NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF: GP

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for
Patent Matters

SUBJECT: Announcement of NASA-Owned U. S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code USI, the attached NASA-owned U. S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U. S. Patent No.	: 3,549,955
Government or Corporate Employee	: California Institute of Technology Pasadena, California 91109
Supplementary Corporate Source (if applicable)	: JPL
NASA Patent Case No.	: NPO-10716

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:
Yes ☒ No ☐
Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of . . ."

Elizabeth A. Carter
Elizabeth A. Carter
Enclosure
Copy of Patent cited above

FACILITY FORM 602

N71-24892 (ACCESSION NUMBER)	(THRU)
6 (PAGES)	00 (CODE)
(NASA CR OR TMX OR AD NUMBER)	09 (CATEGORY)

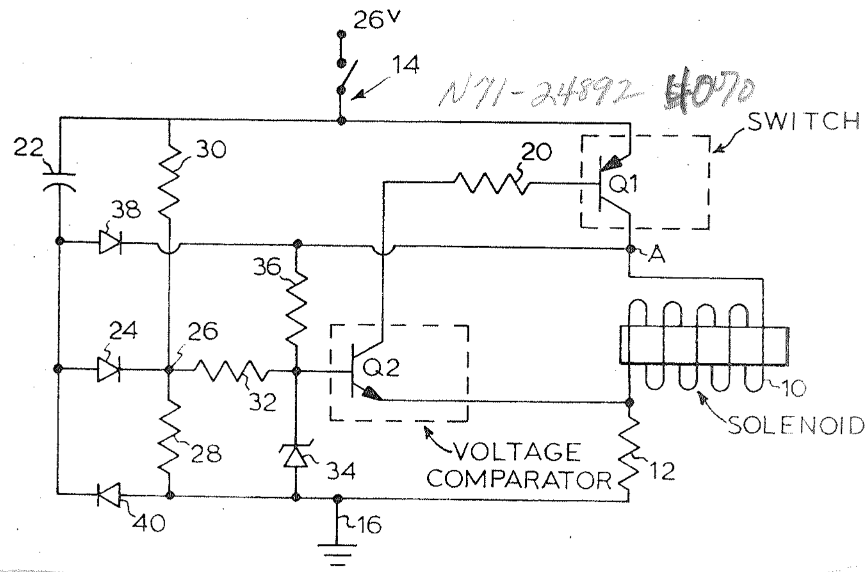


FIG. 1

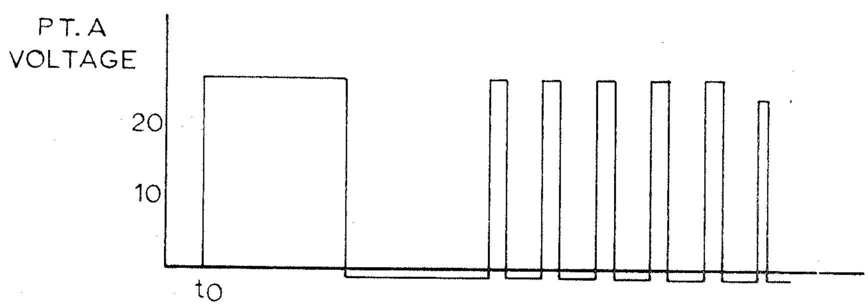


FIG. 2

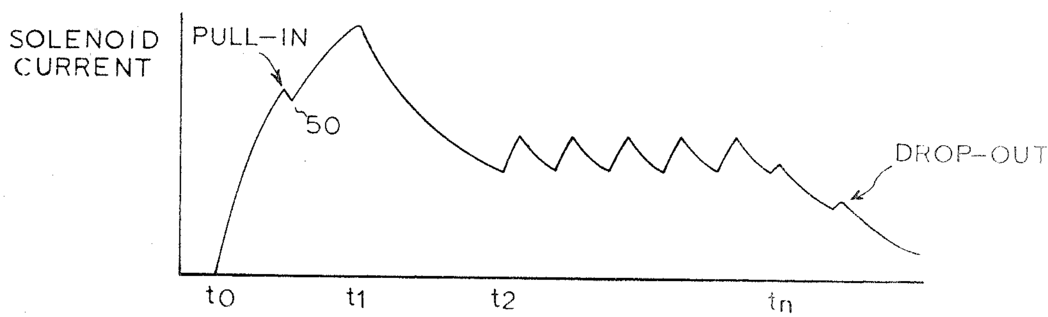


FIG. 3

INVENTOR.
WILLIAM E. CRAWFORD
BY
ATTORNEYS

United States Patent

[11] 3,549,955

[72] Inventors T. O. Paine
Administrator of the National Aeronautics and Space Administration with respect to an invention of
William E. Crawford, Altadena, Calif.

[21] Appl. No. 851,394
[22] Filed Aug. 19, 1969
[45] Patented Dec. 22, 1970

[54] **DRIVE CIRCUIT FOR MINIMIZING POWER CONSUMPTION IN INDUCTIVE LOAD**
16 Claims, 3 Drawing Figs.

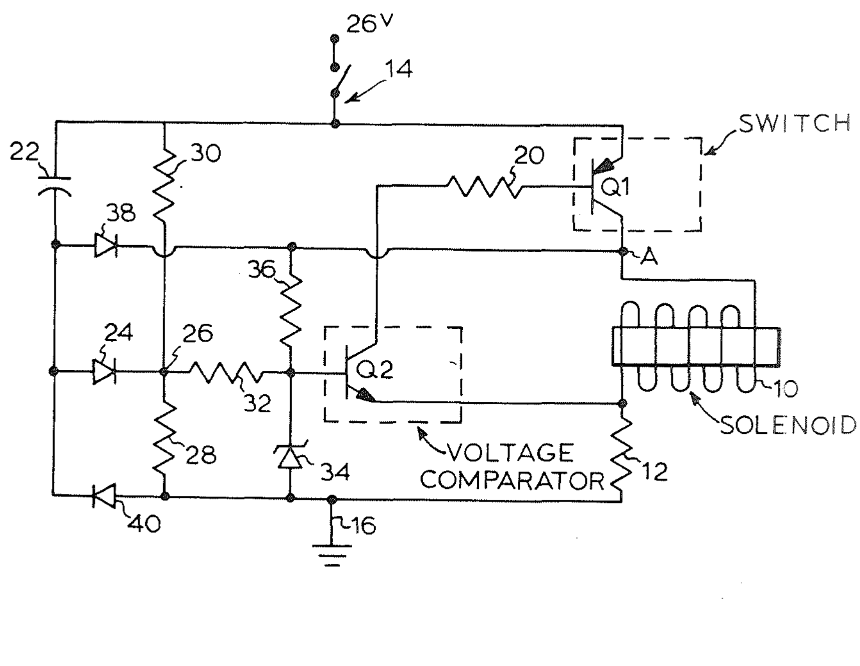
[52] **U.S. Cl.** **317/148.5,** 307/104; 317/123
[51] **Int. Cl.** **H01h 47/32**
[50] **Field of Search** 317/123, 148.5, 33; 317/123CD; 320/31, 39; 307/104

[56] **References Cited**
UNITED STATES PATENTS

3,125,715	3/1964	Brooks	317/33
3,205,412	9/1965	Winston	317/123
3,206,651	9/1965	Proulx	317/123
3,373,341	3/1968	Wattson	317/33
3,453,519	7/1969	Hunter	320/39
3,461,375	8/1969	Nestler	317/123

Primary Examiner—James D. Trammell
Assistant Examiner—Ulysses Weldon
Attorneys—J. H. Warden, Paul F. Mc Caul and G. T. Mc Coy

ABSTRACT: A circuit for driving an inductive load, such as a solenoid, so as to minimize the solenoid power consumption. The circuit parameters are selected so as to apply a driving voltage to the solenoid until the solenoid current exceeds the "pull-in" current. Then the circuit automatically terminates the driving voltage and the current through the solenoid is permitted to decay to a value just exceeding the "drop-out" current. The circuit then continues to cycle on and off to alternately drive current through the solenoid and permit it to decay while always maintaining the solenoid current in excess of the drop-out current but considerably below the pull-in current. This cycling continues until the solenoid activate switch is opened.



DRIVE CIRCUIT FOR MINIMIZING POWER CONSUMPTION IN INDUCTIVE LOAD

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 USC 2457).

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to circuits for driving inductive loads, such as solenoids, and more particularly, to such a circuit which minimizes solenoid power consumption while maintaining the solenoid in an activated state.

2. Description of the Prior Art

There are many applications, of course, in which a valve or other mechanism is actuated in response to the energization of a solenoid. For example only, many valves are solenoid controlled such that the valve is opened (or closed) when the solenoid is energized or closed (or opened) when the solenoid is not energized. In such arrangements, in order to maintain the valve opened for a certain interval, it is the normal practice to drive current through the solenoid until the "pull-in" current level is exceeded and the valve opens and then to maintain this current level for the full interval. In many applications, where power consumption is not critical, this constitutes a very satisfactory technique for operating the solenoid.

However, in certain applications where power consumption is a significant factor, it is inefficient to maintain the pull-in current level through the solenoid for the entire interval.

OBJECTS AND SUMMARY OF THE INVENTION

In view of the foregoing, it is an object of the present invention to provide a circuit useful for energizing a solenoid and for minimizing the power consumption therein.

It is a more particular object of the present invention to provide a drive circuit for maintaining the current through a solenoid at a level in excess of a drop-out current level but considerably below a pull-in current level.

Briefly, a drive circuit is provided in accordance with the present invention for applying a drive voltage to a solenoid until the solenoid current exceeds a pull-in current level. Thereafter, the circuit automatically terminates the drive voltage and the current through the solenoid is permitted to decay to a value just exceeding a drop-out current level. The circuit then begins to cycle, alternately supplying current to the solenoid and permitting the solenoid current to decay, while always maintaining the solenoid current in excess of the drop-out current level and considerably below the pull-in current level.

In a preferred embodiment of the invention, the solenoid is connected in a series path between a transistor switch and a resistor with the path being connected across a source of potential. Voltage comparison means are provided for monitoring the voltage across the series resistor which is, of course, indicative of the current level through the solenoid. The voltage comparison means functions initially to compare the voltage across the series resistor with a first threshold level related to the pull-in current level and subsequently to compare it with a second threshold level related to the drop-out current level. If at any time the series resistor voltage is less than the threshold established at that time, the voltage comparison means closes the series transistor switch to supply more current to the solenoid. When the voltage across the series resistor then exceeds the threshold, the voltage comparison means opens the series switch to permit the solenoid current to decay. The solenoid current range between opening and closing of the series switch is determined by a positive feedback resistor. Thus, the circuit continues to cycle as long as the potential source remains connected across the series path.

In accordance with a significant feature of the preferred embodiment of the invention, means are provided to initially establish a first high threshold to thus permit the current level through the solenoid to build up to the pull-in current level. Thereafter, a second lower threshold is automatically established to maintain the solenoid current at a level below the pull-in current level but in excess of the drop-out current level. In accordance with a further feature of the of the invention, a positive feedback path is provided to establish the solenoid current level range for opening and closing the switch in series with the solenoid thus also establishing the cycling rate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram illustrating a preferred embodiment of the invention;

FIG. 2 is a waveform chart illustrating the voltage at the upper terminal of the solenoid of FIG. 1; and

FIG. 3 is a waveform chart illustrating the current through the solenoid.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Attention is now called to FIG. 1 of the drawing which illustrates a preferred drive circuit embodiment in accordance with the invention for supplying current to an inductive load device such as the solenoid 10. As is well known, it is normally necessary to provide a higher level pull-in current to a solenoid, e.g., in order to actuate a valve mechanism, than it is to maintain the valve mechanism actuated. That is, once the pull-in current level through the solenoid has been exceeded, it is only necessary to maintain the solenoid current in excess of a drop-out level in order to maintain the actuation of the mechanism controlled by the solenoid. The drive circuit of FIG. 1 operates to initially establish a current through the solenoid 10 in excess of the pull-in current level, and to thereafter maintain a current through the solenoid considerably below the pull-in current level but always in excess of the drop-out level.

The circuit of FIG. 1 includes a first series path including a resistor 12 connected in series with the solenoid 10. In addition, the emitter collector path of a first transistor switch Q1 is connected in series with the solenoid 10 and resistor 12. A voltage is applied across the series path including the solenoid 10 by closure of a solenoid activate switch 14. More particularly, the single-pole, single-throw switch 14 connects the emitter of transistor Q1 to a source of positive potential 26. The lower terminal of resistor 12 is connected to ground terminal 16.

Unless otherwise stated, it will be assumed that the solenoid activate switch 14 is always closed. With switch 14 closed, current will be conducted through the solenoid 10 if the transistor switch Q1 is forward-biased. Transistor switch Q1 is controlled by transistor Q2 which, as will be seen hereinafter, functions as a voltage comparator. The emitter of transistor Q2 is connected to the junction between the solenoid 10 and resistor 12. The collector of transistor Q2 is connected through resistor 20 to the base of transistor Q1.

The transistor Q2 functions as a voltage comparator to compare the voltage at the junction between solenoid 10 and resistor 12 with a threshold voltage applied to the base of transistor Q2. As will become more apparent hereinafter, a first higher threshold level is initially applied to the base of transistor Q2 to permit the current through the solenoid 10 to build up to the higher pull-in current level. After the pull-in current level has been exceeded, a second lower threshold level is applied to the base of transistor Q2.

The components for establishing the threshold levels at the base of transistor Q2 includes a capacitor 22 whose upper terminal is connected to switch 14 and whose lower terminal is connected through a diode 24 to a junction 26 formed between a first voltage divider resistor 28 and a second voltage divider resistor 30. Note that the voltage divider resistors 28 and 30 are connected between ground terminal 16 and the switch 14. Junction **26** is connected through resistor **32** to the base of transistor Q2. The base of transistor Q2 is connected to ground through a zener diode **34**.

In addition to the foregoing components, the base of transistor Q2 is connected through a positive feedback resistor **36** to the junction between the collector of transistor switch Q1 and the solenoid **10**. Diode **38** connects the lower terminal of capacitor **22** to this junction which, for convenience, will hereinafter be referred to as point A. Diode **40** connects the lower terminal of capacitor **22** to ground terminal **16**.

In considering the operation of the circuit of FIG. **1**, initially assume that the solenoid activate switch **14** is open and that the capacitor **22** is completely discharged. When the solenoid activate switch **14** is then closed, a large current will initially flow through capacitor **22**, diode **24**, and resistor **28** to thus increase the potential on the base of the NPN transistor Q2. The zener diode **34** will clamp the potential rise on the base of transistor Q2 to a certain level which will be assumed herein to be +6.6 volts. In any event, this current provided to the base of transistor Q2 will forward bias transistor Q2 and in turn forward bias transistor Q1 to thus provide current flow through solenoid **10** and resistor **12**. As the solenoid current level increases, the voltage across resistor **12** will also increase to thus raise the potential on the emitter of transistor Q2. When the potential on the emitter of Q2 closely approaches the first threshold level of +6.6 volts established by the zener diode **34** on the base of transistor Q2, transistor Q2 will cut off and in turn cut off transistor Q1. With transistor Q1 cut off, the +26 volts driving voltage will no longer produce a current flow through solenoid **10**. However, as is the case with all inductive loads, the current therethrough cannot be immediately terminated. Thus, the energy stored in the solenoid **10** produces a current around the loop including resistor **12**, zener diode **34**, and resistor **36**. As should be apparent, this forces the potential at point A to a slightly negative value equal to the sum of the forward drop across zener diode **34** and the drop across resistor **36**. As a consequence of the potential on point A going negative, capacitor **22** will further charge to thereby establish a level thereacross in excess of the +26 volts provided by the power supply. This additional charging of the capacitor **22** effectively biases the capacitor **22** out of the circuit so that is thereafter no longer has any influence, that is at least until switch **14** is opened and again closed to start another operation.

With capacitor **22** effectively out of the circuit, the voltage divider comprised of resistors **28** and **30** will establish the potential on junction **26** which thus constitutes a second threshold level lower than the level initially established by the circuit path through capacitor **22**. As the current provided by the energy stored in solenoid **10** decays, the potential at the emitter of transistor Q2 will also decrease. When it falls below the level established at the base of transistor Q2 by the resistors **28** and **30**, transistor Q2 will become forward biased and thus will close transistor switch Q1 to again supply current to the solenoid **10**. As the current through the solenoid **10** increases, the voltage across the resistor **12** increases to the point of again cutting off the transistor Q2. The width of the current level range between the upper and lower current levels through the resistor **12** which respectively produce conduction and cutoff in the transistor Q2 is determined by the value of the positive feedback resistor **36**. When transistor Q1 is conducting, resistor **36** feeds back a portion of the +26 volt level at point A to the summation point at the base of transistor Q2. When transistor Q1 is not conducting, resistor **36** feeds back a portion of a slightly negative potential at point A to the base of transistor Q2.

In view of the foregoing, it should be apparent that the circuit will continue to cycle with the transistor switch Q1 being closed each time the voltage across resistor **12** decreases to a level below the threshold established at the base of transistor Q2 by voltage divider resistors **28** and **30** and feedback resistor **36**. When transistor switch Q1 closes, the current through solenoid **10** and resistor **12** will then increase to soon thereafter cut transistor Q2 off. This cycling will continue for as long as switch **14** remains closed, When switch **14** is opened, the capacitor **22** is discharged through the solenoid **10**, resistor **12** and diode **40**.

The waveform chart of FIG. **2** illustrates the voltage at point A and the waveform chart of FIG. **3** illustrates the current through the solenoid **10**. Assume that switch **14** is closed at time *t0*. As has been explained, the current through the solenoid from the capacitor **22** charges quickly until time *t1*. The small valley **50** in the current curve represents a change of inductance through the solenoid as the armature thereof is pulled in. At *t1*, the voltage across the resistor **12** is built up sufficiently to cut off the voltage comparator transistor Q2 to thereby drop the voltage at point A to some negative value. When the current decreases to level illustrated at time *t2*, the voltage comparator A2 will then begin to conduct and close transistor switch Q1 to thereby again force the potential at point A up to approximately 26 volts. The circuit will then continue to cycle as illustrated by FIGS. **2** and **3** until switch **14** is opened at time *tn* when the charge stored in capacitor **22** will be discharged through the solenoid.

The cycle rate is determined by the value of positive feedback resistor **36**. That is, if the value of resistor **36** is small, its influence is great causing a wider current range between conduction and cutoff of transistor Q2 and thus a lower cycling rate. On the other hand, if the value of resistor **36** is very high, it will have little influence and thus the second threshold will be very sharply established almost solely by the voltage divider resistors **28** and **30**. In this case, the width of the current level range between conduction and cutoff of transistor Q2 will be very small and thus the cycle rate will be very high.

From the foregoing, it will be recognized that a circuit has been disclosed herein for driving an inductive load, such as a solenoid, and for minimizing power consumption within the load. Power consumption is minimized by permitting the inductive load current to build up to a pull-in current level but to thereafter maintain the current through the inductive load at a level substantially below the pull-in level and always above a drop-out current level. During this latter phase of operation, the circuit cycles between solenoid current charging and decaying states. Although the waveforms of FIGS. **2** and **3** illustrate an exemplary circuit operation in which the duty cycle, i.e., percentage of the total time that the drive voltage is supplying current to the solenoid, is in the order of 33 ⅓ percent, embodiments of the invention can operate with as great as a 10:1 power saving. Table I set forth hereinafter illustrates component values utilized in a typical embodiment of the present invention:

TABLE I

Capacitor 22	microfarads	2
Resistor 28	ohms	5k
Resistor 30	do	50k
Resistor 32	do	10k
Resistor 36	do	500k
Resistor 20	do	10k
Resistor 12	do	100

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and, consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

I claim:

1. A drive circuit useful in combination with an inductive load for supplying current thereto, said drive circuit comprising:

a switch;

a resistor;

means for connecting said switch and said resistor in series with said inductive load across a source of potential;

voltage comparison means for comparing the voltage across said resistor with a threshold voltage signal;

means responsive to said voltage comparison means indicating said voltage across said resistor is less than said threshold voltage signal for closing said switch and to said voltage comparison means indicating said voltage across said resistor is greater than said threshold voltage signal for opening said switch;

means for initially establishing said threshold voltage signal at a first level; and

means responsive to said switch opening for establishing said threshold voltage signal at a second level lower than said first level.

2. The drive circuit of claim 1 wherein said switch comprises a first transistor having a base, a collector, and an emitter; and wherein said means for connecting said switch includes means for connecting the emitter-collector path thereof in series with said resistor and inductive load.

3. The drive circuit of claim 2 wherein said voltage comparison means includes a second transistor having a base, a collector, and an emitter:

means coupling said second transistor emitter to said resistor;

means coupling said second transistor collector to said first transistor base; and

means for applying said threshold voltage signal to said second transistor base.

4. The drive circuit of claim 1 including current decay path means for closing a conductive path solely around said inductive load and said resistor.

5. The drive circuit of claim 1 wherein said means for establishing said threshold voltage at a second level includes feedback means responsive to the state of said switch.

6. The drive circuit of claim 1 wherein said means for initially establishing said threshold voltage signal includes circuit path means connected across a source of potential and comprised of a capacitor connected in series with a first voltage divider resistor for establishing said threshold voltage at the junction therebetween.

7. The drive circuit of claim 6 including a second voltage divider resistor connected in parallel with said capacitor; and wherein said means responsive to said switch opening includes means for charging said capacitor to store a voltage thereacross in excess of that supplied by said potential source.

8. The drive circuit of claim 7 wherein said switch comprises a first transistor having a base, a collector, and an emitter; and wherein said means for connecting said switch includes means for connecting the emitter-collector path thereof in series with said resistor and inductive load.

9. The drive circuit of claim 8 wherein said voltage comparison means includes a second transistor having a base, a collector, and an emitter;

means coupling said second transistor emitter to said resistor;

means coupling said second transistor collector to said first transistor base; and

means for connecting said junction between said capacitor and said first voltage divider resistor to said second transistor base.

10. The drive circuit of claim 9 including means for clamping the potential applied to the base of said second transistor.

11. In combination with a solenoid, a drive circuit for supplying current thereto up to a "pull-in" level and for thereafter maintaining a current therethrough just in excess of a "drop-out" level lower than said "pull-in" level, said drive circuit comprising:

means for connecting a voltage source across said solenoid;

means for monitoring the current level through said solenoid and for initially comparing it with a first threshold corresponding to said "pull-in" level;

means responsive to said current level through said solenoid exceeding said first threshold for disconnecting said voltage source from said solenoid;

means responsive to the current level through said solenoid decaying to a level just in excess of said "drop-out" level for connecting said voltage source across said solenoid;

said means for monitoring including means for subsequently comparing the current level through said solenoid with a second threshold lower than said first threshold; and

means responsive to said current level through said solenoid exceeding said second threshold for disconnecting said voltage source from said solenoid.

12. The combination of claim 11 wherein said means for connecting said voltage source across said solenoid includes a first transistor having a base, a collector, and an emitter; and means for connecting the emitter-collector path of said first transistor in series with said solenoid.

13. The combination of claim 11 wherein said monitoring means includes a resistor connected in series with said solenoid and voltage comparator means responsive to the voltage across said resistor.

14. The combination of claim 11 including means for initially establishing said first threshold including circuit path means connected across a source of potential and comprised of a capacitor connected in series with a first voltage divider resistor for establishing said first threshold at the junction therebetween.

15. The combination of claim 14 including means for subsequently establishing said second threshold at said junction including means for charging said capacitor to store a voltage thereacross in excess of that supplied by said potential source.

16. The combination of claim 15 including a feedback resistor coupling one terminal of said solenoid to said junction.