will be required.

In adjusting the apparatus for type I operation the time-constant of the grid circuit of tube 13 must be long in comparison with the pulse repetition, and condenser 25' is therefore connected in parallel with condenser 25. A reasonable value for resistor 17 is 100,000 ohms; the capacity of condensers 25 and 25' in parallel may be 0.04 μ f., to give a time constant of 4 milliseconds. In setting up the apparatus, with tube 13 cut off, or removed, the cathode resistor 9 is first set so that with the grid of tube 7 at ground potential the tube carries the normal load current of 85 milliamperes. With this adjustment made, potentiometer 28 is set to ground potential and with tube 7 out of circuit or cut off the space current of tube 13 is adjusted to twice the load current or slightly more; i.e., to 170 or, say, 175 milliamperes. With these adjustments made the apparatus is ready for pulsing operation.

Under the conditions thus described the voltage from the source 5, as applied to the plates of the two tubes would have to be in the neighborhood of 300 volts, which is that given as the normal operating voltage for the 6BG6-G tubes specified. With the multivibrator 21 in its stable state, the grid of tube 7 is at its maximum positive potential, i.e., at ground level, due to the operation of the clamp 30. Because of the very short duration of the negative pulses on the grid of this tube, the omission of the clamp 30 would make very little difference, since the A.C. axis would lie very close to the maximum positive swing, but the inclusion of the clamp assures that minor deviations in amplitude of the driving pulses will not affect the tube current. When the multivibrator 21 is triggered, tube 7 cuts off and tube 13 becomes conducting.

By postulate, tube 7 switches from maximum current to complete cut off in 0.5 microsecond and the rate-of-change is uniform, so that the rate-of-change of current in the load coil during the switching period is also sensibly constant. The inductive pulse developed by this change of current in the coil is therefore at the rate of

6

170 milliamperes per microsecond or 170,000 amperes per second. The voltage pulse developed is

$$L_1 \frac{di}{dt}$$

or $E = .015 \times 170,000 = 2250$ volts, L_1 being the inductance of the load coil.

At the same instant tube 13 becomes conducting and the potential of the junction between coils 1 and 3, with respect to ground, drops to substantially zero, so that the full voltage of the source 5 is applied across coil 3 to build up the current carried by it.

That this is so will be apparent from the characteristic curves of the tubes employed, as illustrated in Fig. 2. It will be seen that the curves for each grid voltage, (indicated by the figures adjacent to the curves at the right of the drawing) consist of two distinct portions; a long and nearly horizontal portion at the right, representing the normal operating range of plate voltage, and a very steep portion at the left side of the figure illustrating the operating characteristic in the range where the anode voltage has dropped below the normal operating range. The slope of each of these portions is proportional to the effective conductance of the tube at any point chosen; i.e., the slope of the curves at any point is proportional to the reciprocal of the dynamic impedance of the tube at that point. The curves are non-linear and cannot readily be described analytically. A rough approximation to the behaviour of the tube in the circuit can be computed, however, by considering that each curve is made up of two straight lines, as illustrated by curve 35 in the figure.

It will also be seen that for plate voltages below the normal operating range all of the curves tend to merge, with an average slope, as indicated by the portion 35' of the approximate curve, corresponding to a plate resistance of somewhere in the neighborhood of 300 ohms, as compared to an effective plate resistance of 20,000 ohms in the operating range. In this steep portion of the curve the current carried by the tube is nearly independent of the grid-cathode voltage, whereas in the operating range the tube current is nearly independent of the plate voltage, depending entirely upon the cathode-grid potential.

It will be remembered that it was assumed that in the preliminary adjustment of the apparatus the cathode resistor 15 of tube 13 was adjusted so that with the grid of the tube at ground potential the current carried was 175 milliamperes, the plate potential being 300 volts. This corresponds to the point A on Fig. 2, through which the approximate curve 35 has been drawn.

At the instant that tube 7 was cut off, tube 13 became conducting, its grid being raised to ground potential but not higher, due to the action of the clamp circuit including rectifier 27. The inductance of the coil 3 prevents any instantaneous change in current through it, and the opening of the series load circuit and simultaneous closing of the branch circuit therefore transfers the current previously carried in the load circuit to the tube 13. The voltage across the tube immediately drops to point B on the true characteristic curve, corresponding to 85 milliamperes. This corresponds to a voltage across the tube of approximately 30 volts, leaving 270 volts effective across coil 3 to build up the current in it.

Treating the tube impedance as a constant resistance of 300 ohms, the current builds up at a rate defined by the well-known equation:

$$i = \frac{E}{R} \left(1 - e^{-\frac{Rt}{L}} \right) + I_0 e^{-\frac{Rt}{L}} \quad (1)$$

where i is the instantaneous current, E the voltage of the source, R the circuit resistance, I_0 the current flowing in the inductance at the instant tube 13 starts to conduct, e the Napierian base and t the time elapsing from the instant conduction starts. Substituting the values already given

for the circuit parameters and taking t as 5 microseconds, this equation leads to a value of 171 milliamperes, i.e., the current in this period reaches double the load current value.

At this instant the potentials of the grids of the tubes again reverse. The voltage pulse developed at the junction of the two inductors is such as to cause a current change in each. The change can be expressed by the equation:

$$L_1 \frac{di_1}{dt} = L_3 \frac{di_3}{dt} \quad (2)$$

where L_1 and L_3 represent the inductances of the load and auxiliary coils respectively and i_1 and i_3 represent the instantaneous currents. As L_1 has been taken as equal to L_3 , the rates-of-change of current in the two inductances are therefore equal and opposite. This is the effect that was desired; current in the load coil builds up to the desired 85 ma. in 0.5 μ sec., and is restrained from further increase by the cathode resistor setting.

The equations given do not represent exactly what really happens. Although the resistance of the tube remains sensibly constant during the first part of the rise of current through the inductor the curvature of the plate characteristic of the tube represents a gradual increase in the resistance and a slowing of the current build-up. If the branch circuit is closed for a period of only 5 microseconds the current will not quite have reached the double value desired and the voltage pulse will accordingly be somewhat lower. It will be remembered, however, that the voltage pulse is applied in addition to the voltage from source 5, which may, in some cases, make up for the difference. It does no material harm if the total voltage initiating the current through the load coil is higher than is theoretically necessary to cause the desired short rise-time, for as soon as the current starts to flow the control by tube 7 takes over and limits it to the desired value.

The example chosen illustrates, however, the limitation of type I operation. If the inductance of the load coil were greater, the desired current greater or the time of interruption less, the current through coil 3 could not build up to the required value in time to generate a pulse with the necessary magnitude unless the source voltage were increased proportionally to any one of the changed conditions. Such an increase in source voltage would exceed the safe operating voltages for the tube chosen. These difficulties can be overcome and the use of the apparatus extended by type II operation.

The limitations of type I operation arise from the fact that the current through the auxiliary inductor 3 must be built up to double-load-current value in the brief period during which current through the load coil is interrupted. If the inductance is large and the time of interruption short, voltages in excess of those than can be withstood by receiving-type tubes are required to do this. In type II operation this limitation is avoided by permitting the increment of current through the auxiliary coil to build up during the time when the load coil is carrying current but doing this in a manner that will not materially change the load-coil current. It will be seen that if tube 13 were suddenly to be caused to conduct while the load-current was still required through coil 1, the result would be to drop the voltage at the junction between the two coils nearly to zero, causing a reversal in voltage gradient across the load coil so that the current through it would tend to die out. In type II operation of the present apparatus this is prevented by so limiting the current drawn through the branch circuit that the voltage drops to the tubes 7 and 13 are minimized and the differential drop between the two is kept down to a relatively small value. With proper choice of operating parameters the change in current through the load coil due to the build up of the current increment in the auxiliary coil may be held to

be within a fraction of one percent of the total normal load.

This will be illustrated by an example, using the same circuit constants as were employed in the previous illustration, retaining the same length of current interruption and of current flow through the load coil as in the first illustration but using only one-half the plate voltage on the tubes as was assumed in the example previously given. The requirements in this case would be tantamount to those where the required current through the load coil was doubled or its inductance doubled, with the same current and voltage.

In adjusting the apparatus for type II operation under these conditions, the load current through tube 7 is first adjusted to the desired value of 85 milliamperes, with the grid at ground potential as before. Since the source voltage has been reduced this will require a slightly decreased cathode resistance, below that required for the previous type operation but only slightly below, since the adjustment is within the operating voltage range of the tube where the current is very nearly independent of plate voltage.

The setting of the cathode resistor of tube 13 is in this case identical with that of tube 7; i.e., the setting is such that both tubes operate at or very nearly at the point C of Fig. 2, through which the fragmentary curve 37 is drawn. It will be seen that the point C corresponds to a negative grid-cathode voltage of -12.5, substantially. Since the cathode is at ground potential this requires that the grids be 12½ volts positive to ground when the tubes carry currents of 85 milliamperes. Each of the two cathode resistors will therefore be set to a value of 147 ohms. Switch 29 is then closed and the potentiometer 28 is adjusted until the current through tube 13 is increased to double the previous value, corresponding to point D on curve 35. The increase in current will raise the cathode potential to +25 volts and since the point D corresponds to a grid voltage of -4 with respect to the cathode the contact of the potentiometer will be set at 21 volts positive to ground.

In addition to these changes, switch 26 is opened, removing the auxiliary condenser 25' from the circuit and thus reducing the time-constant of the grid circuit from several milliseconds, long in comparison with the pulse repetition period, to a relatively small value, short in comparison with this period, say, from one-tenth to one-fifth as great. A suitable time-constant under the conditions chosen would be 200 microseconds or one-fifth of the pulse repetition period.

With the apparatus thus adjusted the cycle of operation may be traced in detail, taking as the start of the cycle the instant immediately following the cut-off of tube 13, when normal current has just been established through the load coil. At this instant condenser 25 will have been charged to a voltage somewhat negative to cut-off; say, -45 to -50 volts, cut-off value being taken as -40. The clamp 27 having held the potential of the grid at 21 volts positive to ground during the positive pulse, the peak-to-peak amplitude of the negative swing must be in the neighborhood of 65 volts to accomplish this.

Immediately following this negative swing the charge on the condenser starts to leak off, through the grid resistor 17, at a rate dependent upon the time-constant of the grid circuit. At some instant following the cut-off, (depending upon how far below cut off condenser 25 was charged) the voltage rises to cut-off value, at which instant the tube starts to conduct.

Calling the moment at which this induction starts t_0 , the current carried by tube 13 at any later time t is the product of the difference between the grid-cathode voltage and the grid voltage at cut-off, times the transconductance g_m of the tube, the current increasing as the condenser charge leaks off and the grid approaches ground potential. The transconductance is not a constant, but its average

9

value between the cut-off voltage V_0 (say, -40 volts) and the point C of Fig. 2, corresponding to

$$-12.5 \text{ volts is the fraction } \frac{85 \times 10^{-3}}{(40 - 12.5)} \text{ or } 3.08 \times 10^{-3} \text{ mhos}$$

Referring the grid potential to ground, however, the feedback through resistor 15 raises the cathode potential, as the grid potential rises, in direct proportion to the tube current, reducing the effective transconductance,

$$g'_m, \text{ to } \frac{85 \times 10^{-3}}{40} = 2.12 \text{ millimhos.}$$

The voltage V on the grid at any time t after the instant it has risen to cut-off is

$$V = V_0 e^{-\frac{t}{RC}} \quad (3)$$

The tube current at time t is therefore $(V_0 - V) g'_m$ or

$$i = V_0 \left(1 - e^{-\frac{t}{RC}} \right) g'_m \quad (4)$$

It will be seen that the equation for the tube current is of the same form as that of the current in a resistive-inductance circuit, following a suddenly applied voltage. As viewed from the source 5 the circuit including coil 3 and tube 13 therefore looks like two inductances in series with a resistance. At the instant conduction starts the source voltage divides across the real inductance of the coil and the apparent inductance of the tube in proportion to their respective magnitudes.

Substituting the values of V_0 , g'_m and the assumed time-constant RC (200×10^{-6} sec.) in Equation 4, the equation for the tube current becomes

$$i = 85 \left(1 - e^{-\frac{t}{2 \times 10^{-4}}} \right) \text{ milliamperes; at } t_0$$

when the rate of tube current is greatest, it is $85 \times 10^{-3} \times \frac{1}{2} \times 10^{-4} = 425$ amperes per second. At the instant when conduction started, the full source voltage, minus only a volt or so drop through the resistance of the coil 3, was available across the tube. To supply current changing at the rate demanded by the tube through the inductance L_3 requires a voltage $e = 0.015 \times 425 = 6.375$ volts.

Since the dynamic impedance of tube 7 in the range in which it operates at this point is approximately 14,000 ohms, the current in coil 1 needs to drop but 0.45 milliamperes to bring the plate voltage down this amount, again to balance the two tubes. Percentage-wise, this is only in the neighborhood of one-half of one percent of the load current and there are two reasons why the drop is not actually of this magnitude; first, the drop of itself, by feedback through cathode resistor 9, effectively raises the grid voltage and thus increase the conductance of the tube, and second, while the drop is taking place the rate-of-change of current through tube 13 is decreasing, decreasing the current demand through coil 3 and therefore the drop across it. The result is that the decrease of the current through coil 1 is only about one-quarter of one percent. After no more than one or two microseconds equilibrium is established, with a difference in voltage drop across the two tubes only sufficient to equal the IR drop through coil 1 and in the right direction to maintain and not decrease the load current.

If the amplitude of the negative pulse applied to the grid of tube 13 was sufficient to carry it 5 volts negative to cut-off, the rate at which the charge leaks off of condenser 25 is such as to raise the grid potential the requisite 5 volts to cut-off value in 32.6 microseconds. Starting with this instant as t_0 , this leaves about 970 microseconds for the incremental current through coil 3 and tube 13 to build up exponentially before the next pulse occurs cutting off tube 7. This is 4.85 times the time constant assumed of 200 microseconds, and hence the

10

increment of current will have reached 99.23 percent of its final value at the instant that tube 7 cuts off.

At this instant the grid voltage of tube 13 is simultaneously raised to $+21$ volts with respect to ground, causing tube 13 to demand an additional 85 milliamperes, which is supplied by the current previously flowing through coil 1. By the time the reversal of grid potential occurs, the voltage on condenser 25 has risen substantially to ground potential, and the positive pulse, having an amplitude of 65 volts or so, would swing it far positive if it were not for the clamp diode 27.

It is not necessary to let the incremental current build up so nearly to its ultimate value at the instant tube 7 cuts off unless the period of interruption through it is relatively considerably shorter than the five microseconds that has been taken for purposes of illustration. At the instant tube 7 does cut off the operation of tube 13 transfers from curve 37 to curve 35. Therefore, even if the current through tube 13 at the instant of the switch was considerably below the desired value, the switch will result in the voltage across the tube dropping along curve 35 well toward or onto the steep portion of the curve and the final increment of current through coil 3 can take place in a manner substantially similar to type I operation. There may, in fact, be considerable advantage in permitting the final build-up of incremental current to occur during the time that tube 7 is cut off.

The preceding explanation has been on the assumption that the current waveforms through the coil 1 were truly trapezoidal. For this to be the case would require that coils 1 and 3 were without distributed capacity and that there were no other stray capacities in the circuit, which is impossible in physically realizable apparatus. Because of these capacities the current flow through the inductors does not cease immediately when the tube controlling it becomes non-conductive; current continues to flow until these capacities are charged, this requiring one quarter cycle of the natural period of oscillation of the coil, as determined by its inductance and these capacities.

The capacities charge to a voltage determined by the actual rate of cut off. While the current continues to flow through coil 1 during the charging period, the current is not available to supply that demanded by the tube 13 when operating in its normal range, and the voltage across it therefore drops to a very low value. This will be the case even if type II operation is that employed. During the next quarter-cycle the capacities discharge back through the coil, reversing the current through it until discharge is complete. If tube 13 has not yet reached its full current-carrying capacity by the end of the second quarter cycle when maximum reverse current is flowing, it will absorb the reflected current and "snub" further oscillation.

Experience has proved that a single half-cycle of reverse current can be of value in demagnetizing a ferrite more rapidly, but continued oscillation is disadvantageous. The drop in voltage across tube 13 during the first quarter cycle of oscillation does cause a momentary increase in the voltage across coil 3 and thus tend to build up the current through it somewhat more rapidly than the analysis given above would indicate. The fact that the current through coil 3 may be somewhat greater than double the load current does no particular harm, however, because when the cut-off of tube 13 initiates the wave through inductor 1 the current it carries is limited by tube 7 and the most serious result to be expected is a slight oscillation of both coils, the magnitude of which is dependent on the magnitude of the excess current. In any event it is small in comparison with the amplitude of the load current.

The sudden cut off of tube 13 also results in a charging of its associated capacities. The decrease of current through coil 3 is therefore not instantaneous, even if the tube cut-off could be so, but is gradual to the extent

that it takes a finite period for the capacities to charge. The discharge results in a flow of current both ways through coils 1 and 3; the flow through coil 1 is what initiates the current through it; the condenser discharge through coil 3 is what reduces the current in it to normal load current value. It does not build up any material oscillation unless the incremental current was permitted to build up to a materially higher value than that required.

It will be recognized that in the analysis given above the results are approximate at best, owing to the fact that the various voltage-current relationships involved were treated as linear, whereas, except for the drops through the cathode resistors, this is not, in fact, the case. Nonetheless the approximations are not of a greater order of magnitude than are involved in the assumption that any individual tube responds accurately to the characteristics of the average tube, nor are they so large that they cannot readily be compensated by minor adjustments of circuit parameters.

Numerous modifications can be made in the apparatus thus shown and described. It is by no means necessary that the inductance of coils 1 and 3 be equal; for a given source voltage effective across coil 3, the build-up of current through it when tube 13 starts to conduct will vary inversely as the inductance. Since when coil 3 is cut off the voltage pulse developed by coil 3 will be very nearly proportional to the incremental current times the inductance of the coil, the result will be substantially the same irrespective of its inductance, so long as it is of approximately the same order of magnitude as that of coil 1; it is made equal in value only as a matter of convenience and because its natural period will then correspond most closely to that of coil 1, which results in optimum rise and decay times of the currents.

For type I operation it is not necessary that any current-limiting device be included in the branch circuit. The cathode of tube 13 can be operated at ground potential and if the voltage applied to the plate of this tube from the source 5 is properly coordinated with the period during which the tube is conducting, the increment of current can be made to reach its proper value at the instant the tube cuts off. Under these circumstances tube 13 will operate on the steep portion of its curve during the entire period it is conducting and there will be no negative feedback to reduce the effective mutual conductance of the tube. Hence the build-up will be more rapid than would otherwise be the case. The feedback feature can also be omitted in the series circuit, although in this branch some form of current-limiting device is necessary. This may, however, be the resistor 19; if it is of the proper value the cathode of the tube can be operated at ground potential and the current limited by the effective voltage of the screen grid. This arrangement has the advantage of increasing the effective transconductance of the tube. It is not so advantageous in type II operation since it prevents the partial compensation through feedback of the slight drop in plate potential that occurs when tube 13 starts to conduct.

When using type II operation resistor 19 may also be used to limit the incremental current through tube 13 prior to the cut off of tube 7. This also increases the effective transconductance of the tube and reduces the voltage necessary to cut it off.

Either or both of the clamp circuits 27 and 30 can be omitted in some circumstances, although they are always desirable as they make the amplitude of the driving pulses from the multivibrator 21 non-critical. In their absence, the grids of the tubes will in all cases be effectively biased to ground potential. With relatively very short pulses the A.C. axis of both tubes will then be very near ground and for tube 7 this is substantially the case in any event; the presence or absence of

the clamp 30 makes very little difference. With this type of operation, however, the clamp 27 is a practical necessity, for to swing the grid to cut off during the long period between pulses would require the pulses be of enormous value. Where the off and on periods of tube 7 approach equality, however, clamp 27 can be omitted at the expense of requiring pulsing at greater amplitude and less ready adjustment prior to operation.

Other arrangements are possible that would place the coils in series, and the branch circuit across the auxiliary coil and the source, but most of them are relatively inconvenient.

Most arrangements for providing rectangular wave shapes in inductive circuits are limited by the dissipation permissible in the tubes used. The tube carrying current through the load has been subjected to most severe duty, since, except during the interval when the current is rising, almost the entire voltage of the source is effective across the tube. That this limitation is also effective with the present invention should be evident from what has been said above. The total power that must be dissipated in the two tubes is nearly the same, irrespective of whether type I or type II operation is employed. With short periods of interruption, in type I operation, substantially the entire duty falls on the tube in the series circuit, that in the branch circuit carries current only during a very small fraction of each cycle. In type II operation the duty is divided between the two tubes. As shown above the source voltage can be greatly reduced; in the illustrative case it is cut in half, and therefore the duty on tube 7 is reduced by the same factor, the current carried being the same in both cases. Tube 13, however, carries nearly the same current during the greater portion of the cycle and the dissipation required of it is nearly identical with that of tube 7. This permits the use of smaller tubes.

If the off and on periods of load current are more nearly equal, or if, though unequal, the off period is longer, it is possible to substitute triodes for pentodes in type I operation. In type II operation the use of pentodes (or beam power tetrodes, which operate in much the same manner) is an essential if the load current is to be kept within the very small range desired for the purpose here described. In the choice of tubes for the purpose the preference is for the tube having the highest dynamic impedance within the operating range as this involves minimum current change to compensate for the drop in voltage when the branch circuit tube starts to conduct. Other points to be considered are, of course, the ability of the tubes to withstand the pulse voltages developed when the tubes are cut off and their current carrying capacities. Substantially any of the tubes designed for driving the horizontal scanning circuits of television receivers can be used if they meet the requirements above set forth.

The apparatus is thus capable of numerous modifications and the particular arrangements and values described in detail are intended to be illustrative and not as limiting the scope of the invention; all intended limitations being set forth in the claims which follow.

I claim:

1. A driver for developing substantially rectangular current waves in an inductive load comprising an inductor, a current source and a pentode connected to said load to form a series circuit therewith, a second pentode connected to form a branch circuit connecting from between said inductor and said load across said inductor and said source, pulsing means adapted to develop simultaneous voltages of opposite polarity, connections including blocking condensers for applying said voltages respectively to the control grids of each of said pentodes to interrupt current therethrough when applied negatively, grid resistors connected to bias said control grids, a clamp circuit connecting to the control grid of said second pentode to limit the positive voltage applied thereto and

13

hold said second pentode in cut-off state for a period determined by the time-constant of said blocking condenser and grid resistor connected thereto, and means for limiting the current through said first mentioned pentode to a desired value.

2. The invention as defined in claim 1 wherein said current limiting means comprises a cathode resistor connected in series with said first pentode and including in addition, a like cathode resistor in series with said second pentode.

3. The invention as defined in claim 2 including means for adjusting said clamp circuit to vary the maximum positive voltage applied to the control grid of said second pentode.

4. The invention as defined in claim 3 wherein said pulsing means is adapted to reverse the polarity of the voltages applied to the respective control grids of said pentodes at a substantially constant repetition period and the time-constant of the blocking condenser and grid re-

14

sistor connecting to said second pentode is short in comparison to said repetition period.

5. The invention as defined in claim 2 wherein said pulsing means is adapted to reverse the polarity of the voltages applied to the respective control grids of said pentodes at a substantially constant repetition period and the time-constant of the blocking condenser and grid resistor connecting to the control grid of said second pentode is long in comparison with said repetition period.

References Cited in the file of this patent

UNITED STATES PATENTS

2,543,445	Doolittle	Feb. 27, 1951
2,591,406	Carter	Apr. 1, 1952
2,697,784	Blythe	Dec. 21, 1954

FOREIGN PATENTS

708,012	Great Britain	Apr. 28, 1954
---------	---------------	---------------