May 13, 1969 S. E. ZOCHOLL 3,444,434

STATIC TIME-OVERCURRENT RELAY

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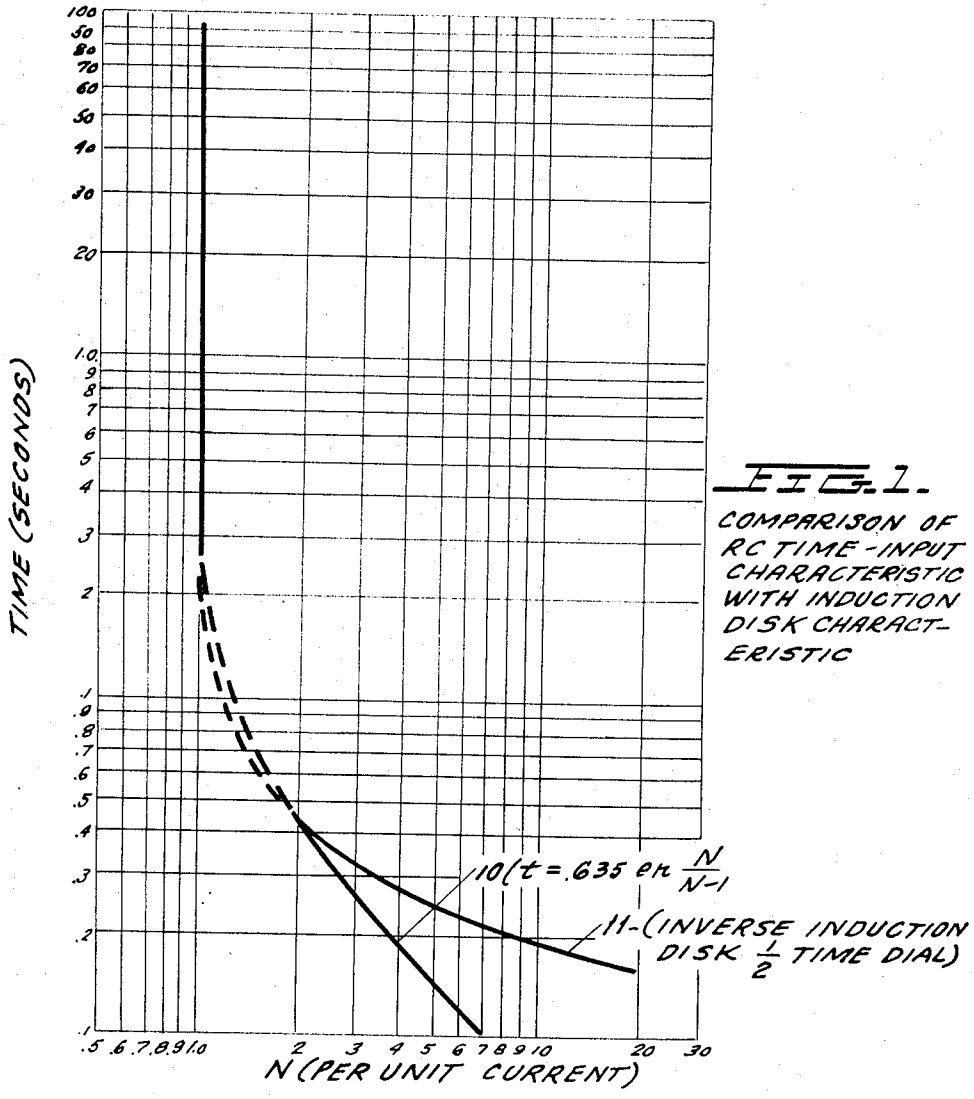


FIG. 1.

COMPARISON OF RC TIME-INPUT CHARACTERISTIC WITH INDUCTION DISK CHARACTERISTIC

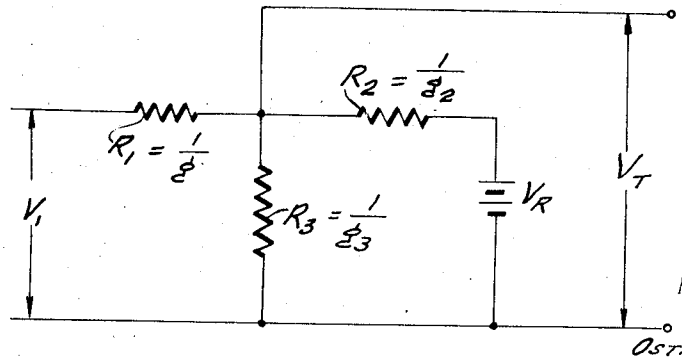


FIG. 2.

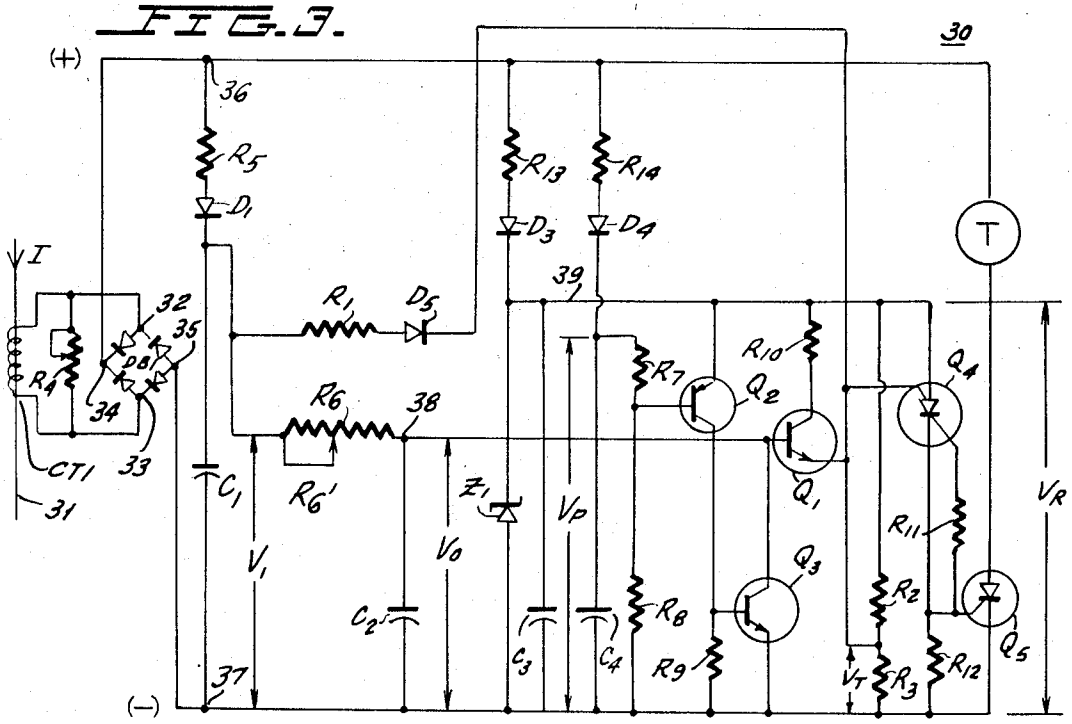
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STATIC TIME-OVERCURRENT RELAY

FIG. 3.



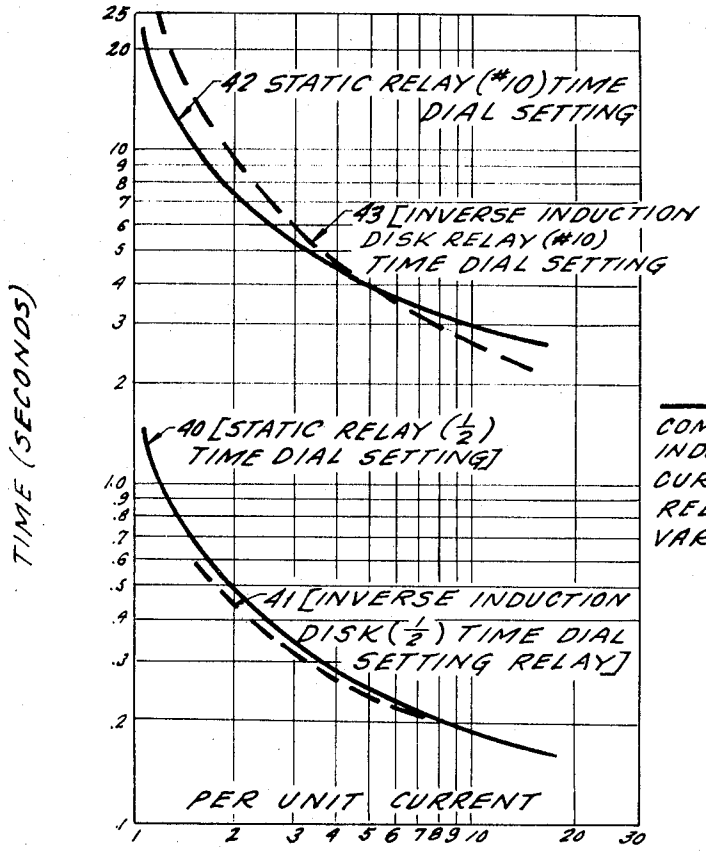


FIG. 4.

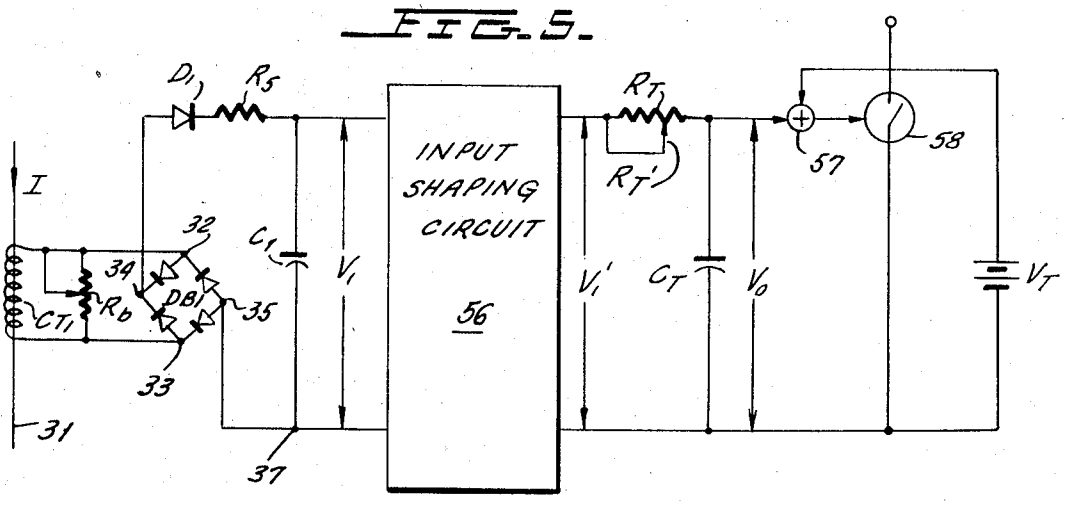
COMPARISON OF INDUCTION DISK RELAY CURVES AND STATIC RELAY WITH VARIABLE REFERENCE

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STATIC TIME-OVERCURRENT RELAY

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FIG. 5.



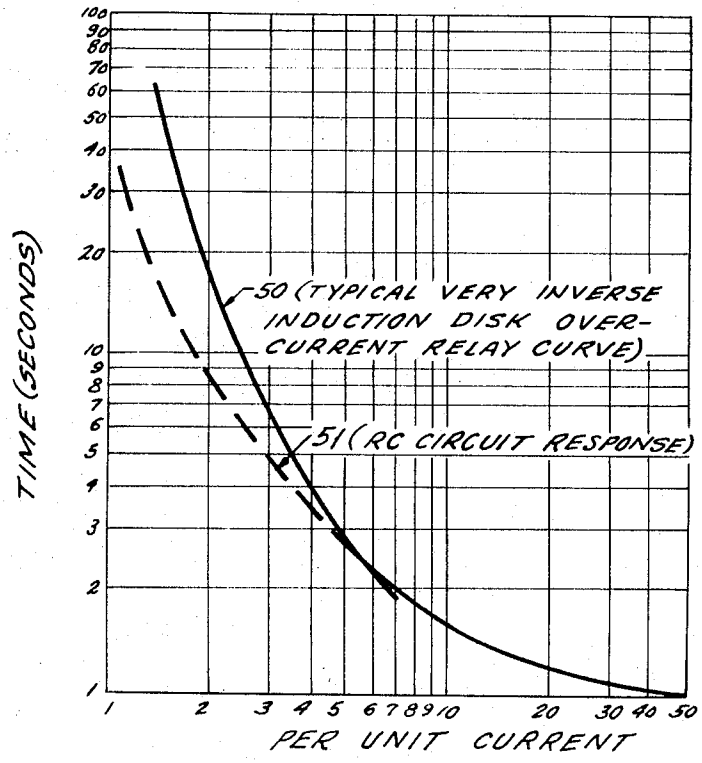


FIG. 5a.

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FIG. 6a.

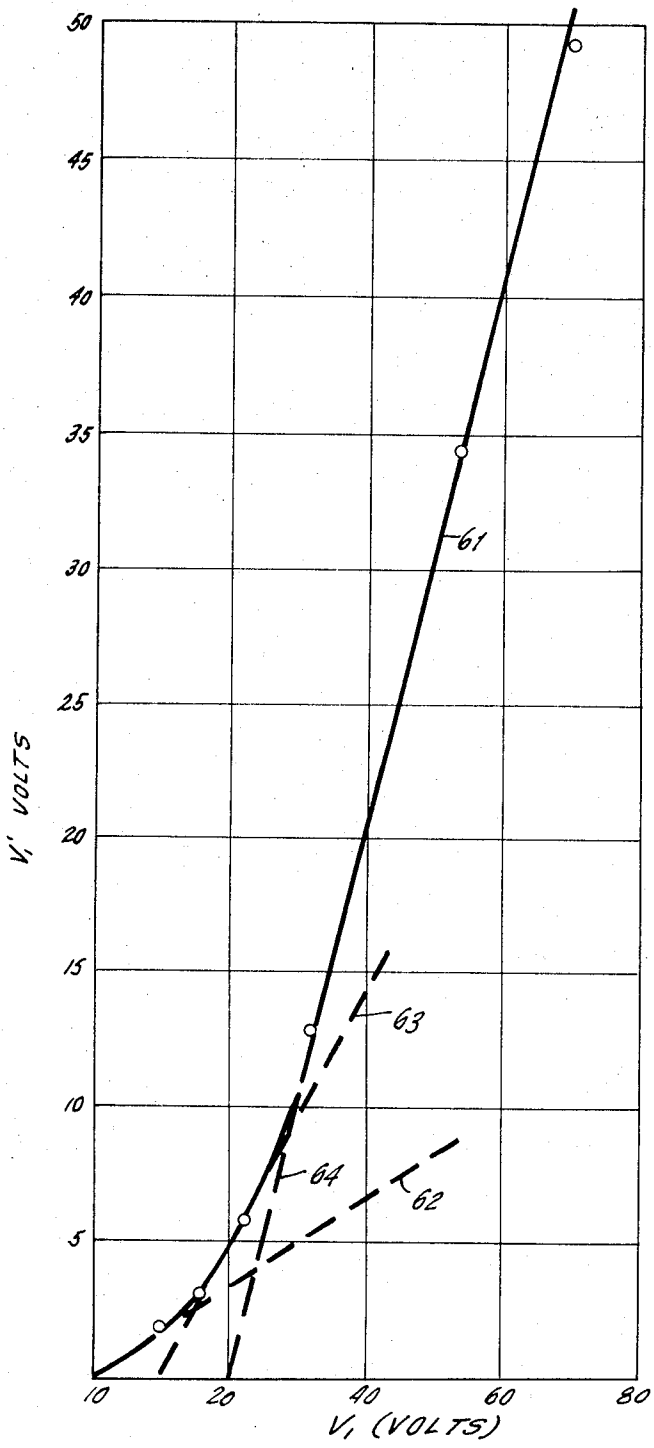
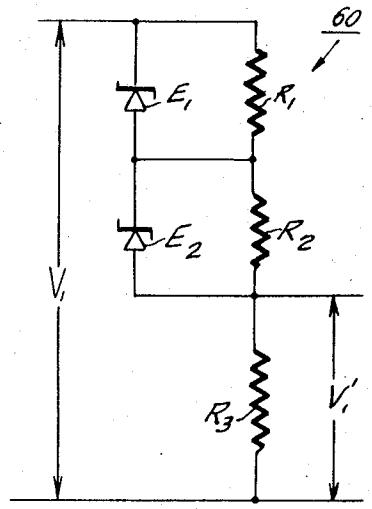


FIG. 6.



$$V_1' \approx \frac{R_3}{R_3 + (R_1 + R_2)} V_1$$

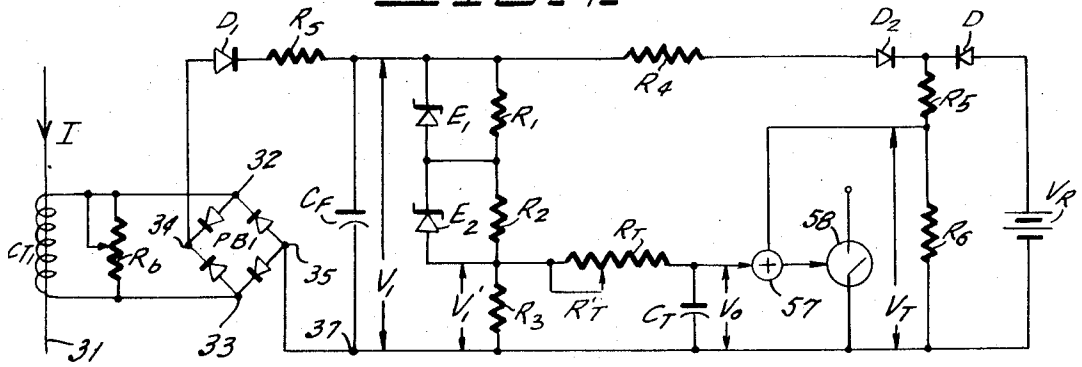
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FIG. 7


D1
R5
D2
D
R4
R5
E1
R1
I
32
CF
E2
R2
RT
58
R6
VR
CT
34
PB1
Rb
35
V1
V1'
R3
R'T
CT
Vo
57
VT
31
33
37

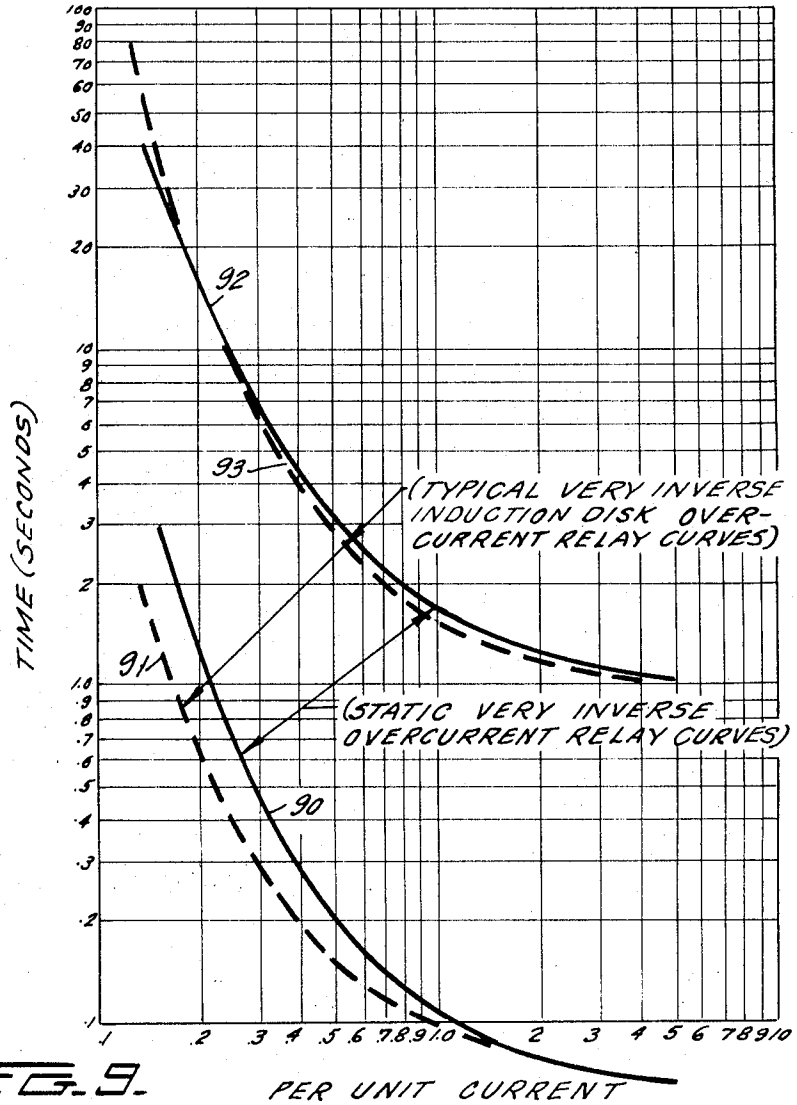

TIME (SECONDS)
92
93
(TYPICAL VERY INVERSE INDUCTION DISK OVER-CURRENT RELAY CURVES)
91
(STATIC VERY INVERSE OVERCURRENT RELAY CURVES)
90
PER UNIT CURRENT

FIG. 9

STATIC TIME-OVERCURRENT RELAY

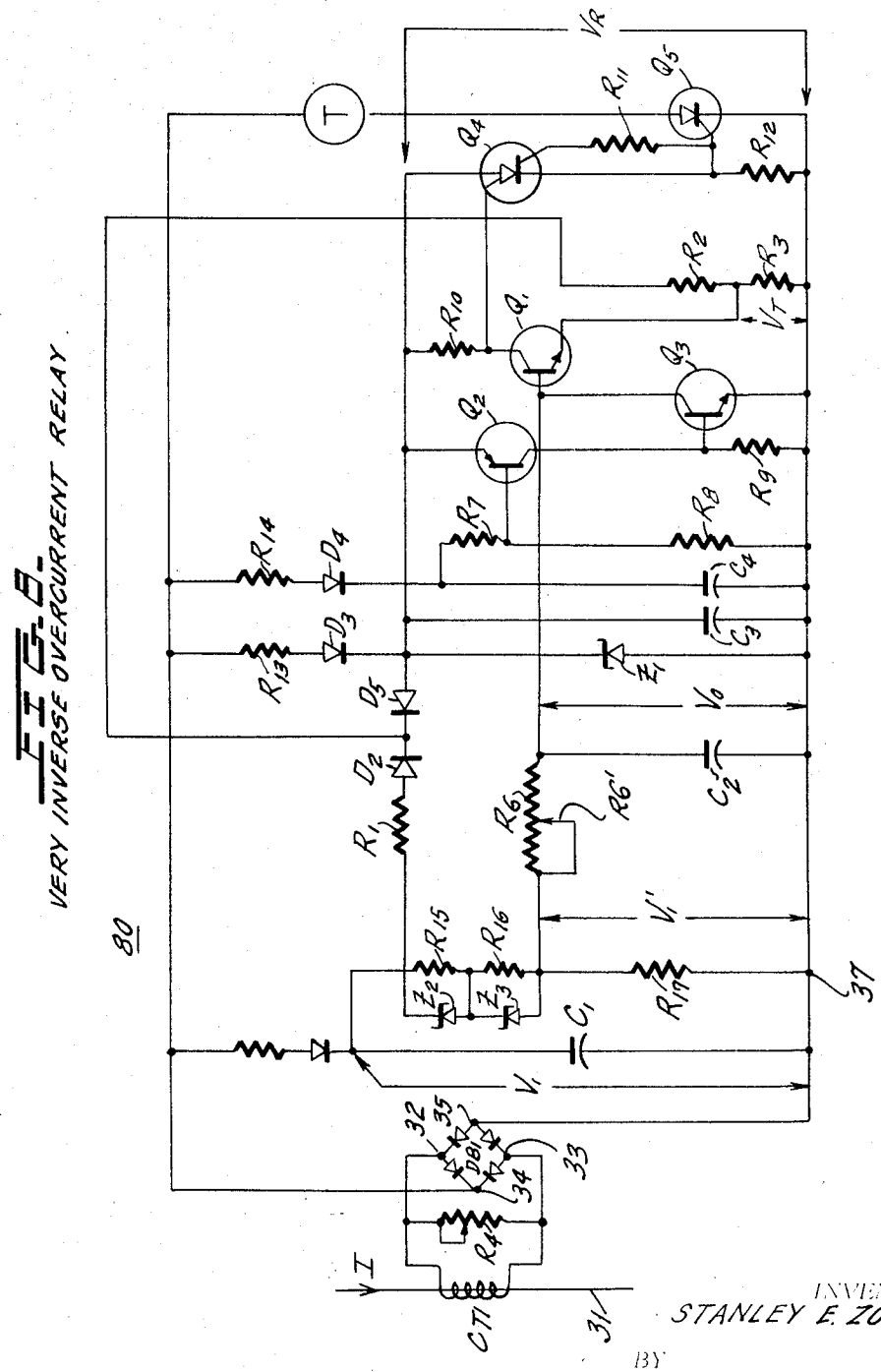


FIG. 8.
VERY INVERSE OVERCURRENT RELAY

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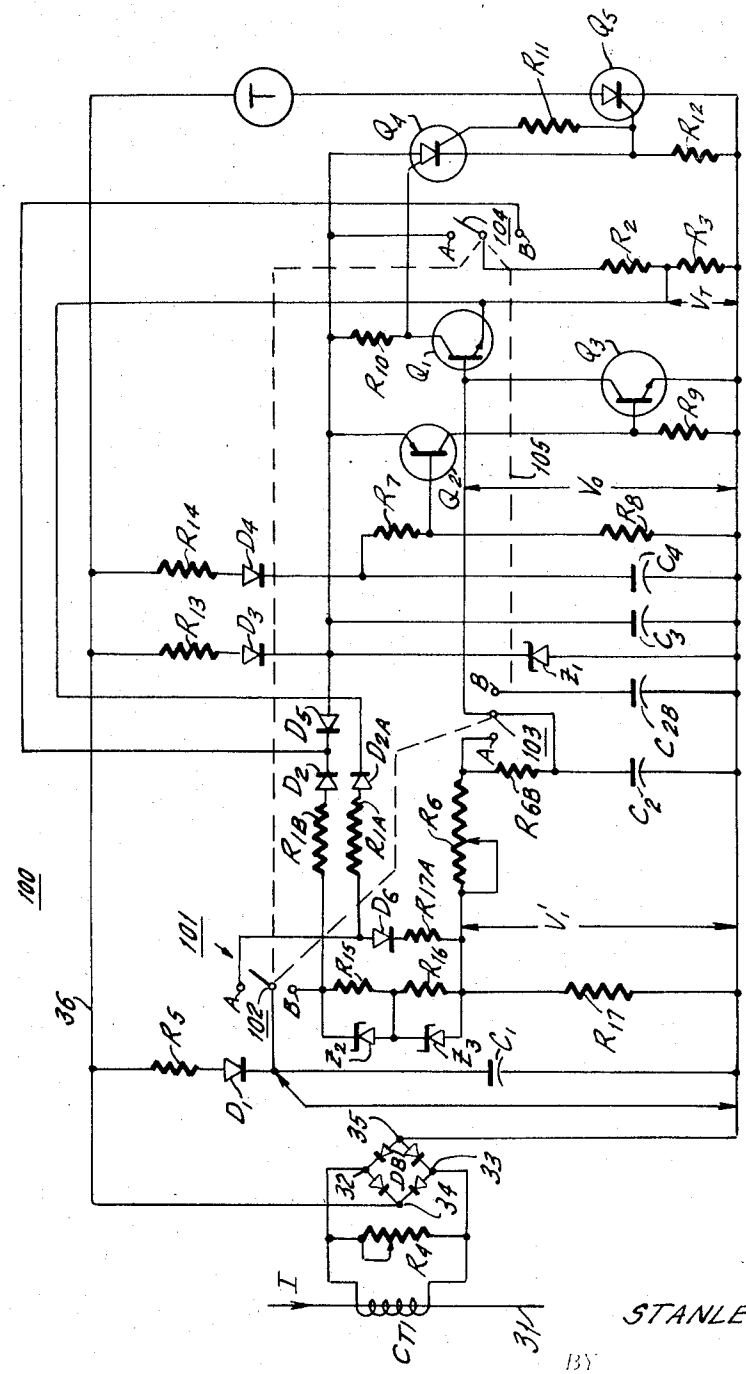
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FIG. 10

INVERSE/VERY INVERSE OVERCURRENT RELAY



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United States Patent Office 3,444,434
Patented May 13, 1969

3,444,434

STATIC TIME-OVERCURRENT RELAY

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Filed Mar. 6, 1967, Ser. No. 620,701
Int. Cl. H02h 3/08
U.S. Cl. 317—36 9 Claims

ABSTRACT OF THE DISCLOSURE

This invention teaches a static overcurrent relay, which category of static relays are conventionally comprised of solid state components designed to emulate inverse time-current characteristics. The most important function of such static overcurrent relays is the ability to substantially exactly follow the inverse time-current characteristic curves which are capable of being emulated only by electromechanical relays insofar as the present state of the art is concerned. The static relay device taught herein employs a variable reference voltage circuit which generates a variable reference output which, in turn, is linearly related to the input signal by a characteristic curve having a slope determined by the value of the resistance elements employed in the variable reference voltage circuit. This arrangement produces a static relay device yielding a time-current characteristic curve having a considerably flatter slope than that obtainable with conventional static relay devices, thereby more closely emulating the ideal time-current characteristic curve.

The instant invention relates to protective equipment employed in power distribution networks, and more particularly to a novel static relay having an inverse time-current characteristic curve so as to yield a tripping signal during a time t which is inversely proportional to current magnitude in the circuit being protected. Since it is not desirable to initiate a tripping operation when current magnitude is at a normal or slightly above normal level, a pickup circuit is conventionally employed to prevent "time-out" of the timing circuit until a predetermined threshold level is achieved. The use of a novel variable reference threshold level in conjunction with the pickup provides an all solid state relay design which is capable of producing a time-current characteristic curve which very closely resembles the time-current characteristic curves fully acceptable by the industry, and further is capable of maintaining operation adherence with the desired curve shape over wider operating ranges than have heretofore been possible with conventional electromechanical relay devices.

Electromechanical relay devices find wide acceptance in the power distribution field for use in isolating faults within power networks. Wide application of such relays can be attributed to the fact that they provide the most accurate timing characteristics and have the widest adjustable operating range that has been available up to the present time.

Such electromechanical relay devices which are exemplified by the rather widely used induction relay disk type, have been found to exhibit the following disadvantages:

Poor overshoot characteristics due to the fact that the movable element continues its movement due to its own inertia even after current is removed from the device. This disadvantageous characteristic affects the lowest time-dial settings of the device.

Such devices have been found to exhibit slow reset characteristics. If the relay is timing-out during the fault current condition and the fault current condition is removed before the tripping condition is reached by the relay, a long time period is required for the movable element to return to its rest or start position.

The operating characteristics of such relays are markedly affected by the presence of mechanical vibration and shock.

Electromechanical relays which have precision-made moving components are susceptible to malfunction due to the introduction of dust, dirt or other external influences.

Efforts to overcome the above enumerated disadvantages of electromechanical relays have led to the design of solid state time-current relay devices which have been made extremely practical due to the availability of low-cost, stable parameter solid state components. However, even though all of the above enumerated disadvantages may be eliminated through the use of solid state relay devices, these present-day designs have been incapable of exhibiting the desirable time-current characteristics which may be obtained only through the use of the electromechanical relay such as, for example, the induction disk relay category.

In those applications where it is desired to integrate overcurrent relays into an existing system, the relays must have characteristics which coordinate with those relays already in service within the system. Solid state relay designs typically employ an RC circuit as the time delay component of the relay. The input to the RC circuit is a D.C. voltage which is proportional to current in the line being protected. The RC circuit output is an exponentially rising voltage. The timing circuit output is applied to a voltage-sensitive switch which is designed to normally open when the input is below a given threshold level and which closes when the input exceeds the predetermined threshold. From a comparison of the solid state relay and electromechanical relay time-current characteristic curves, it can be seen that the rate of change of slope is much greater for increasing current as compared with the static relay curve whereby the static relay device "times out" faster for increasing current than the electromechanical relay device.

In order to flatten the slope of the static relay characteristic curve so as to substantially resemble the preferred characteristic curve presently obtainable only through the use of electrochemical relays, the instant invention is characterized by providing a novel variable reference voltage source for the static relay pickup circuit which serves to provide the flat response desired while, at the same time, yielding all of the other inherent advantages obtained through the use of static relay devices.

The instant invention is comprised of a timing circuit whose output rises exponentially in relationship to the input signal which is a D.C. rectified signal proportional to the current flowing in the circuit being protected. The timing circuit is prevented from timing out under control of the pickup circuit which disables the timing circuit in the presence of normal current flow, or current flow just slightly above normal.

The output of the timing circuit is coupled to switch means which is arranged to be normally in the cut-off state. When the voltage level applied to one input of the switch means from the timing circuit surpasses a predetermined threshold level, controlled by the variable reference circuit whose voltage is applied to another terminal of the switch means, the tripping relay is energized to cause tripping of a protective circuit breaker due to the persistent fault current condition.

The variable reference voltage circuit is comprised of circuit components arranged to generate a variable reference output which is linearly related to the input signal by a characteristic curve having a slope determined by the value of the resistance elements employed in the

circuit. Use of this variable reference voltage as one input to the voltage-sensitive switch means causes the static relay time-current characteristic curve to have a considerably flatter slope for increasing overload current in the circuit being protected.

There are numerous applications in the power network field wherein it is important to provide an inverse time-current characteristic curve which has very steep initial slope which eventually flattens out for increasing overload current. In order to obtain such a steeper initial slope in static relay devices, some means must be provided for altering the input voltage to the timing circuit to obtain the characteristic curve typically referred to as the very inverse time-current characteristic.

The instant invention contemplates the use of a voltage shaping circuit which alters the voltage output of the signal applied to the input of the timing circuit in order to achieve the desired very inverse time-current response.

To achieve this result, the instant invention provides a shaping circuit comprised of solid state components such as, for example, Zener diodes and resistors, which components provide a shaping curve which is a piecewise linear approximation of the voltage characteristic curve needed to yield the very inverse characteristic response over a substantially wide operating range. Whereas the shaping circuit provides the initial deep response, the addition of the variable reference circuit assures substantial flattening out of the time-current characteristic curve for increasing overload current magnitude.

In applications where it is desired to provide overcurrent relay means capable of yielding a time-characteristic curve having both an inverse and a very inverse curve shape, the instant invention provides manually (or optionally automatically) operable switch means for selectively enabling or disabling the voltage shaping circuit in order to respectively operate the relay to yield either an inverse or very inverse characteristic curve, thereby providing a simple one-design static relay device capable of being employed in a wide variety of applications.

It is, therefore, one object of the instant invention to provide a novel static relay device capable of operating in accordance with a time-current characteristic curve not heretofore possible with present-day static relay design.

Another object of the instant invention is to provide a novel static relay capable of operating in accordance with a predetermined time-characteristic curve wherein the slope of the curve is flattened for increasing current magnitude in the circuit being protected by means of a variable voltage reference circuit.

Another object of the instant invention is to provide a novel static relay device capable of operating in accordance with a very inverse time-current characteristic curve not heretofore possible through the use of static relays of present-day design.

Still another object of the instant invention is to provide a novel static overcurrent relay device employing a voltage shaping circuit which enables operation of the device in accordance with a very inverse time-current characteristic curve.

Yet another object of the instant invention is to provide a novel static overcurrent relay device employing a voltage shaping circuit which enables operation of the device in accordance with a very inverse time-current characteristic curve and wherein the flattening of the curve for increasing current magnitude in the circuit being protected is obtained through the use of a variable reference voltage circuit.

Still another object of the instant invention is to provide a novel static relay device employing switch means for controlling the operation of the relay in accordance with either an inverse time-current characteristic curve or a very inverse time-current characteristic curve so as to fit the specific environment for the static relay device.

These and other objects of the instant invention will become apparent when reading the accompanying description and drawings in which:

FIGURE 1 is a log-log plot showing a comparison of static relay and electromechanical relay time-current charauteristic curves.

FIGURE 2 is a schematic drawing showing a variable voltage reference circuit designed in accordance with the principles of the instant invention.

FIGURE 3 is a schematic diagram of an inverse overcurrent static relay employing a variable voltage reference circuit of the type shown in FIGURE 2.

FIGURE 4 is a log-log plot comparing the time-current characteristic curves for static relay and electromechanical relay devices.

FIGURE 5*a* is a log-log plot showing a comparison between inverse time-current characteristic curves obtained through the use of a conventional static overcurrent relay and a very inverse time-current characteristic curve obtained through the use of an electromechanical relay device.

FIGURE 5 shows a circuit partially in block diagram and partially in schematic form useful in describing the design and operation of the shaping circuit employed for the purpose of obtaining a very inverse time-current characteristic response.

FIGURE 6*a* is a plot showing the manner in which the desired wave-shaping curve is obtained through the piecewise linear approximation technique of the instant invention.

FIGURE 6 is a schematic diagram of a circuit which yields the curve of FIGURE 6*a* through the piecewise linear approximation technique.

FIGURE 7 is a schematic diagram of a static relay device employing the shaping circuit of FIGURE 6, wherein portions of the circuit are shown in block diagram form.

FIGURE 8 is a schematic diagram of a very inverse static overcurrent relay employing a voltage shaping circuit of the type shown in FIGURES 6 and 7 and further employing a variable voltage reference circuit of the type shown in FIGURE 2.

FIGURE 9 is a log-log plot showing a comparison of the very inverse time-current characteristic curves obtained through the use of static overcurrent relays and electromechanical relays.

FIGURE 10 is a schematic diagram of a static overcurrent relay capable of operation as either an inverse or a very inverse overcurrent relay through the use of switch means for selecting the desired time-current curve.

The use of an RC circuit as the time delay component in solid state relays is well known. Such timing circuits are set forth in detail in copending applications Ser. Nos. 403,208; 248,463 and 522,185, entitled Static Overcurrent Relay; Static Overcurrent Relay and Recloser Static Control Circuit, respectively, filed Oct. 12, 1964; Jan. 4, 1963 and Jan. 21, 1966, respectively, and assigned to the assignee of the instant invention.

The input voltage to the RC timing circuit is a D.C. voltage proportional to the current flowing in the circuit being protected. The timing circuit develops an output voltage which rises exponentially approaching the input voltage asymptotically. The output voltage of the RC timing circuit is impressed upon a voltage-sensitive switch which is disabled when the input is below a given threshold voltage and which is enabled when the input exceeds the predetermined threshold level. The time required to reach the threshold level as a function of input voltage is given by the equation:

$$t = T \ln \frac{V_1}{V_1 - V_T} \tag{1}$$

where

V_1 is the input voltage (and is proportional to current).
V_T=threshold voltage.

T=time-constant of the RC circuit.

Time-current characteristics are customarily plotted on log-log paper. In order to obtain such a plot, Equation 1 may be presented in per-unit form by setting the

$$V_1=NV_T$$

Making this substitution to Equation 1, we obtain:

$$t=Tln\frac{N}{N-1} \quad (2)$$

The per-unit curve **10** of Equation 2 is shown plotted in FIGURE 1 wherein $T=0.63$. Curve **11**, which is plotted along with curve **10** in FIGURE 1 represents the ½ time dial setting of a widely used electromechanical relay commonly referred to as the inverse induction disk relay.

A comparison of curves **10** and **11** shows that the slope of curve **10** is still quite steep in the region from 2.0–7.0 per-unit current, whereas the curve **11** over the same range (and even beyond this range) is found to flatten quite substantially providing an operating characteristic such that the timing-out period of the electromechanical relay is much longer than the timing-out of the static relay timing circuit for per-unit current values of greater than 2.0. Since curve **11** represents the desired time-current characteristics, it becomes necessary to provide some means to reduce the slope of the RC timing circuit response in order to more closely approximate the slope of the curve **11**.

Two phenomena already inherent in static current design which tend to reduce slope of the log-log plot are:

The A.C. signal output of the current transformer coupled between the circuit being protected and the input of the RC timing circuit is rectified and filtered to produce a D.C. voltage related to the A.C. current. This process results in an effective A.C. voltage which is not strictly linear with respect to A.C. input, and consequently produces a log-log plot having somewhat decreased slope;

Increasing values of relay input current cause saturation of the current transformer core. Consequently, the A.C. output voltage is not strictly linear with current input. The transformer, therefore, can be designed to saturate at a given input current so that the peak A.C. output signal which can be obtained is limited to thereby prevent an over-voltage on the components at high input levels. This technique also acts to decrease the slope of the log-log plot. Detailed description of such a current transformer is set forth in copending U.S. application Ser. No. 575,020 filed Aug. 25, 1966 and assigned to the assignee of the instant invention.

The above phenomena cause the static relay response curve to somewhat approach that of the inverse time-current curve obtained through electromechanical relays. However, substantially similar resemblance of the static relay and electromechanical relay curves can best be obtained through use of the following technique:

The Equation 1 threshold voltage V_T is a constant. If, however, V_T varies as a function of the input voltage to the RC circuit, this results in a time-current characteristic curve having a substantial decrease in slope of the log-log plot and consequently, a curve which is a very close approximation of the desired inverse time overcurrent curve is thereby obtained. This technique of linearly varying the value of threshold voltage hereinafter will be referred to as the "variable reference" technique.

For a wide range of current transformer saturation characteristics and D.C. filter designs, the value of V_T as a function of the D.C. input voltage V_1 can be approximated by a straight line of the form

$$V_T=mV_1+b \quad (3)$$

where V_T is the threshold voltage necessary to give the inverse response.

V_1 is the effective D.C. input to the RC circuit (and is related to current).

b and m are constants.

The linear relationship represented graphically by Equation 3 may be obtained through use of the circuit shown in FIGURE 2 having an input voltage V_1, an output voltage V_T, a reference voltage V_R and resistive elements R_1 through R_3 whose conductances are respectively equal to $1/g_1$ through $1/g_3$.

Solving the branch equations for the circuit of FIGURE 2, we obtain:

$$V_T=\frac{g_1}{g_1+g_2+g_3}V_1+\frac{g_2V_0}{g_1+g_2+g_3} \quad (4)$$

where

$$m=\frac{g_1}{g_1+g_2+g_3} \text{ and } b=\frac{g_2V_0}{g_1+g_2+g_3}$$

V_1 and V_T are defined above and V_0 is a constant reference voltage.

FIGURE 3 shows a static overcurrent relay circuit **30** employing a variable reference circuit of the type shown in FIGURE 2.

The static overcurrent relay circuit **30** is adapted to monitor the current I flowing in the circuit **31** being protected. The conductor **31** acts as the primary winding of a current transformer CT1. Current flow therethrough establishes an output voltage across the secondary winding of the current transformer which is applied across terminals of an adjustable burden resistor R4, made adjustable for the purpose of limiting current magnitude in the output circuit of the current transformer. The A.C. voltage drop developed across burden resistor R4 is impressed across the input terminals **32** and **33** of a full wave rectifier diode bridge DB1. The diode bridge develops a full wave rectified voltage at its output terminals **34** and **35** which, in turn, are coupled to the positive and negative busses **36** and **37**, respectively. The full wave rectified D.C. voltage is further filtered by the series connected components comprised of resistor R5, diode D1 and capacitor C1. The charge developed across capacitor C1 establishes the voltage V_1 across its terminals. Resistor R5 limits the surge current through this series connected circuit.

The voltage V_1 is applied as an input signal to an RC timing circuit formed by a variable resistor R6 and a shunt connected capacitor C2. The output voltage V_0 of the timing circuit rises exponentially causing the output voltage V_0 appearing at their common terminal **38** to asymptotically approach the voltage value V_1 after a predetermined time period determined by the RC time constant of the timing circuit.

A fixed reference voltage V_R is established by Zener diode Z1 which is connected in series with diode D3 and resistor R13 between the positive and negative busses **36** and **37**. A capacitor C3 connected across the terminals of Zener diode Z1 filters or smooths the wave form of the reference voltage V_R, while diode D3 improves the filtering operation by preventing the discharge of capacitor C3 into adjacently connected circuit components.

The voltage V_0 appearing at the output of the RC timing circuit is applied to the base electrode of transistor Q1. The emitter of Q1 is referenced to a voltage V_T. The voltage V_T assumes a value in accordance with the Equation 4, the slope of which is determined by the variable reference circuit components R1, R2, R3 and the applied voltaegs of which are the values V_1 coupled to one terminal of resistor R1 and V_R coupled across the series connected resistors R2 and R3. Diode D5 coupled in series with resistor R1 prevents any backward current flow toward capacitor C1.

When the output voltage V_0 across capacitor C2 exceeds the reference voltage V_T, the base electrode of transistor Q1 becomes more positive than the emitter electrode, causing current to flow in the base of Q1. This turns transistor Q1 on, causing a collector current flow which, in turn, develops a voltage drop across resistor R10.

The terminals of resistor R10 are coupled across the anode and anode gate electrodes of a silicon controlled switch Q4. The voltage drop being applied across the anode and anode gate of Q4 causes the silicon controlled switch to turn on, and thereby establish a current flow through Q4 and resistor R12 to negative bus 37. The terminals of resistor R12 are coupled between the anode and anode gate of a silicon controlled rectifier Q5. The voltage drop across resistor R12 has a fast rising leading edge, causing the silicon controlled rectifier Q5 to turn on and energize trip coil T. Resistor R11 is connected between the cathode gate of silicon controlled switch Q4 and the anode gate of silicon controlled rectifier Q5 to carry leakage current and to prevent the turn-on of Q4 due to any ambient temperature effects.

In order to prevent the RC timing circuit from timing-out during normal current, or slightly above normal current conditions in the conductor 31 being monitored, a pickup circuit is provided, which circuit is comprised of the components R7–R9, R14, C4, D4 and Q2 and Q3. The pickup circuit functions to prevent capacitor C2 from charging until the input current reaches the desired fault level. The series connected components comprised of resistor R14, diode D4 and capacitor C4 establish a filtered voltage V_T across capacitor C4. The voltage V_T is applied across the terminals of a voltage divider circuit comprised of series connected resistors R7 and R8. The common terminal of resistors R7 and R8 is connected to the base electrode of transistor Q2. The emitter of (P-N-P) transistor Q2 is coupled to the voltage reference V_R bus 39. The values of resistors R7 and R8 are chosen such that when the fault current I reaches a predetermined fault threshold level, the voltage at the base electrode of transistor Q2 equals the reference voltage V_0. If the current remains below this level, current flows in the base of Q2 and Q2 conducts, causing a voltage drop across the collector connected resistor R9. This voltage drop is coupled across the base and emitter electrodes of transistor Q3, thereby making the base electrode more positive than the emitter electrode so as to turn on Q3. Q3, in the conducting state, is a virtual short which is applied directly across the terminals of capacitor C2, thereby preventing C2 from charging.

If the current I flowing in conductor 31 exceeds the threshold fault level, the base of Q2 becomes reverse biased driving Q2 into cut-off, thereby removing the voltage drop from collector connected resistor R9 so as to turn off transistor Q3. Turn-off of Q3 moves the virtual short circuit from the terminals of capacitor C2, allowing it to charge toward the input voltage level V_1. The fault level is set by means of the variable burden resistor R4, since this resistance value determines the voltage level developed across the secondary of the current transformer corresponding to the input primary current I.

FIGURE 4 shows the resulting time-current characteristic curves obtained through the circuit of FIGURE 3, which curves are compared with two time dial settings of a typical inverse induction disk relay. The circuit of FIGURE 3 has been designed to yield a time-current characteristic curve which is designed to substantially resemble the (½) time dial setting of a typical induction disk relay device.

As shown in FIGURE 4, curve 40 represents the (½) time dial setting of a static overcurrent relay of the type shown in FIGURE 3. Curve 41 represents the inverse induction disk relay curve for a (½) time dial setting. It can clearly be seen that these curves very closely resemble one another.

Curve 43 represents the time-current characteristic curve for an inverse induction disk relay having a (10) time dial setting, whereas 42 represents a (10) time dial setting for a static relay of the type shown in FIGURE 3. Again, it can be seen that there is a very close resemblance between the two curves.

The time constant of the RC circuit is adjusted by varying the adjustable resistor R6 having an adjustable arm R6′ in order to select curves between the (½) and the (10) time dial curves. Consequently, in the case of the static overcurrent relay device 30 shown in FIGURE 3, the curve 42 is displaced from the curve 40 by a fixed multiple amount, and the case of curves 40 and 42 are identical to one another. From an examination of curves 41 and 43, it can be seen that exactly uniform displacement between the curves is not obtained for changing time dial settings. This is due to the fact that the inertial effects of the electromechanical relay disk member prevent such induction disk relay from being capable of yielding uniform curve displacement.

Very inverse static overcurrent relay

A second type of induction disk time-overcurrent relay which finds widespread use is commonly referred to as the very inverse-type relay. The log-log plot of its characteristic is shown in FIGURE 5*a* as curve 50. It can clearly be seen that the curve 50 has a much steeper initial slope than does the initial portion of an RC circuit response curve 51 which represents the response of an RC timing circuit in accordance with Equation 2.

In order to make the static RC timing circuit applicable for use in simulating the curve of the very inverse-type relay, means must be provided for modifying the input voltage to the timing circuit so as to yield the desired time response. In designing the required voltage shaping circuit, the degree of current transformer saturation and the effectiveness of the filtering of the rectified input must be taken into account, as was previously explained with regard to the phenomena which are inherently present in a static circuit design.

FIGURE 5 shows a static overcurrent relay circuit 55 containing those elements necessary to construct a very inverse response relay wherein like circuit components as between FIGURES 3 and 5 are designated with like numerals. As was previously the case, the primary current I applied to current transformer CT1 develops a secondary current which, in turn, develops a voltage drop across burden resistor R*b*. The A.C. voltage developed across burden resistor R*b* is full wave rectified by diode bridge DB1, appearing at the output terminals 34–35. The series connected elements comprised of diode D_1, resistor R5 and capacitor C1, further rectify and filter the D.C. voltage to establish a D.C. voltage V_1 related to the primary current I in the same manner as was previously described.

The voltage V_1 is applied to the input terminals of an input shaping circuit 56 to generate at its output terminals a shaping circuit output voltage V_1' which is applied to the timing circuit comprised of adjustable resistor R_T and capacitor C_T in order to produce an output voltage V_0 having the desired very inverse time-current response. Resistor R_T of the RC timing circuit is made adjustable through its arm R_T' in order to provide a plurality of time dial adjustments for the static relay circuit.

The output voltage V_0 of the timing circuit is applied to one input terminal of a normally open voltage-controlled switch represented by the symbol 57. Switch 57 closes when the output voltage V_0 exceeds the fixed reference voltage V_T applied to another input terminal of switch 57. When the output voltage V_0 exceeds level V_T, switch 57 operates a relay means 58 to provide a tripping signal for isolating the circuit being protected from the power network:

$$V_T = V_1'\left(1-\epsilon^{\frac{-t}{T}}\right) \qquad (5)$$

where $R_T C_T = T$.

By assigning convenient values for V_T and T, values of V_1' can be extracted for values of time (t) taken from the desired very inverse time-current curve.

These values paired with the V_1 values for corresponding per-unit currents give the response required of the shaping circuit.

FIGURE 6 shows a circuit **60** comprised of the resistor elements **R1** through **R3** and the Zener diodes Z_1 and Z_2 which form a circuit which yields the desired voltage shaping characteristics. The unique feature of the circuit **60** is that it is capable of yielding the desired curve **61**, shown in FIGURE 6*a*, by a piece-wise linear approximation technique in which the curve is colsely approximated by three (3) straight line segments **62**, **63** and **64**, shown in dotted line fashion. Each of the segments are of the form:

$$V_1' = mV_1 - b \tag{6}$$

where m and b are constants.

Each of the straight line segments can be represented by a circuit having a constant voltage device and resistors to yield each linear approximation segment of the curve. The circuit **60** of FIGURE 6 has been designed to generate the curve **61** shown in FIGURE 6*a*. In the circuit **60**, the constant voltage devices are Zener diodes Z_1 and Z_2. The parameters of circuit **60** have the following values in order to generate the piecewise linear segments of FIGURE 6*a*:

$$\begin{aligned} E_1 &= E_2 = 10 \text{ volts} \\ R_1 &= 3.08\ R_3 \\ R_2 &= 1.13\ R_3 \end{aligned} \tag{7}$$

Considering the operation of circuit **60** from a non-rigorous viewpoint, V_1 is related to V_1' by the following equation:

$$V_1' \approx \frac{R_3}{R_3 + (R_1 + R_2)} V_1 \tag{8}$$

As the input voltage V_1 increases, the Zener diodes selectively (substantially) short out resistors **R1** and **R2** to move from curve **60** at approximately a value of 15 volts to curve **63** and to move from curve **63** at a value of approximately 25 volts to curve **64**. The piecewise linear approximation technique described above allows the circuit of FIGURE 5 to yield the very inverse characteristic response over a substantially wide per-unit range. However, for very high values of per-unit current, the desired characteristic response flattens out, and the approximation remains steep. This condition can be corrected by employing the variable reference technique previously described. The resulting static overcurrent relay circuit **70** is shown in FIGURE 7 which is substantially similar to the circuit **65** of FIGURE 5 with the shaping circuit **56** being replaced by the circuit components Z_1, Z_2, **R1**, **R2** and **R3** and with the fixed reference voltage V_T being replaced by the fixed voltage source V_R, the diodes D_2 and D_3 and resistors **R5** and **R6**. The operation of the circuit of FIGURE 7 is substantially the same as that shown in FIGURE 5.

For values of per-unit current I below a particular value I_A, V_T is a constant value equal to $V_R R_6/(R_5+R_6)$.

The circuit is so designed that for $I < I_A$

$$\frac{R_5 + R_6}{R_4 + R_5 + R_6} V_1 < V_R$$

For values of I greater than I_A,

$$V_T = \frac{R_6}{R_4 + R_5 + R_6} V_1$$

This type of variable reference allows the circuit to have the desired very inverse time current characteristic over the total published range of the induction disk relay.

The operation of the very inverse static overcurrent relay **80** is substantially identical to the inverse overcurrent relay circiut **30** shown in FIGURE 3, except that the voltage shaping circuit comprised of Zener diodes Z_2 and Z_3 and the resistors **R15** through **R17** vary the voltage signal applied to the input terminal of the timing circuit resistor **R6** in accordance with the curve **61** shown in FIGURE 6*a* so as to yield the time-current characteristic having a very steep slope for initial per-current values. The initial steep slope is flattened out through use of the variable reference voltage technique manifested by the variable voltage reference circuit comprised of the diodes D_2 and D_5 and resistors **R1**, **R2** and **R3**.

The time-current characteristics obtained for the circuit **80** of FIGURE 8 are shown in FIGURE 9 compared with similar curves representing the time-current characteristics of typical induction disk overcurrent relay circuits. Curve **90** represents the time-current characteristic response of static overcurrent relay circuit **80** having a (½) time dial setting. Curve **91** represents the time-current characteristic curves for a typical induction disk overcurrent relay having a (½) time dial setting. Curves **92** and **93**, respectively, represent the time-current responses for static relay circuit **80** and typical induction disk overcurrent relays wherein both relay types have a time dial setting of (10). The curves **90** through **93**, shown in FIGURE 9, are plotted for relay devices wherein the circuit **80** was designed to fit the No. 10 time dial curve of the very inverse electromechanical relay device. Again, it can be seen that the changing time constant (resistor **R6**) of the static relay circuit **80** which yields the required time dial adjustment, displaces the static relay curves **90** and **92** by a constant multiple amount. No constant multiple displacement is possible in electromechanical relay devices due to the inertia of the moving component of the electromechanical relay which affects the shape of the lower time dial curves **90** and **91**, shown in FIGURE 9.

Combined inverse-very inverse static overcurrent relay

Considering the similarity in circuitry between the inverse relay **30** of FIGURE 3 and the very inverse relay circuit **80** of FIGURE 8, a logical design extension is that of combining the two response characteristics into a single circuit having the desired inverse or very inverse characteristics which are selectable by means of either a manually or automatically operated switch.

FIGURE 10 shows a combined inverse and very inverse static overcurrent relay circuit **100** substantially identical in design and function to the static relay devices **30** and **80** shown in FIGURES 3 and 8, respectively. In FIGURE 10, those components which function only in the inverse characteristic circuit are suffixed with the letter A. In a like manner, components which function only in the very inverse characteristic circuit are suffixed with the letter B.

Selective switching for the desired time-current characteristic curves is performed by means of switch **101** which is a three-pole double-throw switch comprised of the poles **102**, **103** and **104** mechanically ganged together. The mechanical linkage is schematically represented by the dashed line **105**. When the switch **101** is in the A position, the switch movable poles are engaged with their associated stationary terminals A. In this position, the variable reference circuit consists of resistors R1A, diode D_{2A}, and resistors **R2** and **R3**. The variable reference voltage circuit functions to give the proper emitter voltage V_T at the emitter of transistor **Q1** in the same manner as was explained previously with reference to the inverse static relay **30**. In addition thereto, the RC timing circuit feeds a voltage V_1' input terminal to resistor **R6**, which voltage is proportional to V_1. The voltage divider comprised of resistors **R17A** and **R17** is employed so that the voltage V_1' has the same value at one (1) per-unit current regardless of the position of switch **101**.

In the selection of either the inverse or the very inverse characteristic response, the switching action (i.e., the operation of switch **101**) must modify the RC timing circuit time constant to appropriately position the curves **40** and **42** of FIGURE 4 and **90** and **92** of FIGURE 9. The design of the static relay **100** shown in FIGURE 10, requires a larger time constant for the very inverse circuit arrangement than that required in the inverse circuit arrangement. In position A the switch **101** inserts capacitor **C2** and shorts out the resistance **R6B**. In this position

the inverse timing circuit then consists of resistor R6 and capacitor C2.

When the switch 101 is placed in the position B the timing resistor is made up of resistances $R6+R6B$. In addition thereto, capacitor C2B is coupled in parallel with capacitor C2 thereby increasing the capacitance of the circuit to the sum of C2 and C2B so as to increase the time constant and thereby to properly position the very inverse response curves in the manner shown in FIGURE 9.

Resistance R6B has a novel circuit function in that the addition of R6B to the circuit allows the calibration of adjustable resistor R6 to be the same regardless of the switch position. Thus, with switch pole 103 in the A position, R6B is shorted out so that the time constant is dependent upon the R6 and C2 parameters. With switch pole 103 in the B position R6B and C2B are added into the circuit to provide the necessary offsetting effects to permit the dial settings of the resistor R6 for both the inverse and very inverse circuits to be identical.

It can therefore be seen from the foregoing description that the instant invention provides a novel variable reference circuit technique for use in static relay devices to provide the desired flattening of the time-current response curve slope so as to permit the design of a static relay having a time-current characteristic curve which is completely compatible with present electromechanical relay design. Very inverse response characteristics are obtainable in static relay devices through the use of a novel shaping circuit to provide steep initial response in the time-current characteristic curve. Flattening of the very inverse characteristic response may be obtained in a similar manner through the use of the above mentioned variable voltage reference circuit. Combining the above techniques into a single static overcurrent relay further comprised of suitable switch means yields a static relay structure which is capable of being used to provide either inverse or very inverse characteristic response thereby broadening the applications of such devices in power networks.

Although there has been described a preferred embodiment of this novel invention, many variations and modifications will now be apparent to those skilled in art. Therefore, this invention is to be limited, not by the specific disclosure herein, but only by the appending claims.

What is claimed is:

1. For use in protecting current distribution networks, static overcurrent relay means responsive to overcurrent conditions for operating circuit protective devices after a predetermined time period and before the network is damaged comprising first means for generating a D.C. voltage representative of the current being monitored in said network; second timing circuit means coupled to said first means for generating a predetermined voltage level after a predetermined time delay; third pick-up circuit means coupled to said first means and normally inhibiting the operation of said second means until the output voltage level of said first means achieves a predetermined magnitude; fourth variable reference circuit means coupled to said first means for generating a reference voltage linearily related to the voltage applied to its input; fifth voltage sensitive switch means coupled to said second means and said variable reference circuit means for energizing a circuit protective device when the output voltage of said second means achieves the level of said fourth means output.

2. The device of claim 1 wherein said fourth means generates a reference voltage V_R related to the voltage signal V_1 applied to the input of said fourth means by the equation $V_R=mV_{IN}+b$, where m and b are constants.

3. The device of claim 1 wherein said fourth means is comprised of a plurality of resistors connected in series between the output of said first means and ground potential; a common terminal between two of the series connected resistors being connected to one input of said fifth means; at least one Zener diode being coupled in parallel across one of the series connected resistors connected between said common terminal and the output of said first means.

4. The device of claim 3 wherein said fifth means is a transistor having emitter, base and collector electrodes; said common terminal of said fourth means being coupled to the emitter of said transistor; the output of said second means being coupled to the base of said transistor.

5. For use in protecting current distribution networks, static overcurrent relay means responsive to overcurrent conditions for operating circuit protective devices after a predetermined time period and before the network is damaged comprising first means for generating a D.C. voltage representative of the current being monitored in said network; second timing circuit means coupled to said first means for generating a predetermined voltage level after a predetermined time delay; third pick-up circuit means coupled to said first means and normally inhibiting the operation of said second means until the output voltage level of said first means achieves a predetermined magnitude; fourth means coupled between said first means and ground potential for establishing a reference voltage; fifth voltage sensitive switch means coupled to said second means and said fourth means for energizing a circuit protective device when the output voltage of said second means achieves a second predetermined magnitude established by said reference voltage; sixth signal shaping circuit means coupled between said first means and said second means for modifying the signal applied to said second means to generate a time-current response curve having a very steep initial response.

6. The device of claim 5 wherein said sixth means includes means for generating an output signal whose voltage increases in a non-linear fashion with increasing voltage of the signal applied to the input of said sixth means.

7. The device of claim 5 wherein said sixth means is comprised of a plurality of series connected resistors coupled between said first means and ground potential; a common terminal between two of said series connected resistors being coupled to the input of said timing circuit means; at least one Zener diode being coupled in parallel across one of the series connected resistors connected between said first means and said timing circuit means.

8. The device of claim 5 wherein said fourth means includes means for generating a variable reference voltage level V_R related to the voltage V_{IN} of the signal applied to said fourth means by the equation $V_R=mV_1+b$, where m and b are constants.

9. The device of claim 8 further comprising switch means for selectively enabling said sixth means when in a first position and for disabling said sixth means when in a second position to control the initial slope of the time-current response curve.

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