

THE SILICON CONTROLLED RECTIFIER AS A RELAY

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CHAPTER I

INTRODUCTION

In almost every segment of industry today, it is desirable to be able to control large amounts of power with control devices which themselves require relatively small amounts of power. Since a large proportion of the industrial apparatus in use is at least partially electrical in nature, electrical and electronic devices which can effect a large power gain (ratio of power controlled to control signal power required) are in great demand. Devices being used today in this mode would include, among others, electromagnetic relays, thyratrons, and magnetic amplifiers.

The rapid expansion of the semiconductor industry has produced many new devices, one of which is particularly suited for efficient power control. This device is called the silicon controlled rectifier. Its closest analogy among electron tube devices is the thyatron. The controlled rectifier differs from ordinary silicon rectifiers in that it can block voltages in the forward direction which are below a certain value in magnitude. This magnitude is controlled by the current flowing into the third terminal of the device, which is called the gate. Thus, the device possesses characteristics similar to those of a thyatron. That is, in the forward direction it has both an "off" condition (very high impedance) and an "on" condition (very low impedance). This gives the device the qualifications of an electronic switch.

Since an electromagnetic relay is, basically, a switch which is actuated by some type of electrical signal, it seems reasonable to investigate the use of silicon controlled rectifiers in roles usually filled by relays. Some of the advantages and disadvantages of such operation become obvious with study of the device. Most notable among the advantages held by the silicon controlled rectifier are its rapid switching speed, very high power gain, and its lack of mechanical vibration problems. Its most obvious disadvantage is the electrical connection, through the device itself, between the control circuit and the controlled or power circuit. The feasibility of using the device as a relay in any given application must be determined by considering the switching requirements and the circuit conditions of that particular application. It will be shown that there are some relay applications where the silicon controlled rectifier cannot be used.

It is the purpose of this thesis to investigate the use of silicon controlled rectifiers to perform functions which have in the past been performed by electromagnetic relays. In order to restrict the scope of the thesis, only two general types of relay circuits will be considered. These two types will, however, include a multitude of presently used applications for electromagnetic relays. It is hoped that the approach is general enough to establish the silicon controlled rectifier as being quite useful as a relay.

CHAPTER II

THE DEVICE AND ITS CHARACTERISTICS

The basic crystalline structure of a silicon controlled rectifier and its symbol are shown in Figure 1. It consists of four layers of doped silicon, alternating p-type and n-type, with ohmic connections as shown.



Figure 1. (a) Crystalline Structure of a Silicon Controlled Rectifier.
(b) Symbol of a Silicon Controlled Rectifier.

The development of the device as shown followed the development of the two terminal p-n-p-n switch, which was first extensively described by Moll, Tanenbaum, Goldey, and Holonyak.¹ The two terminal device, which has many applications of its own, does not have the gate connection indicated above.

¹J. L. Moll, M. Tanenbaum, J. M. Goldey, and N. Holonyak, "P-N-P-N Transistor Switches", Proceedings of the IRE, Vol. 44, September 1956, pp. 1174-1182.

It seems best to approach an analysis of the silicon controlled rectifier by first analyzing the behavior of the two terminal device. If it is connected as shown in Figure 2, then its characteristic is found to be that shown in Figure 3. J_1 , J_2 , and J_3 represent the p-n

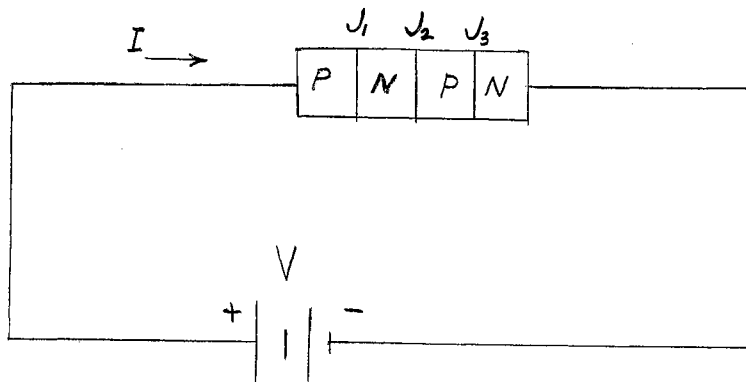


Figure 2. Two Terminal Device with Applied Bias.

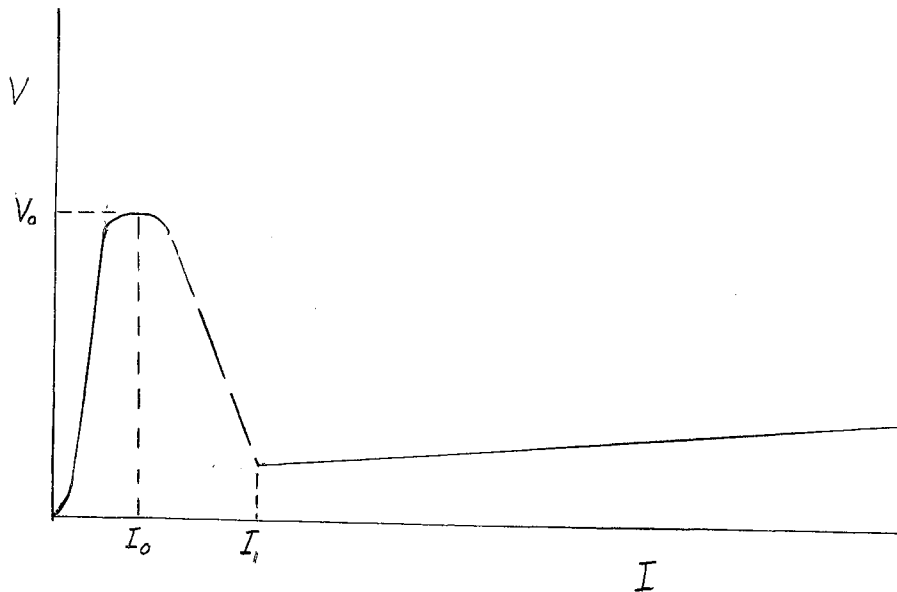


Figure 3. Characteristic of the Device in Figure 2.

junctions in the device. The analysis is facilitated by thinking of the structure as being two transistors (one p-n-p type and one n-p-n type) having a common collector junction at J_2 and emitter junctions at J_1 and J_3 , respectively. Then, with the polarity shown for V , J_2 is reverse biased while the emitter junctions are forward biased. For reverse bias conditions at J_2 , the current at J_2 is

$$I = I M_p \alpha_{1n} + I M_n \alpha_{2n} + I_{co} \quad (1)$$

where α_{1n} is the fraction of the current at J_1 which is collected at J_2 (essentially, the alpha of the "first transistor") and α_{2n} is the fraction of the current at J_3 which is collected at J_2 (the alpha of the "second transistor"). M_p and M_n are, respectively, the avalanche multiplication factors for holes and electrons². I_{co} is the normal current which would flow through J_2 if it were reverse biased and isolated.

Rewriting (1),

$$I = \frac{I_{co}}{1 - M_p \alpha_{1n} - M_n \alpha_{2n}} = \frac{I_{co}}{1 - \alpha_T} \quad (2)$$

where α_T , which can be called the total alpha, is $(M_p \alpha_{1n} + M_n \alpha_{2n})$.

Since at voltages which are appreciably less than the breakdown voltage of the center junction, M_p and M_n are both essentially unity, then with this condition prevailing, $\alpha_T \doteq \alpha_{1n} + \alpha_{2n}$. The high impedance region of the characteristic (Figure 3) results when the total alpha is less than

²Avalanche multiplication is a result of the strong electric field across p-n junctions. Electrons or holes moving in this field interact with valence electrons to produce electron-hole pairs. In a manner somewhat analogous to multiplication in a photo-multiplier tube, the process is cumulative and near the critical voltage for the junction, the current begins to increase quite rapidly. M_p and M_n are essentially a measure of the magnitude of the avalanche effect at voltages below the actual avalanche breakdown voltage.

unity. For this situation, the current that flows is of the order of magnitude of I_{CO} .

When α_T is increased until it reaches unity, then equation (2) is obviously invalid. When this condition prevails, the current which flows is essentially limited by the external circuit. Two phenomena are responsible for the breakdown action. The first of these phenomena is the increase of the multiplication factors as V approaches V_0 . As the voltage is increased, M_p and M_n are no longer unity and as they increase, the current begins to increase. Here the second phenomena begins to take effect. It is well known to transistor technology that in a certain region of operation, alpha increases with current. Thus the slight increase in current due to the increase in multiplication factors causes an increase in both α_{1n} and α_{2n} . Eventually, the condition $\alpha_T = 1$ is reached and a region of differential negative resistance is traversed by the device. The low impedance region of the characteristic is reached when $\alpha_{1n} + \alpha_{2n} > 1$. (At these low voltages, M_p and M_n are again approximately unity). This is the "on" region of the device. In this state, the center junction J_2 is actually forward biased due to the saturation of the two center layers with carriers.³

If some method of increasing the current independently of the voltage could be found, the "on" region could be reached without depending on multiplication effects.⁴ This, of course, is the purpose of the gate terminal. A current flowing into the gate can increase α_{2n} independently of V and I until switching occurs.

³Moll et al., pp. 1174-1177.

⁴I. M. Mackintosh, "The Electrical Characteristics of Silicon P-N-P-N Triodes", Proceedings of the IRE, Vol. 46, June 1958, p. 1229.

The addition of the third terminal will result in a set of device V-I characteristics as shown in Figure 4. Each characteristic corresponds to a certain value of gate current, I_g . Thus as I_g is increased, the voltage at which switching occurs is reduced.

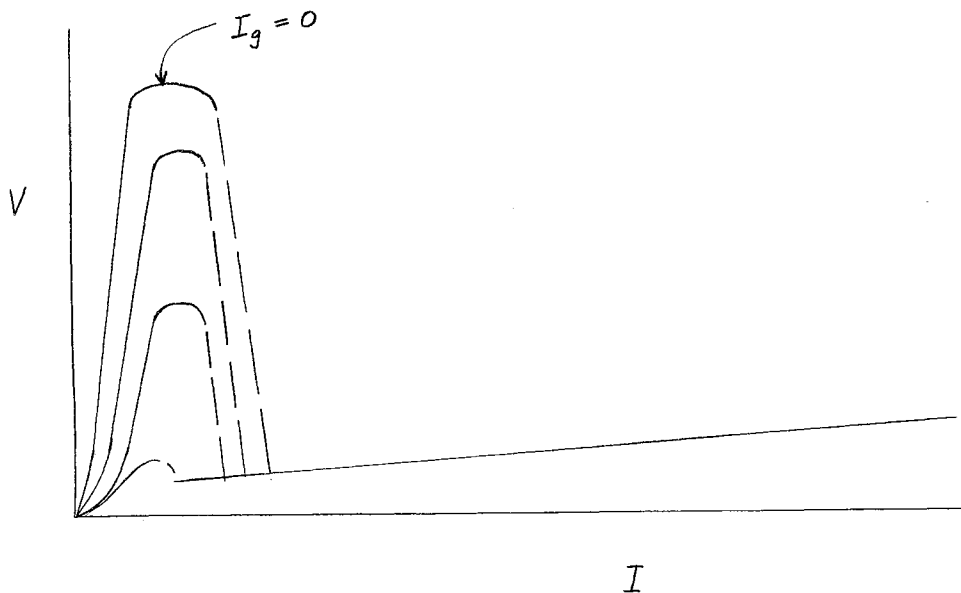


Figure 4. Characteristics of the Three Terminal Device.

The V-I characteristics of the device show the nature of several of the important parameters of the device. Several of these will be mentioned and discussed briefly.

Referring again to Figure 3, the slope of the characteristic in the "off" region can be called R-off. This represents the off impedance of the device. In practice, it can be made very high, of the order of 10^9 or 10^{10} ohms. In almost any practical application, this is large enough to be negligible.

The breakover current, I_0 , is closely related to R-off. This is usually quite small, in the neighborhood of one microampere. Thus, R-off and I_0 can be classed as parameters which can be made to have insig-

nificant effect on circuit operation.

Other parameters can be controlled by the construction geometry of the device. V_0 , the breakover voltage, is such a parameter. If the low-current alphas of the device are of the order of 0.1 to 0.2, then V_0 is essentially the breakdown voltage V_b of the center junction J_2 . In any case, the alphas determine the relation between V_0 and V_b . Thus, V_0 can be varied over a wide range.

The "off" capacitance (anode to cathode) of the device is the series combination of the capacities associated with J_1 , J_2 , and J_3 . These capacitances are functions of impurity gradients, applied voltage, and area, and therefore can be controlled to some extent in manufacture.

The "on" resistance of the device (the slope of the "on" region of the characteristic) is usually low, of the order of 0.1 to one ohm. Obviously, it is the resistance of three forward biased junctions in series. This low resistance in the on state constitutes one of the major advantages of the device over a thyatron.

I_1 , the turn-on current, is determined by the current at which the quantity $(\alpha_{1n} + \alpha_{2n})$ reaches unity. Although the mechanisms which affect I_1 are not well enough understood to make exact analysis possible, it can be empirically controlled.⁵

The parameters discussed above are all applicable to the two terminal device. In essence, they are also meaningful for the three terminal device when modification of device characteristics due to gate current is considered. In very general terms, as gate current is increased, R_{off} decreases, I_0 increases, V_0 decreases, "on" resistance is unchanged, and I_1 decreases.

⁵Moll et al., pp. 1178-1179.

The speed of the device, both in turning on and in turning off, is quite important in some applications. Turn on time is dependent on both gate and anode circuit conditions. It can be reduced by using higher gate currents, but increases when anode current is increased. It can easily be made as small as one or two microseconds.

Turn off time, while quite sensitive to circuit parameters, is ordinarily considerably greater than turn on time. This is primarily due to the fact that a finite time is required for the carriers in the vicinity of the center junction J_2 to redistribute so that J_2 changes from forward bias to reverse bias conditions. Circuit variables which are important in determining turn off time are the magnitude of the forward current immediately prior to turn off and the rate of rise of reapplied forward voltage.⁶ The device is turned off by reducing the anode current below I_1 , by removing the supply voltage, by temporarily applying a reverse voltage to the device, or by applying sufficient negative gate current bias. The latter method is possible only at relatively low values of anode current for most devices presently in manufacture.

Like those of any semiconductor device, the parameters of the silicon controlled rectifier are temperature sensitive. Temperature considerations are not treated in this thesis, except for the mentioning of necessary heat dissipation methods.

The actual devices used for research for this thesis were Texas Instruments types TI 131 and TI 132. Both types are rated at three amperes average rectified forward current, the difference between the

⁶D. K. Bisson and R. F. Dyer, "A Silicon Controlled Rectifier--Its Characteristics and Ratings--II", Unpublished paper presented at A. I. E. E. Winter General Meeting, New York, N. Y., 1960, p. 5.

two types being the peak inverse voltage ratings. These two types and others in the same current category cover a peak inverse voltage rating range of 50 to 400 volts. Since the magnitude of the supply voltage will specify the necessary peak inverse voltage rating in any circuit, no mention of the unit type will be made in what follows.

The external appearance of the device is shown in Figure 5. The stud and bulk of the exterior housing are connected electrically and thermally to the anode of the device crystalline structure. A heat sink is necessary when the device is operated at currents which are of the order of magnitude of its rating. As is the case frequently with power transistors, the heat sink will limit the minimum space required for the device in most circuit structures.

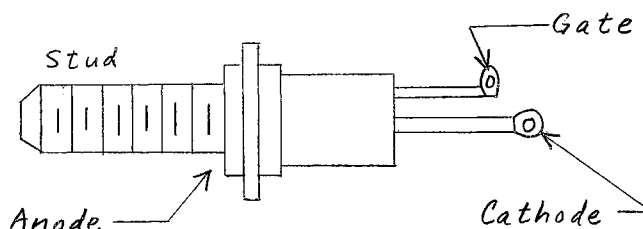


Figure 5. External Appearance of the Device.

Other ratings and specifications of the device which are most pertinent in the circuits to follow are given below. These are presented only to provide numerical figures for manipulation and should not necessarily be interpreted as limits of manufacturing technique.

Maximum ratings:

Maximum Forward d-c Gate Current	100 ma.
Gate Peak Inverse Voltage	5 v.

Specifications at 25° Centigrade:

Maximum Forward Voltage Drop at Three Amperes d-c . . .	2 v.
Maximum d-c Reverse Current at Rated Peak Inverse Voltage	-1 ma.
Typical Gate Current Required to Turn Device on with 50 Volts Anode Source Voltage	5 ma.
Typical Forward Current Required to Hold Device in On Condition with Gate Open	5 ma.

The above specified typical gate current required to turn the device on with 50 volts anode source voltage is much greater than that required by most units. Tests were conducted on several units and it was found that, while there was wide variation in device sensitivities, the least sensitive unit tested would turn on with approximately one milliamperere gate current and a 50 volt anode supply. Thus a more appropriate "typical" figure for this specification would be 0.5 milliamperes.

Another useful result of basic tests made on the devices will now be presented. It was found that by connecting a resistor between the cathode and gate terminals of the device, the anode break-over voltage for any value of gate current is increased. In other words, the sensitivity of the device is decreased. This decrease in sensitivity is greatest for small values of resistance between gate and cathode, so that when the gate is shorted to the cathode, the device will not turn on until the avalanche breakdown voltage of the center junction is reached. This phenomena is quite easily explained by examining the theory of operation of the device. This resistor shunts the junction J_3 , and part of the current through the device flows around J_3 through

the resistor. Thus the increase in α_{2n} as anode current increases is not as great as when no resistor is connected between gate and cathode. Such a method of controlling device sensitivity is quite useful for adapting a circuit to operate from a particular level of control signal.

Tests on the device also revealed the fact that the device will fire below the "normal" breakover voltage for a given gate bias condition when the rate of rise of the anode voltage is very large. That is, the actual breakover voltage is inversely related to the slope of the applied anode voltage. This is probably due to the large initial current surge through the junction capacities of the device. The effect of the slope of the applied anode voltage varies greatly from unit to unit. The ratio of breakover voltage for a slowly increasing anode voltage to that for a step anode voltage (rise time of the order of ten millimicroseconds) was found to vary from slightly over unity to approximately ten. In any case, the use of the device in any circuit must obviously preclude the presence of excessive sharp transients at the anode.

CHAPTER III

GENERAL CONSIDERATIONS FOR USE AS A RELAY

In considering the usefulness of the device as a relay, the circuit requirements can be divided into two categories. Basically, the "contacts" of the relay are connected into a circuit such that their closure delivers either (1) d-c (unidirectional) power or (2) a-c power to a load. The reason for making this particular category division is more or less obvious after the device characteristics have been studied. If the voltage across the device is alternating in polarity, then there is usually no problem involved in turning the device off unless the frequency of the voltage is high. If, however, the polarity of the voltage across the device is always the same, some method must be developed to turn the device off at the appropriate time.

It should be emphasized that there are some applications for electromagnetic relays for which silicon controlled rectifiers are not suitable. Some of these applications will be mentioned and briefly explained.

When no voltage (or very small voltage) is present across the open contacts of a relay, the silicon controlled rectifier obviously cannot perform the function of the relay. This is due to the fact that a certain minimum voltage at the anode of the device is necessary for turn on, even with the maximum permissible gate current bias. For both d-c and a-c applications, tests indicated that it is impractical to use the device where the off voltage is less than 3 or 4 volts.

For the silicon controlled rectifier to be used as a relay, a

voltage drop across the device in the on condition of approximately a volt must be tolerable in the circuit. This will ordinarily be intolerable only in low voltage, high current circuits, if the full current capacity of the device is being utilized.

The circuit in which a silicon controlled rectifier is to be used as a relay must be free from sharp positive transients at the anode of the device, for reasons discussed in the previous chapter.

Obviously, in some electromagnetic relay applications, one function of the relay is to provide electrical isolation from the control signal source. In some applications it is feasible to achieve isolation by using transformer coupling into the gate circuit of the silicon controlled rectifier for the control signal. This, of course, is the case when the control signal is of the pulse or alternating current type. When the control signal is a d-c or very slowly varying type of signal, there is no practical way to isolate electrically the signal source and the controlled circuit.

Another necessary condition for use of the silicon controlled rectifier as a relay is the minimum current which must flow through the "contacts" while the device is in the on condition. The current must always be greater than I_1 , the holding current of the device, or the device will revert to the off condition.

To justify its consideration as a relay, the silicon controlled rectifier must certainly have definite advantages to offset the mentioned limitations. It does, of course, have several advantages, and these will be briefly discussed.

In some types of operation, the silicon controlled rectifier has a power gain of the order of several hundred thousand. This is much larger than the power gain possible with electromagnetic relays.

A tremendous advantage in many situations is the switching speed of the silicon controlled rectifier. While electromagnetic relays are considered high-speed when they operate or release in one millisecond, it was indicated in the previous chapter that the silicon controlled rectifier switches in a few microseconds.

In a circuit using d-c power, it is possible to "close the contacts" of the silicon controlled rectifier with a brief pulse at the gate, with the "contacts" remaining closed until the device is turned off in some manner by another signal. Analogous operation with electromagnetic relays (latching relays) requires specially constructed, complex units.

Of course, the silicon controlled rectifier has the inherent advantages of an electronic switch over a mechanical one such as the contacts of an electromagnetic relay. These include the elimination of mechanical acceleration problems, of contact sticking, bounce, and wear, and of arcing as contacts make or break under high voltage conditions. Consequently, the silicon controlled rectifier will have a much longer life expectancy than electromagnetic relays in most applications.

CHAPTER IV

CIRCUITS USING A-C POWER

The silicon controlled rectifier can be used as a relay in a circuit where closure of the contacts effects the delivery of a-c power to a load. As used here, "a-c" refers in general to the situation in which the polarity of the supply voltage changes sign in a repetitive, cyclic fashion. Although sinusoidal power with no d-c superimposed is the only specific case considered here, it is felt that the analysis presented will point out the important factors to be considered in using the circuits for any type of a-c waveform.

Figure 6 shows the basic circuit, as well as the analogous circuit using an electromagnetic relay. The apparent relative simplicity of the electromagnetic relay circuit is deceiving. To actuate the electromagnetic relay from a control device operating on light, heat, pressure, or some other physical quantity, it will be necessary to use auxiliary circuitry, such as a vacuum tube amplifier. For the silicon controlled rectifier circuit, power is delivered to the load when the terminals A and B are connected through any resistance from zero to a maximum value to be explained later. In no instance is this connection required to carry more than the maximum allowable gate current of the silicon controlled rectifier (in this case, 100 ma.). Thus, the connection can be relatively poor electrically, such as that made by a bimetallic heat sensing element.

The purpose of the diodes is to conduct a turn on signal through

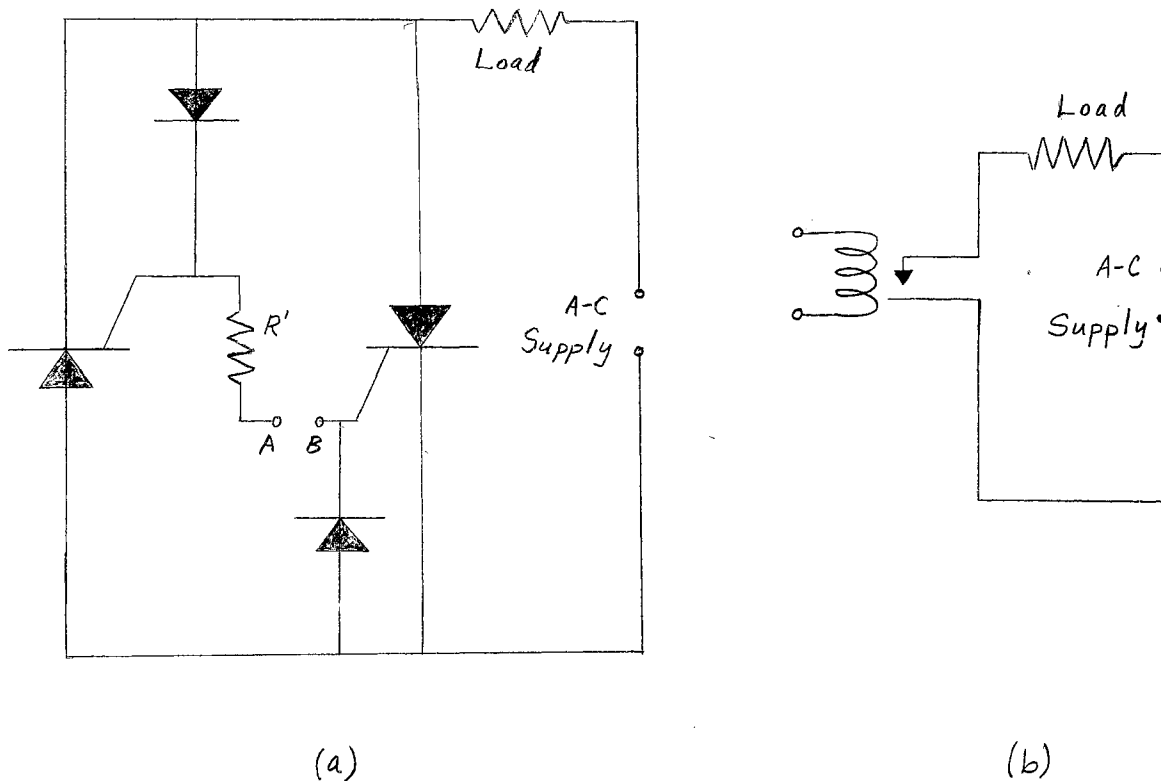


Figure 6. (a) Circuit Using Silicon Controlled Rectifiers. (b) Circuit Using Electromagnetic Relay.

R' to the appropriate silicon controlled rectifier gate at the proper time. The sole purpose of R' is to limit gate current to a safe value. Thus, the minimum value of R' , assuming zero resistance in the control device, is $\sqrt{2} E_S / 0.1$ ohms where E_S is the R. M. S. value of the supply voltage. Actually, R' can in some instances be the resistance of the control device, provided this is large enough. In general, the series combination of R' and the control device resistance determines the magnitude of the gate current which flows.

Examination of the circuit shows that as the instantaneous voltage at the anode of one of the controlled rectifiers is increasing during the positive half-cycle, the gate current for that device is also increasing

proportionally. When the condition is reached where the anode voltage present is the critical (breakover) value for the gate current flowing at the same instant of time, the device turns on. Ideally, this occurs at the instant when the anode voltage first goes positive. In practice, it occurs a finite time later. If the total series resistance of R' and the resistance of the control device is small (near the minimum permissible value), then the device will turn on in negligible time after the anode goes positive. As this total resistance is increased, a value is reached for which the delay of turn on of the device is significant. Figure 7 shows a typical load voltage waveform for such a situation.

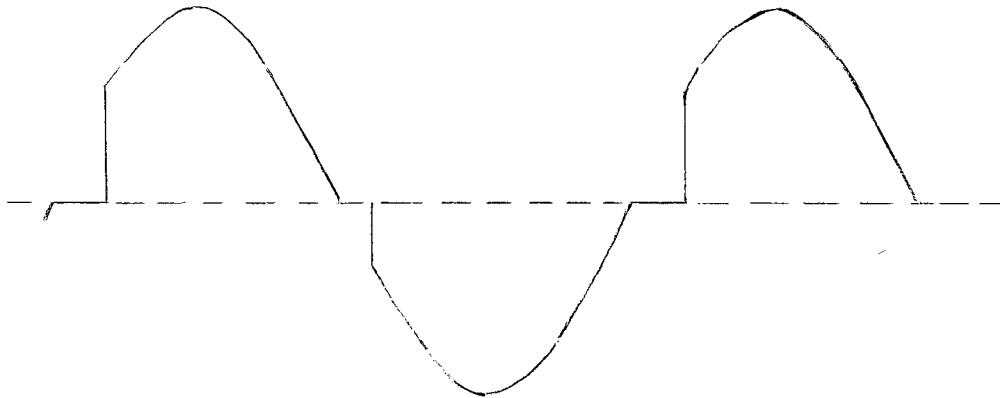


Figure 7. Load Voltage Waveform when Total Resistance to Gate Current is Too Large.

This waveform also points out the fact that for unmatched silicon controlled rectifiers, the delay in turn on is not the same for both half-cycles. Of course, when the total resistance is large enough, neither device will turn on, and no power is delivered to the load.

The maximum feasible value of the total of R' and the control device resistance is a function of individual device characteristics (in effect, device sensitivity). Using two devices selected at random, a mechanical

switch for the control device, 117 volts R. M. S. supply voltage, and a variable resistance for R' , it was found that R' could be increased to approximately 100,000 ohms before appreciable waveform degeneration was noticed. Here, "appreciable" degeneration was considered to be that for which the notch in the waveform was of the order of 8 to 10 electrical degrees.

It should be noted that the control device can be a device which changes from a very large resistance to a smaller resistance in response to a change in some physical quantity. The large resistance must be great enough so that neither silicon controlled rectifier turns on. The smaller resistance should be less than the maximum value discussed in the preceding paragraph. If the change in resistance is slow, then during the transition period, the load voltage waveform will be a portion of a sinusoid, as the delay in turn on of the controlled rectifiers follows the resistance decrease. Whether such a situation is desirable depends upon the particular application. If R. M. S. power in the load is the only concern, then this type of circuit would provide a crude form of continuous control rather than strict on-off switching.

This type of operation was executed successfully using a thermistor as the control device in place of the mechanical switch. As the thermistor was heated from 25° C. to 180° C., its resistance decreased from approximately 100,000 ohms to approximately 2,000 ohms. This factor of resistance change of 50 was sufficient to change the circuit from the off condition to essentially the on condition. That is, when the total resistance to gate current flow was approximately 2,000 ohms, there was essentially a perfect sinusoidal voltage waveform across the load.

It is well to note that the peak voltage ($\sqrt{2} \times 117$ v.) divided by the maximum thermistor resistance (100,000 ohms) is well over 1 ma.

This current at the gate would be sufficient for turn-on for most of the units if the resistance from gate to cathode is very high. This problem was solved by shunting each diode with a 100 ohm resistor, thus decreasing the sensitivity of both silicon controlled rectifiers in the manner described in Chapter 2. The merits of this method are somewhat limited, however, since the series total of the diode-shunting resistors, the control device resistance, and R' shunts the off or blocking resistance of either device. Therefore, the maximum value of control device resistance should be very large compared to the load resistance when this method is used.

If maximum sensitivity is required (in effect, if a high-impedance control device is to be used), then units should be selected for high sensitivity. Of course, when the control device goes from essentially infinite to essentially zero resistance, such considerations are not necessary.

As the magnitude of the supply voltage is decreased, it is evident that an operating condition is eventually reached where the gate current necessary for turn-on near the beginning of the positive half cycle is large. This places a limit on the minimum feasible supply voltage for the circuit. Tests using randomly selected units indicated that this minimum is of the order of 5 volts R. M. S. If a low-resistance control device and high-sensitivity units are used, then the minimum supply could probably be reduced to 2 or 3 volts.

CHAPTER V

CIRCUITS USING D-C POWER

The circuits to be considered here utilize the silicon controlled rectifier as a relay which controls the delivery of d-c power to a load. It is assumed that the source voltage is essentially free of a-c components. If a-c components are present, they must be small in amplitude relative to the d-c voltage, and relatively low in frequency, so as not to cause the difficulties associated with sharp rises in anode voltage.

As was previously mentioned, the principal problem involved in using the silicon controlled rectifier to switch d-c power is that of providing a method for turning the device off. One method has been developed which is, for most situations, generally superior to other methods. This method is called the shunt capacitor method. Basically, it involves charging a capacitor to almost the full supply voltage in such a manner that it can be connected from the anode to the cathode of the controlled rectifier, negative side to anode and positive side to cathode. The circuit for accomplishing this is shown in Figure 8. The action of the circuit is explained as follows: When SCRL is in the on condition, its anode is only slightly above ground potential due to the small voltage drop across the device itself. Thus, the capacitor C charges to a voltage slightly less than the supply voltage, of the polarity shown, through the resistance R_1 . When the switch S is closed, C is connected directly across SCRL so that the anode is momentarily made negative with respect to the cathode. If C is large enough, the anode of SCRL will

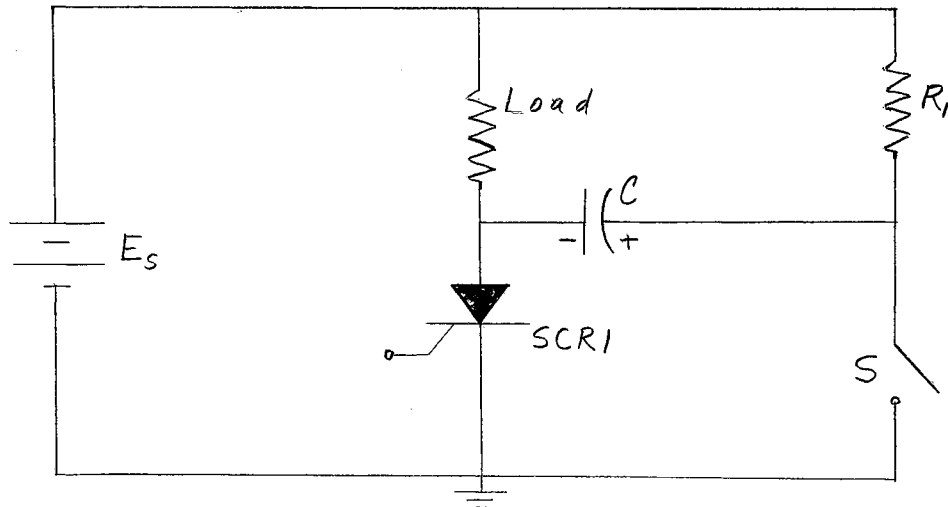


Figure 8. Basic Shunt Capacitor Turn-off Circuit.

be reverse biased long enough to effect turn-off of the device.

Of course, if a mechanical switch is used for S , nothing has been gained by using the silicon controlled rectifier to switch the load power. The obvious solution to this dilemma is to use another silicon controlled rectifier as the switch S . Then a low-power signal can be used to turn the load power off as well as to turn it on.

One essential portion of a practical circuit was omitted from Figure 8. It is necessary to limit the reverse surge current through SCR1 in some manner. An inductance-resistance parallel combination of 10 microhenrys and 100 ohms, in series with C , is satisfactory for this purpose.

The practical circuit is shown in Figure 9. Obviously, SCR2 can be turned off by turning SCR1 on again. In general, the resistor R_1 is a part of the switching circuitry. However, when it is desirable to switch power from one load to another (such as switching to a "dummy" load), R_1 can be an auxiliary load. Such a switching arrangement would correspond to a single pole, double throw relay.

When R_1 is functionally only a part of the switching circuitry, three factors usually will determine the size resistor chosen. The first is the fact that since C charges through R_1 , R_1 determines the time required for C to charge to its maximum voltage. In other words, the size of R_1 specifies the minimum time SCR1 must be on before turn-off is possible. For example, if $C = 1$ microfarad and $R_1 = 1000$ ohms, then the minimum "on time" for SCR1 is of the order of $R_1 C = (10^3)(10^{-6}) = 10^{-3}$ seconds. This assumes, of course, that a capacitance of 1 microfarad is necessary to make turn-off possible.

The second factor affecting the selection of R_1 is the power dissipated when no power is delivered to the principal load. Obviously, the larger R_1 is, the less will be the power dissipated with SCR2 on and SCR1 off.

The third factor places a definite maximum on the size of R_1 . This is the value of holding current necessary for SCR2 to remain in the on condition. From the specifications given in Chapter 2, this current is typically 5 ma., so that the condition $R_1 < E_S/0.005$ ohms must be satisfied.

In selecting the size of capacitor to use for C, the problem usually is to find the minimum necessary value of C. It is usually desirable to keep C reasonably small so that it will charge rapidly through R_1 . To determine how large C must be is, at best, a rather complex problem. However, by making a few justifiable simplifications, an analysis was developed by the author which makes possible the determination of the necessary size of C well within an order of magnitude. What follows is an explanation of this analysis.

To determine what simplifications are possible, it is desirable to examine in greater detail the physical mechanism for turn-off. As

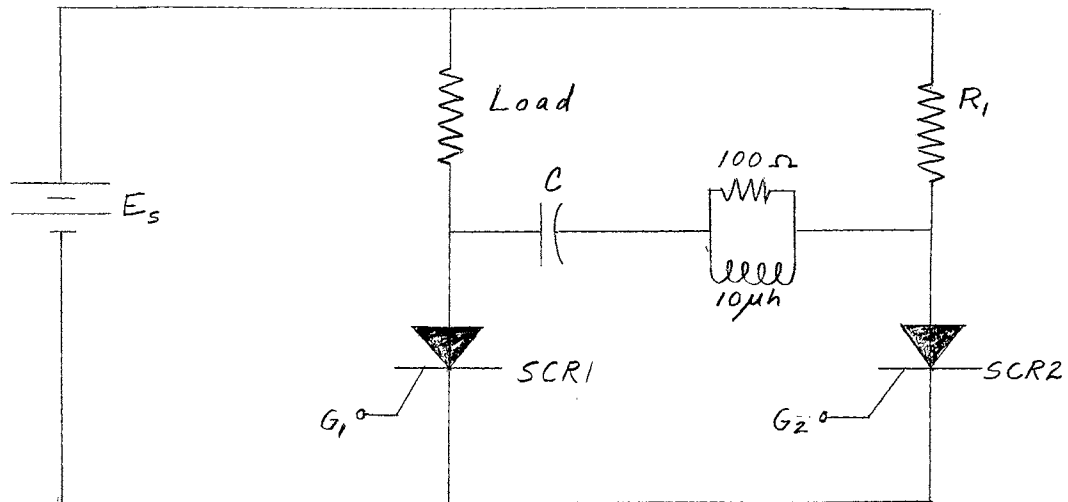


Figure 9. Practical D-C Relay Circuit.

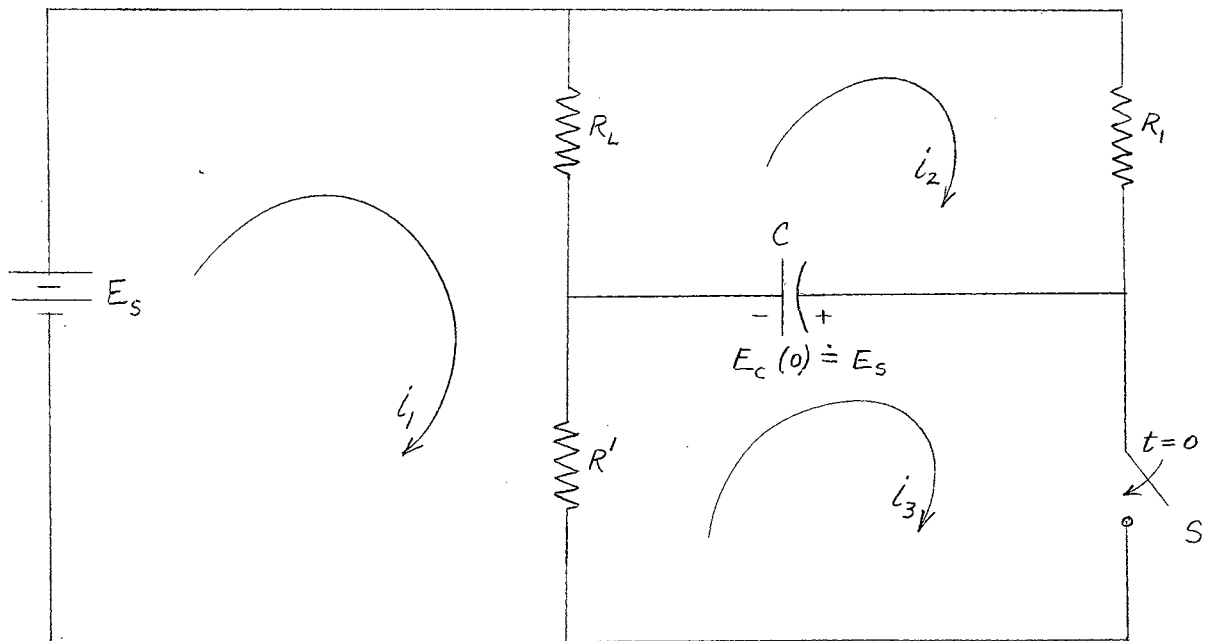


Figure 10. Approximate Equivalent Circuit for Turn-off.

previously stated, when the silicon controlled rectifier is in the on state, each of the three junctions is in a condition of forward bias, and the center p and n layers are heavily saturated with holes and electrons, respectively. When a reverse voltage is applied, the holes and electrons in the vicinity of the two end junctions (J_1 and J_3) will diffuse to these junctions and result in a reverse current in the external circuit. After these carriers in the vicinity of J_1 and J_3 have been removed, the reverse current will decrease to a very small value as J_1 and J_3 assume a blocking state as reverse biased junctions. However, there still exists a high concentration of carriers near the center junction (J_2). Turn-off is not complete until these concentrations have been reduced to a low value. These concentrations decrease by the process of recombination in a manner which is essentially independent of external bias conditions.⁷

The turn-off time thus consists of two parts. The first part is the time for J_1 and J_3 to reach the blocking state, and the second part is the additional time required for the carrier concentrations near J_2 to reduce to a low value. One simplification of the problem will be that the first part of the turn-off time is small compared to the second portion. This is reasonable since it has been found that the transition from peak forward to peak reverse current occurs in less than one microsecond.⁸ Thus C will be determined in terms of a turn-off time t_0 which is considered to be the second part discussed above.

The time constant of the surge-limiting R-L circuit is $10^{-5}/10^2 = 10^{-7}$ seconds. This is very small compared to typical turn-off times (of the order of 10^{-5} seconds). Therefore, for the analysis, the R-L parallel

⁷Ibid.

⁸Ibid.

combination of 100 ohms and 10 microhenrys will be considered a short circuit. The resulting approximate equivalent circuit is shown in Figure 10. The silicon controlled rectifier has been replaced by a resistance R' which is the approximate slope of the V-I characteristic for reverse voltage. This is consistent with the assumption that J_1 and J_3 assume the blocking state immediately. The initial voltage on the capacitor is considered to be the same as the supply voltage, E_s . This, of course, is a slight simplification in that it neglects the voltage drop across SCR1 in the on state. This drop will obviously be significant only for very small supply voltages.

Using loop current analysis as indicated, the loop equations are:

$$A. \quad E_s = i_1 (R_L + R') - i_2 (R_L) - i_3 (R')$$

$$B. \quad 0 = -i_1 (R_L) + i_2 (R_L + R_1 + \frac{1}{pC}) - i_3 (\frac{1}{pC}) + E_s$$

$$C. \quad 0 = -i_1 (R') - i_2 (\frac{1}{pC}) + i_3 (R' + \frac{1}{pC}) - E_s$$

The Laplace Transform technique will be used. After rearranging, the transformed equations are:

$$A'. \quad \frac{E_s}{s} = I_1 (R_L + R') - I_2 (R_L) - I_3 (R')$$

$$B'. \quad \frac{-E_s}{s} = -I_1 (R_L) + I_2 (R_L + R_1 + \frac{1}{sC}) - I_3 (\frac{1}{sC})$$

$$C'. \quad \frac{E_s}{s} = -I_1 (R') - I_2 (\frac{1}{sC}) + I_3 (R' + \frac{1}{sC})$$

where I_k represents the transform of i_k . The voltage across R' is

$R'(i_1 - i_3)$. Solving the above system of linear equations and simplifying,

$$V_{SCR1}(s) = R'(I_1 - I_3) = \frac{-E_s}{s} \frac{s - 1/\tau_1}{s + 1/\tau_2}$$

where $\tau_1 = R_L C$, $\tau_2 = R_p C$, and $R_p = R' R_L / (R' + R_L)$. Taking the inverse transform, the voltage across SCR1 is

$$V_{SCR1} = E_s \left[\frac{R'}{R' + R_L} - \left(1 + \frac{R'}{R' + R_L} \right) e^{-\frac{t}{R_p C}} \right]$$

A sketch of V_{SCR1} as a function of time is shown in Figure 11. At $t = 0$, when the switch is closed, $V_{SCR1} = -E_s$. Obviously, $V_{SCR1} = 0$ when

$$\frac{R'}{R' + R_L} = \left(1 + \frac{R'}{R' + R_L} \right) e^{-\frac{t}{R_p C}} \quad (3)$$

From the previous discussion, it can be seen that the voltage across the device should be negative for a time of t_0 , the turn-off time. Therefore, when $V_{SCR1} = 0$, $t = t_0$. Solving equation (3) for C and setting $t = t_0$,

$$C = \frac{t_0}{-R_p \ln \left(\frac{R'}{2R' + R_L} \right)}$$

Subject to the simplifications made, this is the minimum value of capacitance necessary to accomplish turn-off.

Since $R' \gg R_L$ for most applications, $R_p \doteq R_L$ and

$$\ln \frac{R'}{2R' + R_L} \doteq \ln 0.5 = -0.692$$

Then the formula for C becomes

$$C = \frac{t_0}{-R_L (-0.692)} = 1.44 \frac{t_0}{R_L} \quad (4)$$

As an experimental test of the validity of this result, the circuit was connected with a load resistor of 70 ohms and a supply voltage of 135 volts. R' was determined from a curve tracer to be approximately 1.5×10^6 ohms for the particular unit used. C was increased until it was large enough to effect turn-off when S (a mechanical switch) was closed. For the unit used, the critical value of C was approximately 0.25 microfarads. From equation (4), this corresponds to a turn-off time of

$$t_0 = (70)(0.25 \times 10^{-6})(0.692) = 12.1 \times 10^{-6} \text{ seconds}$$

According to the specifications for the device, this would be a very typical figure for turn-off time for these circuit conditions. (Specifications state that turn-off time is of the order of ten times the turn-on time.)

Of course, in order to accurately determine the minimum necessary value of capacitance, the exact turn-off time of the device to be used with the given circuit conditions must be known. In Chapter 2, it was indicated that forward current immediately prior to turn-off and the rate of rise of reapplied forward voltage are important in determining t_0 . These two factors together with the device geometry will largely determine the magnitude of t_0 . Since device geometry will vary slightly from unit to unit, the longest expected turn-off time for a given set of circuit parameters of any device in the group to be used should be used to calculate C. Similarly, the minimum expected value of reverse resistance

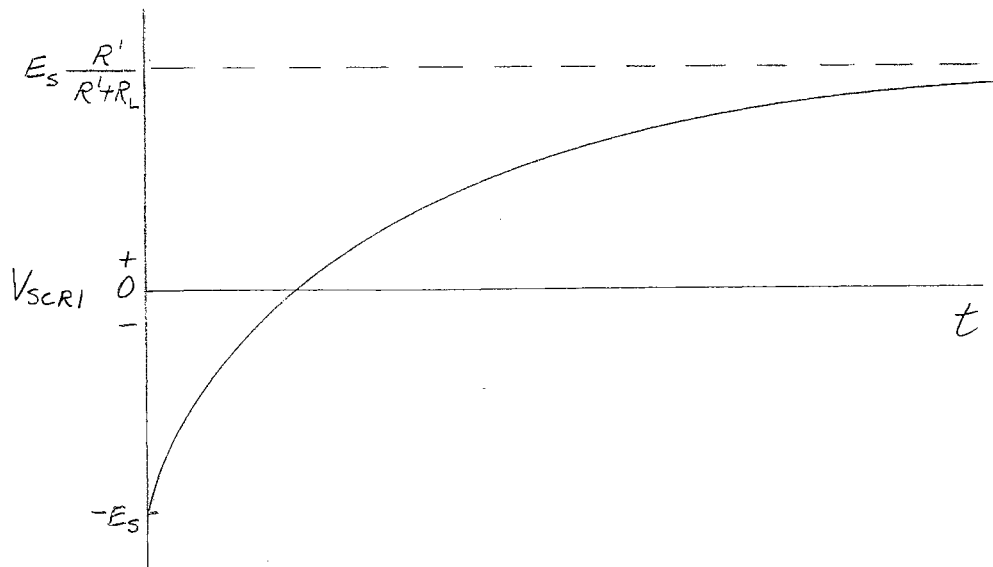


Figure 11. V_{SCR1} as a Function of Time.

(R') should be used. Finally, a safety factor of something like 1.5 to account for errors due to simplifications made in the analysis would seem advisable.

Examination of the circuit operation points out that care must be taken not to allow both units (SCR1 and SCR2) to reach the on condition at the same time. When such a condition exists, the circuit is in a "helpless" state; that is, there is no way either device can be turned off unless special provision has been made. Such a condition can result from either of two causes. One is a simultaneous positive signal at both gates. The other is a simultaneous transient at the anode of both devices which would turn the off device on and prevent the on device from turning off. The latter situation might, for instance, arise when the supply voltage is first connected into the circuit. For this reason, it is advisable to arrange some scheme to gradually increase the supply voltage to its final value. As an alternative, a small inductor could be inserted in series with each device at the anode to limit the current surge through the capacity of the device.

Should both devices be in the on condition, either can be turned off by momentarily shorting the anode to ground, with the gate open. Obviously, all that has been said presupposes that the breakover voltage with no gate current for both SCR1 and SCR2 is greater than E_s .

In general terms, the control signal requirements for this circuit are a positive signal at G_1 to deliver power to the load, and a positive signal at G_2 to turn off load power. The signal may be a pulse or a d-c signal. If pulse operation is used, the pulse should, of course, be longer than the turn-on time (usually of the order of 1 to 2 microseconds). In both cases, provision must be made to limit gate current to a safe value and to prevent positive signals from appearing at both gates simultaneously. As always, the sensitivity of either device can be modified by connecting a resistor from gate to cathode.

One of the most familiar examples of relay operation is that of a relay operated by a light signal actuating some type of photosensitive device. Figure 12 shows one way in which such a circuit can be synthesized using silicon controlled rectifiers. It is analogous to an electromagnetic relay circuit in which the relay contacts close, delivering d-c power to a load, when light intensity changes from a low to a high value. The photosensitive device used was a type 1N2175 n-p-n diffused silicon photo-duo-diode. This device is non-polarized, has a typical dark current at 50 volts of 0.01 microamperes and has a typical light current at 10 volts of 200 microamperes. The transistors are type 2N338 n-p-n switching transistors which have a maximum collector voltage of 45 volts. The circuit is designed so that with normal light intensity, T_1 is practically at cut-off and T_2 is saturated (conducting heavily). This in turn means that SCR2 is turned on and SCR1 is turned off. When the light intensity is increased sufficiently, T_1 is driven to saturation

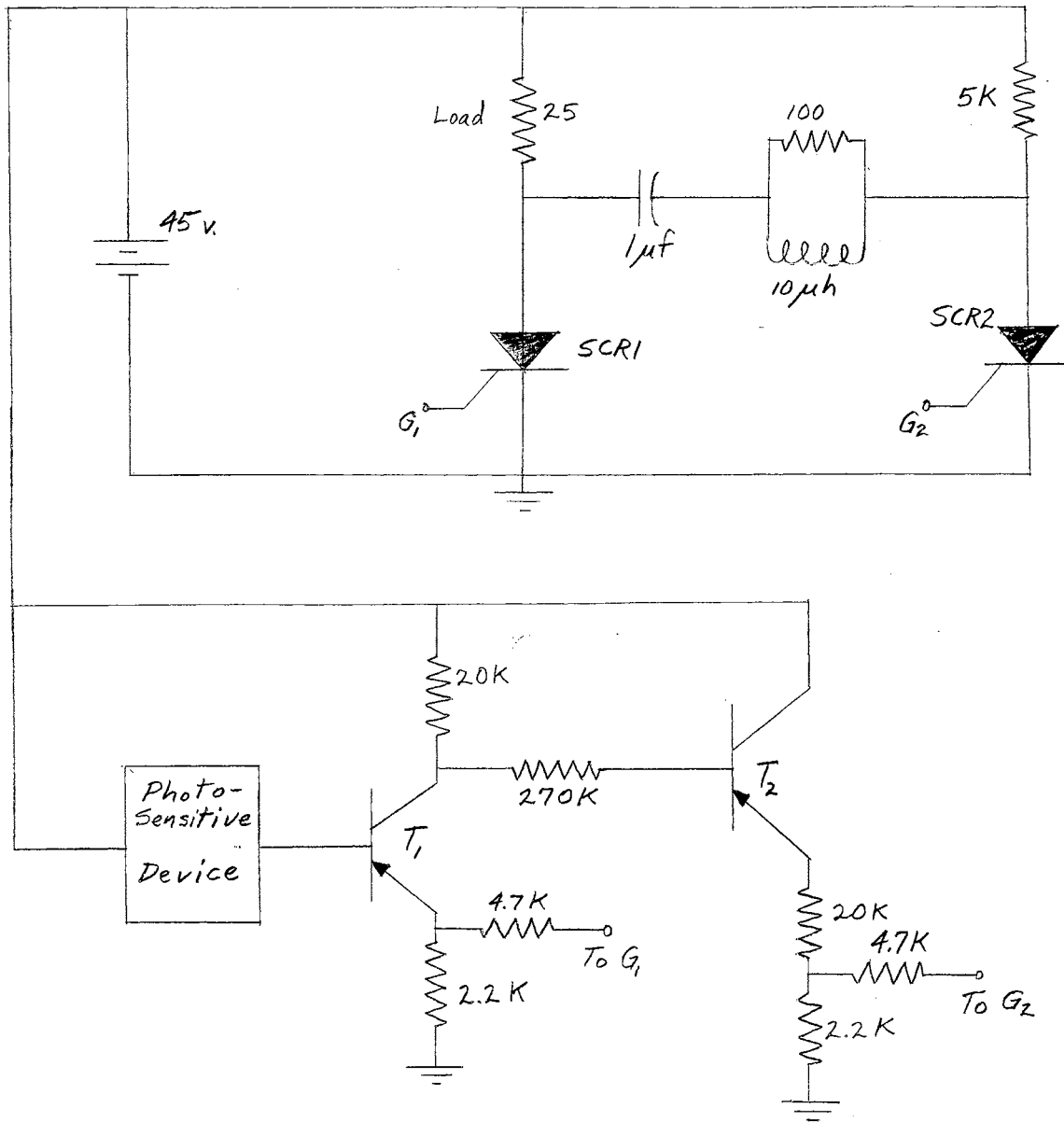


Figure 12. Circuit for Switching Power to a Load with a Light Signal.

which in turn causes T_2 to approach cut-off. Thus power is delivered to the load when the light intensity is great enough. Obviously, if the gate connections are reversed, power will be delivered to the load when the light intensity is low.

This circuit was found to operate quite satisfactorily. Since the photo-duo-diode could be replaced by any of many other types of signal

devices, the circuit represents a general circuit for controlling the switching of the silicon controlled rectifiers. There will generally be little difficulty in supplying power for the transistors. If the main supply voltage is higher than the voltage rating of the transistors, several schemes can be used. Since the current required by the transistors will normally be about two orders of magnitude less than the load current, a simple two resistor bleeder divider network across the main supply voltage will usually suffice. When the regulation of the supply voltage is poor, a Zener reference diode can be used to advantage.

Examination of the basic shunt capacitor turn-off circuit reveals that the circuit could be made free-running by proper coupling from one controlled rectifier to the other. In this way, d-c power can be switched to and from a load at variable repetition rates and duty cycles which are dependent on the time constants of the circuit. Such operation was executed successfully, and it was found that several different coupling schemes could be used. However, since this type of operation digresses from the main thesis objectives, it was not explored extensively.

CHAPTER VI

SUMMARY

This thesis was principally concerned with investigation of the use of silicon controlled rectifiers to perform some of the functions for which electromagnetic relays have commonly been used. The problem was divided into two broad categories on the basis of whether a-c or d-c power was to be delivered to a load.

To facilitate the understanding of the operation of the silicon controlled rectifier, a brief discussion of its theory of operation, important parameters, and typical characteristics was presented. Several basic tests were performed to determine the actual typical characteristics of the devices to be used in the thesis research. The aspects most pertinent to the use of the device as a relay were stressed.

The limitations of the device in relay applications were mentioned and explained. Its several advantages over conventional electromagnetic relays were pointed out.

The basic circuit for utilizing silicon controlled rectifiers to switch a-c power was tested and found to operate satisfactorily when suitable values of circuit parameters were used. Pertinent design considerations were given.

The shunt capacitor turn-off method was considered to be most satisfactory for use of the silicon controlled rectifier to switch d-c power. The bulk of the analysis of this circuit was the determination of the minimum necessary value of capacitance to effect turn-off for a given

set of circuit conditions. The circuit was made to operate quite satisfactorily, and a transistorized light-sensitive circuit was used to demonstrate the development of control signal circuitry.

While the devices used for this research are intended for relatively high power switching, other units are available for use where the power levels are much smaller. Thus the analysis presented in the thesis would be useful for many types of low power relay applications, such as use in logic circuits.

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