# United States Patent

**Galetto et al.**

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[54] **ADJUSTABLE ACTIVE CLAMP CIRCUIT FOR HIGH SPEED SOLENOID OPERATION**


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[52] **U.S. Cl.**.....**317/148.5 R,** 307/237, 317/DIG. 6, 323/22 T

[51] **Int. Cl.**.....**H01h 47/32**

[58] **Field of Search**..317/9 R, 9 D, 11 R, 11 B, 11 C, 317/11 E, 14 R, 14 B, 16, 148.5 R, DIG. 6; 322/73; 307/237; 323/22 T



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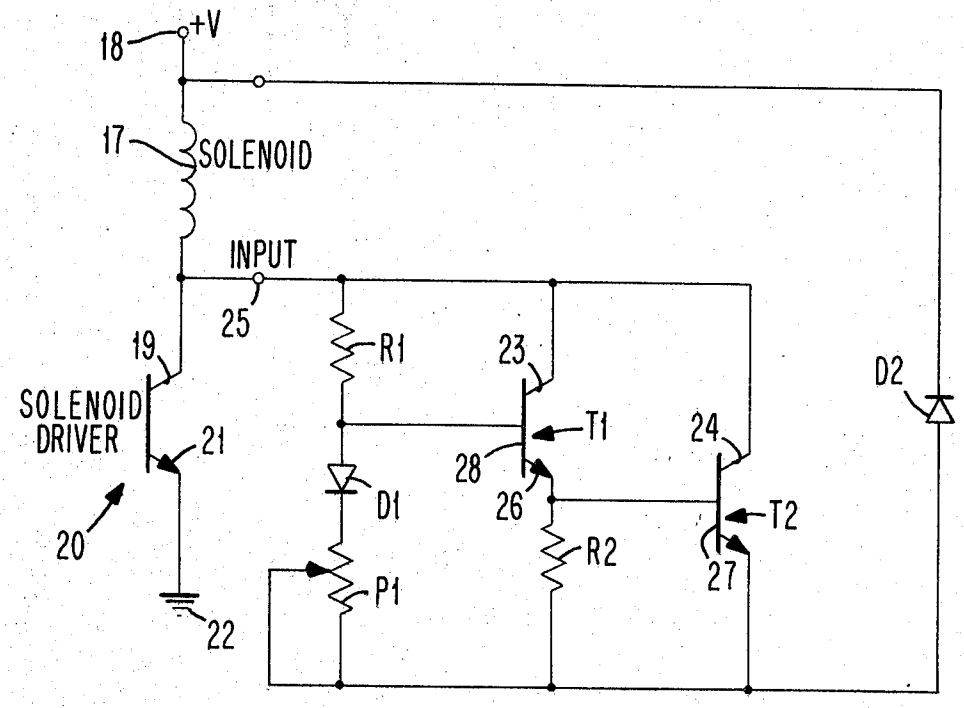
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[57] **ABSTRACT**

An adjustable clamp circuit comprising a Darlington switching pair of transistors biased by a voltage divider for permitting the maximizing of a solenoid repetition rate without exceeding the breakdown limit of the solenoid driving transistor.


**7 Claims, 4 Drawing Figures**



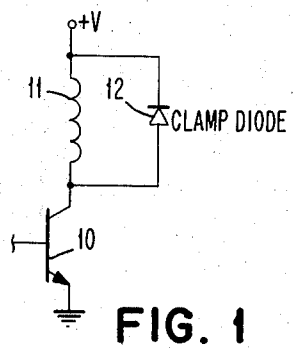



FIG. 1

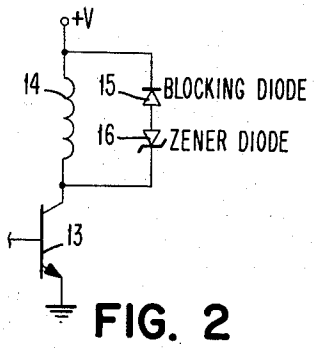



FIG. 2

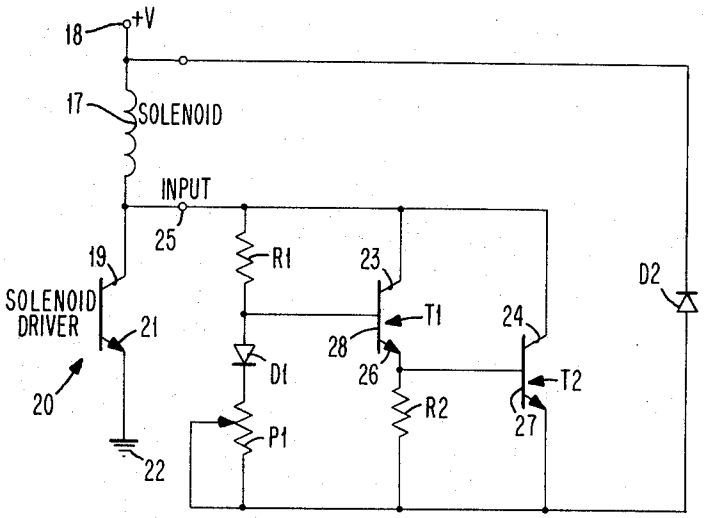



FIG. 3

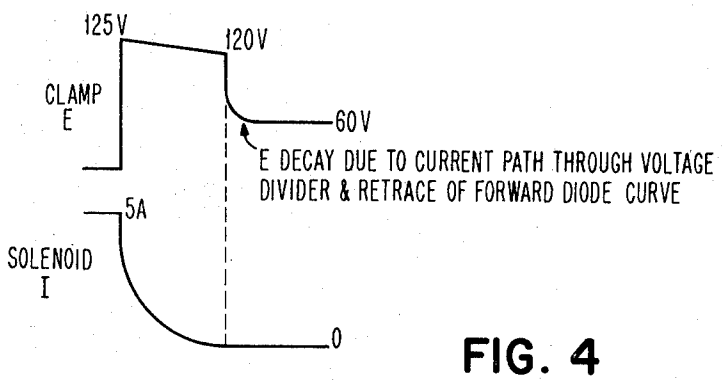



FIG. 4

# ADJUSTABLE ACTIVE CLAMP CIRCUIT FOR HIGH SPEED SOLENOID OPERATION

## BACKGROUND OF THE INVENTION

In an application where high speed operation of a solenoid is required, the energy stored in the inductance must be removed rapidly to achieve a fast drop out time. This release time is a direct function of the magnitude of back EMF permitted across the inductance and how much impedance is presented in the de-energization path. An example of where high speed operation of a solenoid is required would be in drivers for printer platens and print hammers where the maximum repetition rate of operation is desired to achieve high speed printing.

Two approaches have been made to maximize the solenoid repetition rate. First, a high voltage Zener diode could be employed. This method has the disadvantages of: high cost, tolerance on voltage which must be accounted for worst case, limited sourcing of a device operable at 60 volts and 5 amps, and operation of the Zener involves an excursion back and forth across its knee which softens the characteristic thereby reducing circuit response. A second method would be to let the device clamp the energy under a repetitive breakdown mode of operation. While devices are available which can withstand the magnitude of energy involved, reliability information is not available to quarantee this mode of operation over an anticipated machine life period.

An attempt was made to develop driver circuitry for a platen solenoid wherein the output transistor would have the capability to drive the solenoid unclamped which meant that it could withstand a repetitive breakdown mode of operation without degradation of its critical parameters. However, no device was found on the market which had this capability and an intolerable failure rate resulted. It became evident that a suitable clamping circuit would be needed in order to achieve the desired high speed operation.

## SUMMARY OF THE INVENTION

The present invention provides an active clamp circuit which is adjustable and which is the only means that is presently known which will perform the required high speed operation of, for example, a platen solenoid without degrading the reliability of the driver circuitry. The clamp circuit comprises a Darlington switching pair of transistors which is biased by a voltage divider having a resistor, a diode and an adjustable potentiometer. The voltage divider is sized such that the voltage appearing at the input, which is the collector voltage of the solenoid driver, will turn on the switch pair at a level which is approximately the breakdown level of the solenoid driver device. When the solenoid driver is saturated, the clamp circuit will be held off. When the solenoid driver turns off, the resulting fast rising voltage transition will be clamped at a level dependent on the setting of the potentiometer. The Darlington switch pair will dissipate the energy stored in the inductor under a forward biased "on condition," where the energy being dissipated is spread uniformly across the entire junction area.

The adjustable active clamp circuit permits the coil EMF to rise to the breakdown capability of the driving transistor, and then offers a very low impedance to minimize the de-energization time. The drive transistor in this manner is not subjected to possible catastrophic failure or parameter degradation by repetitive operation at a voltage level in excess of its blocking capability. The breakdown limit of the driving device is not exceeded, thus, maximum circuit efficiency can be achieved for a given device by utilizing its full voltage capability. The circuit also has the advantage that it is lower in over-all cost than comparable Zener clamp methods.



It is, then, a primary object of the present invention to provide a novel and improved clamp circuit means for permitting the maximizing of a solenoid repetition rate.

A further object of the present invention is to provide a novel and improved adjustable clamp circuit for permitting the maximizing of a solenoid repetition rate without exceeding the breakdown limit of the solenoid driving device.

Another object of the present invention is to provide a novel and improved adjustable clamp circuit which permits a coil EMF to rise to the breakdown capability of the coil driving transistor and then provides a very low impedance to minimize the de-energization time.

A still further object of the present invention is to provide a novel, improved and low cost adjustable clamp circuit comprising a Darlington switching pair of transistors biased by a voltage divider for permitting the maximizing of a solenoid repetition rate without exceeding the breakdown limit of the solenoid driving transistor.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of a preferred embodiment of the invention as illustrated in the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of one form of prior art circuit for speeding up the operation of a solenoid.

FIG. 2 is a schematic diagram of another form of prior art circuit for speeding up the operation of a solenoid.

FIG. 3 is a schematic diagram of the adjustable clamp circuit embodying the principles of the present invention.

FIG. 4 shows waveforms of the clamp voltage and the current for the solenoid in the circuit of FIG. 3.

## DESCRIPTION OF A PREFERRED EMBODIMENT

Looking at two prior art attempts first, there is shown in FIG. 1 a transistor 10 for driving solenoid 11 which has a clamp diode 12 connected across it. This solution is effective where the drop out time of the solenoid is not critical. The current decay in the solenoid is extended because of the low EMF permitted across the coil. In FIG. 2, transistor 13 drives a solenoid 14 which has a blocking diode 15 and a Zener diode 16 connected across it. This solution is an improvement over the circuit of FIG. 1 in that it permits a voltage equal to the Zener diode plus the blocking diode as the upper limit on the coil EMF. In this manner, the current decay time is reduced but this approach is limited by the availability of Zener diodes in the voltage and power rating required.

Referring now to FIG. 3, there is shown the circuit of the present invention. This solution offers the flexibility of an adjustable voltage level to optimize the drop out time by utilizing the full blocking voltage capability of the driver transistor. Thus, the solenoid drop out time can be minimized for a given device type. As shown, a solenoid coil **17** is connected between a positive voltage supply terminal **18** and the collector **19** of the solenoid driver transistor **20**. The emitter **21** of the transistor **20** is connected to a source of ground potential **22**.

The adjustable clamping circuit for solenoid **17** comprises a Darlington switching pair of transistors T1 and T2 which have their respective collectors **23** and **24** connected in common to an input terminal **25** which in turn is connected between the solenoid and the collector of the driving transistor **20**. The emitter **26** of transistor T1 is connected directly to the base **27** of transistor T2. The Darlington switch pair T1 and T2 is biased by a voltage divider circuit connected to the base **28** of transistor T1 and which comprises a resistor R1, a diode D1 and an adjustable potentiometer P1. The voltage divider is sized such that the voltage appearing at the input terminal **25**, which is the collector voltage of the solenoid driver **20**, will turn on the switch pair T1 and T2 at a level which is approximately the breakdown level of the solenoid driver. By proper selection of the values of R1 and P1, a wide range of voltage adjustment can be obtained. The silicon diode D1 biases up the divider at low currents to improve the range of the potentiometer P1. A resistor could also be inserted in this position at a cost saving if the absolute range of adjustment is not critical. A resistor R2 connected to the base **27** of transistor T2 provides a path for holdoff bias current on transistor T2. A diode D2 connected between the voltage supply terminal **18** and the voltage divider is provided to block current flow from the supply terminal back through the divider when the solenoid driver **20** is on.

From the preceding circuit description, the operation of the circuit in a solenoid driver application would have a transient behavior as follows: With the solenoid driver transistor **20** saturated, transistors T1 and T2 will be biased off and the clamp circuit will be held off with diode D2 blocking any reverse divider current. This eliminates exposure to the base emitter breakdown of transistors T1 and T2. When the solenoid driver turns off, the voltage at its collector **19** and the input terminal **25** will rise instantaneously until limited by external means, such as device breakdown, clamp potential, etc. The value of this voltage will be of the form:

$$e = L\,di/dt$$

The energy contained in the coil can be represented in one of two ways:

$$E = eIt \quad (1)$$

where:

$e$ = voltage across solenoid
$I$ = magnitude of solenoid current prior to turn-off
$t$ = time for the current to decay

$$E = \tfrac{1}{2} LI^2 \quad (2)$$

where:

$L$ = inductance of solenoid
$I$ = magnitude of solenoid current prior to turn-off

Since $E = E$: $eIt = \tfrac{1}{2} LI^2$

$et = \tfrac{1}{2} LI$

$t = LI/2e$

This equation shows dramatically that the decay time of the current, which directly controls the drop time of the solenoid, is an indirect function of the voltage across the coil. In other words, the greater the voltage across the coil, the less the current decay time.

The adjustable active clamp permits the solenoid EMF to rise to the breakdown capability of the driving transistor thus minimizing the current decay time for the selected driver configuration. This phenomenon is accomplished in the following manner: When the solenoid driver **20** turns off the resulting fast rising voltage transition, described by the equation $e = L\,di/dt$, will be clamped at a potential dependent on the setting of the clamp circuit voltage divider which as previously described comprises resistor R1, diode D1 and potentiometer P1. This divider biases up the Darlington switching pair T1 and T2. The voltage across D1 and P1 is also the voltage across the base-emitter junctions of T1 and T2. When this voltage increases to a potential which is beyond the cut-in voltage of the two silicon junctions, T1 and T2 will be forward biased and turn on and provide a path for the current of solenoid **17** to decay. The clamp voltage will experience a small decay due to the increase in the base-emitter voltages of T1 and T2 as the current decays. For example, referring to FIG. 4, assume a clamp voltage of 125 volts, a solenoid current of 5 amps and a positive voltage supply of 60 volts. From the waveforms shown, it can be seen that the clamp voltage, which is the voltage across the solenoid plus the supply voltage, will remain essentially constant until the solenoid current approaches an insignificant level. The decay in voltage which follows is of no consequence since the solenoid is already de-energized.

Once the voltage at the solenoid driver **20** returns to the supply voltage, the clamp circuit is no longer active until once again during turn-off the voltage excursion reaches the threshold level determined by the setting of P1. As was previously mentioned, diode D2 blocks any current flow from the voltage supply back through the divider when the solenoid driver is on. The primary concern here is to protect the base-emitter junctions of T1 and T2 from breakdown, with the actual value of current flow as only a second order effect.

The equation for the actual value of the clamp voltage is:

$$V_{clamp} = V + V_{F_{D2}} + (V_{BE_{T2}} + V_{BE_{T1}} - V_{F_{D1}}) \frac{(R_1 + P_1)}{P_1}$$

In implementing the clamp circuit configuration shown in FIG. 3, the breakdown capability of T1 should be equal to that of T2, the clamp voltage should not be set to higher level than the limit imposed by the sum of the supply voltage and the breakdown rating of T2, and the device selected for T2 must be capable of withstanding the peak power during transition.

Additional features to be noted are the accurate level of detection of the clamp circuit, the basic circuit configuration remains the same regardless of the level to be detected, and it provides an excellent test vehicle to assess circuit voltage requirements to attain desired solenoid operation speeds. Also, the one basic circuit

design can cover a wide range of clamp voltage levels providing the previously mentioned precautions on breakdown and power dissipation are taken.

While the invention has been particularly shown and described with reference to a preferred embodiment thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. A solenoid system having an adjustable clamp circuit for maximizing the repetition rate of a solenoid which comprises;

a source of supply voltage connected to said solenoid;

a driver transistor having a collector connected in series with said solenoid and supply voltage for driving said solenoid;

a Darlington switching pair of transistors having an input terminal connected in circuit with said solenoid and the collector of said driver transistor; and

a clamp circuit voltage divider connected between said input terminal and said switching transistors for biasing the transistors, said switching transistors being turned off during saturation of said solenoid driver transistor;

said voltage divider being effective upon turn off of said driver transistor to clamp the resultant rising voltage at said input terminal and to forward bias said switching transistors on and provide a path for current in said solenoid to decay.

2. A solenoid system as defined in claim 1 wherein the voltage at said input terminal will be clamped at a level which is approximately the breakdown level of said driver transistor.

3. A solenoid system as defined in claim 1 wherein said voltage divider includes adjustable means for varying the clamp level of the voltage at said input terminal.

4. A solenoid system having an adjustable clamp circuit for maximizing the repetition rate of a solenoid which comprises;

a source of supply voltage connected to said solenoid;

a driver transistor having a collector connected in series with said solenoid and supply voltage for driving said solenoid;

first and second switching transistors each having a base, emitter and collector, with the emitter of said first transistor being connected to the base of said second transistor;

an input terminal for said switching transistors connected in circuit with said solenoid and the collector of said driver transistor, the collectors of said switching transistors being connected to said input terminal; and

a clamp circuit voltage divider connected between said input terminal and the emitters of said switching transistors for biasing the transistors, said switching transistors being turned off during saturation of said solenoid driver transistor;

said voltage divider being effective upon turn off of said driver transistor to clamp the resultant rising voltage at said input terminal at a level which is approximately the breakdown level of said driver transistor and to forward bias said switching transistors on and provide a path for current in said solenoid to decay.

5. A solenoid system having an adjustable clamp circuit for maximizing the repetition rate of a solenoid which comprises;

a source of supply voltage connected to said solenoid;

a driver transistor having a collector connected in series with said solenoid and supply voltage for driving said solenoid;

first and second switching transistors each having a base, emitter and collector, with the emitter of said first transistor being connected to the base of said second transistor;

an input terminal for said switching transistors connected in circuit with said solenoid and the collector of said driver transistor, the collectors of said switching transistors being connected to said input terminal; and

a clamp circuit voltage divider comprising a resistor, a diode and an adjustable potentiometer connected in series between said input terminal and the emitters of said switching transistors and also having a connection to the base of said first switching transistor for biasing the transistors, said switching transistors being turned off during saturation of said solenoid driver transistor;

said voltage divider being effective upon turn off of said driver transistor to clamp the resultant rising voltage at said input terminal at a level which is approximately the breakdown level of said driver transistor, and also effective when the voltage across said diode and potentiometer exceeds the cut-in voltage of the junctions of said switching transistors to forward bias the switching transistors on and provide a path for current in said solenoid to decay.

6. A solenoid system as defined in claim 5 and including means for blocking any current flow from said supply voltage back through said voltage divider when the driver transistor is on to protect the base-emitter junctions of said switching transistors from breakdown.

7. A solenoid system as defined in claim 5 wherein the rising voltage at said input terminal is clamped at a level dependent on the setting of said clamp circuit voltage divider.

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