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R. C. GREENBLATT

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CIRCUITRY FOR PULL-IN SOLENOIDS

Filed April 15, 1959

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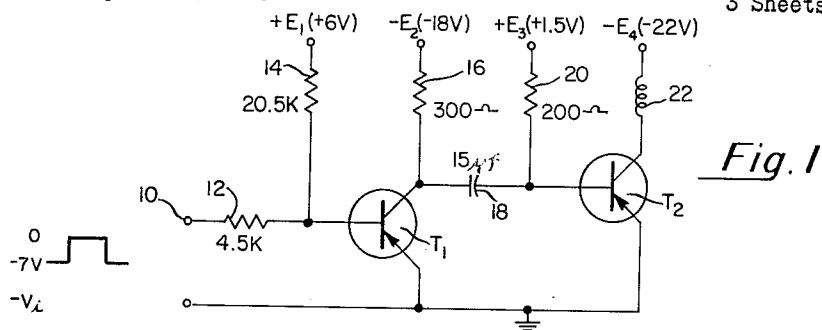
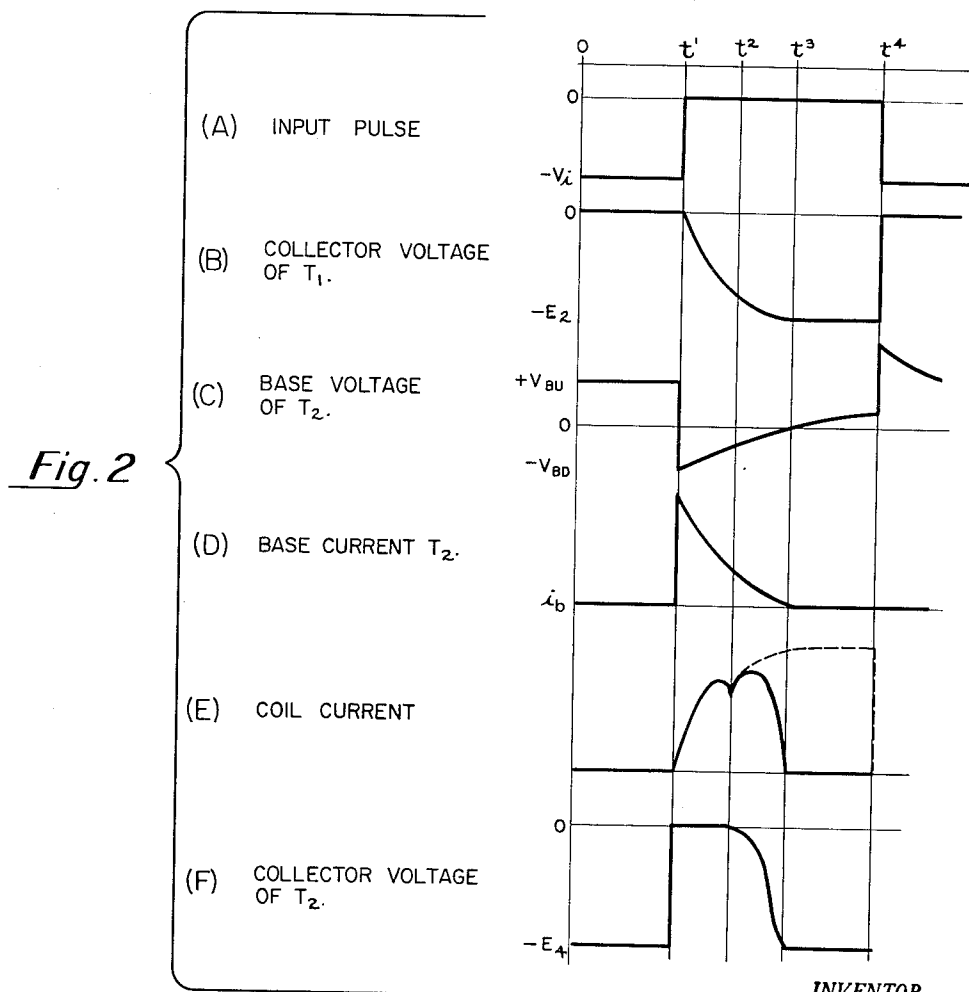


Fig. 1



INVENTOR.
RICHARD C. GREENBLATT

BY

James J. Wood
ATTORNEY

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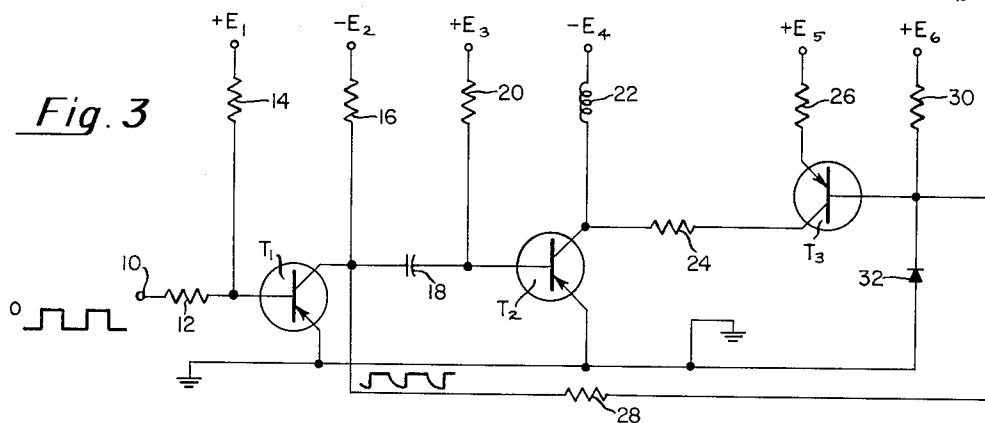


Fig. 5

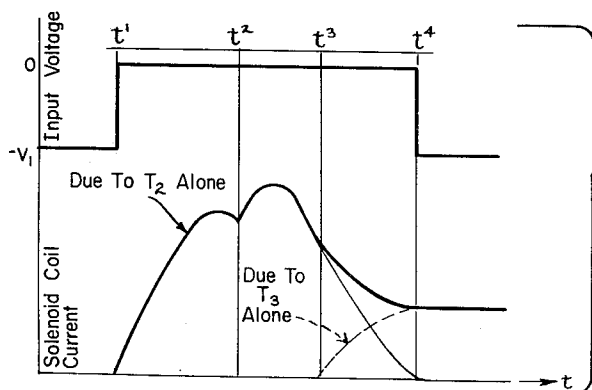
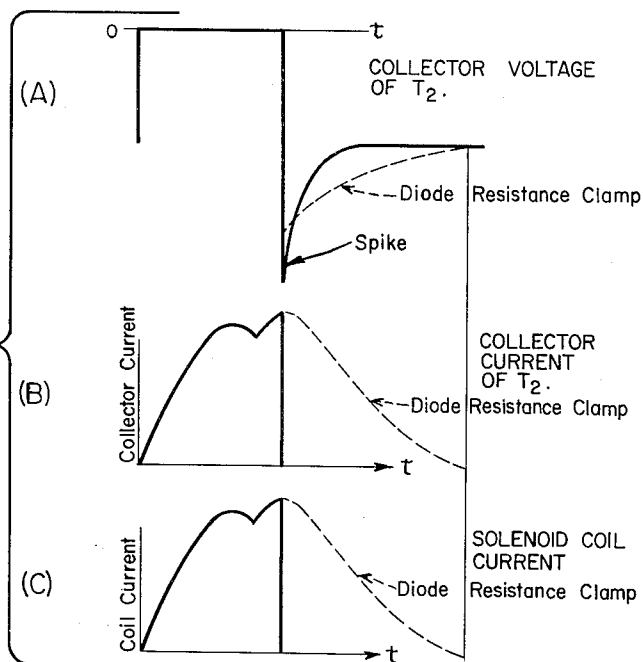


Fig. 4

INVENTOR.

RICHARD C. GREENBLATT

BY

James J. Wood

ATTORNEY

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R. C. GREENBLATT

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Fig. 6

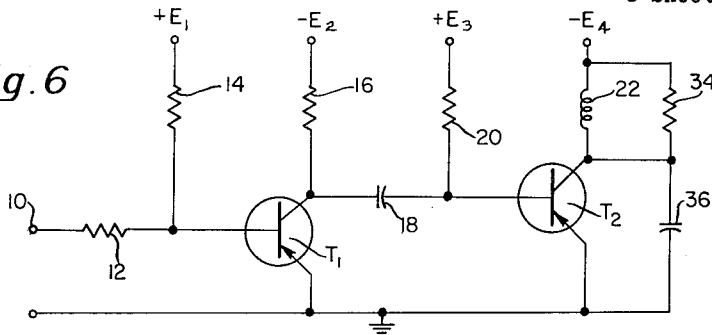
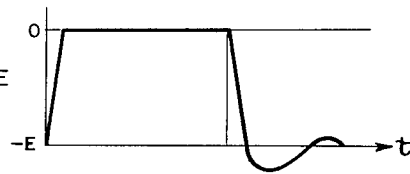
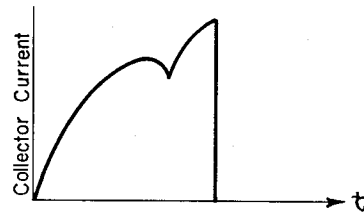


Fig. 7

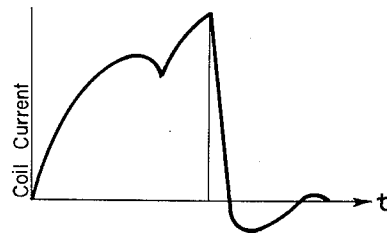
(A) COLLECTOR VOLTAGE
OF T_2 .



(B) COLLECTOR CURRENT
OF T_2 .



(C) COIL CURRENT



INVENTOR.

RICHARD C. GREENBLATT

BY

James J. Wood

ATTORNEY

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CIRCUITRY FOR PULL-IN SOLENOIDS

Richard C. Greenblatt, Malvern, Pa., assignor to Burroughs Corporation, Detroit, Mich., a corporation of Michigan

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4 Claims. (Cl. 317-148.5)

This invention relates to a circuit for the operation of miniature pull-in solenoids and more particularly to transistorized solenoid driver circuitry operating upon transient voltage-current principles.

In modern applications involving electrical and mechanical systems, there is a perennial requirement for a reliable low-cost solenoid driver which is capable of operation under rigid electrical conditions. The present day demands for compactness impose a geometry on the coil which at once dictates electrical maxima and minima which must be observed in operating the solenoid. The miniature solenoids in present day use are required to develop a pull equal to or greater than that of their structurally larger predecessors. In addition to these considerations, it is also necessary that the miniature solenoid coil and its supporting circuitry be capable of responding to input pulse signals of varying time widths and to duty cycles which are of considerable duration. For reliable operation, the miniature solenoid must be capable of both one-shot and sustained hold-in operation under the worse anticipated conditions without a significant increase in coil temperature. Finally, the solenoid coil must be capable of operation under conditions which are equivalent to changes in coil supply voltage as high as 50% above and 50% below nominal. These wide supply voltage excursions are, of course, not experienced in practice, but in design these voltage magnitudes are used to simulate the effects of aging and/or wear of the mechanical components, in order to insure long term reliability of the overall system.

The solenoid coil itself presents an inductive load to its driver. It is a well known phenomenon that where the driver is a transistor operating with such an inductive load, the problem of backswing arises, the so called backswing being evidenced by a high voltage spike waveform which is a function of the magnitude of the instantaneous transistor current at cut off. These voltage spikes do not cause instantaneous failure, but their effects are cumulative, and after a period of time, the transistor fails.

In some instances, it may be possible to mitigate the situation by favorably changing the causative factors. However, in the overwhelming bulk of practical problems encountered, these environmental conditions are immutable and one must operate within the metes and bounds which they delineate.

In accordance with a preferred embodiment, there is provided a circuit for utilization in operating a pull-in solenoid. A transistor having a base, an emitter and a collector is arranged in common emitter configuration. Means are used for connecting the solenoid coil between the collector and a source of biasing potential. Means are arranged for connecting one end of each of first and second resistors to biasing potential sources respectively, a condenser being serially connected respectively between the other ends of these resistors. The connection of the first resistor with the condenser defines a junction point. The connection of the second resistor with the condenser is also common to the base of the transistor, and means are arranged for alternately changing the potential of the junction point from ground to a predetermined negative potential.

In accordance with another preferred embodiment, there is provided additional circuitry cooperatively connected

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with the embodiment previously described. This circuitry includes a second transistor having a base, a collector and an emitter, the latter collector being connected to the collector of said first transistor. Means are provided for connecting the emitter of the second transistor to a third resistor in series with a source of biasing potential. A source of D.C. potential having a magnitude greater than that of said latter biasing potential is also utilized. A diode having a cathode and an anode has its cathode connected to the base of the second transistor and to the D.C. potential source, the anode thereof being returned to ground. Finally a current limiting resistor is arranged in a closed loop connecting the base of the second transistor with the junction point.

Accordingly, it is an object of this invention to provide an improved transistor driver for a pull-in solenoid which is capable of operating under a variety of adverse environmental conditions.

A further object is to provide an improved transistor driver of reliable operation which consumes a minimum of power and is of low-cost to manufacture.

The novel features which are believed to be characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings in which:

FIG. 1 is a circuit diagram of an improved transistor driver in accordance with the invention, the driver being for use in one-shot operation;

FIG. 2 includes a number of voltage and current waveforms used in explaining the operation of FIG. 1;

FIG. 3 is a circuit diagram of an improved transistor driver for a pull-in solenoid for utilization in sustained holding operation;

FIG. 4 includes a number of voltage and current waveforms used to explain the operation of FIG. 3;

FIG. 5 includes a number of voltage and current waveforms used to explain the problem posed by backswing in driver operation;

FIG. 6 is a circuit diagram of an improved driver for a pull-in solenoid utilized to solve the problem of backswing when the input signals are of certain time magnitudes; and

FIG. 7 includes a series of voltage and current waveforms used to explain the operation of FIG. 6.

Referring now to FIG. 1 of the drawings, two transistors T_1 and T_2 are connected in the common emitter configuration. The input signal is applied via terminal 10 and ground, through resistor 12 to the base of transistor T_1 . Bias potentials $+E_1$, $-E_2$ for the base and collector of transistor T_1 are applied through resistors 14 and 16 respectively. The transistor T_1 is coupled to transistor T_2 by means of a capacitor 18.

Bias potentials for the base and collector of transistor T_2 are indicated at $+E_3$ and $-E_4$ respectively, the battery $+E_3$ being connected to the base through resistance 20, while battery $-E_4$ is connected to the collector of T_2 through the solenoid coil 22.

The transistors in the illustrative embodiment are of the PNP type; however, it is within the scope of this invention to utilize NPN types if proper attention is given to the biasing potentials and triggering signals.

At this point it will be helpful to briefly discuss the operation of the circuit of FIG. 1 and for this purpose reference will be had to FIG. 2.

The input signal pulse shown in FIG. 2A is positive going during the interval t^1 to t^4 . As we shall see as this description proceeds, some desired objective is accom-

plished during this interval, and appropriately enough, the time ratio of this period to the entire period of signal duration is called the duty cycle. The circuitry of the invention is intended for operation in an environment which may require a duty cycle in the order of 50% or higher. These environmental desirata are dictated by the fact that the input signal may not be specifically tailored to trigger the solenoid driver of FIG. 1; instead this input signal may drive other circuitry in an overall system in which the solenoid driver of FIG. 1 is only a part.

In the interval $0-t^1$, the transistor amplifier T_1 is "ON," and the transistor driver T_2 is cut off. The base of transistor T_1 is at its negative conducting potential (in order -2 v.), while the collector thereof is substantially at ground. The base of transistor driver T_2 is at a positive potential with respect to its emitter; this voltage is indicated at $+V_{BU}$ in FIG. 2C, and it is the result of the biasing voltage $+E_3$ acting through resistor 20. The notation $+V_{BU}$ and $-V_{BD}$ are merely used as convenient means for "voltage base up" and "voltage base down" respectively. The collector voltage of transistor T_2 is at $-E_4$ so that it is cut off.

At time t^1 , the positive going pulse depicted in FIG. 2(A) is applied to the base of T_1 , driving it more positive until it is substantially at ground or slightly positive. The transistor T_1 cuts off and its collector reaches a potential of $-E_2$. This cutting off of transistor T_1 is effective to cause transistor T_2 to saturate. The effect of cutting off T_1 is equivalent to the sudden application of a step voltage of magnitude $-E_2$ to an R-C circuit which may be traced: from ground through the emitter and base of T_2 , through condenser 18, resistor 16, $-E_2$ battery and return to ground. This charging base current rises to its maximum and then begins to decay exponentially. The initial high base current of T_2 , FIG. 2(D), is of sufficient magnitude to turn it "ON" and drive it well into saturation. In the collector circuit of T_2 , the opposite condition prevails because of the high impedance of coil 22. The coil current as shown in FIG. 2(E) builds up in magnitude, until the time t^2 is reached, at which time the clapper or armature of the solenoid pulls in.

The slight cusp in coil current at t^2 may be explained as follows. At a time slightly greater than t^1 , the current in the solenoid coil 22 begins to increase. There are a number of factors which determine the shape of the coil current, the role played by each factor varying in importance depending on the instant of time then under scrutiny. The inductive properties of the coil are a function of both the current level and the instantaneous rate of change of current passing through it. This is so because the electromagnetic circuit of the coil includes an air gap which is rapidly changed at a given coil current level, and because the armature and spring system have inertial and restoring properties respectively.

The armature starts to close during the interval t^1-t^2 ; this displacement results in a rapid increase in the magnetic flux density in the core and hence a back voltage is developed to oppose the build up of coil current in accordance with the relationship:

$$e = -N \frac{d\phi}{dt}$$

where

e = the back voltage

N = the number of turns of the solenoid coil

ϕ = the magnetic flux lines linking the core.

As is well known, the negative sign indicates that when $d\phi/dt$ is positive, e is negative and tends to oppose the voltage causing the increase in current.

The advance of the armature toward the closed position takes place in incremental steps of increasing magnitude, the final steps being sufficiently large to cause a

change in flux linkage which develops a back voltage of sufficient magnitude to cause an instantaneous back voltage which momentarily reduces the coil current to produce the cusp.

At t^2 the armature is fully closed and the magnetic flux linking the coil is a maximum and is constant, and the back voltage is momentarily zero. The full applied voltage is now applied to the coil. With the armature in closed position the effective inductance (L) is increased, and current buildup continues toward the asymptotic value determined by the magnitude of $-E_4$ and the series resistance of coil 22.

The exponential decay of the base current of transistor T_2 FIG. 2(D) is intended to provide a minimum collector current which is equal to the pull-in current required at the longest actual pull-in time of the solenoid under the worse environmental conditions.

At the instant just prior to t^1 , the base of transistor T_2 is at $+V_{BU}$ as a result of biasing voltage $+E_3$ acting through resistor 20. The cut off of T_1 is equivalent to the application of a step voltage of magnitude $|-E_2|$ through resistor 16, condenser 18, to the base of transistor T_2 . Thus as may be seen in FIG. 2(C) the base to emitter voltage is driven in a negative direction, by an amount determined by the individual transistor characteristics to $-V_{BD}$.

The base current of transistor T_2 rises to its maximum instantaneously in the manner shown in FIG. 2(D); this current now begins to decay exponentially, and as it does the voltage begins to increase exponentially, and it will approach zero at time t^3 . The base voltage is now at ground, and transistor T_2 is cut off. However, the base to emitter voltage continues to increase in positive direction as shown in FIG. 2(C); this is due to the fact that capacitor 18 continues to charge by virtue of battery $+E_3$ acting through resistor 20.

At time t^4 , the capacitor 18 is almost fully charged. Upon the termination of the input pulse, the base voltage of T_1 goes to $-V_1$; this is a negative going pulse. Since the transistor T_1 is operated in the common-emitter configuration, the negative going pulse at the base of T_1 results in a positive going step pulse at the collector of T_1 . Since the charge on condenser 18 cannot change instantly, a positive going step pulse is transmitted to the base of transistor T_2 which adds to the positive voltage already present just prior to t^3 . The condenser 18 then discharges to the base voltage of T_2 , decaying exponentially toward $+V_{BU}$ as indicated at FIG. 2(C).

In the illustrative embodiment just described, the components therein utilized had the following magnitudes:

$E_1 = +6$ v.

$E_2 = -18$ v.

$E_3 = 1.5$ v.

$E_4 = -22$ v.

Resistor 12 = 4.5K ohms

Resistor 14 = 20.5K ohms

Resistor 16 = 300 ohms

Resistor 20 = 200 ohms

Condenser 18 = 15 μ farad

Coil 22 = 1000 turns #31 wire

$R_c \approx 20$ ohms

$L \approx 20$ millihenrys

Input ≤ -7 v. to ground

The transistor T_1 may be a 2N527, while transistor T_2 may be either a 2N1138A or a 2N285A, both of which are of the PNP type.

The circuit just described has utility where the armature need not be held closed for the full duration of the input cycle (t^1 to t^4); accordingly, the coil current is zero at t^3 because its mission is accomplished, and there is no further need for the coil to carry current. If it is necessary to hold the armature closed for the entire width of the input cycle, holding current must be supplied. This

may be done most advantageously by the arrangement shown in FIG. 3.

In the circuit of FIG. 3, similar components are given the same numerical designation as in FIG. 1; this arrangement includes a third transistor T_3 having its collector connected to the collector of T_2 through a resistance 24. The emitter of transistor T_3 is connected to a source of positive potential $+E_5$ through a resistor 26. The base of transistor T_3 is connected to the collector of transistor T_1 through resistor 28 so as to form a closed loop. A source of positive potential $+E_6$ is connected to the base of T_3 through resistor 30. A diode 32 has its cathode connected to the base of transistor T_3 , while the anode thereof is returned to ground.

The transistor T_3 is a constant current driver added for the purpose of supplying constant holding current to the solenoid coil 22. The mechanism for accomplishing this is as follows:

When transistor T_2 is conducting and transistor T_1 is cut off, the transistor T_3 is held off by reason of the fact that the base is slightly positive with respect to the emitter because of the biasing potential $+E_6$ acting through resistor 30. It would also be possible to keep T_3 cut off without using resistor 30, by making $|E_6| > |E_5|$ in the order of magnitude of 1 volt or so. The biasing voltage E_6 is dropped across resistors 30 and 28 in series; this circuit may be traced from ground, battery $+E_6$, resistors 30 and 28 in series, and through transistor T_1 (which is conducting) and return to ground. At this point, when the positive going pulse is applied to the input, the transistors T_1 and T_2 respond exactly as described in connection with the description of FIG. 1. As T_1 is cut off by the positive going input pulse, the collector voltage of T_1 decays exponentially toward the values $-E_2$, and this voltage change is applied to the base of transistor T_3 through resistor 28. Electrically the potential of the base of transistor T_3 is also the potential of the cathode of diode 32, and as soon as the cathode becomes sufficiently negative, the diode conducts, clamping the base of T_3 substantially at ground. The transistor T_3 is now effectively operated in the grounded base configuration. This means that conditions for conduction (since T_3 is of the PNP type) require that the emitter and collector be positive and negative respectively with reference to the base.

At the time indicated as t^2 , in FIG. 2, the collector voltage of T_2 begins to decay toward the level $-E_4$. The collector of transistor T_3 becomes more and more negative with respect to its own base, as the collector voltage of T_2 , FIG. 2(F) decays toward the $-E_4$ level. T_3 now conducts in a circuit which may be traced: Ground, battery $+E_5$ through resistor 26, through the emitter, base, and collector of transistor T_3 , through resistor 24, through solenoid coil 22, battery $-E_4$ and return to ground.

The transistor T_3 is a constant current driver. The collector current i_c is approximately equal to the emitter current i_e and

$$i_c \approx i_e = \frac{+E_5}{R_o}$$

where

$+E_5$ is the bias voltage
 R_o is the resistance of the emitter

As long as the transistor T_3 continues to conduct, the collector current i_c will remain substantially constant at this value. Hence the circuit will continue to provide a constant holding current for the full duration of the input pulse independent of the current gain variations of transistor T_3 . The solenoid current and the input pulse signal are depicted in FIG. 4. The individual contributions of transistors T_2 and T_3 to the total solenoid current are indicated in this latter figure; by superposition principles the heavy black line indicates the sum or total solenoid current as a function of time. Because of the fact that the armature is in the closed position, the current neces-

sary to hold it in is of smaller magnitude than that required for the initial pull-in.

In the circuit of FIG. 3 the transistor T_3 may be a PNP transistor 2N527 and the diode 32 may be a T6G.

In those situations where the input pulse width is of the order of time magnitude slightly greater than the maximum pull-in time of the solenoid, i.e., the duty cycle is of an order only slightly greater than $(t^2 - t^1)$, then excessive backswing of the collector voltage of transistor T_2 will result. This backswing is depicted in FIG. 5(A) as a high negative voltage spike. It is well known that the backswing of a transistor with an inductive load is proportional to the magnitude of the instantaneous current at cut off. The transistor does not fail instantly but the damage is cumulative so that it deteriorates gradually with time. The theory offered in explanation of this phenomena is that these spikes cause a localized destructive heating of the junction.

A conventional means of reducing the backswing is to use a diode-resistance clamp in parallel with the solenoid coil. This arrangement is efficacious in reducing the backswing; however, this circuitry has the disadvantage that a much longer time is required for the coil current to decay to zero, after the transistor is cut off. The recovery time is also a function of the magnitude of the coil current at cut off. The resulting waveforms of the collector voltage, collector current and the coil current are shown in dotted form in FIG. 5(A), (B) and (C) respectively. Such a solution may provide tolerable results in relatively low duty cycles. However, where recovery time problems arise as in the case with large duty cycles, the arrangement shown in FIG. 6 is superior.

In FIG. 6 there is shown the same circuitry as in FIG. 1, with the exception that a resistor 34 is connected across the solenoid coil 22, and a condenser 36 is connected between the collector and emitter of transistor T_2 . In the D.C. sense, resistor 34 and coil 22 are in parallel, this parallel combination being in series with the condenser 36.

The magnitudes chosen for the resistor 34 and the capacitor 36 will determine whether the circuit is under damped, critically damped, or over damped, the particular choice depending upon the magnitude of backswing that can be tolerated. In one practical embodiment, resistor 34 was of the order of 200 ohms and capacitor 36 was in the order of 10 μ farad.

The relatively large capacitance present in the collector circuit does not affect the rise time of the coil current appreciably, since the initial base current is large enough to permit the condenser 36 to discharge through the transistor T_2 faster than the coil current can rise. In FIG. 7(A), (B), (C) there is shown the collector voltage of T_2 , the current of T_2 , and the coil current respectively, which results are obtained using the damping technique of FIG. 6.

The values and/or types of components and the voltages appearing on the drawings are included by way of example only, as being suitable for the device illustrated. It is to be understood that the circuit specifications in accordance with the invention may vary with the design for any particular application.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced other than as specifically described and illustrated.

What is claimed is:

1. A circuit of the type described for utilization in operating a pull-in solenoid relay comprising, first, second and third transistors, each having a base, an emitter and a collector, the first and second transistors being arranged with the emitters at ground potential, means for connecting the solenoid coil between the collector of the first transistor and a source of biasing potential, first and second resistors, means for connecting one end of each of said first and second resistors to biasing potential sources re-

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specitvely, a condenser serially connected between the other end of each resistor respectively, the connection of said first resistor with said condenser defining a junction point, the connection of said second resistor with said condenser being electrically common with the base of said first transistor, means for connecting the collector of said second transistor with said junction point, means for connecting the base of said second transistor to a source of biasing potential, input means for applying signals to the base of said second transistor, the collector of the third transistor being connected to the collector of said first transistor, a third resistor, means for connecting the emitter of said third transistor to said third resistor in series with a source of biasing potential, a source of D.C. potential having a magnitude greater than that of said latter biasing potential, a diode having an anode and a cathode, the cathode of said diode being connected to the base of said third transistor and to said D.C. potential source, the anode being connected to ground, and a current limiting resistor in a closed loop connecting the base of said third transistor with said junction point.

2. A circuit of the type described for utilization in operating a pull-in solenoid relay comprising, a first transistor having a base, an emitter and a collector arranged with the emitter at ground potential, means for connecting the solenoid coil between the collector of said first transistor and a source of biasing potential, first and second resistors, means for connecting one end of each of said first and second resistors to biasing potential sources respectively, a condenser serially connected between the other ends of each of said resistors respectively, the connection of said first resistor with said condenser defining a junction point, the connection of said second resistor with said condenser being also connected to the base of said first transistor, means for alternately changing the potential of said junction point from ground to a predetermined negative potential, a second transistor having a base, a collector and an emitter, the latter collector being connected to the collector of said first transistor, a third resistor, means for connecting the emitter of said second transistor to said third resistor in series with a source of biasing potential, a source of D.-C. potential having a magnitude greater than that of said latter biasing potential source, a diode having an anode and a cathode, the cathode of said diode being connected to the base of said second transistor and to said D.-C. potential source, the anode being connected to ground, and a current limiting resistor in a closed loop connecting the base of said second transistor with said junction point.

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3. A circuit of the type described for utilization in operating a pull-in solenoid relay comprising, a transistor having a base, an emitter and a collector arranged with the emitter at ground potential, means for connecting the solenoid coil between said collector and a source of biasing potential, first, second and third resistors, means for connecting one end of each of said first and second resistors to biasing potential sources respectively, a first condenser serially connected between the other ends of each of said first and second resistors respectively, the connection of said first resistor with said first condenser defining a junction point, the connection of said second resistor with said first condenser being also connected to said base, means for alternately changing the potential of said junction point from ground to a predetermined negative potential, a second condenser being connected between said collector and ground potential, the third resistor being serially connected with said second condenser and arranged in shunt with the solenoid coil.

4. A circuit of the type described for utilization in operating a pull-in solenoid relay comprising, first and second transistors, each having a base, an emitter, and a collector and arranged with the emitter at ground potential, means for connecting the solenoid coil between the collector of said first transistor and a source of biasing potential, first, second and third resistors, means for connecting one end of each of said first and second resistors to biasing potential sources respectively, a first condenser serially connected between the other end of each of said first and second resistors respectively, the connection of said first resistor with said first condenser defining a junction point, the connection of said second resistor with said first condenser being electrically common with the base of said first transistor, means for connecting the collector of said second transistor with said junction point, means for connecting the base and collector of said second transistor to sources of biasing potential respectively, a second condenser connected between the collector of said first transistor and ground, the third resistor being serially connected with said second condenser and arranged in shunt with the solenoid coil, and input means for applying signals to the base of said second transistor.

References Cited in the file of this patent

UNITED STATES PATENTS

2,843,762	Trent	July 15, 1958
2,896,130	Tompkins	July 21, 1959
2,901,639	Woll	Aug. 25, 1959