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COMPARISON AND OPTIMIZATION OF REVERSE CURRENT SWITCHES

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INTRODUCTION

Reverse current electrolysis switches have been used for many years to minimize stray current corrosion damage to underground metallic structures. Various types of systems have been utilized with varying degrees of success.[1,2,3,4] During the past thirty years the power electronics industry has come of age resulting in new, more reliable, higher power devices for the corrosion engineer to utilize in the fabrication of reverse current switches. This paper will examine the need for such units as well as compare and optimize their usage.

NEED FOR REVERSE CURRENT SWITCHES

Figure 1 indicates the various possible classifications of stray current sources. Stray current sources can be defined as electrical currents in the earth which can cause deleterious effects to equipment and/or personnel.

Stray current sources can be divided into two categories as depicted in Figure 1. Dynamic sources can be defined as current sources that change polarity, and/or magnitude as viewed from a fixed reference point while static sources are ones that have constant magnitude and polarity.

Regardless of the type of stray current source the effects of these sources can be catastrophic to underground metallic structures.

Although H.V.A.C. systems have been included in Figure 1, the majority of the discussion will be limited to D.C. sources and very low frequency A.C. sources ($\ll 60H_z$).

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The most significant effect of stray currents is the corrosion of underground metallic structures. At locations that the stray current discharges through the metal-electrolyte interface dissolution of the metallic structure occurs. The amount of dissolution of a metal is a function of the magnitude of current discharged, the time of discharge, the discharge current density as well as the type of metal involved. An approximate value of 10 kg per amp year of current discharge is assumed for mild steel. The corrosion rate is inversely proportional to the discharge surface area.

At the locations where the current is received by the structure cathodic protection results. Any stray current received by a structure must return (sinked) to the source. All stray current mitigation schemes attempt to discharge this current from the structure to the source or expendable electrodes (anodes) through an electronic path as opposed to the electrolytic path. As a result, assuming that all of the stray current is discharged in this manner no additional corrosion of the structure will occur.

Reverse current switches are required in series with the metallic path if dynamic stray currents are present and have a tendency to reverse polarity. The effects of static stray current sources can be minimized without the use of reverse current switches.

MITIGATION OF STATIC STRAY CURRENT SOURCES

The usual method to mitigate static stray current is the simple installation of a wire interconnected between the structure and stray current source. Unfortunately, the wire conducts in both directions negating the effectiveness of this device in areas of dynamic stray currents. However, this technique is utilized extensively to mitigate the effects of static stray current sources such as conventional cathodic protection systems.

The premise for use of this technique is that the magnitude and direction of current flow is constant and the bond wire is only installed at areas of current discharge and not current pickup locations. Any change in the magnitude and/or direction of the current source may cause damage to the structure that is supposed to be protected from the stray currents.

IDEAL REVERSE CURRENT SWITCHES

Assuming the stray current source is of a dynamic nature the ideal reverse current switch would have infinite impedance to current flow in one direction and zero impedance to current flow in the opposite direction.

As a result, the switch can be installed so as to allow only a undirectional drain of current from the structure. This is important as any current flow in the opposite direction entering the structure may return to the source through another electrolytic path resulting in dissolution of the metal. The characteristics of the ideal switch are shown in Figure 2.

It should be noted that this characteristic I vs V (I-V) curve should be exhibited by the switch and connecting wire. As a result it is imperative that the impedance of the connecting hardware be as low as possible. Figure 3 depicts the actual I-V characteristic of an ideal switch with various interconnecting cables (3 meters long). This data is for comparison purposes only as several of the wire sizes are not rated for the required ampacity.

TYPES OF REVERSE CURRENT SWITCH

Various types of switches have been utilized and several types are commercially available.

ELECTROMAGNETIC SWITCHES

One of the first unipolar type reverse current switch suitable for use on structures subject to dynamic stray currents was the electromagnetic switch or controlled relay. Figure 4 depicts a typical installation of a electromagnetic switch. This type of switch performed reasonably well subject to inherent limitations.

Sense electronics are utilized to close the relay whenever the structure becomes more positive than the ground point. The full load current passes through the relay contact and as a result the contact must be capable of conducting the maximum current expected. Unless the relay is a special polarized type, A.C. power is required to power the relay reducing the possible locations where this device can be utilized. In order to prevent chatter in the relay the electronics must contain a hysteresis characteristic as shown in Figure 5. This results in a somewhat non-ideal I-V characteristic. Unless the load current is greater than the contact rating damage should not result to the contacts. The only time the contacts are opened or closed is when the potential across the relay is approximately zero. As a result sparking of the contacts should not occur.

There are two major disadvantages of this type of switch. Unfortunately the relays are designed for a limited number of open and close cycles resulting in a finite lifetime. Secondly slow response of the switching mechanism can be a serious limitation. If reversal of current flow occurs suddenly the relay will conduct current from the ground point to the structure (opposite than desired) until the relay can open resulting in possible corrosion damage to the structure. If the frequency response of the switch is less than the frequency of the stray current the majority of stray current will not discharge to the ground point.

DIODE SWITCHES

The ideal diode has the identical characteristics of the ideal reverse current switch. The ideal diode should conduct infinite current in one direction with zero impedance while in the other direction zero current should flow even with infinite voltage applied in the reverse direction.

Unfortunately, the ideal diode does not exist except in text books. Figure 6 shows the typical I-V characteristics of various types of diodes. As can be ascertained none of the diodes are ideal. Each type has been optimized for a typical characteristic. Schottky and copper oxide diodes have been optimized for low forward voltage drop at the expense of poor reverse voltage breakdown characteristics. Silicon diodes provide high forward current capabilities and high reverse voltage breakdown but have the highest forward voltage drop.

A typical application of a diode as a reverse current switch is shown in Figure 7.[2] Whichever diode is selected, it is important to realize the limitations of the device.

The rated forward current capacity of a diode as stated in data sheets is the average current allowable through the diode assuming it is operating as a single phase 60 Hz rectifier. The limiting value of current is defined by the amount of heat generated in the diode as excessive junction temperatures will destroy the diode. The power dissipated in the diode during conduction is I^2_{rms} x R or V x I_{rms} where R and V are defined as the incremental resistance and forward voltage drop of the diode respectively. Both R and V are non-linear function of current resulting in the power dissipation being a function of the current waveform. Further the device has a very small heat capacity and as a result the temperature of the diode junction varies with the instantaneous current.

Assuming the average current through the diode is the same for D.C. and rectangular wave operation the junction temperature resulting from rectangular wave operation will contain temperature peaks well above that of D.C. operation. In order not to violate the maximum junction temperature condition the average current ratings for rectangular wave operation must be derated.

The derating of the diode below the D.C. value is greater when the current pulses are parts of a sine wave than in the case of the rectangular wave. This is due to the higher form factor of the sinusoidal wave, where form factor is defined as the ratio of the rms to the average value of the waveform. For given values of forward current a wave of sinusoidal pulses has a higher peak value than does a rectangular pulse and allowance is made for this factor by further derating in the curves.

Figure 8 and 9 show the average allowable current vs waveform for a schottky and silicon diode. Thus the 60 amp schottky diode can be used up to 85 amps if the current was purely D.C. while the 60 amp silicon unit can be utilized to approximately 95 amps D.C. Unfortunately, the upper current rating assumes pure D.C. current. Although the frequency of the stray current sources is generally much lower than 60 Hz the resulting current drain will not be true D.C. Further, any 60 Hz induced current on the structure due to the electric power grid operation will be half wave rectified. This will introduce some component of 60 Hz rectified current which will necessitate derating of the operational average current. If any component of the drain current results from the operation of an unfiltered potential controlled rectifier the average value must be derated still further as the phase controlled output of the rectifier can be phased back from 180° to 0° Unfortunately a D.C. ammeter will not detect the waveform factor. Consequently, preliminary tests should be undertaken prior to selection of the diode current rating. This testing should be conducted utilizing an oscilloscope in order to determine the waveform factor.

The repetitive reverse voltage breakdown of a diode is an important parameter. Maintained reverse voltages in excess of rating can result in failure of the device. It is important to realize that this voltage is the vector sum of all sources present on the structure not just the voltages associated with the stray current source. Possible A.C. potentials due to induction or fault conditions, arising from the proximity of H.V.A.C. powerlines must be taken into account in the design of the system. Table 1 lists the repetitive reverse voltage breakdown characteristics of the most common types of diodes utilized in reverse current switches. Copper oxide or schottky diodes can be installed in series to increase the reverse breakdown voltage however the forward voltage drop will also increase proportionately negating the benefits of these types of diodes.

During the past several years the breakdown voltage of schottky diodes has increased substantially however it is apparent that in the foreseeable future voltage rating equivalent to those available for silicon diodes (200V to 1000V range) are not likely to become available. Whichever type of device is selected it is imperative that the diode is installed on an adequate sized heat sink to prevent over heating.

HYBRID SYSTEMS

As discussed in previous papers the predominant desirable characteristic of a reverse current switch is the minimization of forward voltage drop.[1,2,3,4] Assuming the ground point or substation bus has a structure-to-soil potential of -700 mV. (wrt Cu:CuSO$_4$ electrode) the most efficient diode (Schottky) if connected between the structure and the ground point will not conduct until the structure-to-soil potential is more positive than -400 mV (i.e. 300 mV. across the diode). Assuming 50 amps of current flows through the switch, a not unreasonable value, the graph shown in Figure 8 indicates that the structure being drained will exhibit a structure-to-soil potential more positive than -100 mV.

Using the same reasoning assuming the ground point is copper (-300 mV. to Cu:CuSO$_4$) the threshold of current flow will occur at a potential of 0 mV. and with 50 amps of drain current flowing the resulting structure-to-soil potentials will be in the order of +300 mV. The above scenario assumed no IR drop in the connecting cables or ground point resulting in a conservative estimation of the depressed potential.

Clearly, the stray current problem has not been totally mitigated as the resulting potentials are more anodic than permitted, by the protective criterion normally used on protected piping systems resulting in continuing corrosion damage of the drained structures. These examples show that the diode type reverse current switch can reduce the damage but not eliminate it.

Several hybrid systems[1,2] have been developed to reduce the voltages required to initiate conduction and still maintain good reverse voltage characteristics. Germanium and/or schottky diodes are paralleled with silicon diodes in an attempt to optimize the characteristics of the switch. Generally the low voltage conduction units (germanium and schottky) require a current limiting resistor in series to prevent failure due to excessive current. This resistor also ensures that at higher voltage drops the majority of current is conducted by the silicon diode. This technique optimizes the forward conduction voltage drop however the germanium or schottky diodes are still subject to reverse voltage breakdown. The other hybrid system combines a silicon diode in parallel with an electromagnetic switch. Figure 10 depicts a typical switch of this type. The switch can be optimized to produce a custom I-V curve for any situation. A typical I-V curve is shown in Figure 11.

This type of system can possess the same disadvantages as outlined for the electromagnetic switch however much smaller relays can be utilized as the diode drains most of the current at the higher drain current levels. Generally, the relay requires 115 V. A.C. power to operate.

CONTROLLED POTENTIAL RECTIFIERS UTILIZING GROUND BEDS

Several types of reverse current switches can be fabricated utilizing the potential controlled rectifier as the basic operating element. Figure 11 depicts the operation of a controlled potential rectifier as usually applied to a pipeline in a stray current area. Although not truly a reverse current switch this type of system has both advantages and disadvantages as compared to previously mentioned types of switches. The potential of the structure can be set to a desired value (such as -850 mV.). As a result the structure-to-soil potential will not be affected by the IR drop in the cables or ground point.

If a reference electrode is not desirable the system can be implemented as in Figure 13. In this case the potential between the structure and ground point is controlled. If this selected value is zero the system will operate as an ideal reverse current switch. Unfortunately the cost of this type of system is comparably high as it requires a groundbed and rectifier capable of discharging the total amount of stray current in addition to supplying cathodic protection current . Further the output voltage of the rectifier must be designed to discharge all of this stray current through the ohmic resistance of the groundbed resulting in the need for high occasional voltages and hence a larger unit to handle peak loads.

HYBRID SYSTEM - DIODE AND CONTROLLED RECTIFIER

Due to recent developments in potential controlled rectifiers this type of reverse current switch is the closest to the ideal switch. The majority of potential controlled rectifiers are phase controlled units in which the output voltage is controlled by changing the conduction angle of the rectifier stack. The degree of phase back is a function of the difference between the desired set point, and actual potential. Generally these rectifiers have a current limit circuit incorporated to ensure the unit is not damaged due to sudden current demands.[6] Due to the characteristics of silicon controlled rectifier bridge circuits the current limit must operate in a fold back mode. Figure 14 shows the operation of this type of current limit. Once the preset limit current output is attained this current will be maintained assuming the load impedance is constant. However if the load impedance is reduced the output current is also reduced so as not to damage the rectifier stack. Taken to the extreme, lowering the load impedance to zero will result in virtually zero output current.

This fold back characteristic is the primary reason why prior potential controlled rectifier were not utilized as the active element in reverse current switches.

Recently, tapless automatic potential controlled rectifiers[5,6] have been introduced by a cathodic protection rectifier manufacturer. Unlike prior designs this rectifier is a centre tapped unit with a special control card and efficiency filter. The advantage of this unit is that the amount of output current while in the current limit mode is not a function of load impedance. In fact the rectifier can be short circuited and the output current will be the preset current value.

Figure 15 shows how this new type of rectifier can be utilized in conjunction with a silicon diode to produce an ideal reverse current switch. The potential across the diode (set potential of the rectifier) is set to zero. The rectifier size is determined by the particular characteristic desired. In Figure 16 it can be seen that the rectifier will discharge the current up to the current limit of the rectifier or until the I-V curve of the rectifier intersects that of the silicon diode. The value of resistor R determines the slope of the I-V curve as shown in Figure 16. Ironically under certain conditions this type of rectifier will operate as an inverter converting the D.C. voltage across the diode to fixed frequency A.C. (60 Hz). Assuming these conditions are fulfilled the actual A.C. power consumption of the rectifier will in fact be reduced as the stray current source is utilized to supply some of the necessary operating power.

The voltage output of the rectifier need not be greater than the voltage drop across the diode operating at maximum current drain. In the majority of systems this operating voltage will not exceed 2 volts minimizing the cost of the rectifier. This type of reverse current switch, is cost competitive with diode electromagnetic type units, however several important differences exist. Unlike the relay operated units the diode-controlled rectifier system has a much greater frequency response, contains no mechanical parts and can be custom designed to any situation.

The higher frequency response will prevent discharge of current from the ground point to the structure, unlike the characteristics of the diode-electromagnetic combination. The silicon controlled rectifiers in the stack are modified silicon diodes and as a result are available with repetitive reverse voltage breakdowns similar to that available for silicon diodes.

SUMMARY

Various types of reverse current switches have been utilized for the mitigation of stray current damage to underground structures with varying degrees of success. Each type has both advantages and limitations and in fact several different types are frequently utilized at various locations on the same underground plant. The diode-controlled rectifier switch is the most ideal type of reverse current switch presently available and can be utilize as a building block to ensure that underground corrosion due to stray current electrolysis can be minimized and/or entirely mitigated.

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6. Garrett, J. I., "Recent Developments in Cathodic Protection Rectifiers"
Good-All Electric Technical Bulletin TB-10 Presented at N.A.C.E. Eastern Canadian Regional Meeting - September 1979

TABLE I – COMMERCIALLY AVAILABLE REPETITIVE REVERSE VOLTAGE BREAKDOWN FOR VARIOUS DIODE TYPES.

DIODE TYPE	COMMERCIALLY AVAILABLE REPETITIVE REVERSE VOLTAGE BREAKDOWN (VOLTS)
COPPER OXIDE	8, 17
SCHOTTKY	10, 20, 45
SILICON	50, 100, 200, 400, 600, 800, 1000, 1200

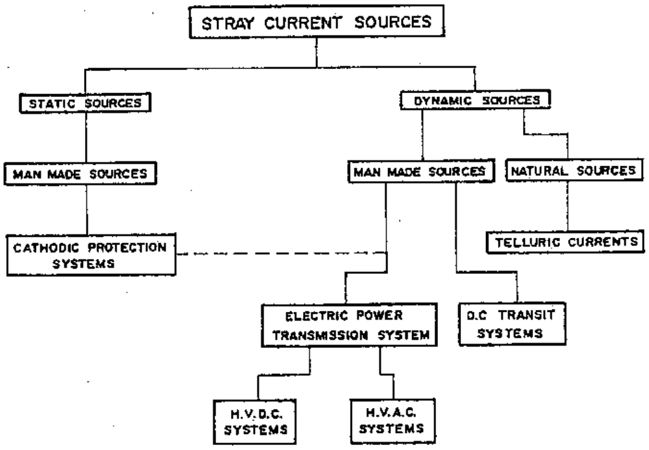

FIGURE NO. 1 - Classification of Stray Current Sources

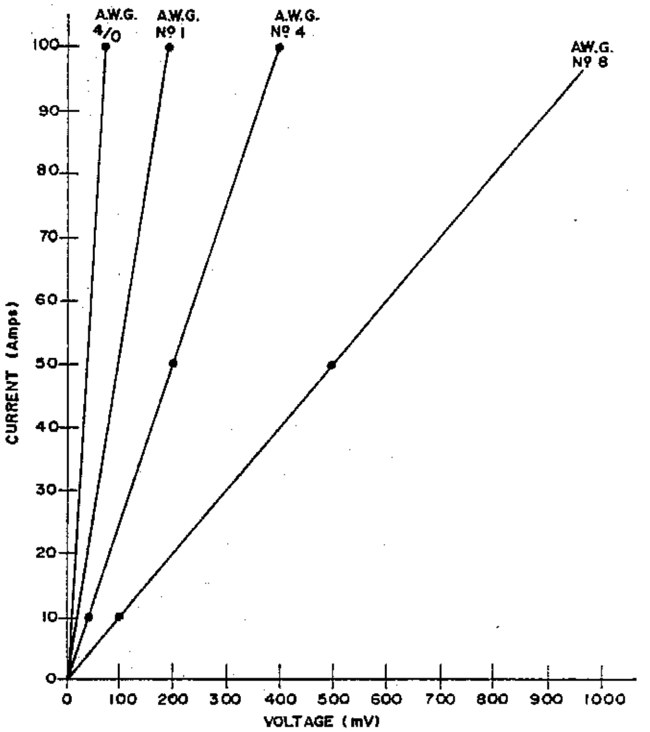

FIGURE NO. 3 - Effect Of 10' Length Of Wire On Ideal Switch Characteristics

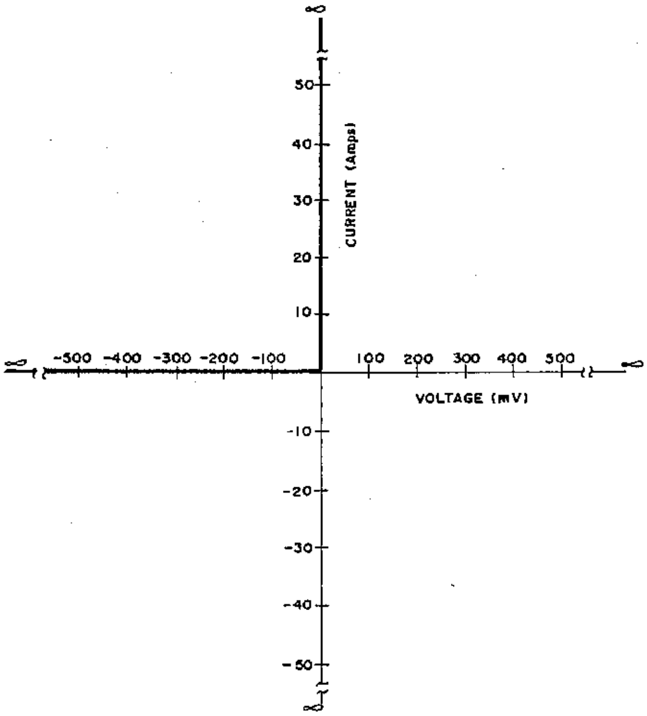

FIGURE NO. 2 - I-V Characteristics Of An Ideal Reverse Current Switch

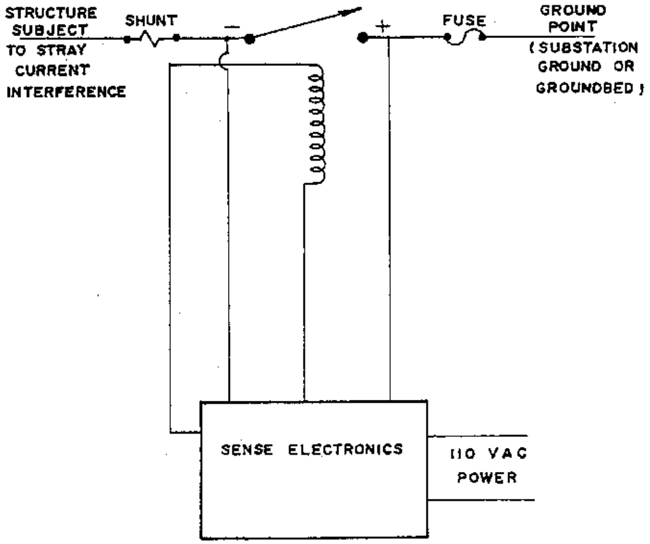

FIGURE NO. 4 - Electromagnetic Type Reverse Current Switch

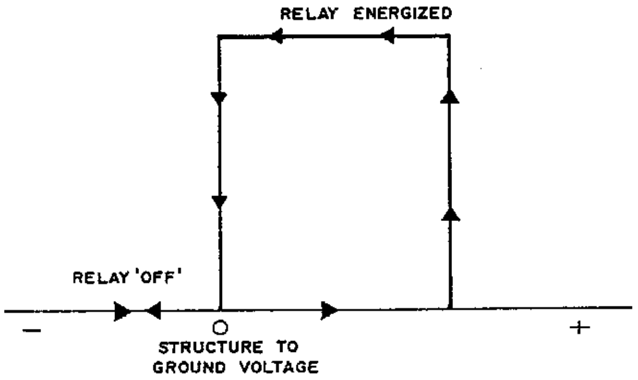

FIGURE NO. 5 - Hysteresis Characteristics Of An Electromagnetic Switch

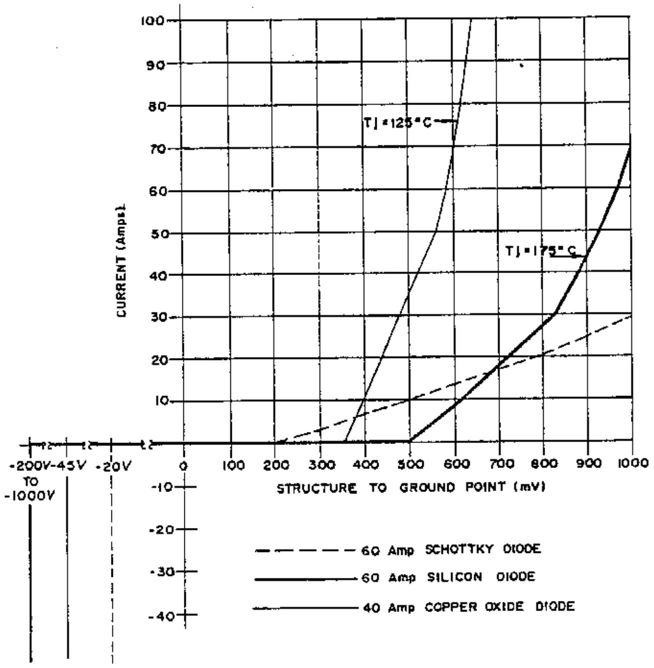

FIGURE NO. 6 - Characteristics of Various Types Of Diodes

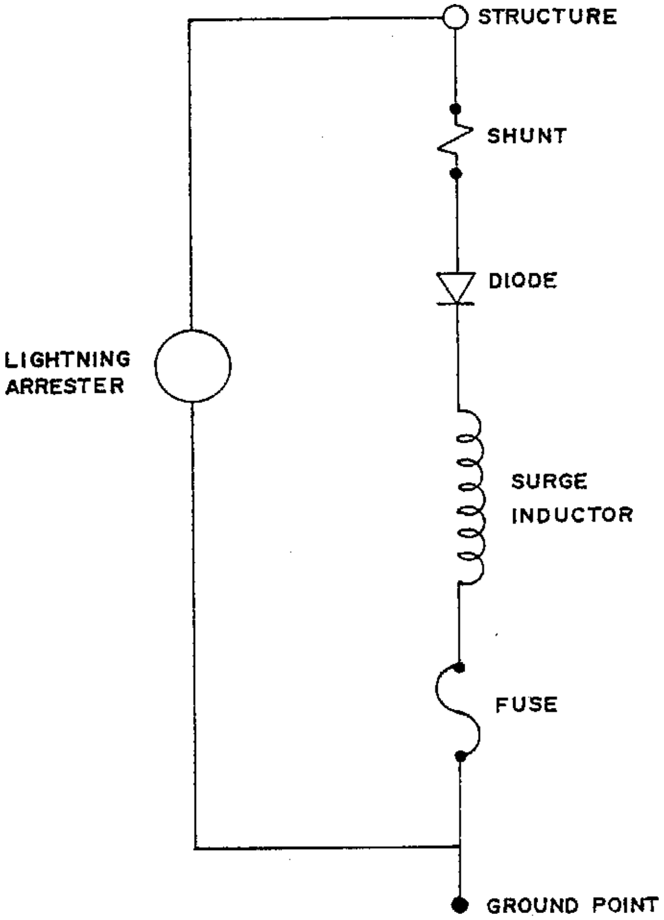

FIGURE NO. 7 - Typical Diode Reverse Current Switch

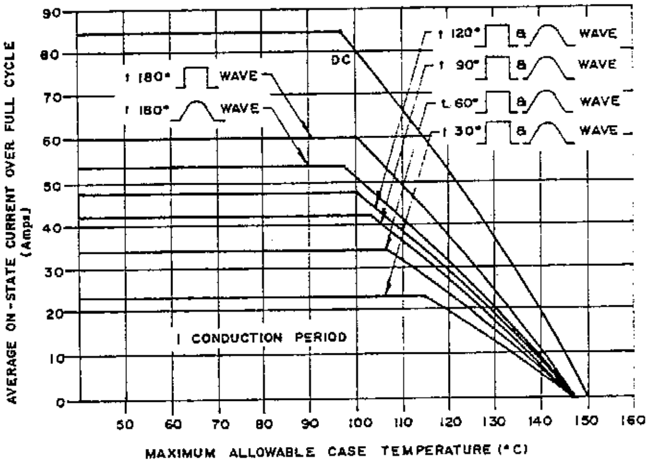

FIGURE NO. 8 - Average On-State Current Vs Maximum Allowable Case Temperature for 60 Amp Schottky Diode

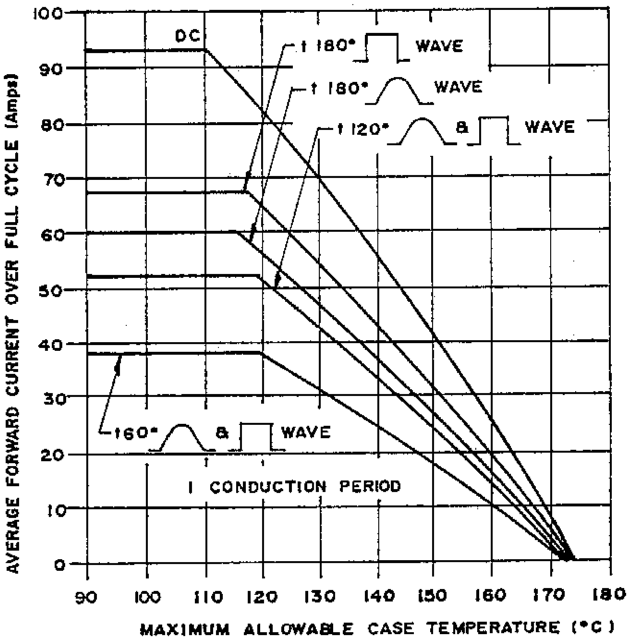

FIGURE NO. 9 - Average Forward Current Vs Case Temperature For 60 Amp Silicon Diode

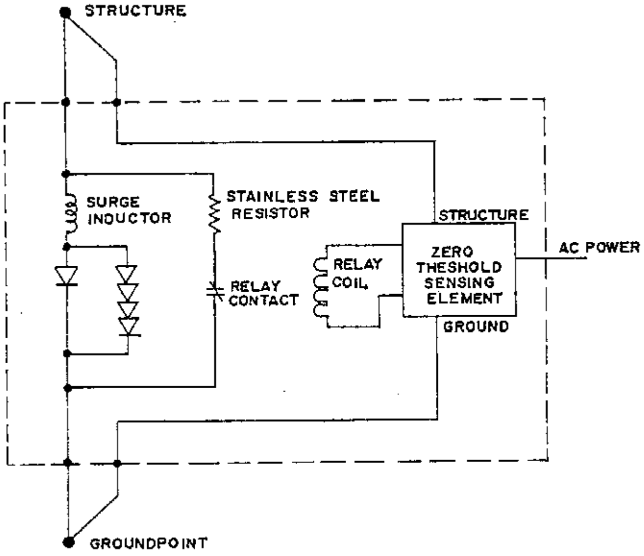

FIGURE NO. 10- Hybrid Silicon Diode - Electromagnetic Type Switch (Courtesy Good-All Electric)

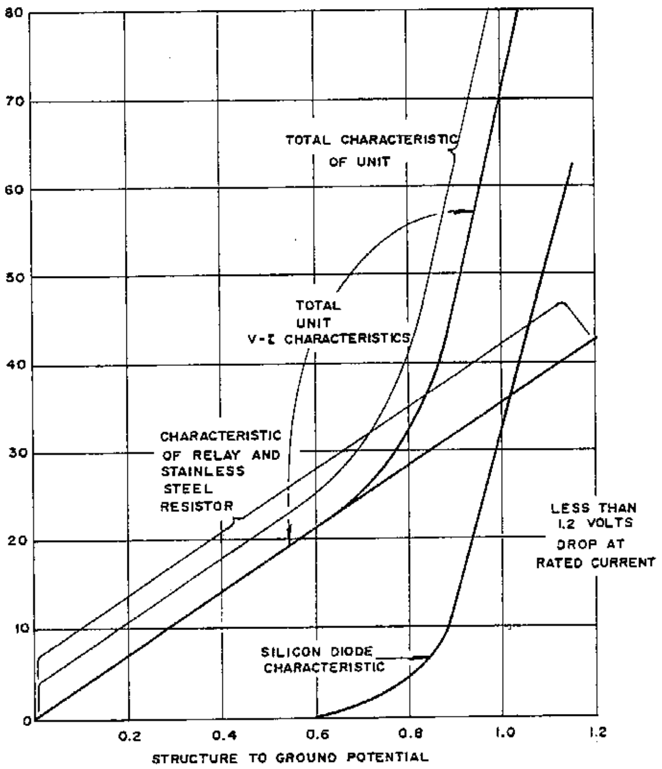

FIGURE NO. 11- Zero Threshold Reverse Current Switch Typical Characteristics

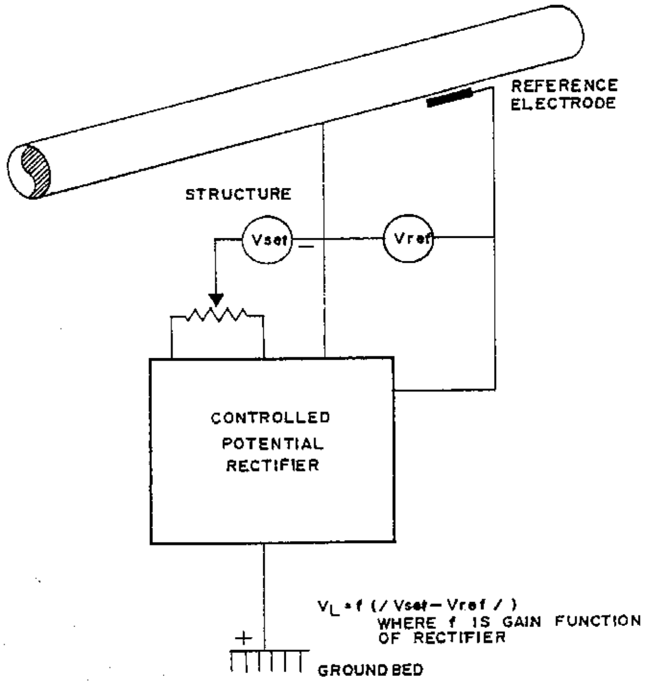

FIGURE NO. 12- Typical Operation Of A Controlled Potential Rectifier

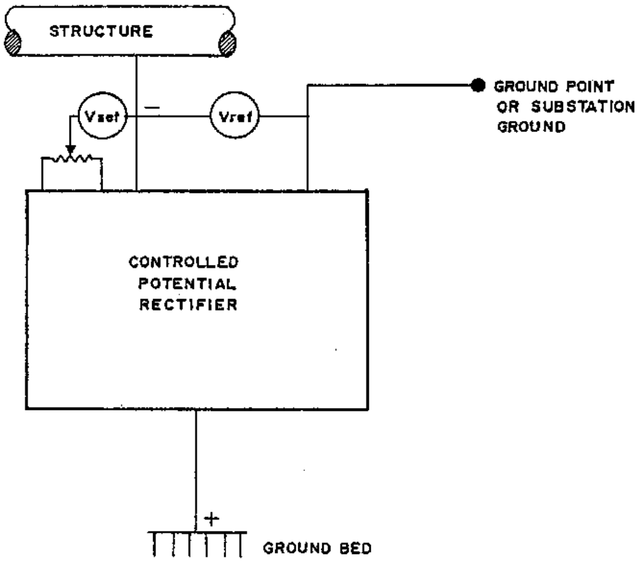

FIGURE NO. 13- Operation of a Controlled Potential Rectifier Utilizing The Structure To Ground Potential As The Control Signal

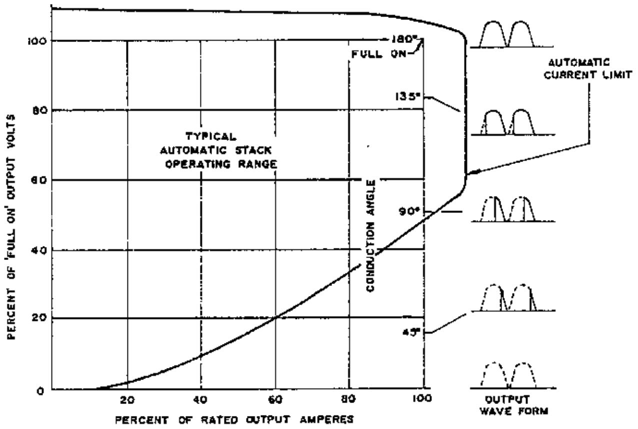

FIGURE NO. 14- Operation Of A Fold Back Type Current Limit Circuit (Courtesy Good-All Electric)

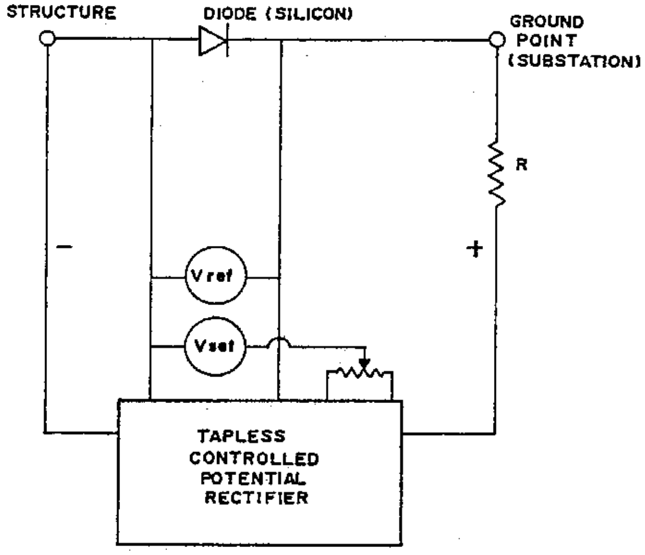

FIGURE NO. 15- Application of Tapless Rectifier And Diode As a Reverse Current Switch

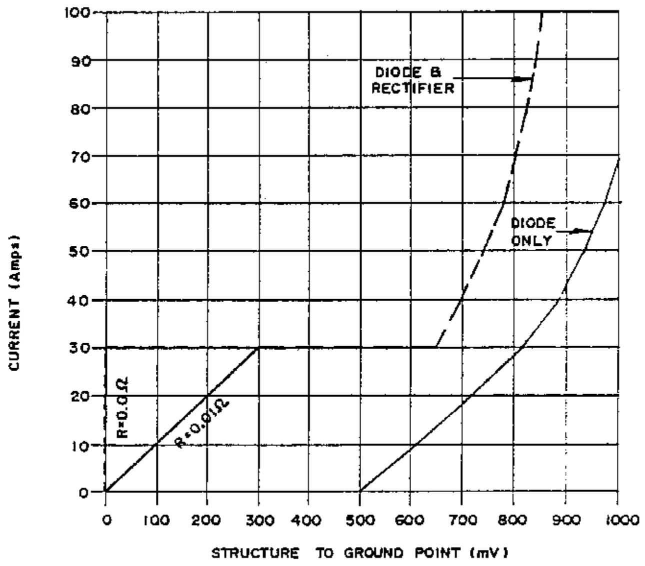

FIGURE NO. 16- I-V Curve For 30 Amp Tapless Rectifier And Silicon Diode