ELECTRICAL

ENGINEERING

ENGINEERING EXPERIMENT STATION

AUBURN UNIVERSITY

AUBURN, ALABAMA

FINAL TECHNICAL REPORT

INVESTIGATION OF DESIGN OF HIGH VOLTAGE, HIGH CURRENT SOLID STATE SWITCHING DEVICES

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April 24, 1968

CONTRACT NAS8-21081

GEORGE C. MARSHALL SPACE FLIGHT CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This is a final technical report of a study conducted by the Electrical Engineering Department of Auburn University under the auspices of the Auburn Experiment Station toward the fulfillment of the requirements prescribed by NASA contract NAS8-21081.

ABSTRACT

In the past, the switching of thousands of amps and thousands of volts has been almost exclusively limited to mercury pool, gas-filled tubes like the ignitron. Using the ignitron tube has several disadvantages, however, and with the increase in solid-state technology it is desirable to ascertain where these large tubes can be replaced. This report is a study of the application of Semiconductor Controlled Rectifiers, (SCR's) in power switching in general and for static switches in particular.

The inherent problems associated with P·N·P·N devices like the SCR are discussed, and the problems of variable loads, large transients, and extremely short duty cycles are considered along with the necessary triggering mechanisms to achieve proper switching.

When the ratings of a single SCR are exceeded, it becomes necessary to resort to series and parallel operation to adequately perform the switching application. However, parallel and series operation of controlled rectifiers introduces many problems related to triggering, load voltage sharing, load current sharing, and heat removal. Design techniques for compensation of these factors are included in this report, with series and parallel operation considered separately.

To illustrate the problems associated with very high power SCR switches, a prototype switch capable of switching 10,000 volts and 10,000 amperes in a 30 microsecond duty cycle is designed using SCRs'

that are presently available. The limitations of these presently available SCRs for applications of this nature will be discussed, and means to circumvent these limitations are given where possible.

Finally, and most significantly, this report will recommend possible changes in SCRs to better enable the device to perform static switching. These changes will vary from moderate modifications to improve the ability of SCRs to switch moderate powers, to very basic changes that could possibly enable the SCR to compete with very large tubes for static switches.

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INVESTIGATION OF DESIGN OF HIGH VOLTAGE, HIGH CURRENT SOLID STATE SWITCHING DEVICES

F. R. McDevitt and E. R. Graf

I. Introduction

Recent advances in the art of growing large silicon crystals, allied with improved doping techniques, have yielded a line of silicon controlled rectifiers with high voltage blocking ability and large current capacities. With these new controlled rectifiers it is desirable to determine how well semiconductor devices can compete with large tubes like the ignitron and thyratron in static power switching.

Static switching may be defined as the switching of a direct current or as the switching of a pulse of current with a long time lag between pulses. Although either of these definitions could be applied to this report, the applications involving the switching of large pulses spaced several seconds apart will be the primary concern.

The ignitron tube, which is basically a mercury-pool rectifier capable of being externally fired, has been used for several years in large voltage, large current switching. However, the ignitron has several significant limitations:[1]

(1) First, the ignitron requires large amounts of external power in its triggering circuit. In fact, it is not uncommon to need about one-tenth as much triggering current as there is load current, and in

applications involving the switching of thousands of amperes and thousands of volts the trigger circuit design is often as critical and difficult as the main switching circuit. The SCR, on the other hand, is contrasted by having the ability to switch thousands of amperes with milliampere triggering currents.

(2) Secondly, being a mercury pool device, the ignitron cannot be used in space applications, since the mercury pool must remain level in the tube. Actually, if parallel operation is necessary, the ignitrons in parallel must be nearly perfectly level with respect to each other since the resistance of the ignitron is determined by the level of the mercury pool. In contrast, the SCR can be used in any physical position, and as long as the temperature remains between -40 degrees centigrade and 125 degrees centigrade, the SCR can function properly as a switch.

The basic characteristics of the PNPN device needs to be known before it can be applied to any situation. The static and dynamic characteristics yield information about the properties of the SCR in the blocking and conducting states, and the variation of these properties under a wide range of applications dictates the controlled rectifiers' usefulness.

There are two major ways to trigger the SCR, namely gate triggering and anode triggering. Gate triggering is the most commonly used firing means, and is adequate except in those cases demanding very fast switching times. Anode triggering, which yields a much faster turn on time, demands fast rising voltage pulses of a large magnitude to induce triggering.

Knowledge of the SCR, and its triggering means enables the designer, with presently available SCRs, to handle switching powers of several thousands of amperes and around a thousand volts. Series and parallel operation produces problems in terms of load voltage sharing and load current sharing. The applications of series and parallel operated SCRs at the present time are limited to situations involving slow rising voltage and current waveforms. With this in mind, it is useful to attempt a switch design which equals or exceeds the limitations of presently available SCRs, since then the difficulties and shortcomings are brought out.

Finally, there are several major improvements that can be made on SCRs to better adapt the device to static switching. Consolidated packaging in cases involving series operation with short load pulses could easily be implemented. Multiple gate SCRs are currently being investigated by manufacturers, and eventually will greatly enhance the SCRs ability to perform static switching. Light triggering has tremendous possibilities in cases where the isolation problems with gate or anode triggering are excessive. If large 4 layer diodes were available with electrical characteristics comparable with the larger SCRs, a new area of static switching is possible. The current densities allowable with 4 layer diodes are much higher than with gated SCRs, which essentially means that this device may be very competitive with large mercury tubes in the future.[2]

II. THEORY OF OPERATION

A. Theory of PNPN Operation

The Semiconductor Controlled Rectifier, hereafter called the "SCR," or just simply "controlled rectifier" is a three terminal, four layer device that has the voltage-current static electrical characteristics shown in Figure 1. As the Figure illustrates, the SCR is basically a bistable device with a very high resistance in the "off" state (normally around 100,000 ohms), and a very low resistance in the "on" state (normally around .01 ohms). The function of the gate electrode is to control the transition from the "off" to the "on" state, and it is significant that there is no intermediate stage of SCR operation, the device is either "off" or "on." The SCR has been compared to the thyratron tube, and the two devices are alike in that once the gate electrode turns the SCR to the conducting state it loses control over the rectifier. The similarity ends here, however, since the thyratron is basically a voltage-controlled device and the SCR is a current-controlled device. The gate electrode shown can be connected to either the inner "P" or "N" material in Figure 1, and,therefore,it is possible to have "P" gate and "N" gate SCR's that can be thought of in much the same manner as PNP and NPN transistors. In this report only "P" gate SCRs' will be considered, since any discussion would apply equally well to both except for polarity differences.[3]

The most common means of explaining the switching operation of the SCR is the two-transistor analogue, and although it has some

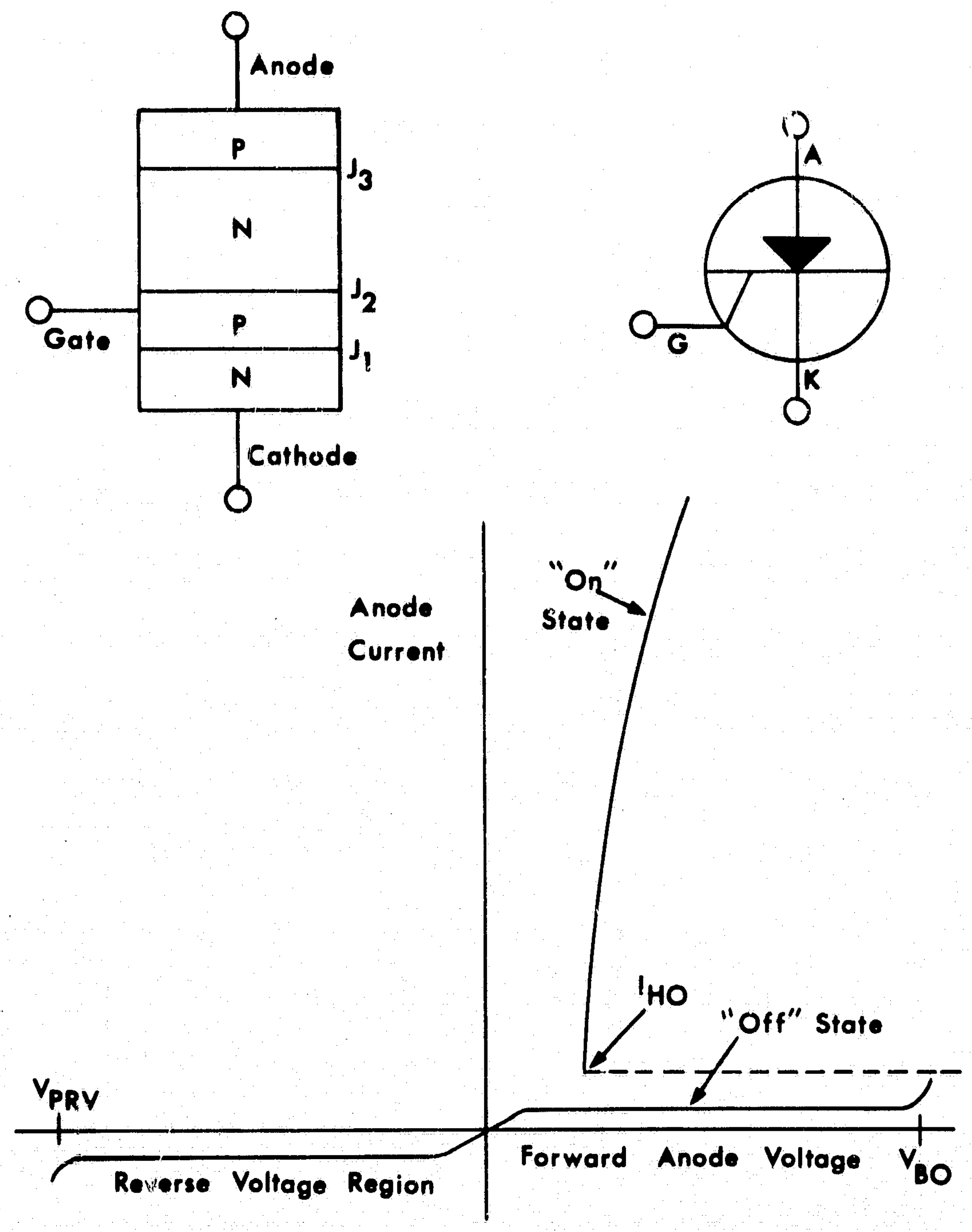


Figure 1.--SCR Forward and Reverse Characteristics.

theoretical limitations, this analogue is probably the best way to first-approximate the SCR's operation.[4] As illustrated in Figure 2, the SCR can be thought of as two transistors having a common collector, with each transistor receiving its base drive from the collector of the other transistor. With positive voltage applied to the SCR anode, and no base drive, the junction J_1 and J_3 are forward-biased, whereas J_2 is reverse-biased. No large current flow is possible, and the device is in its' high resistance or "off" state. However, as soon as sufficient positive base-drive is applied to Q_2 junction J_2 becomes forward-biased and a small current begins to flow. By transistor action in Q_2 a larger current exists in the collector of Q_2, which in turn flows into the base of Q_1. By similar transistor action in Q_1 the current is amplified and fed again to the base of Q_2. It can be shown by simple transistor equations for the circuit in Figure 2 that when this loop gain equals one a regeneration situation exists and both transistors are driven very quickly into saturation. This yields the low resistance "on" state for the SCR. The statement that this loop gain equal one is essentially the same as saying that certain current levels must exist in the device to cause switching. If the gate drive is powerful enough to insure this current level then the SCR will switch "on" in about 5 microseconds. The SCR is therefore "self-latching" in that is requires definite current levels to switch to the conducting state. Also, as stated earlier, once in the "on" state the SCR will remain "on" unless some external means is applied to reverse-bias junction J_2 in Figure 2. This can be achieved by applying a gate pulse of the proper polarity, but it is usually done

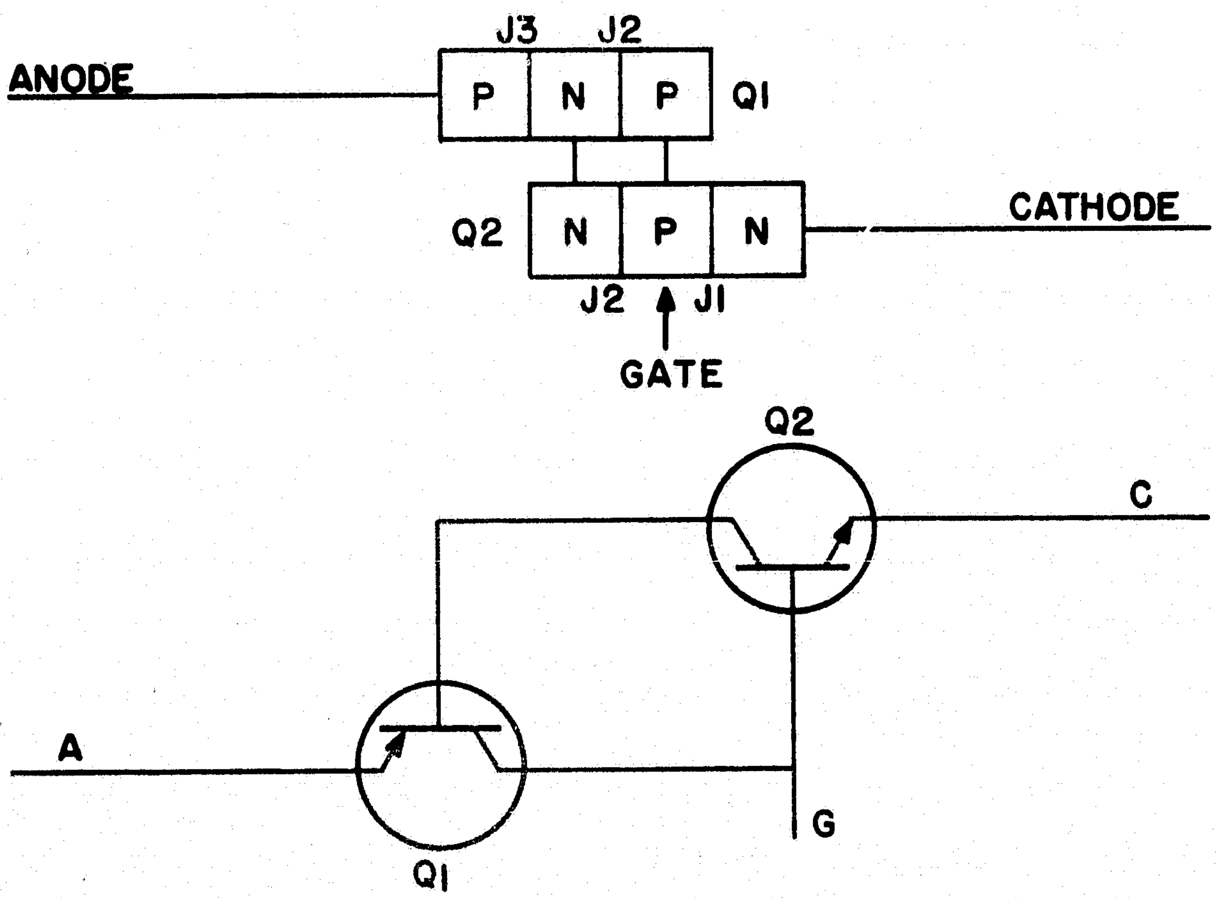


Figure 2.--Two-Transistor Equivalent Circuit for SCR.

by forcing the anode current to fall below the "latching" level. Also, it is possible to create an "effective" base drive by sufficient increase in temperature or anode voltage large enough to switch "on" the SCR, and the compensation of these effects will be discussed later.[3]

With negative voltage applied to the SCR anode, junctions J_1 and J_3 in Figure 2 are reverse-biased, whereas junction J_2 is forward-biased. Transistor action cannot occur in Q_2 when the gate is driven, since J_1 is reverse-biased. Switching cannot occur in this configuration.[3]

From this analogy it is seen that the SCR is a regenerative, self-latching switch which turns "off" if the anode current falls below a certain level, and once is "on" attempts to stay "on." In contrast to other types of switches the SCR has a very high "turn on gain," which means it takes very little trigger power to switch very large load powers. Typical turn-on gain values for SCR's are 10^5-10^6, whereas for mercury pool tubes like the ignitron it is of the order of 10^1-10^2.[5]

B. Static Characteristics

Although the two transistor analogy gives a simple explanation for SCR behavior, it is obvious that a more precise discussion of the static characteristic given in Figure 1 is necessary in order to design SCR switches. Since the controlled rectifier has two basic states, the discussion of the characteristic will be divided into two categories, the "off" or blocking state, and the "on" state.

1. "Blocking State"

When the gate of the SCR is held at cathode potential, and the device is in the blocking state, the SCR has the same basic properties as two rectifier diodes connected in opposition in series. Therefore, the magnitude of the voltages labeled V_{PRV} and V_{BO} on the blocking characteristic in Figure 1 are usually the same, and only one value is usually given with SCR ratings. When these two voltages are approached along the characteristic curve, and avalanche effect occurs, but this avalanche effect is very different for the two voltage points. V_{PRV} is the maximum negative voltage that can be applied to the anode without avalanche, and if this voltage is exceeded the SCR will draw a large avalanche current and will be destroyed. V_{BO} is the maximum value of positive voltage that can be applied to the anode without avalanche occuring, but the forward avalanche effect is a non-destructive one and the device switches to the conducting state. The actual breakdown voltage in both directions is highly temperature sensitive, and Figure 3 shows this dependence for the forward breakover voltage of three different types of SCRs. From this figure it can be seen that at low temperatures V_{BO} is much higher than the value given by the SCR manufacturers.[5] This is a common practice among SCR manufacturers, and for the design of static switches, which involve little long term heating problems, the value of V_{BO} given in the specification sheet by the manufacturer can possibly be the value actually used. Also, it should be pointed out that the SCRs with higher values of break-over voltage exhibit the largest voltage changes over the temperature range shown.

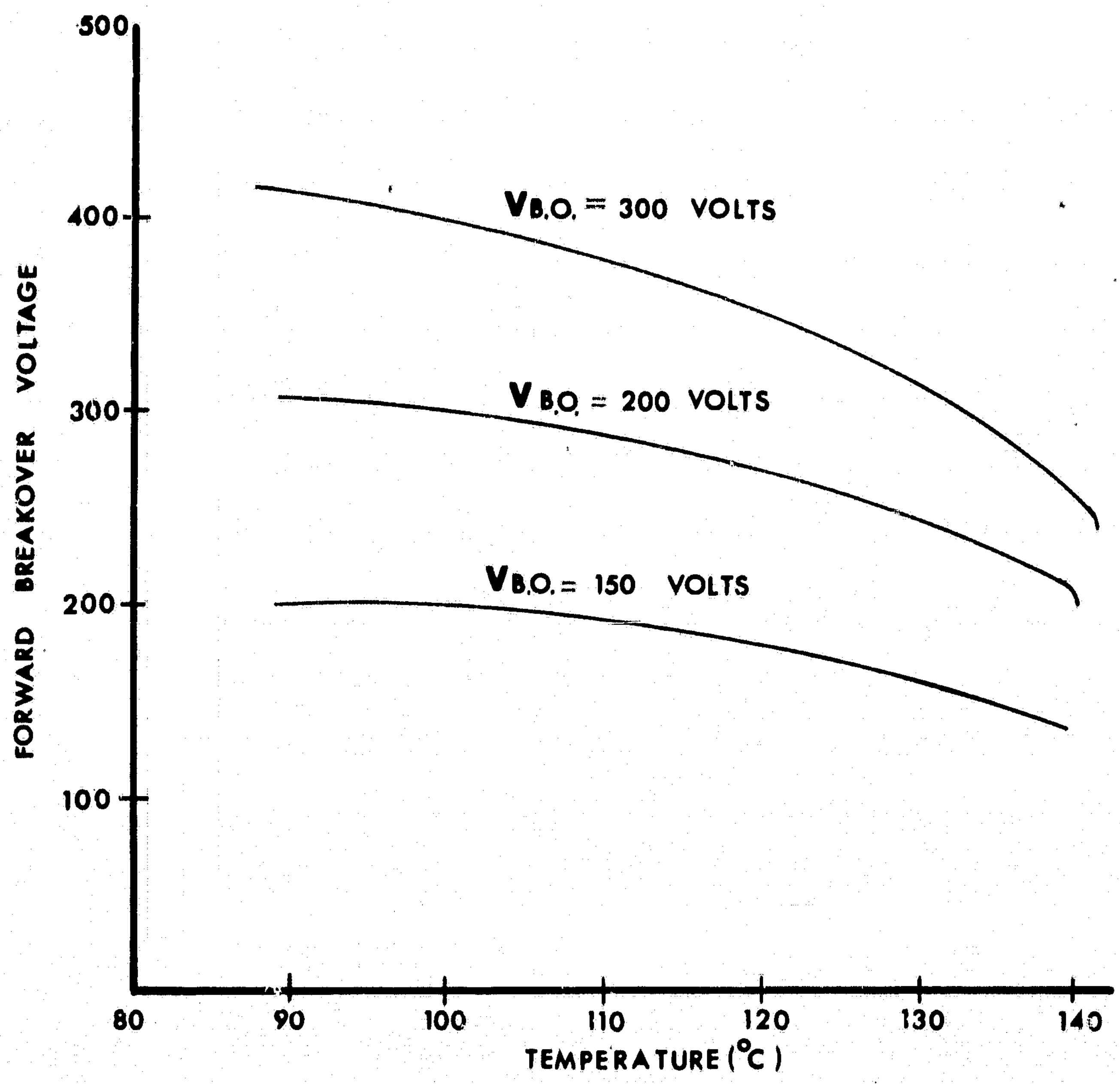


Figure 3.--Breakover Voltage as a Function of Temperature.

There are also values of leakage current associated with the blocking state, and although these values are usually small, they can drastically affect turn-on if the temperature increases. The temperature dependence of these leakage currents is shown in Figure 4. The characteristics of SCRs' of the same type can vary drastically from one device to another, and the only parameters that are guaranteed by SCR manufacturers are static values such as V_{PRV} and V_{BO}, which are limiting values. This means that any SCR can (and usually does), have a completely different curve slope and a completely different value of leakage current than another SCR of the same type. Also, the variation of leakage current with temperature is drastically different from one device to another of the same type, and, therefore, curves such as shown in Figure 4, should be used only to get typical value for design use.[5]

2. Gate considerations

In the previous paragraphs the gate was assumed to be at cathode potential, and when a small gate current is allowed (not large enough to turn the SCR "on"), the blocking characteristic is changed significantly. Allowing positive gate drive while a negative voltage is being applied to the anode causes an increase in the leakage current, which causes the controlled rectifier to overheat and can easily destroy the device. In the forward blocking direction a positive gate current increases the leakage current and can lead to switching. This increase in leakage current causes a drastic change in V_{BO}, as shown in Figure 5, and the SCR can switch

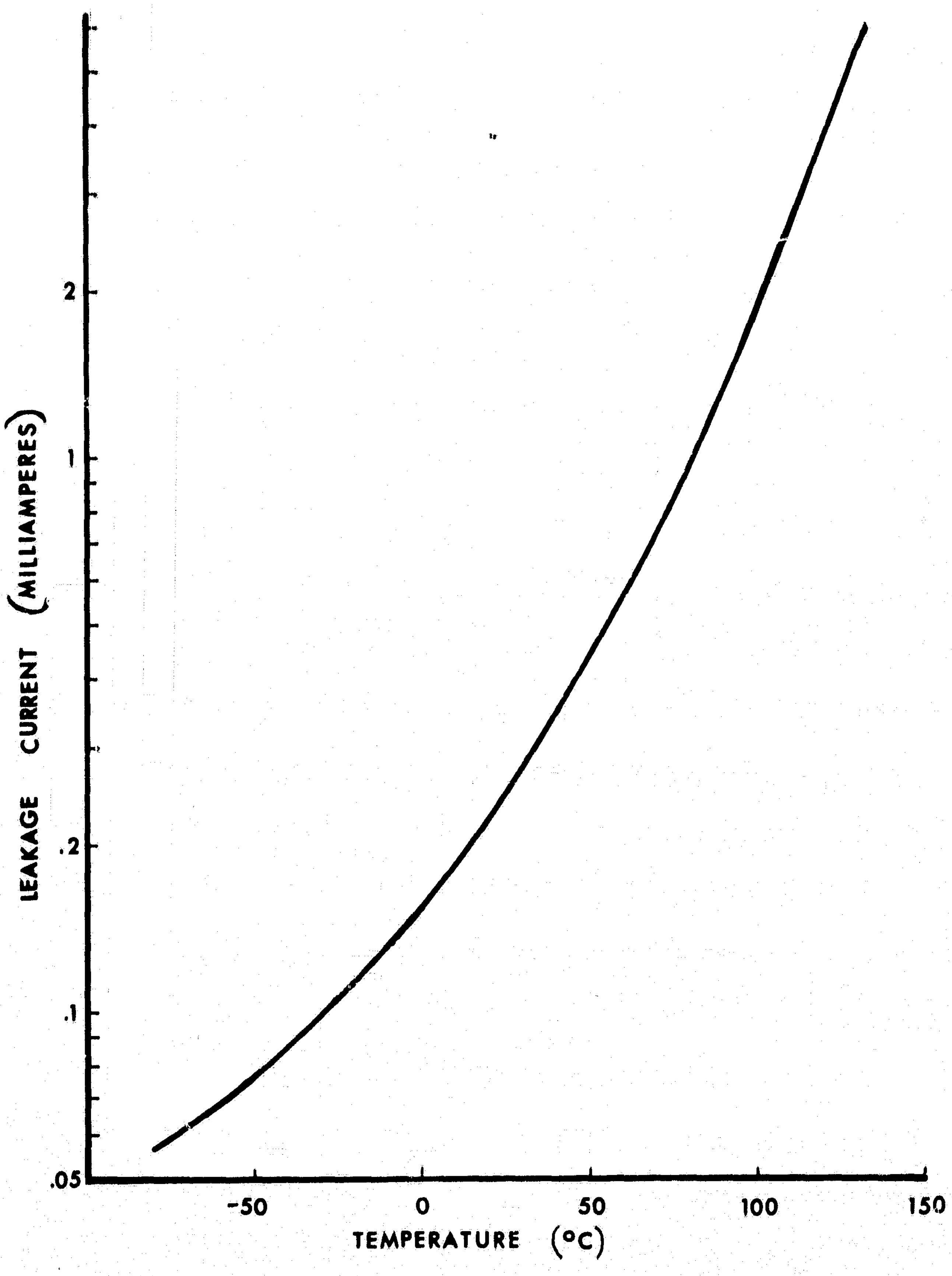


Figure 4.--Leakage Current as a Function of Temperature.

at some unknown value much lower than V_{BO}. Also, the increase in leakage current causes unnecessary heating in the SCR.[3] This discussion of the effects of gate current on blocking is given to show why some type of clamping device in the gate cathode circuit is commonly used to prevent temperature effects and residual gate currents from deteriorating SCR performance.

3. "On" State

The various ways of switching the SCR to the "on" state will be covered in the section on dynamic characteristics, since a lengthy discussion of these effects will be necessary. In this section it will be assumed that the SCR has previously been switched to the "on" state.

The forward conduction state of the controlled rectifier is much like the forward state of a normal rectifier diode, as is shown by the "on" state portion of the curve in Figure 1. The slope of this curve is determined by the total internal resistance of the SCR, and this slope can vary drastically from one SCR to another. The forward voltage drop in the conducting state is not as sensitive to temperature as other SCR parameters, and the device can withstand large overload currents for short periods of time. The static characteristic in Figure 1 does not properly indicate the wide range of forward currents possible over short time periods with SCRs, and the vertical axis in Figure 1 would have to be logarithmic if the values of current were put on the Figure. Actually, except for the heating effect due to small internal resistance, for the SCR there is no limit to the forward

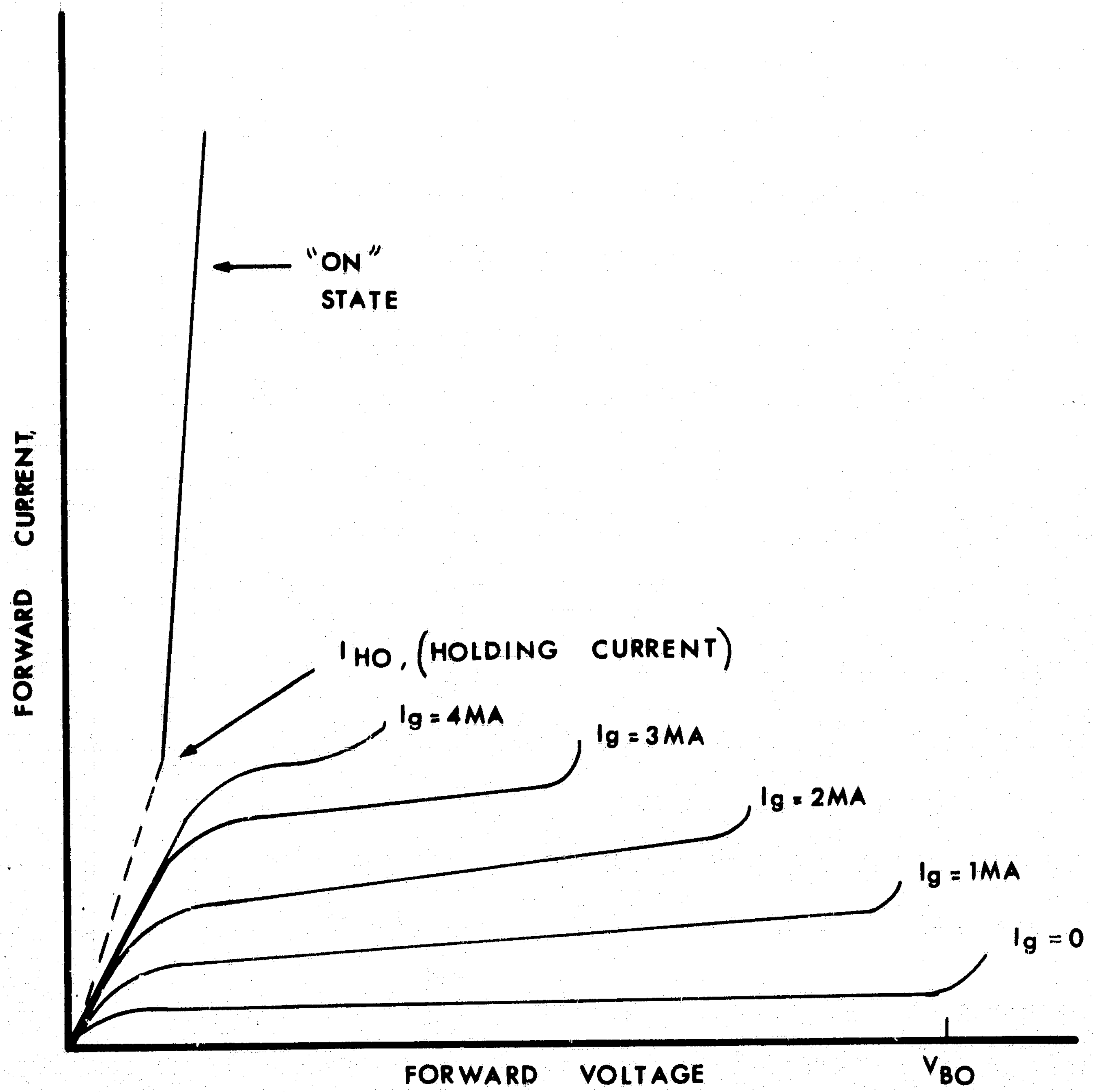


Figure 5.--Gate Current Effect on Forward Current
Forward Voltage Characteristic.

current that can be carried. The circuit impedance external to the SCR usually is the current limiting factor. Therefore, it is easily possible to exceed the rms forward current rating of the SCR by a factor of 10 or even 100 for low duty cycles without inducing failure.[5]

Unlike the forward voltage drop in the conduction state, the values of current around point I_{HO} in Figure 1 exhibit large variations with temperature change. I_{HO} is the lowest value of current that can exist and maintain the rectifier in the "on" state, and is called the "holding current." The holding current is very temperature sensitive, and this variation of I_{HO} with temperature for a typical large junction SCR is shown in Figure 6. The SCR is not designed to be operated in the area of I_{HO} on a steady state basis, and the device is metastable in that any transient or temperature decrease will tend to initiate turn off. For these reasons a value of current above the actual I_{HO} is usually given in SCR specifications, and this value may even be called a "latching current" by manufacturers instead of the holding current. Even if the holding current is given it must be of a value large enough to maintain all of the SCR's of a given type in the "on" state, and therefore any particular SCR of this group may have a much lower value of I_{HO}. This value is of course the best value to use in designing switching circuits.[5]

There is a limit to the maximum switching repetition rate for SCRs, and although this report concerns static switching this limit has bearing in cases where the switching cycle is large, or in cases where an external means is used to create blocking.

When the forward current rapidly attempts to return to zero the static characteristic in Figure 1 must be modified, and an enlarged

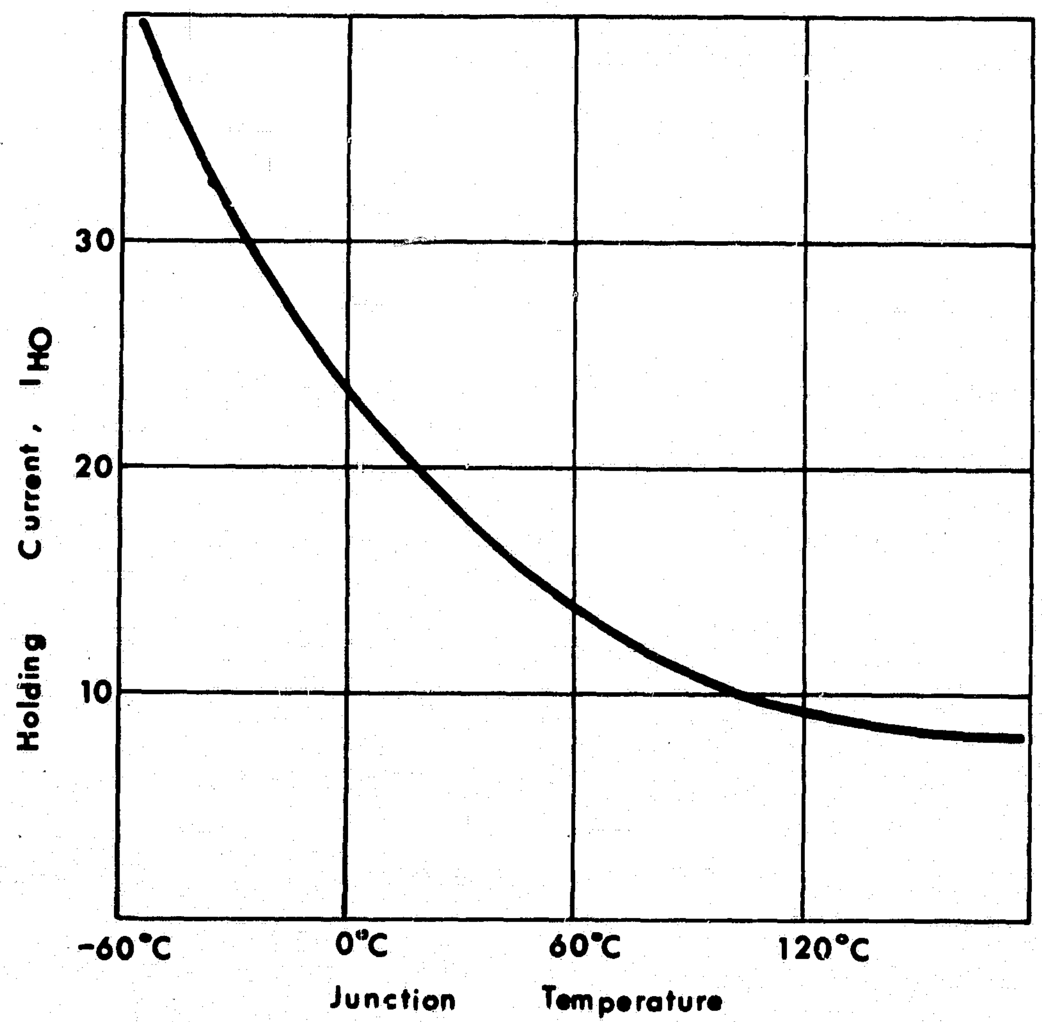


Figure 6.--Holding Current as a Function of Temperature.

view of this modification is shown in Figure 7. It has been observed experimentally that when the rate of decrease of forward current, measured in milliamps per microsecond is of the same order of magnitude as the holding current, there is a considerable lengthening of the time it takes the SCR to reach the forward blocking state. The dotted line in Figure 7 shows the effect of a rapidly decreasing anode current on the static characteristic. Since it takes a longer time period for forward blocking to occur, if the switching cycle were too great a positive pulse could be applied to the anode before blocking occurred, and the SCR would never switch off. As an example of this problem, consider the application of a 10 Hertz sine wave with a 100 ampere peak current being applied to the anode. The rate of decrease can be calculated as $2\pi \times 10 \times 100 = 6{,}283$ amps per second, or 6.283 milliamps per microsecond. If the holding current of the SCR is around 6 milliamperes, there is a very good chance the SCR will never turn off once it has been turned on. Knowledge of the holding current and the peak applied current can therefore give the switch designer an idea as to the maximum static switching cycle time possible in a given system.[5]

C. Dynamic Characteristics

Static switching of large powers puts severe demands on the turn on operation with SCR's, and the relative merits of the several triggering schemes need to be discussed at this point. The most desirable triggering means for SCRs are light pulse triggering, gate triggering by applying a gate pulse of proper polarity, and voltage triggering by applying a rapidly rising voltage waveform to the anode. It is also possible to induce switching by sufficient temperature increase,

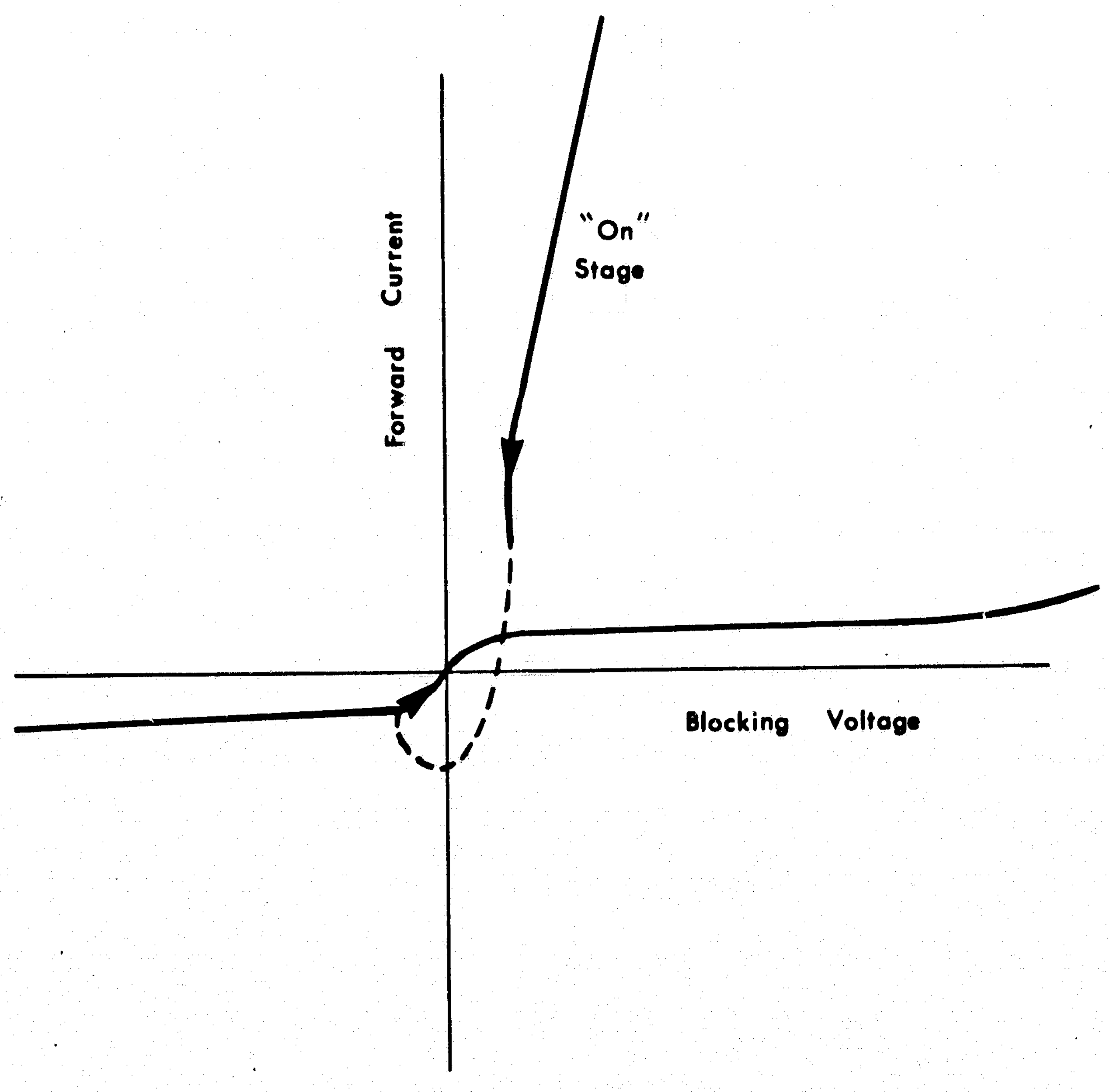


Figure 7.--Dynamic Voltage-Current Characteristic.

transients, or by slowly exceeding the breakover voltage, and the compensation for these undesirable effects will be considered in a later section. There are also a wide variety of ways to turn off the SCR, but only the means of turn off that apply to static switches will be considered in this report.[3]

1. Turn On - by current.

For a P-type SCR the application of a positive current of sufficient magnitude to the gate will switch the SCR to the conduction state. The amount of gate current required depends on the magnitude of V_{BO}, the forward blocking voltage, as shown previously in Figure 5. A detailed discussion of gate firing based on temperature effects and SCR tolerances will be presented in a later section, since before this is possible the definitions of the various turn-on times should be given.

The total turn-on time, T_t, is usually defined as the time elapsed between the application of a fast rising gate pulse and the time that the forward resistance of the SCR has fallen from its high value to its low value. This time period is usually measured in practice by taking the time difference between the application of the gate pulse and the time at which the anode current is 90 per cent of its final value. The total turn on time is then subdivided into the "delay time," td, and the "rise time," t_r.[5]

The delay time is defined as the first part of the total turn on time from the application of the gate pulse until the anode current reaches 10 per cent of its final value. The delay time can be decreased by using the highest possible gate current magnitude without exceeding the rated gate power, and by using the highest possible rate of rise of gate current. For these reasons the gate circuits of SCRs usually employ pulse circuitry, and the inductance of this circuitry is kept at a minimum to allow high values of current rate of rise. Once this criterion of a fast rising, high amplitude gate pulse is filled, no further decrease in the delay time is possible.[5]

The "rise time," t_r, is the remainder of the time required for the current to go from 10 per cent to 90 per cent of its final value. These times are illustrated in Figure 8, and are always given with SCR specification sheets. The rise time is very dependent on the circuitry external to the controlled rectifier, as the two waveforms of current and voltage as a function of time shown in Figure 8 indicates. It is obvious that the rise time in a purely resistive anode circuit is largely a function of the eventual anode current. However, an inductive load in the anode circuit lengthens the rise time, and this means that the application of a large current pulse could damage the SCR if applied before the device was sufficiently "on."

In addition to lengthening the rise time, inductive loads also greatly affect the duration of the gate pulse necessary to insure proper firing. As shown in Figure 9, the gate pulse duration must be long enough to allow the latching current to be reached, or the SCR will not switch when the pulse is applied. For this reason maintained triggering is often used in inductive SCR circuits, but here care must be taken that the gate is not driven positively while the anode becomes negative with respect to the cathode, since this causes large internal power dissipation. Turn-on times $(t_d + t_r)$, for large area SCRs in inductive load applications are of the order of 50 to 100 micro-

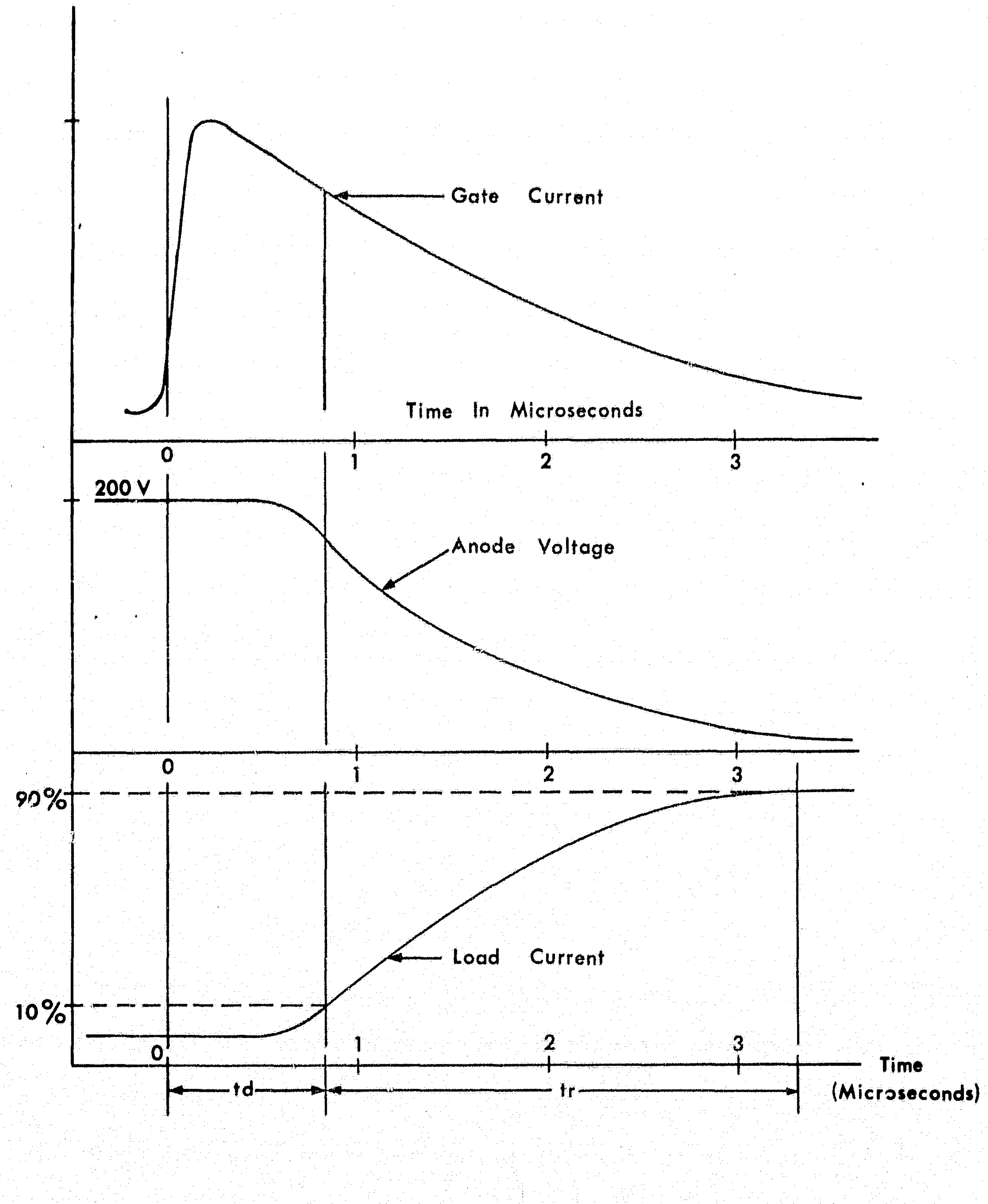


Figure 8.--Dynamic Turn-On Curves for Gate and Load Current, Anode Voltage.

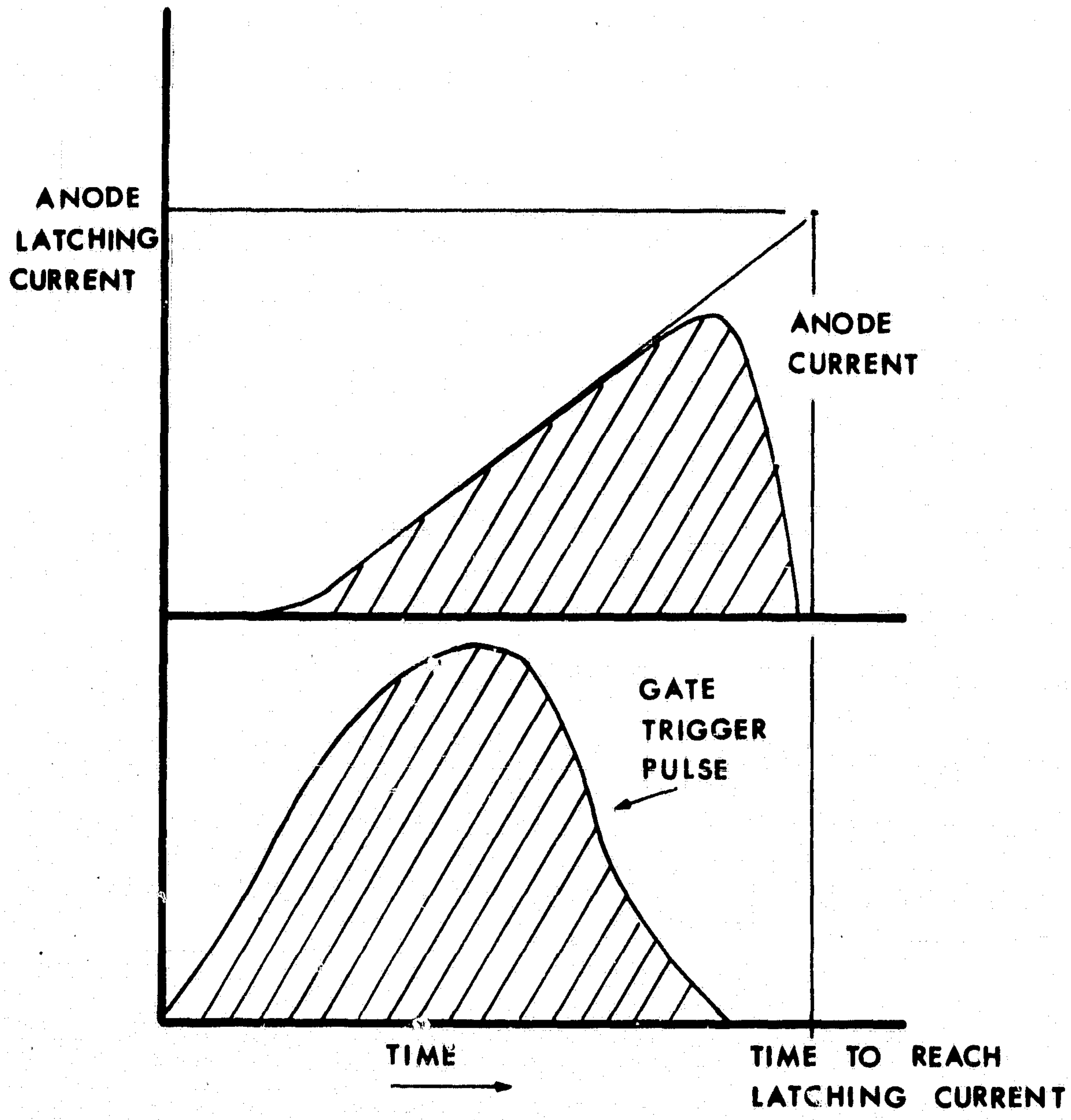


Figure 9.--Illustration of need for Maintained Triggering for Gate-Firing

seconds. For this reason it is a common practice to put a saturable reactor in the anode circuit to limit the anode current while driving the SCR to the on state by a powerful gate pulse.[3]

2. Turn On - by voltage

It is impossible to manufacture SCRs without having a small value of inter-device capacitance, and this small value of capacitance can be utilized to turn on SCRs without using the gate lead. If dv/dt is called the rate of rise of anode voltage, and C_i the inner-rectifier capacitance. Then it is obvious that the current in the SCR due to the capacitance when anode voltage is being applied at a certain rate is

$$i_C = C_i \; dv/dt \qquad (1)$$

If the rate of rise of voltage is large enough (usual figures are around a KV/microsecond), it is possible for i_C to reach the holding current level and therefore possibly switch the device to the conducting state. This phenomena is called the "Rate effect." and is usually avoided.[6] However, the Rate effect can be used to an advantage in some cases. If the forward voltage in the blocking state is reduced to about 50 per cent of the breakover voltage, and a voltage pulse is then applied to the anode in a very short period of time the entire junction area of the SCR will avalanche and the SCR will go into the full conducting state very rapidly. Due to lateral inhomogeneities across the base regions it is very difficult to determine exactly when forward break-down will occur, since a localized spot on the junction could easily have a much lower V_{BO} than the rest of the area. This means that if forward voltage was applied slowly, this spot would be the first point to experience avalanche breakdown, and would be forced to carry the total load current. According to some authors the "Rate effect" method of turn on has several distinct advantages over gate turn on methods.[2]

First, since the rapidly rising waveform is applied to the total anode junction area at the same time, more area is brought into the conducting state in a given time period than can be turned on by gate methods. This means that some decrease in turn on time is possible with this technique, which is very important in applications where the SCR is to be operated at or above rated currents in very short periods of time.

Secondly, this method reduces the probability of transients and other unknown effects exceeding V_{BO} and causing breakdown, since the static forward voltage is held at a much lower value than when gate firing is used. The temperatue sensitivity of the forward breakover voltage would then also be of lesser importance.

Finally, this method of turn on has the advantage of good accuracy in selecting the firing point. The firing voltage pulse may be introduced into the anode circuit by capacitance or pulse transformer coupling, as shown in Figure 10. The anode triggering circuit may be either in shunt or in series with the controlled rectifier.[3] The SCRs are drawn without their gate leads connected to any part of the circuit, since no gate lead would be brought out of the controlled rectifier in actual use. The switching of large powers using this method puts severe requirements on the isolation of

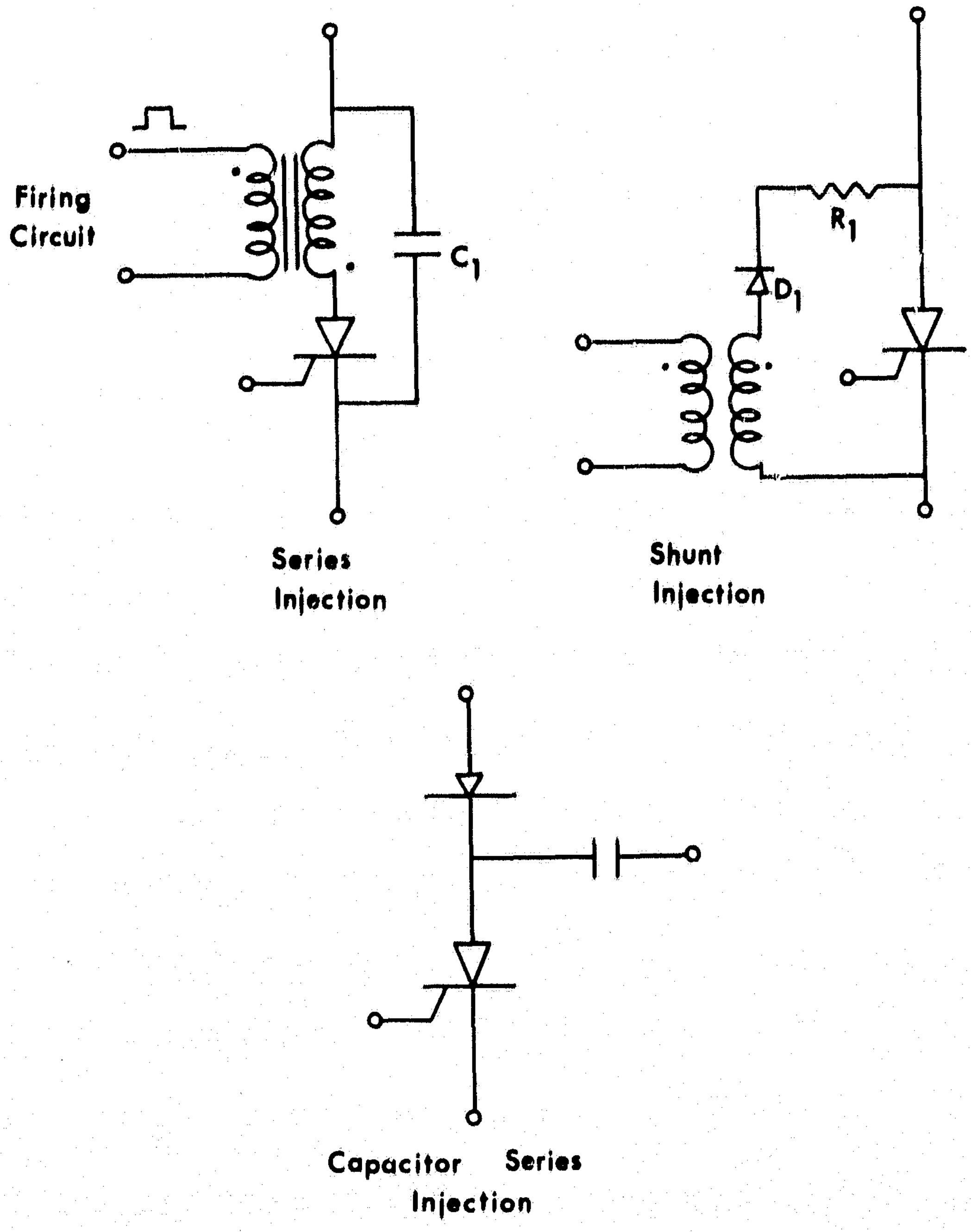


Figure 10.--Anode Triggering Circuits.

transformers and the peak voltage ratings of capacitors.

We have introduced two feasible means of turning on the SCR for static switch purposes, and the selection of the best means depends on the application. Turn-on by anode voltage techniques is relatively untried, but it has been used sucessfully, particularly in applications involving series operation of SCRs. However, the practicality of this method for applications involving large overload currents as well as series operation is presently unknown, and this particular facet of anode turn on will be covered in a later section of this report.

3. Turn Off-Static

There are basically two ways to turn off the controlled rectifier, a static means of allowing the anode current to fall below the latching level, and a dynamic means of driving the anode negative with respect to the cathode. The first method requires no external circuitry and applies to D.C. switching, whereas the second method requires external circuitry and will work for both A.C. and D.C. switching. Turn off by the gate electrode is extremely hard to achieve, and for large area SCRs it is almost impossible; therefore, it will not be mentioned further.[3]

As just mentioned, static turn off consists of merely letting the anode current fall below the latching level or holding current, and this method is not commonly used because of the length of time necessary for the controlled rectifier to reach forward blocking by itself. It has already been pointed out that the turn off time is greatly dependent on the rate of decrease of anode current. The slower the decay, the shorter the turn off time, since the SCR follows the static curve and not the dotted dynamic curve shown in Figure 7. Static turn off usually takes several milliseconds for a large area SCR when a large anode current pulse has been applied, and if the application intended for the SCR can withstand this amount of time delay, static switching is very feasible. Since this report deals eventually with a static switch where the anode pulses are spaced several seconds apart, this means of turn off will be employed. Finally, it must be remembered that the holding current given by SCR specification sheets is often larger than the actual hold off current value, since a safety margin for switching the device "on" is usually included by manufacturers. This means that when possible it is safer to use a much smaller value of holding current than is listed when calculating turn off times.[3]

4. Turn Off - Dynamic

A much more positive means of controlled rectifier turn off is achieved by applying a large negative voltage pulse to the anode of the SCR, which attempts to allow a negative current flow. The turn off time should here be defined as the time between application of a large negative pulse to the anode and the resumption of forward blocking. This turn off time can be reduced to about 50-100 microseconds by applying the negative pulse with a large rate of rise value.[3]

Both static and dynamic turn off are greatly affected by temperature change, and the higher the temperature the shorter the turn off time. There is a limit, of course, to the amount of temperature rise that can safely be allowed, but it is interesting to note that for this instance the temperature rise can be helpful to some degree!

The effect of the gate electrode on turn off has not been mentioned, and as expected the gate current can cause a significant change in turn off times. If the gate is allowed to "float" during anode conduction, it will charge up to the forward voltage across the cathode junction. If there is any capacitance between the gate and cathode this capacitance will be charged during conduction and will discharge through the gate - cathode circuit when the controlled rectifier is being turned off. This will lengthen turn off times considerably, as would any positive gate signal coming from any other source. Although causing a slightly negative gate potential during turn off helps reduce this effect for small area SCRs, the large area SCRs still experience this effect. If the inductance is small between the gate and cathode it is possible to keep the gate at cathode potential during turn off and eliminate gate lengthening turn-off.[5]

Finally, turn off time is affected by the forward voltage and the rate of rise of forward voltage, as shown in Figure 11. A standardized rate of rise of 20 volts/microsecond is used in giving turn off times by manufacturers, and if this value is not used the turn off time will be affected.[5]

D. Gate Firing Point

If gate firing has been selected as the switching means for a particular application, then in order to design the gate circuit it is necessary to find the proper values of voltage and current (hereafter called the gate "Firing Point"), for a given SCR. Manufacturers aid in the selection of the firing point by supplying a gate-to-cathode voltage-versus-current characteristic, as shown in Figure 12.

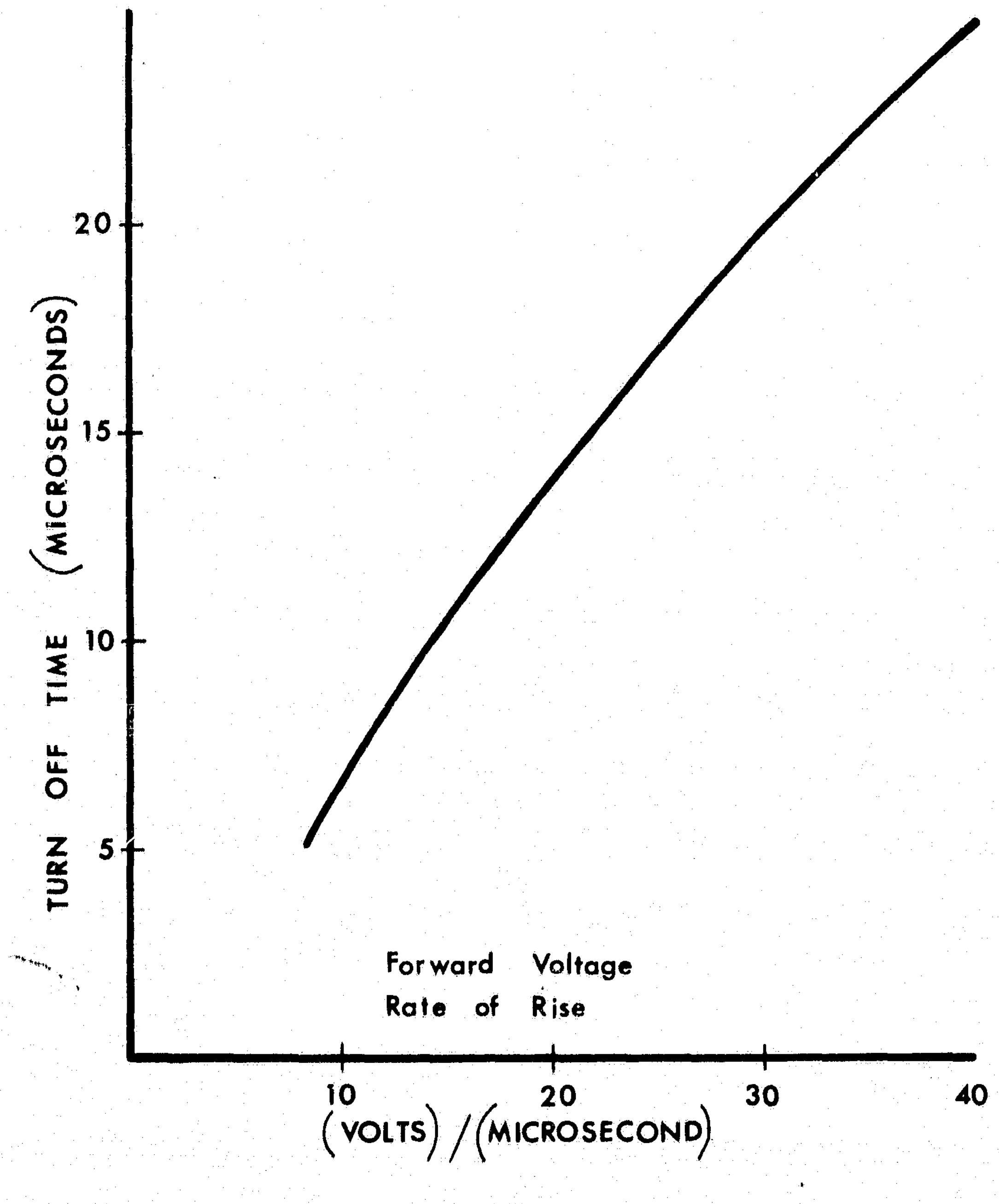


Figure 11.--Turn-Off Time as a Function of Voltage Rate of Rise.

Due to the inability of SCR Manufacturers to make all SCRs of a given type exactly alike, a SCR of a given type can have various values of resistance, as Figure 12 illustrates. The top curve is labeled the "high resistance" curve, and represents the upper limit of expected values of resistance for this particular type of SCR. Similarily, the curve labeled "low resistance" limit is the other extreme for the same type of SCR. The middle curve represents the most commonly found values of resistance for this controlled rectifier. Actually, these curves are only drawn to define "firing region" for this SCR, since the slopes and general curves can differ from the three curves used in Figure 12.[5]

The upper and lower limits for both gate voltage and gate current are fixed for gate firing at a given temperature. The shaded area marked area "A" on Figure 12 is one such example of the possible firing area for this type of SCR at 25 degrees centigrade. Each point in this area corresponds to a voltage and current which together will induce triggering. Notice that for this temperature there is a value of gate voltage labeled "Maximum required gate voltage to fire." This is the lowest value of gate voltage that will fire all units with certainty at 25 degrees centigrade. For 25 degrees there is also a value of the lowest gate current to fire all units with certainty, and this is labeled "Maximum required gate current to fire." The curve labeled "Minimum required gate current to fire" is the current below which no units of this type will fire. The firing area is then completed by the minimum value of gate voltage to fire all units successfully.[5]

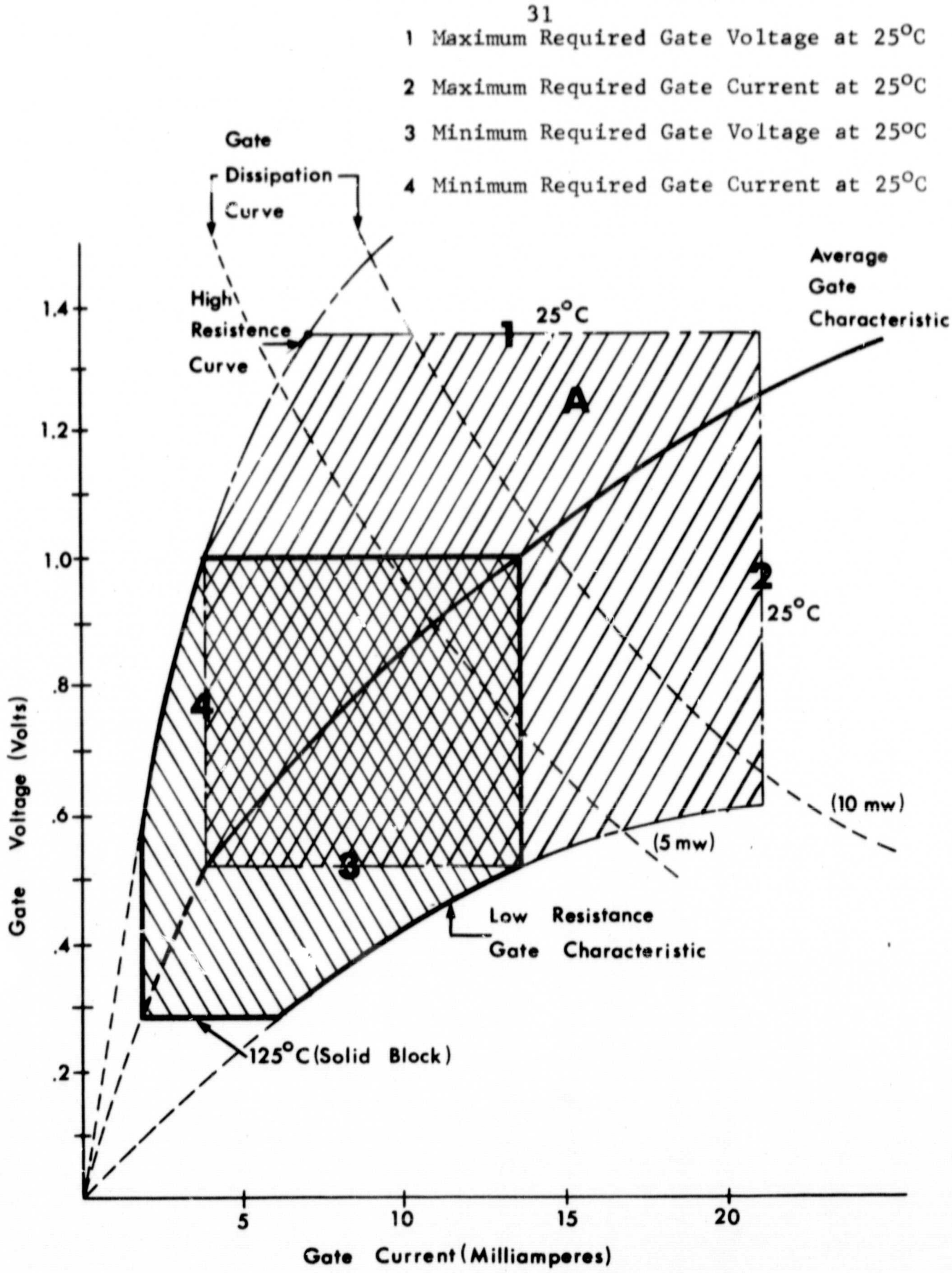


Figure 12.--Gate Firing Point Diagram.

Since it is easier to turn "on" an SCR at high temperatures, it is reasonable that the firing area will be reduced or lowered if the temperature is increased. This lowering of the firing area is shown in Figure 12 for a temperature of 125 degrees centigrade. Likewise, if the temperature is lowered below 25 degrees centigrade the firing area moves upward, with the high and low resistance curves still serving as boundaries on two sides.[5]

As mentioned earlier, it is desirable to drive the gate as strongly as possible without exceeding the gate power rating, and for this reason the use of pulse circuitry in gate circuits has become standard. To aid in selecting the pulse duration and other parameters a curve showing gate voltage, current, and duty cycle can be obtained, as shown in Figure 13. For this particular SCR, 10 volts and 2 amperes are the maximum values of voltage and current. If the gate is driven for a long period of time, which is not normal, the 100 percent duty cycle curve must be used. For this particular SCR the gate pulse duration must be less than 10 microseconds before it is possible to use the 10 percent duty cycle curve. It is to be remembered here that the pulse duration is often fixed by external rise time considerations in the anode-cathode circuit, and extremely short gate pulses only apply when the inductance is very low. Since the static switch to be included in this report will have inductive loads, this method of selecting gate pulse duration and final values of gate voltage and current will be used if gate triggering is the triggering means.

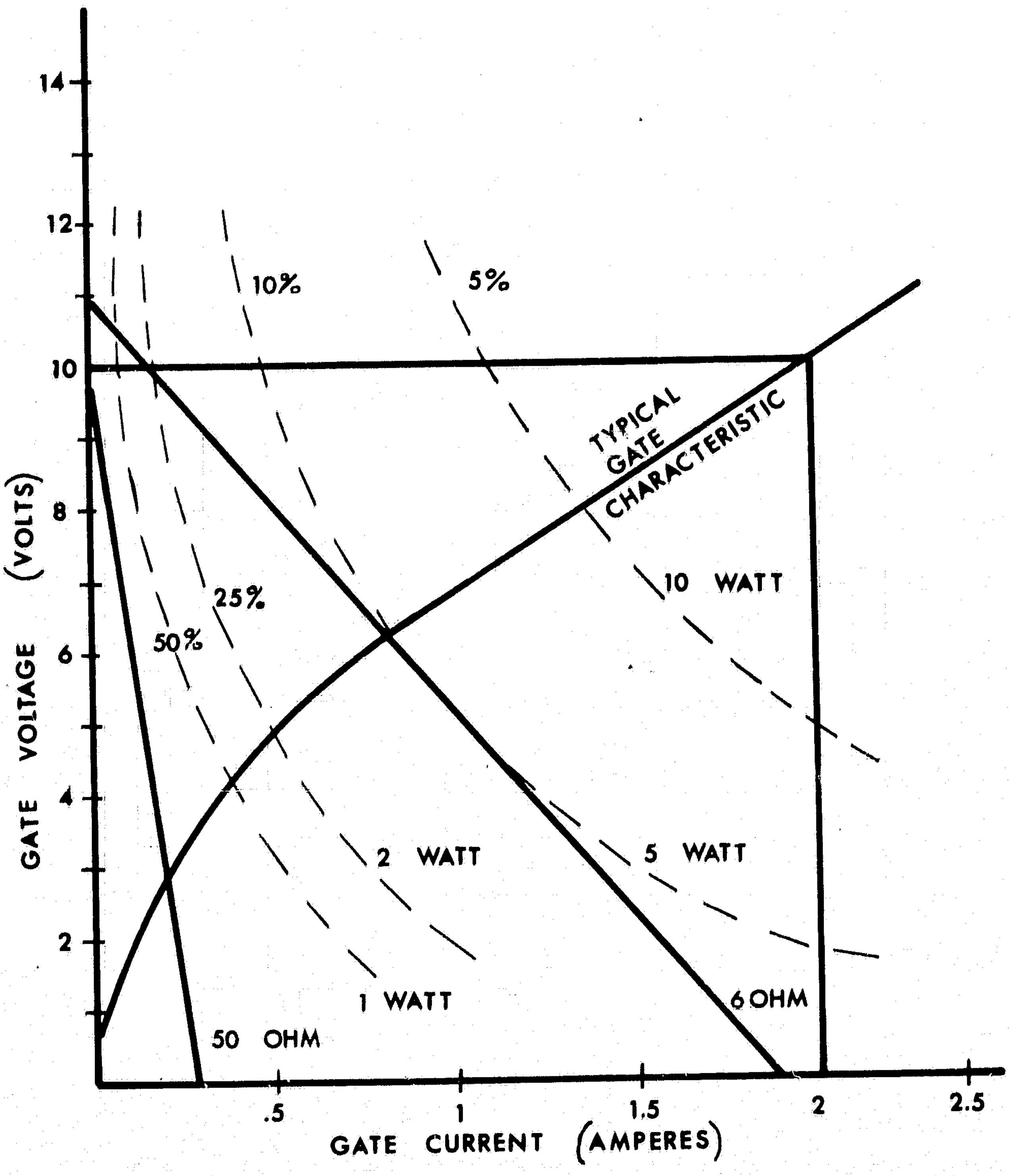


Figure 13.--Gate Characteristics for Various Loads.

vidual differences in shunt capacity, along with recovery and delay times, creates a problem of equal voltage division in the forward and reverse directions. Since the controlled rectifier will not switch in the reverse direction, forward voltage compensation is usually used to correct both directions. Series operation requires further compensation for cases where the sum of the leakage currents in the series chain approximates the value of the holding current of a single controlled rectifier, since this leads to unpredictable switching.

A formula has been derived[7] to predict the number of SCRs in series necessary to provide the proper degree of safety in switching a voltage of magnitude V_T. The total voltage to be switched is related to the blocking voltage of a single SCR, (V_P), and the number of SCRs, N, by the equation;

$$V_T = \left(\frac{.9N + .20}{1.10}\right) \times V_P \qquad (2)$$

Equation (2) is based on the use of 5 percent resistors. Also, V_P is the peak voltage which will normally be applied to a SCR in the series chain, and this value is usually picked well below the breakover voltage in order to prevent transient voltage triggering. The effectiveness of this formula will be shown in a later section.

Figure 14 shows the most commonly found means of assuring equal voltage division in series operation.[7] Resistors R_3 and R_4 are shunted across the controlled rectifiers to form a voltage divider circuit. These shunt resistors are used to bleed off the leakage current from each SCR so that the total leakage current is not impressed

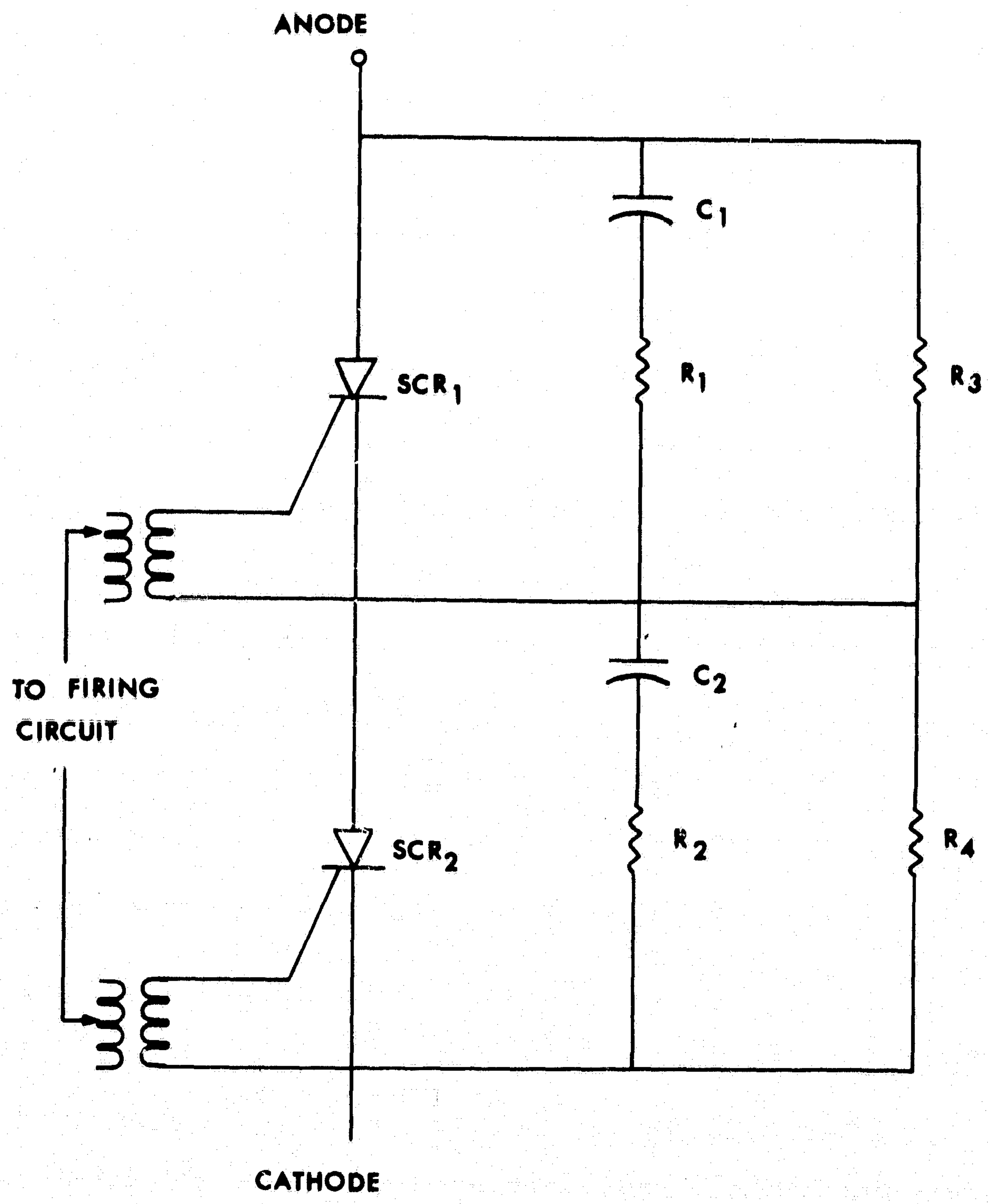


Figure 14.--Voltage Compensation for Series Operation.

on any single rectifier in the series. The values of R_3 and R_4 are selected by finding the equivalent leakage resistance of the individual SCRs, which is the ratio of peak inverse voltage of blocking voltage, (which are usually the same in magnitude), to the peak leakage current in the forward or reverse directions. If the leakage current is higher in one direction than the other select the largest value, since this will yield the smallest value of leakage resistance. By the same token, if the peak inverse voltage and breakover voltage are not the same, use the smaller of the two values. This yields an equivalent resistance that can be represented as

$$R_{EQ} = \frac{V_{PBV}}{I_L} \qquad (3)$$

In equation (3) V_{PBV} and I_L are the values of blocking voltage and leakage current selected above.

If the value of resistance calculated in equation (3) were parallel with the SCR, it would divide the leakage current that flows through a single SCR by approximately one-half. However, if a large number of rectifiers in series is necessary for a particular application, this amount of division is inadequate. A more conservative value of shunt resistance is obtained by taking one-fourth the value found in equation (3). The published value of leakage current must usually be doubled to yield the peak value of leakage current for equation (3). This finally yields the value of R_S as;

$$R_S = \frac{V_{PBV}}{4I_L} \tag{4}$$

Equation (4) will yield the values of resistance for resistors R_3 and R_4 in Figure 12.

The wattage of the shunt resistors can now be approximated by multiplying the leakage current by the blocking voltage. By solving equation (4) for I_C and multiplying by V_{PBV} we obtain;

$$W_S = \frac{V_{PBV}}{4R_S} \times V_{PBV} = \frac{(V_{PBV})^2}{4R_S} \tag{5}$$

Again, it is desirable to include a safety factor for the wattage rating of the shunt resistors, and if a factor of two is selected equation (5) becomes

$$W_S = \frac{(V_{PBV})^2}{2R_S} \tag{6}$$

Resistors R_3 and R_4 will not provide adequate transient voltage equalization, since they must often be wire-wound resistors to provide the necessary wattage, and therefore will have appreciable inductance. Also, the distributed capacitance of the SCRs in the chain needs to be swamped out in order to provide proper voltage equalization. For these reasons each SCR in the series chain is often shunted with a capacitor, as shown by capacitors C_1 and C_2 in Figure 14 the values of C_1 and C_2 usually range from .001 to .1 microfarads, and can usually be obtained from SCR manufacturers.[7] During turn-on these capacitors will discharge through the controlled recifiers, and it is often necessary to put a resistor in series with the capacitors to prevent rectifier damage due to a short discharge time constant.[8] Resistors R_1 and R_2 serve this purpose in Figure 14, and their value is often fixed at twice the load resistance. To maximize this voltage compensation technique, it is recommended that all resistors be matched to within 1 percent and have as little inductance as possible.

There are two methods of gate firing controlled rectifiers in series, and the advantages and disadvantages of each needs to be covered at this point, since it is not obvious which method is best.

First, each controlled rectifier in the chain can be individually gate triggered, as is shown for the two series rectifiers in Figure 14. Since each rectifier must be electrically isolated from the other, this method of firing demands an output circuit for each SCR. Pulse transformers are usually used to provide the isolation, as shown in Figure 14, but it must be remembered that for power circuits a large degree of insulation will be necessary in order for the windings to withstand the transient and working voltages present.[7] Also, the stray capacitances of the windings must be much smaller than the controlled rectifier shunting capacitances. Since it is very important that the gate signal for a single SCR be very powerful and have a short rise time, it is obvious that the firing circuit for a long series of controlled rectifiers using this method would require extremely careful design at best, and is probably impractical for a series chain of more than several rectifiers.[7]

The external firing of one gate and then forcing the other gates to fire simultaneously yields the second method of gate triggering. This slave firing technique eliminates the need for separate isolated firing circuit for each SCR, and one possible means of slave firing is shown in Figure 15. This circuit has voltage equalization and transient suppression as previously discussed, with resistors R_1 and R_2 along with capacitors C_1 and C_2 serving this purpose. When SCR_2 is triggered it quickly drops in voltage and impresses this voltage change across SCR_1. This causes a surge of current through C_3 and the gate of SCR_1, since resistor R_5 is selected to be about 10 times the gate to cathode resistance of SCR_1. This turns on SCR_1, and if several SCRs were in series each one would be switched on in the same manner. Rectifier diode RD_1 is in this circuit to prevent the gate from being made negative while the capacitor C_3 is charging in the reverse direction. A further sophistication can be included if this diode is a zener diode which will break-down and conduct when the voltage across it exceeds the maximum allowed gate voltage. The value of C_3 is usually chosen by;

$$\frac{10^6}{12.6 \text{ X } f \text{ X } R_S \text{ X } V_T} \geq C_3 \geq \frac{I_{GM}}{10} \qquad (7)$$

where

f = frequency of applied A.C.

I_{GM} = Maximum gate current to fire

R_S = Shunt resistance

V_T = Maximum voltage applied to the series string of SCRs

C_3 = Capacitance in micro-farads

A further improved firing circuit is shown in Figure 16. In this circuit the capacitors and series damping resistors that are used to create voltage equalization are also used to fire the SCR. This reduces the number of components needed, but puts further restrictions on the capacitor and series damping resistor that parallel each SCR.[7]

In a series chain, such as Figure 16, it is possible to attach the external firing electrodes to any of the gate-cathode circuits. However, if the series limiting resistors have appreciable inductance, turn on of SCRs that are distant from the externally fired SCR may not occur instantly. This "laddering" effect of successive SCRs turning on at later and later times can be appreciable for a long series, and for this reason it is usually desirable to externally fire the SCR that is the closet to the load.[7]

The shunt capacitors in Figure 16 must now satisfy equation (7), and although this usually requires a somewhat larger value of capacitance than is necessary for voltage equalization, the increase in capacitance is not unreasonable. Also, the series resistor must be increased from the previous value of around twice the load resistance to a value of about ten times the gate-cathode resistance of a single controlled rectifier.[7] Since this resistor was put in the circuit initially to give a longer discharge time constant, the increase in its value can only improve the ability of the SCR to withstand capacitor discharge.

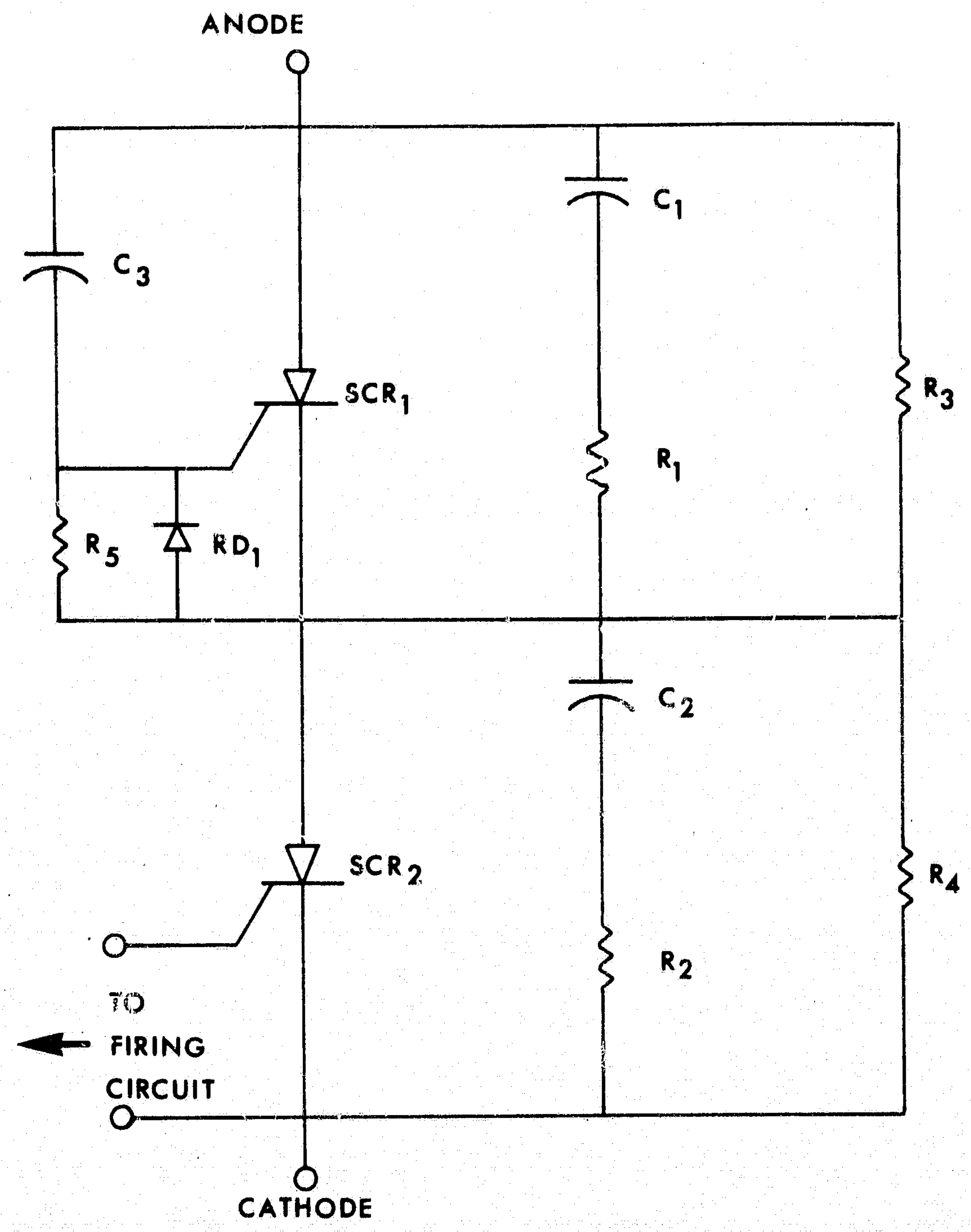


Figure 15.--Slave-Firing Method for Series Operation.

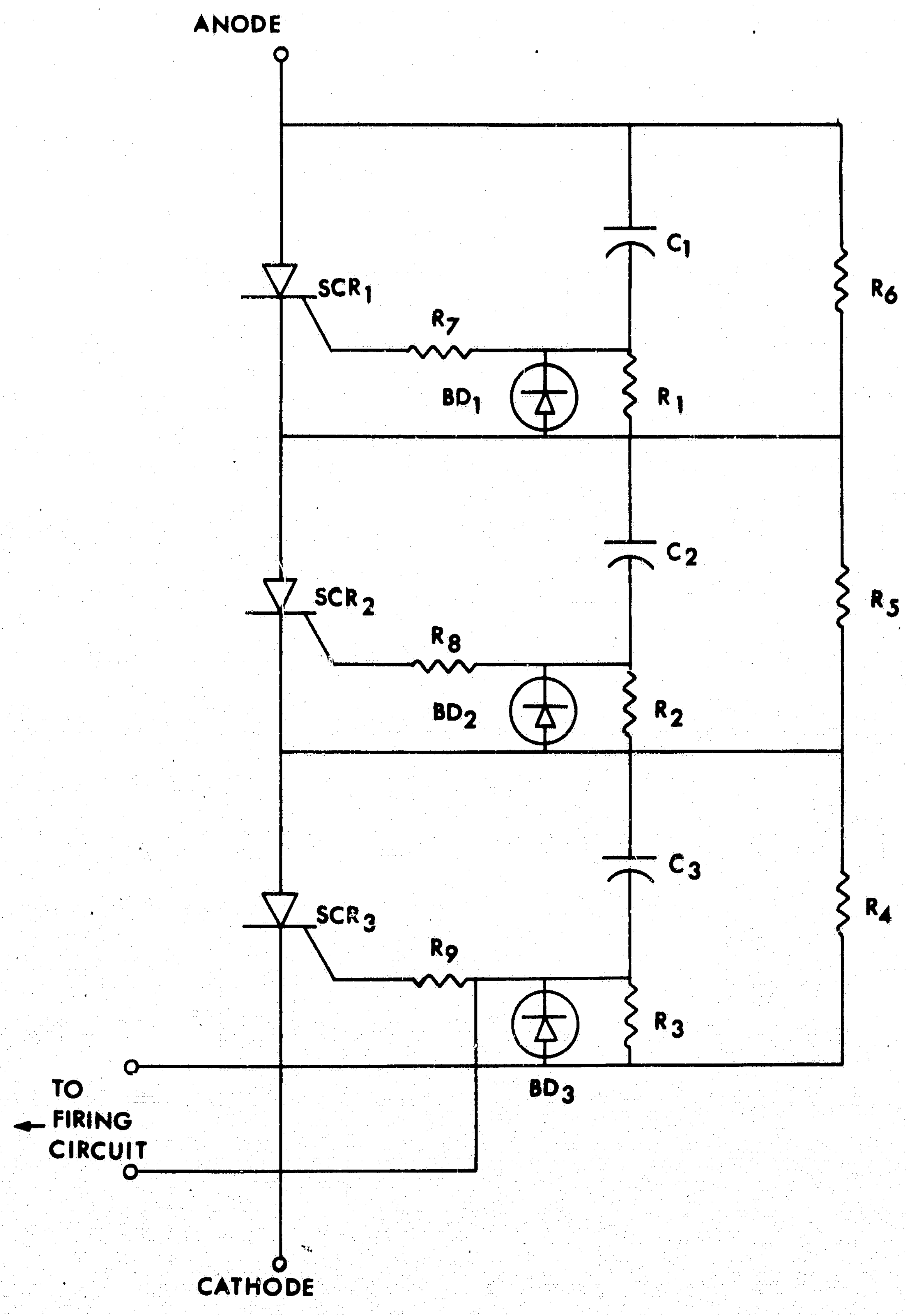


Figure 16.--Improved Slave-Fired Series Circuit.

Diodes BD_1 through BD_3 serve the dual purpose of gate voltage protection and negative clamping, as described earlier for Figure 15. If the change in voltage across any SCR gate, when the first SCR is externally fired, is large enough to induce currents that exceed the maximum gate current for the device, it may become necessary to put a resistor in series with the gate to give limiting action. Resistors R_7 through R_9 serve this purpose in Figure 16. The selection of these values and the other circuit values for this circuit will be illustrated in the next section.

G. Parallel Operation of SCRs

On a static switching basis, the maximum allowable surge current for a controlled rectifier depends on the duration of the load pulse. For instance, SCRs can be purchased today that will switch a surge current of over 6,000 amperes, applied over several milliseconds.[9] This means that a somewhat larger value of surge current could be allowed if the load pulse duration were in the microsecond region, and a smaller value could be allowed if the pulse duration were on the order of several seconds. However, if these conditions cannot be met, the possibility of parallel operation must be considered. Several possible ways of employing parallel operation and their attendent problems will be discussed in this section.

The most obvious problem involving parallel operation of controlled rectifiers is that of accepting and distributing the current evenly among the devices. This problem is lessened if the leads connecting the parallel controlled rectifiers all have the same inductance and resistance, and this implies a symmetrical and uniform layout of the devices. The controlled rectifiers should be positioned as close to each other as possible without causing a heat dissipation problem.[7]

When two controlled rectifiers are in parallel and both are in the "on" state, a problem of thermal runaway exists. Since the forward drop across a rectifier is an inverse function of temperature, if one rectifier assumes more than half of the load current it will get hotter than the other SCR, which makes it conduct even harder than before. This cyclic heat-current increase effect can easily destroy the SCR if not checked. Controlled rectifiers can be purchased that are matched at several points to help eliminate these problems, but even then it is not uncommon to have to resort to forced current sharing by other techniques.

The simplest method of forced current sharing is by putting series resistors in each path to swamp out the forward resistances of the controlled rectifiers.[7] This helps to eliminate the "on" state resistance variation for SCRs of the same type. The value of these series resistors therefore needs to be several times the value of the forward resistance of the controlled rectifier.

Figure 17 shows the effect of putting an equal amount of resistance in series with each anode for 2 SCRs in parallel. The curves marked SCR_1 and SCR_2 are the on state characteristics of the two SCRs without any current equalization. SCR_2 is carrying the most current and if the differential current is as large as shown here thermal runaway is very possible. Putting the resistors in series with each SCR gives the second set of curves shown in the figure. The

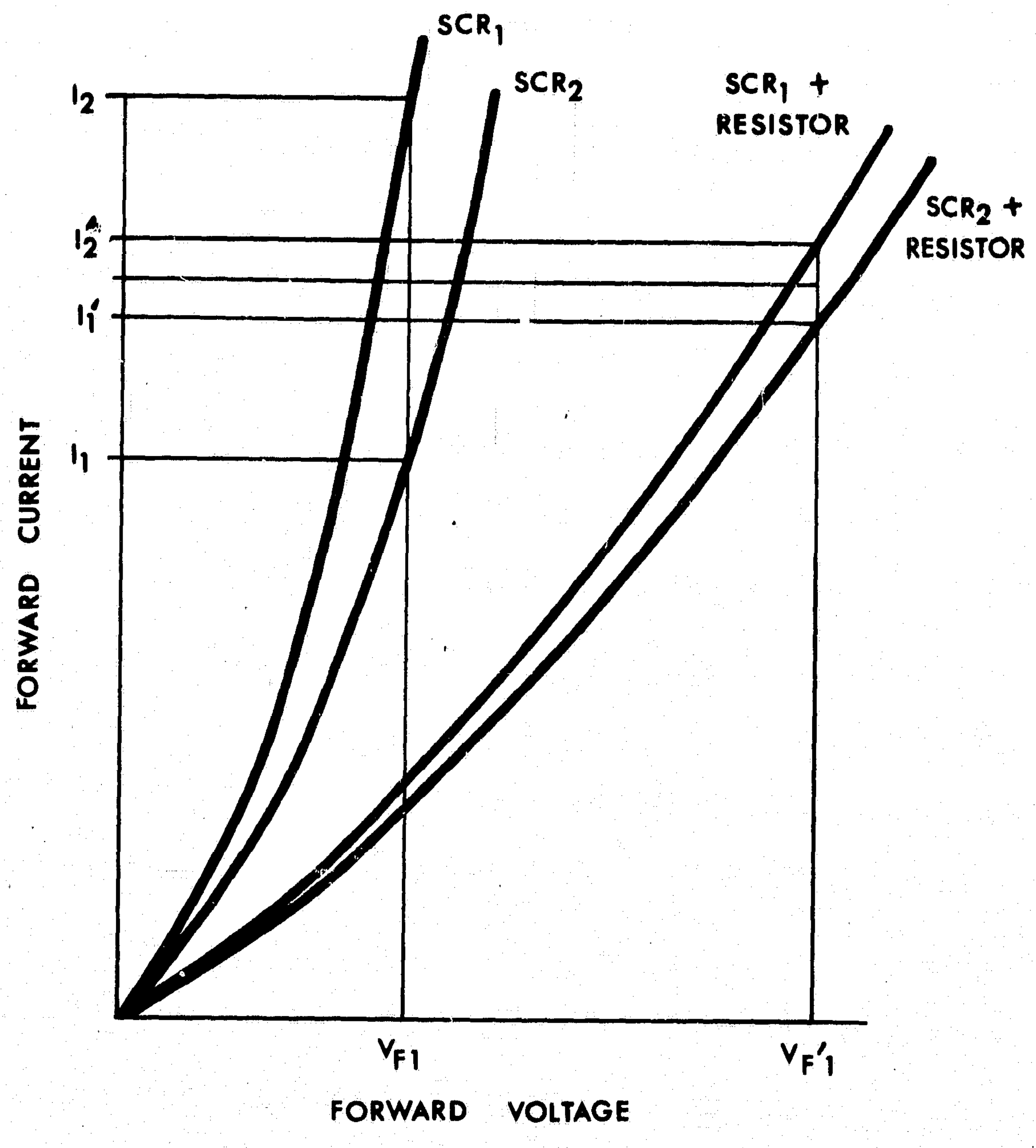


Figure 17.--"On" State Characteristics for Parallel Operation with and Without Series Resistance.

large decrease in the current differential from one SCR to the other greatly reduces the thermal runaway problem and also allows the individual SCRs to be operated closer to their maximum current values.

While this series resistor method adds more power loss and reduces efficiency, it is a very simple method to use in cases involving a large number of units in series and parallel operation. Also, it will be shown later that in some cases it is necessary to include a certain amount of resistance in series with a switch to improve the ability of the SCR to withstand the anode current rate-of-rise.

If the amounts of power loss imposed by using series resistors is impractical, the use of paralleled reactors to force current sharing is possible, as shown in Figure 18.[7] The paralleled reactors can be thought of as one-to-one current transformers, with the currents in to two windings magnetizing the core in opposite directions. The cores should have an air gap to help prevent saturation. The use of paralleled reactors gives a large delay between the time the gate is fired and the time when the predominance of the load current reaches the SCR anode. For this reason this technique could possibly be used in static switching applications where the rate of rise of current is so fast that it is impossible to get the SCRs adequately turned "on" by other means. Of course, the requirements then put on the paralleling reactors in terms of power and isolation ratings often makes this approach unfeasible, especially in cases involving many SCRs in both series and parallel operation.

As Figure 18 shows, paralleled SCRs can also be made to slave fire.

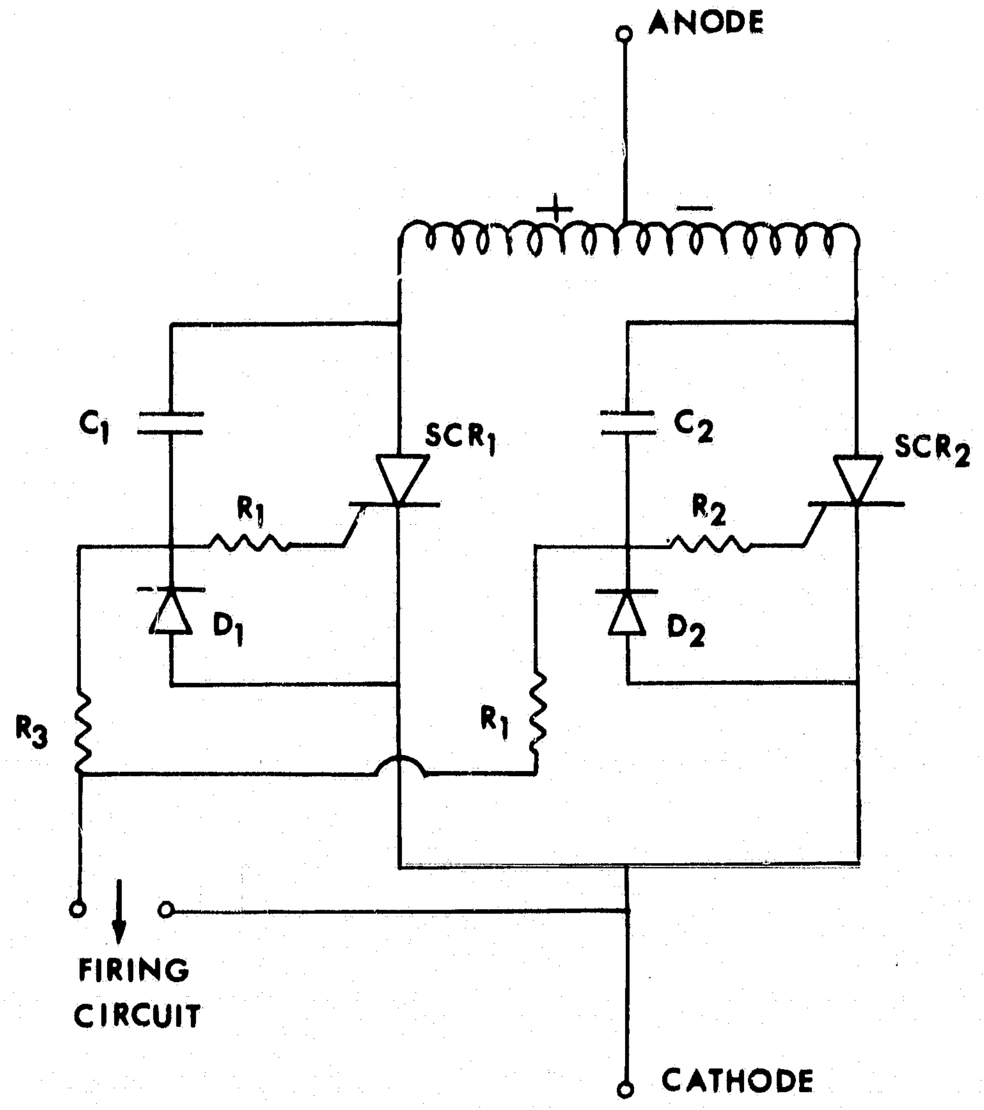


Figure 18.--Circuit with Reactors for Parallel Operation.

If for some reason one of the SCRs in parallel is not triggered when the gate pulse is applied, the coil induces a high reverse voltage across the non-conducting SCR until it fires. This gives an additional safety factor for the switch.

The simultaneous operation of controlled rectifiers in parallel and series can create many problems. In fact, if a very large number of SCRs have to be put in both series and parallel, then it is questionable that SCRs are the most desirable approach. Reference 7 is probably the best source of additional information for both series and parallel operation of controlled rectifiers.

III. PROTOTYPE SWITCH DESIGN

In this section a prototype SCR switch will be designed to discharge a high energy capacitor bank into an inductive load. The load consists of a 4 microhenry coil that has approximately 10^{-6} ohms resistance. The source is a 120 microfarad capacitor bank charged to 10,000 volts. The energy storage can then be calculated as:

$$W = 1/2\ CE^2 = 1/2\ (120)(10^4)^2 10^{-6}$$
$$W = 6000 \text{ Joules} \tag{8}$$

The basic configuration of the switching circuit is shown in Figure 19. The capacitor bank is charged by an external source to the 10,000 volt limit. The SCR switch will discharge the 6000 Joules into the inductive load when the pulse generator fires. To initially determine the feasibility of using SCRs' for this switch, an approximation of the peak current and rate of rise of current for Figure 19 should be obtained.

For an approximation of the current waveform for Figure 19, it will be assumed that the capacitor bank will discharge into a 1 ohm resistor in series with the coil. This resistor will then represent the total resistance due to the coil, SCR switch, and connecting leads. This approximate circuit is shown in Figure 20, where the voltage generator represents the initial 10,000 volt charge on the

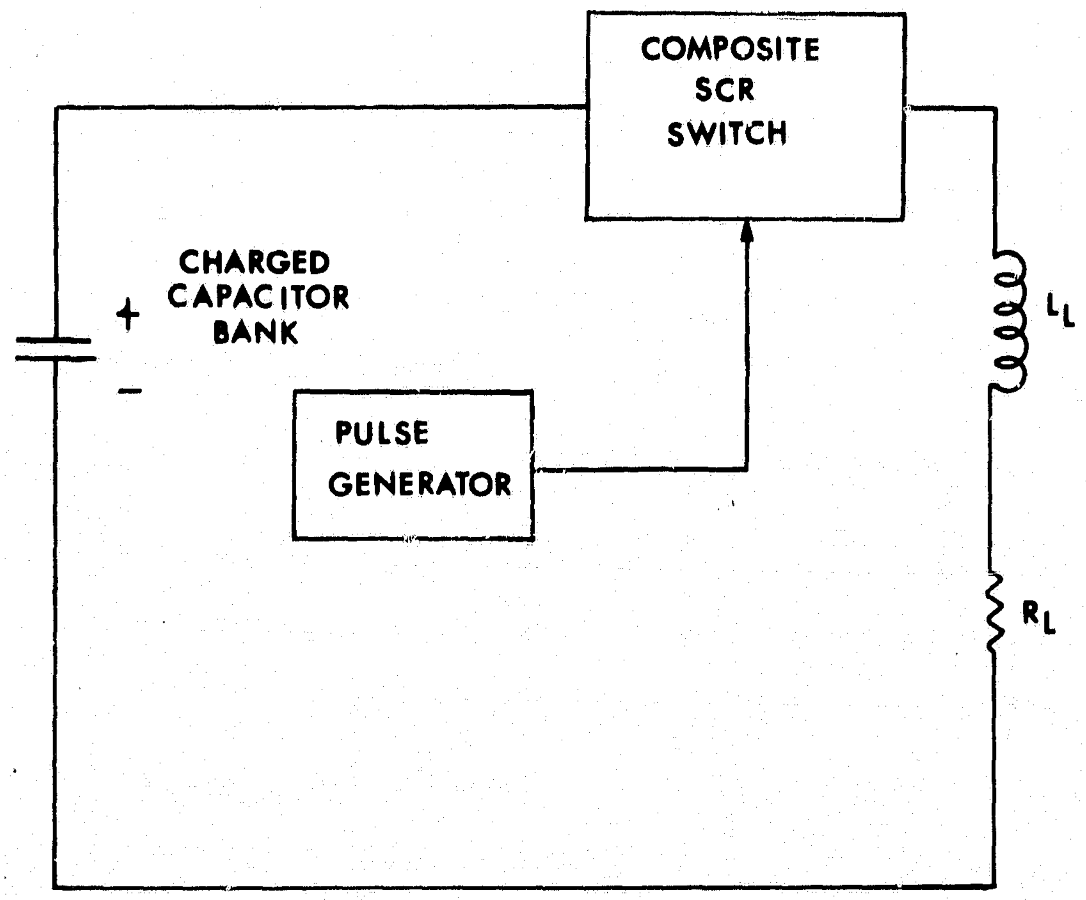


Figure 19.--Basic Static Switch Configuration.

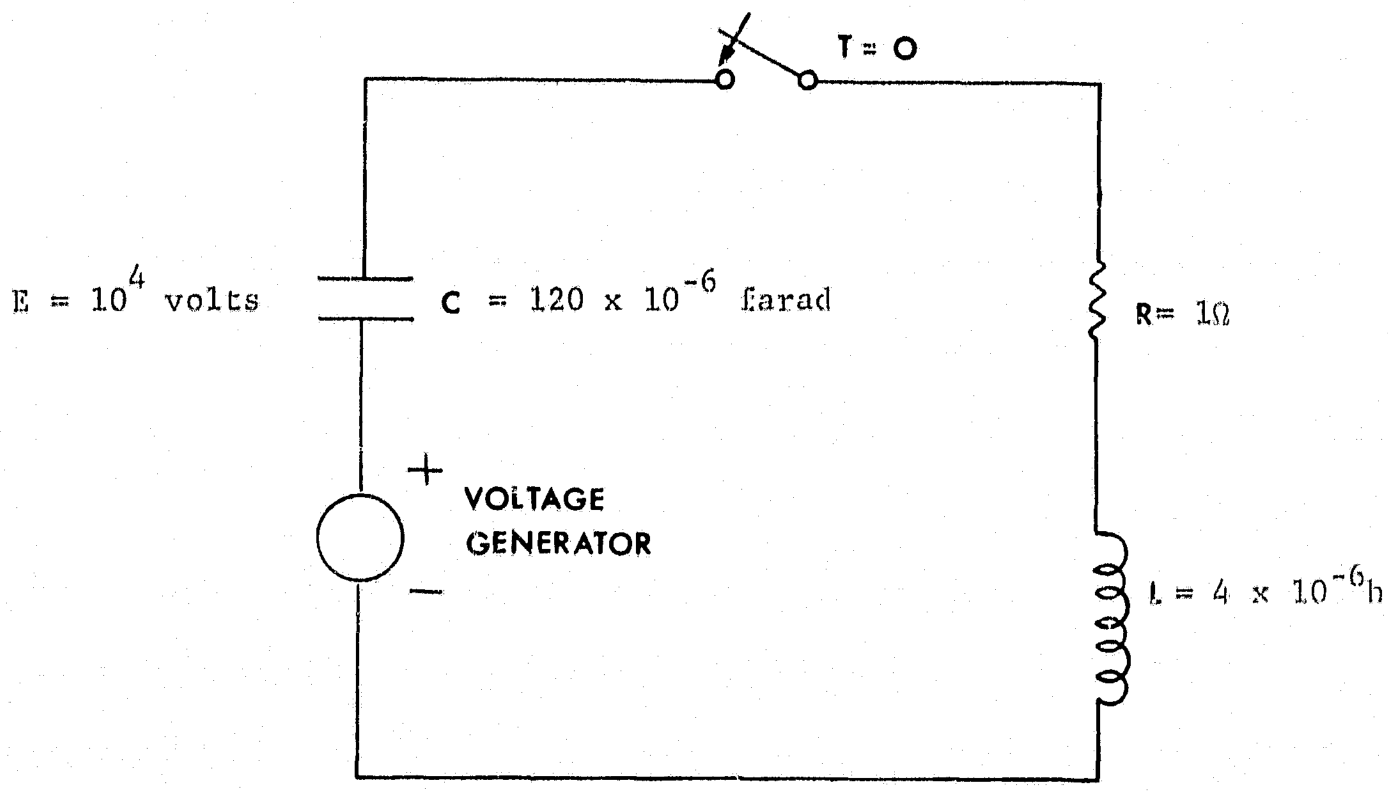


Figure 20.--Equivalent Circuit for Switch.

capacitor.

This circuit can easily be solved using Laplace transformations, and the method of obtaining the transformation for this circuit can be found in reference books.[13] The Laplace transform for the circuit, solved in terms of the current, can be written as;

$$I(S) = \frac{V_0}{L} \left[\frac{1}{S^2 + \frac{R}{L} S + \frac{1}{LC}} \right] \tag{9}$$

where

$V_0 = 10^4$ Volts $\qquad$ L = 4 microhenries

R = 1 ohm $\qquad$ C = 120 microfarads

The denominator of equation 9 is factored, and the resulting factors are expressed as the sum of partial fractions. Since 4/LC is much greater than $(R/L)^2$ for this case, the resulting expression for equation 9 is;

$$I(S) = \frac{V_0}{L\frac{1}{LC}} \left[\frac{1}{2i} \left\{ \frac{1}{S - [-\frac{R}{2L} + i\frac{1}{LC}]} - \frac{1}{S - [-\frac{R}{2L} - i\frac{1}{LC}]} \right\} \right] \tag{10}$$

The time domain solution for the current in equation 10 is obtained by taking the Inverse Laplace transform[13], and this yields;

$$I(t) = \frac{V_0}{\sqrt{\frac{L}{C}}} e^{-\frac{RT}{2L}} \sin\left(\sqrt{\frac{1}{LC}}\, t\right) \tag{11}$$

On substituting the appropriate values for the components in equation 11, the final solution of the current is;

$$I(t) = 54{,}700\, e^{-\frac{10^6}{8} T} \sin(45.7 \times 10^3 T) \tag{12}$$

Although this equation would indicate that negative values of load current are possible, the circuit in Figure 20 does not take into consideration the fact that a SCR will not allow negative current to flow from anode to cathode. For this reason only the first half cycle of equation 12 is valid. The current waveform is plotted in figure 21. As the figure shows, the predominance of the current has been switched in 40 microseconds, and the peak magnitude of the current is about 7,200 amperes.

The largest commercially available SCR on the market at this time cannot block 10,000 volts or withstand 7,200 amperes on a steady state basis. There are, however, controlled rectifiers capable of blocking 1,200 volts and withstanding 350 amperes on a steady state basis. This particular unit is the International Rectifier model 350Ra controlled rectifier, and the major specifications of this device are shown in Table 1. This particular SCR was selected because it has the highest peak RMS current rating presently available.[9]

It is obvious at this point that a number of SCRs will have to be put in series to block 10,000 volts. The exact number will depend on how much of a safety margin is allowed between the operating forward voltage and the rated blocking voltage. It is a common practice to have the ability to withstand a peak voltage across the chain that is one and one-half to two times the total voltage to be blocked. In this case these lower and upper values are 15,000 and 20,000 volts, respectively. If each SCR can block 1200 volts, then it can be seen that at least 13 controlled rectifiers should be put in series to at least exceed the 15,000 volt limit.

A more direct method of determining the number of SCRs to put in series can be obtained from equation 2[7] from section II. This

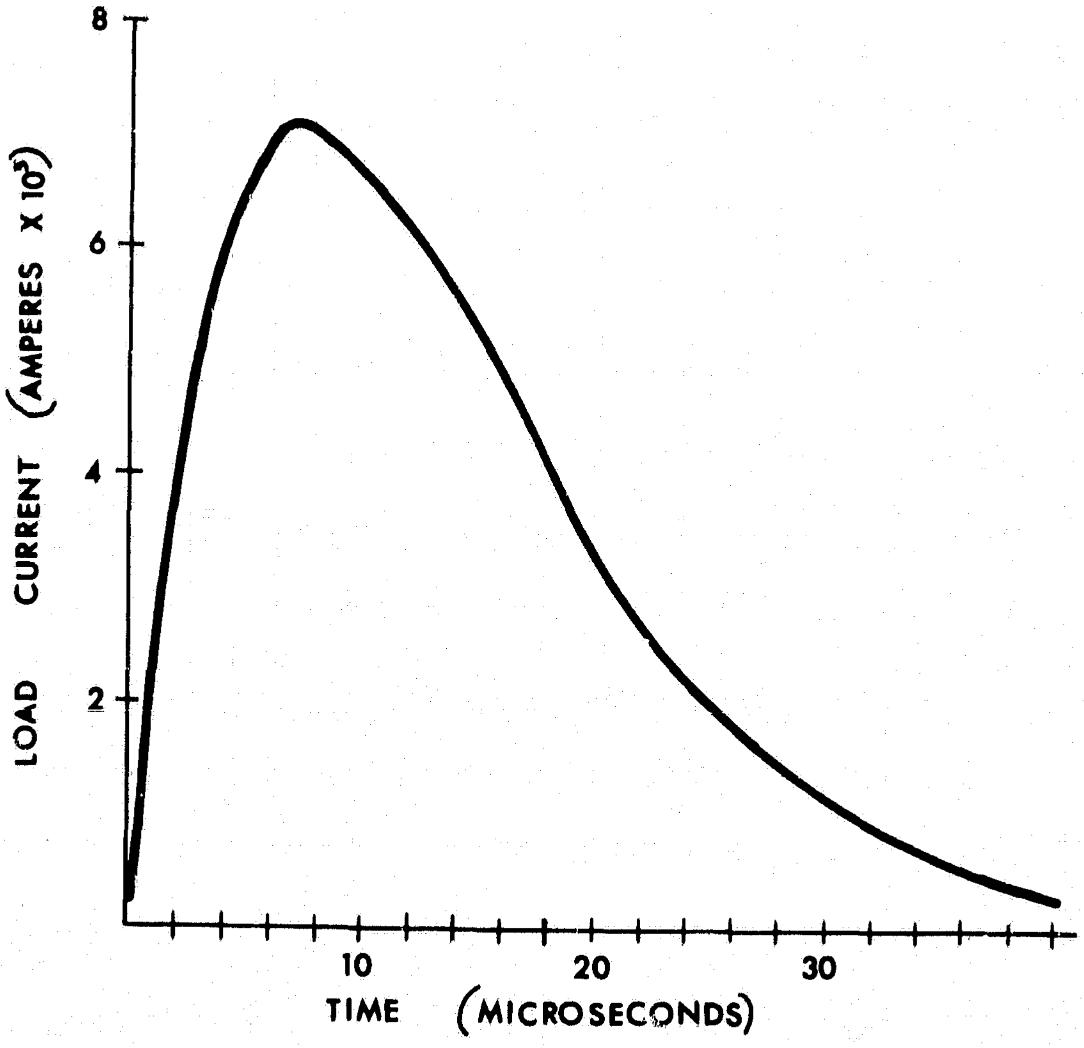


Figure 21.--Current Waveform of Equation 12.

TABLE 1

Electrical Specifications	350 RA
FORWARD CONDUCTION	
V_{FM} Maximum Peak Forward Voltage Drop at Rated IF * Current	1.48
I_F(RMS) Maximum RMS Forward Current	550
I_{FM} Maximum Surge Current	6,250
I^2t Fusing for 8.3 m sec.	160,000
I_{HO} Holding Current at 25°C	100 MA
$T_d + T_r$ Turn on Time (Microseconds)	5
T_d Delay Time (Microseconds)	1
T_r Rise Time (Microseconds)	4
FIRING	
P_{GM} Peak Gate Power (Watts)	16
$P_{G(AV)}$ Average Gate Power (Watts)	3
I_{GFM} Peak Gate Current	4A
V_{GFM} Peak Forward Gate Voltage	20
V_{GRM} Peak Reverse Gate Voltage	5
I_{GT} Maximum Required Gate Current to Fire 25°C 125°C	150 MA 70 MA
V_{GT} Maximum Required Gate Voltage To Fire at 25°C 125°C	3V .15V
I_{GT} Typical Gate Current to Fire	40 MA
V_{GT} Typical Gate Voltage to Fire	1.2V

equation, solved for N, the number of rectifiers in series, can be written as:

$$N = \frac{V_{PT}\,(1.10) - .20\,V_{PK}}{.9\,V_{PK}} \qquad (13)$$

V_{PT} = total voltage to be blocked, (10,000 volts)

V_{PK} is the expected value of forward blocking voltage on each SCR in the chain, assuming all SCRs will have approximately the same voltage across them. If V_{BO} is set at 800 volts, which is 400 volts below the rated blocking voltage, and then put in equation 13, it can be seen that the rounded off value of N is 15. Likewise, if a value of 900 volts is set for V_{BO}, a value of N can be calculated from equation 13 as N = 13. These figures agree well with the value of N obtained from the "rule of thumb" approach. From this an intermediate value, like 14 SCRs' in series, should be more than adequate to switch the 10,000 volts without transients causing misfirings.

From equation 13 it can be seen that if N = 14, the value of V_{PK} can be calculated as 860 volts across any SCR in the chain. Actually, if 10,000 volts is divided by 14, the resulting figure is 715 volts per SCR, but the descrepency is due to the fact that exactly equal division is impossible and the 860 volt figure accounts for 10 percent tolerances on components. This 860 volt value is 340 volts below the rated blocking voltage of the model 350Ra. This gives a considerable safety margin, especially in light of the fact that actual blocking voltages can be over a hundred volts higher than rated blocking voltages if room temperatures are assumed.

It is necessary to determine at this point whether or not parallel operation of the SCRs will be necessary in order to withstand the 7,200 ampere current flow. As Table 1 shows, the maximum non-recurrent surge current for the 350RA is 6250 amperes.[9] However, this rating is based on a 5 millisecond rectangular pulse with this current magnitude. If the load cycle were considerably shorter than this, the SCR should be able to withstand a large value of surge current. Considering the fact that the 40 microsecond pulse duration anticipated in this switch is over 100 times shorter than the 5 millisecond rating, it should be possible to switch the 7200 amperes without resorting to parallel operation. On consulting the manufacturer of this device, it was found that the 350RA can handle 10,000 amperes in 30 microseconds if the device is completely turned on prior to the arrival of the bulk of the current.

Another rating given in Table 1 should be discussed at this point, since it also has bearing on the decision on whether or not to use parallel operation. The di/dt rating, measured in amperes per microsecond, is the maximum allowable rate of rise of anode current, assuming that the controlled rectifier has been completely turned on before this large value of current is applied. For the model 350RA, this value is 50 amperes per microsecond[9], and if the anode current of any circuit using this SCR has a larger value than this the SCR will be destroyed. The rate of rise of the current waveform shown in Figure 21 can be approximated as 1500 amperes per microsecond, which is much too large for any SCR available today.

This particular model SCR has a relatively low value of di/dt.

This is due to the fact that at the present time as the rectifiers get larger physically they generally have lower values of di/dt. Therefore, if the maximum current to be switched could be lowered below 10,000 amps, then it might be possible to use a smaller model SCR and allow higher values of di/dt. Also, in a situation where the voltage to be switched were lowered well below 10,000 volts, thereby demanding fewer SCRs in series, it might be more practical to parallel several smaller model SCRs to handle the current. This would then also allow higher values of di/dt.

For instance, the model I.R. 151 REA SCR can withstand a 3,500 ampere pulse 5 milliseconds long,[9] which means it could probably stand around 5,000 amperes in the 40 microsecond time for the above mentioned switch. This particular model SCR has a di/dt rating of 300 amperes per microsecond, which is a factor of 6 times better than the di/dt rating of the model 350RA. If 5 of these units were paralleled, and were dividing the load current evenly, the current rate of rise of 1500 amps per microsecond could be withstood, and the peak current handled with ease. However, in the original application of switching 10,000 volts, this would mean it would take 14 X 5 or 70 SCRs to perform switching. The cost and complexity of this switch would probably make it unpractical in most cases.

All of the above comments were made assuming that no saturable reactor was in series with the switch to provide a "soaking time" for the SCRs. Although the use of saturable reactors could make a significant change on the calculations above[11], any application that exceeded even 2 parallel chains of 14 SCRs would probably be too cumbersome and complex. The use of multi-gate SCRs with very high values of di/dt appear to be in the near future, but high power units of this type are not presently available. This innovation will be discussed in detail later .

The next task in the switch design is the determination of the best means of triggering the series chain of 14 controlled rectifiers. As mentioned previously, the series chain could be gate fired, or treated like a 4-layer diode and anode fired. For this switch gate firing was selected for reasons discussed below.

First, the use of pulse transformers, with an isolated secondary for each of the 14 gates, would probably put requirements on the transformer that could not be met, especially since each of the 14 secondaries would need at least 20,000 volts isolation each. For this reason, slave gating, as described previously, is the best practical means to turn on a series chain of this length.

Since slave firing will be used, the advantages of anode firing will be lost. Even if one SCR of the chain were turned on very quickly by anode firing the remaining 13 SCRs would turn on by the slave fired gates, and no large improvement in turn on time would be gained.

Secondly, if it were possible to anode fire each SCR in the chain the resulting switch would have a much faster turn on time with all of its attendent advantages. However, again due to the large number of SCR's in the chain, the firing circuit would be extremely difficult to construct. This firing circuit would be forced to apply a fast rising pulse of around 600 volts to each of the 14 SCRs, and the problems envolved with this are obvious. For this reason, anode firing of the whole chain is impractical.

Finally, the anode firing technique, forces only resistive elements to be used as voltage compensation devices. This occurs because the capacitor that is normally used for voltage equalization would probably attempt to hold the voltage across the SCR constant while the anode pulse were trying to drive it to zero. Without capacitors to perform dynamic voltage equalization the probability of failure due to excessive transients is very high.

At this point the switching mechanism consists of 13 series SCRs to be slave fired after the fourteenth SCR has been externally fired. The configuration of this switch is shown in Figure 22. From equation 7, and Table 1 the minimum value for capacitor C_1 for Figure 22 can be found from;

$$C_1 \geq \frac{I_{GF}\text{ (AMPS)}}{10} \geq \frac{.150}{10} \geq .015 \text{ Microfarads.} \tag{14}$$

A value of .1 microfarads for capacitor C_1 is chosen, since this is well above the .015 microfarad minimum. Resistor R_g in this figure can be calculated from knowing the effective gate-cathode resistance of the SCR. This can be approximated by;

$$R_{GC} = \frac{V_{GT}}{I_{GT}} \tag{15}$$

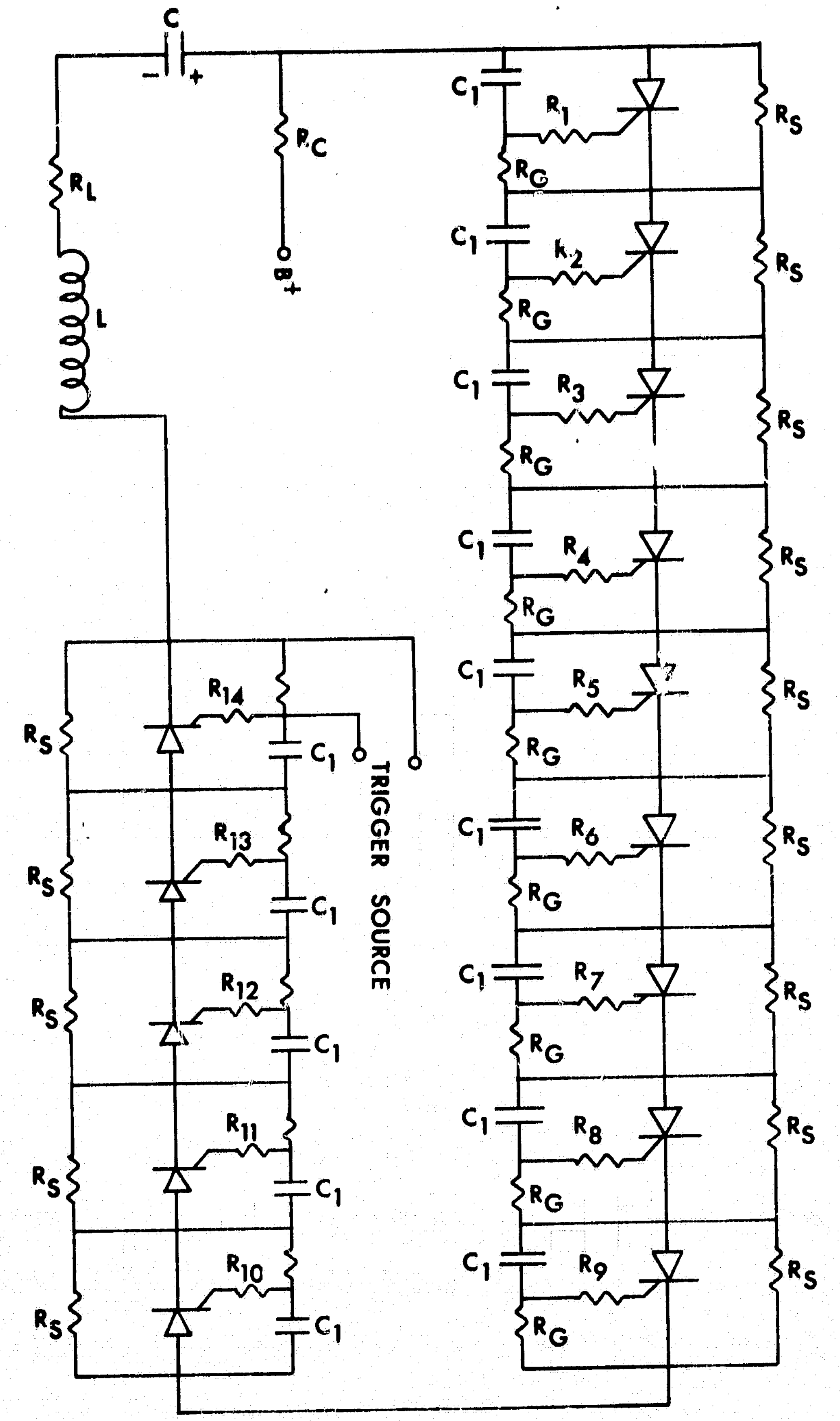


Figure 22.--10,000 Volts Switch Showing SCR Configuration.

From Table 1 R_{GC} is found to be 20 ohms. Therefore, as discussed in section II, the value of R_g should be about 10 times R_{GC}, or

$$R_g = 10\ R_{GC} = 200 \text{ ohms}. \tag{16}$$

The purpose of resistors R_1 through R_{14} is to provide series limiting in case the gate currents get to large upon firing.[7] In a long series chain of this type, it is more desirable to leave these resistors out of the circuit if possible, since this makes the gate circuits more sensitive to small changes in current. These resistors were omitted in the calculation of R_G, and their need for them will be discussed later.

From equations 4 and 6, a value of R_S and the wattage of R_S can be calculated as;

$$R_S = \frac{V_{PRV}}{4 \times I_r},\ W_S = \frac{(V_{PRV})^2}{2R_S} \tag{17}$$

From Table 1, (with a value of 10 ma for I_r) these values are found to be 30K ohms and 20 watts, respectively.

The final selection of the values of resistance and capacitance for the gate firing circuits of the SCRs, and the determination of the necessity of the gate series limiting resistors, is difficult without first finding an equivalent circuit for the firing network. This equivalent circuit can be obtained from Figure 22. In this circuit the SCRs are all considered to be in the blocking state, and the capacitors across each SCR are charged such that the sum of the series voltages equals 10,000 volts. When the externally controlled SCR is triggered, the voltage across the SCR decreases at a very rapid rate, after about a 1 microsecond time delay. Therefore, as an approximation, the total capacitance seen by the charging source is the series combination of the 13 other capacitors across each SCR, since the voltage across the last SCR is being externally driven to zero. Also, the total resistance seen is the sum of the effective gate-cathode resistances of the 13 SCRs'.

This equivalent firing circuit is shown in Figure 23. The capacitor C_T is the effective series capacitance of the 13 values of C_1, or $C_1/13$. Assuming that the parallel combination of R_G and R_{GC} is approximately R_G, then the resistance is approximately the series resistance of the gate cathode junctions, or 13x(20) ohms. The voltages shown are the initial voltages on the capacitors before triggering. When the last SCR is fired, the voltage across it can be represented by the ramp function shown in the figure. Actually, the slope of the ramp should be much steeper than shown, but this particular value was selected because it would give a "worst case" estimation. This circuit is only valid for the 5 microsecond time period indicated by the ramp function, but this is more than an adequate time period to study the triggering circuit.

This circuit is easily analyzed by Laplace transform methods,[13] and the transform can be written as;

$$\frac{V_0 - V_2 - 715 + \frac{143 \times 10^6}{s}}{S} = I(S)\left[\frac{1}{SC_0} + \frac{1}{SC_1} + R + SL\right] \quad (10)$$

where

$V_0 = 10^4$ volts

$V_2 = 13(715) = 9285$ volts

$R = 13(20) = 260$ ohms

$C = .05 \times 10^{-6}/13 = .00385 \times 10^{-6}$ farads

$L = 4 \times 10^{-6}$ henries

Solving this equation for I(S), and using partial fractions on the result yields;

$$I(S) = \frac{143 \times 10^6}{L}\left[\frac{LC}{S} + \frac{2}{\left(\frac{R}{L}\right)^2 - \frac{R}{L}\left(\frac{R}{L}\right)^2 - \frac{4}{LC} - \frac{4}{LC}}\right.$$

$$\frac{1}{\frac{-R}{2L} + \frac{1}{2}\left(\frac{R}{L}\right)^2 - \frac{4}{LC}} + \frac{2}{\left(\frac{R}{L}\right)^2 + \frac{R}{L}\left(\frac{R}{L}\right)^2 \frac{4}{LC} \quad \frac{4}{LC}}$$

$$\left. + \frac{1}{S - \left[-\frac{R}{2L} - \frac{1}{2}\left(\frac{R}{L}\right)^2 - \frac{4}{LC}\right]}\right] \qquad (19)$$

The time domain solution for the current is found by taking the inverse Laplace transform,[13] remembering that the solution is only valid for the first 5 microseconds.

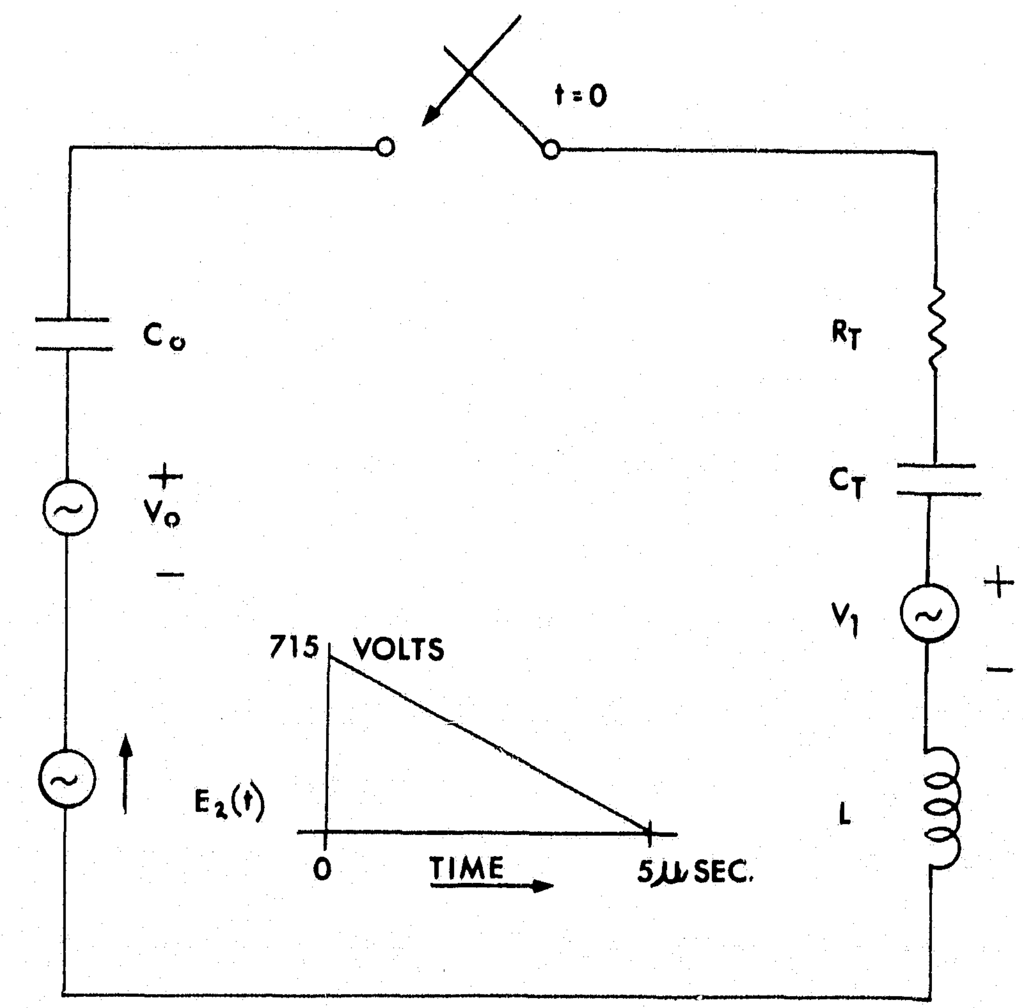


Figure 23.--Equivalent Circuit for Firing of Static Switch.

$$I(t) = 143 \times 10^6 \left[C + \frac{2e^{\left[-\frac{R}{2L} + \frac{1}{2}\left(\frac{R}{L}\right)^2 - \frac{4}{LC}\right]t}}{\left(\frac{R}{L}\right)^2 - \frac{R}{L}\left(\frac{R}{L}\right)^2 - \frac{4}{LC} - \frac{4}{LC}} \right.$$

$$\left. + \frac{2e^{\left[-\frac{R}{2L} - \frac{1}{2}\left(\frac{R}{L}\right)^2 - \frac{4}{LC}\right]t}}{\left(\frac{R}{L}\right)^2 \frac{R}{L}\left(\frac{R}{L}\right)^2 \frac{4}{LC} \quad \frac{4}{LC}} \right] \tag{20}$$

By inserting the proper values in this equation the current has the form

$$I(t) = 1.10 - 1.109e^{-.5 \times 10^6 T} + .009e^{-64.5 \times 10^6 T} \tag{21}$$

Equation 21 gives the current flow in the triggering circuit for the first 5 microseconds. Therefore if a value of 2 microseconds is used for T, the current can be calculated as 702 milliamperes. This current is divided by R_{GC} and R_G in parallel, and the value of current at any time in each resistor can be found by current division as

$$I_G = \frac{R_{GC}}{R_G + R_{GC}} \cdot I, \quad I_{GC} = \frac{R_G}{R_G + R_{GC}} \cdot I \tag{22}$$

For I = 702 milliamperes, I_G is found to be approximately 64 milliamperes, and the gate current for each SCR is 638 milliamps. The gate voltage here would be R_G I_G, or 12.8 volts. Actually, since at 25 degrees centigrade 3 volts and 150 milliamperes will fire all SCRs of this type, the 13 SCRs in this chain should fire well before 2 microseconds after the gate of the externally controlled rectifier is triggered.[9]

Now that all values for the switch have been determined, it is necessary to go back to equation 11 and determine whether or not the current waveform puts excessive demands on the circuit in Figure 23. The value of R in equation 11 is the only value that is different. If the resistance of the SCR can be assumed linear in the conducting state, a value of resistance for the model 350RA can be found from;

$$R_0 = \frac{V_{FM}}{I_F\ (AV)} = \frac{1.21\ \text{Volts}}{550\ \text{A}} = .0022\ \text{ohms} \qquad (23)$$

Since there are 14 rectifiers in series, the total resistance is 14 x (.0022) or .030 ohms. When the value is inserted into equation 11 the resulting equation is;

$$I(t) = 54.7 \times 10^3\ e^{(-3.75 \times 10^3)t}\ \sin(45.7 \times 10^3 t) \qquad (24)$$

Again this equation is only valid when all of the SCRs are completely turned on, and for only the positive half of the sine cycle. This waveform is plotted in Figure 24. The peak value of current is approximately 20,400 amperes, and the rate of rise of this waveform is about 2000 amps per microsecond.

The switch just designed cannot operate satisfactorily with available SCRs without some means to delay the rate of rise of current. Also, a additional series resistance will be necessary to prevent the current from exceeding 10,000 amperes. As stated previously, saturable

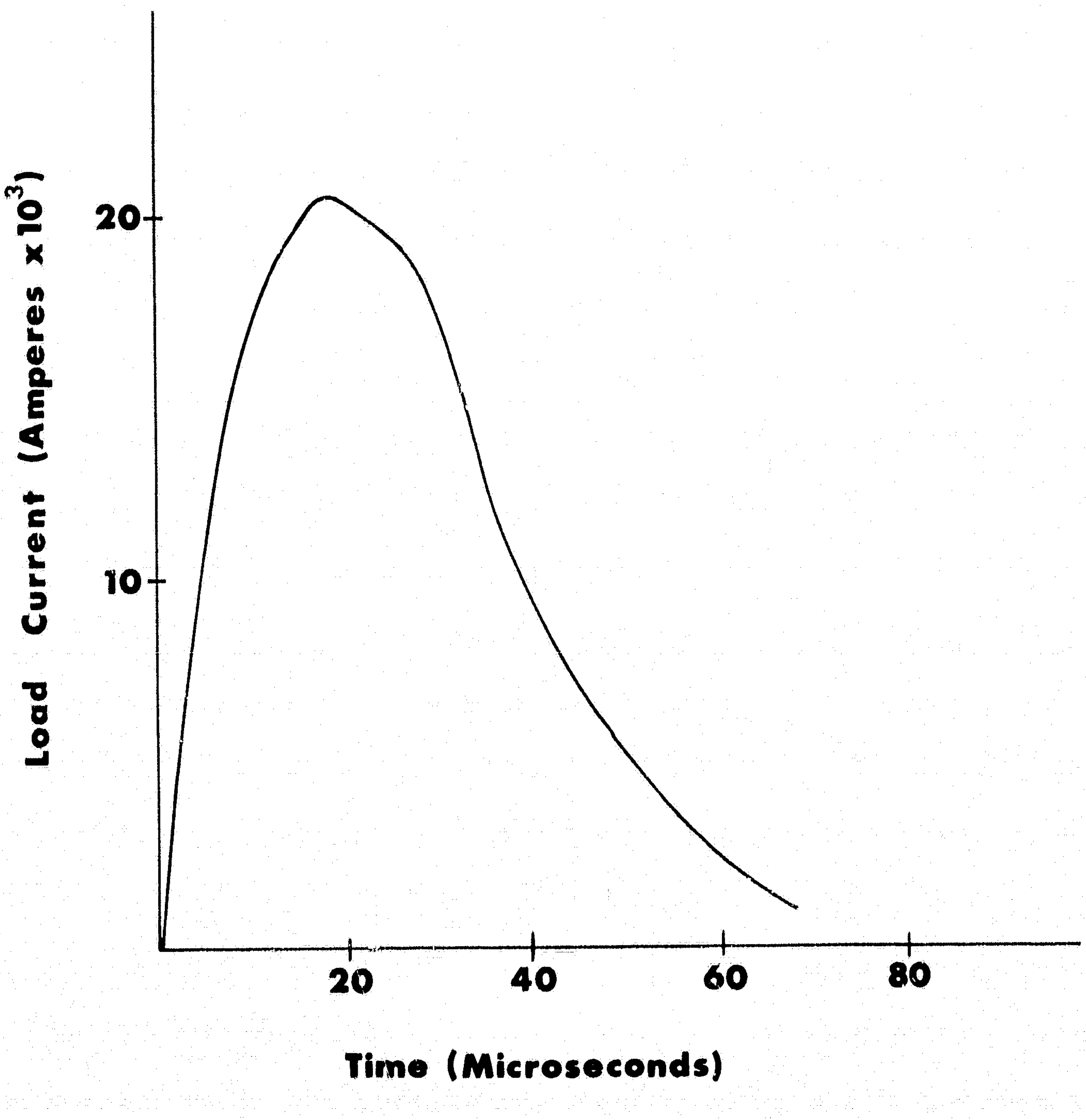


Figure 24.--Current Waveform of Static Switch.

reactor would help limit the rate of rise and give a much needed time delay to adequately have all SCRs fully conducting.

The preceding discussion was based on the SCR ratings specified by manufacturers, and these ratings are usually very conservative. One author[15] has conducted fairly extensive tests on the current handling ability and di/dt rating for several different brands and sizes of SCRs. A saturable reactor was put in series with each unit while it was tested. The results of these tests indicate that with the proper "soaking time" the peak current rating and di/dt rating can be greatly exceeded without SCR damage.

With this in mind, the use of a large saturable reactor in series with the 10,000 volt switch may allow the flow of 20,000 amps without SCR damage. The design of this self saturating reactor, which would need a soaking time of at least 25 microseconds, can be gotten from reference 15. However, even though the peak current could now possibly be handled, and the di/dt of the anode current lowered, these values would probably be excessive for any single SCR available today. The design of the 10,000 volt switch was included in this report for the following reasons;

First, a demand on this switch was that the voltage to be switched was fixed at 10,000 volts. If this value could be lowered, then the design equations used in this section could be used to determine the feasibility of using SCRs for the new application.

Secondly, the usefulness of the equations given in the theoretical section are shown by this switch application. In particular, the decisions made for this switch in terms of how many SCRs to put in series, whether or not to use parallel operation, etc., could be used for many other applications involving static switching.

Finally, the attempt to design a switch of this nature points out the undesirable characteristics of SCRs for this application. This naturally leads to an investigation of possible improvements to be made on SCRs in order for the device to better perform static switching. This discussion is the subject of the next section.

IV. RECOMMENDATIONS-IMPROVEMENTS

In order for any feasibility study of a given area to adequately fulfill its function there should be a list of suggested "paths" to follow for future work in that area. In this section several aspects of controlled rectifiers in relation to the specific application of high voltage, high current, static switching will be discussed in terms of how the device could be better adapted or modified to serve this purpose. The more inexpensive modifications are presented first, with the most expensive, (and therefore most beneficial), modification concluding the section.

A. Consolidated Construction of SCRs

The physical configuration for connecting about 14 units in series needs to be examined at this point, since there are several possible ways to reduce the size and weight of the chain.

First, the standard stud-mounted SCR unit could be better adapted for series operation by removing the heavy flexible cathode lead and replacing it with a threaded terminal. Also, the anode terminal could be machined flat, and then held to a heat sink by a spring clamp. The other side of this heat sink would be threaded to accept the cathode terminal of the next series SCR. The series chain would then consist of a ridigly mounted string of SCRs with a heat sink mounted between each unit.

Secondly, a new physical configuration for packaging SCRs has recently been introduced, and this new unit adapts well to series operation. The anode and cathode terminals are machined flat, and the gate lead is brought out of the side of the package. The result is a thin circular disk that resembles a hockey puk, and this is the name given this construction by one manufacturer. These "Hockey Puk" units offer improved heat dissipation, higher power per device, and increased reliability. They can be readily connected in series by pressing a separate flat heat sink surface between each circular pole piece, and then putting a common spring and ball joint at one end to put pressure on the whole stack. These units are presently not available for all models of SCRs, but should be on the SCR market in the near future.[16]

A third possibility is the stacking of a number of wafers together in a single package, with a brazed metallic wafer between each SCR. A possible connection of this type is shown in Figure 25, where 4 units are put in series in one package. This method could only be used in situations where the load pulse duration is in the microsecond range, since no heat sinks are provided.[10] The only leads coming from the device would be the gate leads and voltage equalization leads. This technique should greatly reduce the inner-device capacitance, which would allow a greater effective rate of rise of anode voltage and thus help protect the SCRs from turn on by transients. Actually, for a linearly rising anode voltage there is a charging current, I_q, in the SCR that could be represented as:[8]

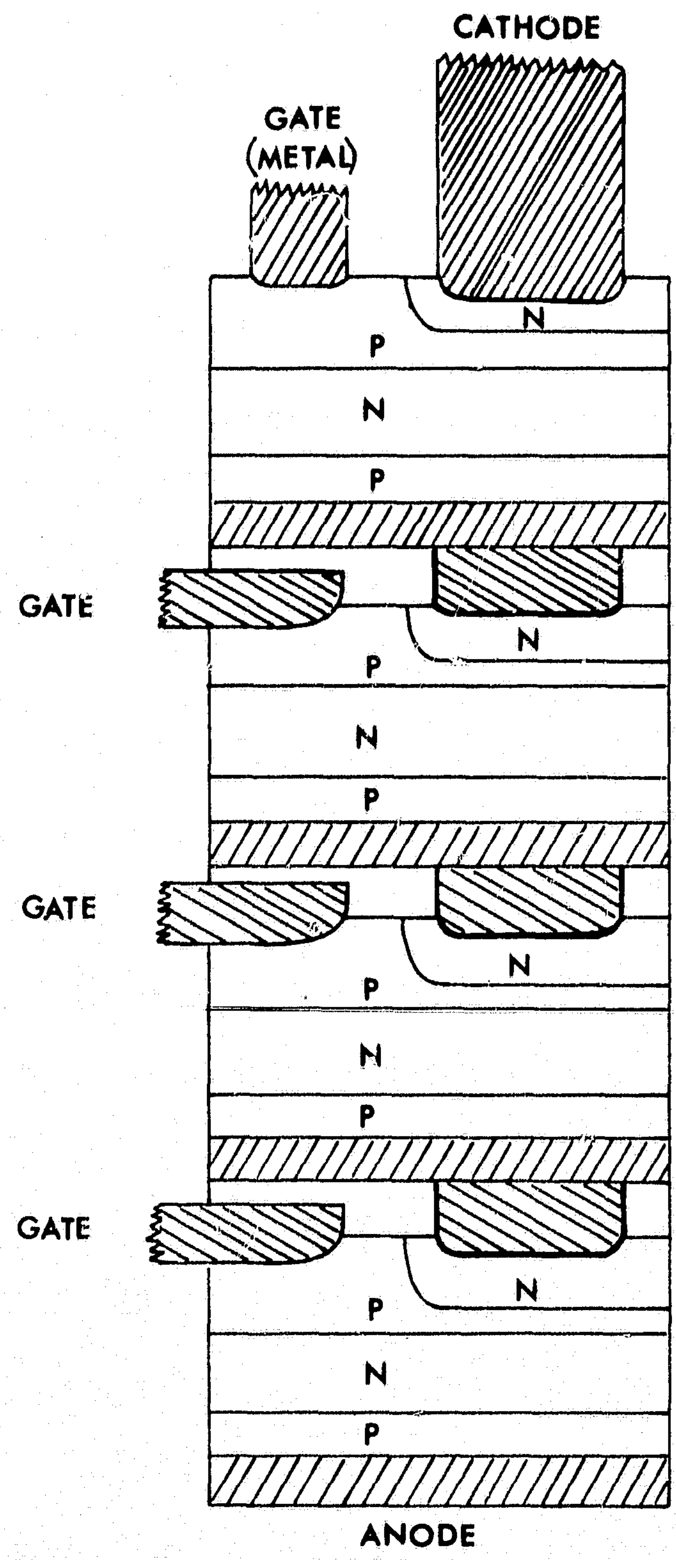


Figure 25.--Typical Packaged Construction of Series SCR's.

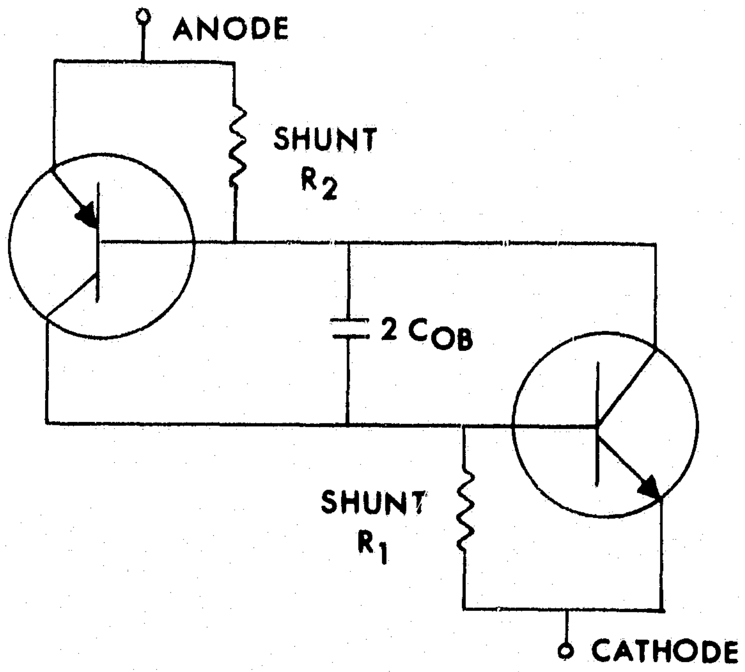
$$I_q = C_{ob}\, dv/dt \qquad (25)$$

where C_{ob} is the inner device capacitance and $\frac{dv}{dt}$ is the rate of rise of anode voltage.

Equation (25) shows how I_q could reach the holding current value if the rate of rise of anode voltage is to large, or if the capacitance was large. Also, it is implied in equation (25) that a small anode voltage applied very rapidly could induce turn on, but this is not obvious if it is remembered that the SCR is a charge-controlled device. The current I_q must be applied long enough to sweep clean the blocking junction, and since this charge required is inversely proportional to the frequency response of the SCR, every controlled rectifier can have a voltage rating that could be applied instantly without turn on occuring.

Secondly, this packaging technique allows a new lead to be easily connected to the "N" region of the SCR next to the anode, and brought out of the package. As one author states, putting a resistor of suitable size between this "N" electrode and the anode effectively puts the resistor in series with C_{ob}, which gives a longer time constant for the shunt path and allows much faster rising anode pulses without triggering. Figure 26 shows figuratively how this resistor could prevent turn on by C_{ob}.[8] If it is found that high frequency techniques used in pulse forming in the gate circuits causes difficulty due to the rate effect, this method could easily be employed.

Thirdly once the SCR is "on", the only current limiting factor in the device is the actual forward resistance of the rectifiers and their



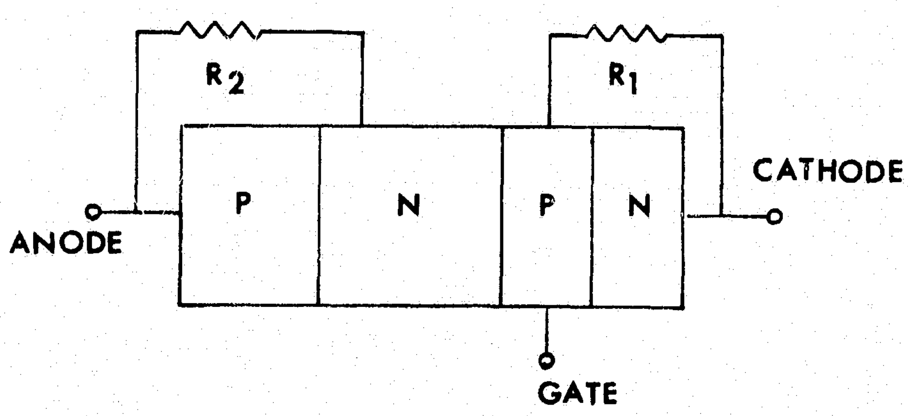


Figure 26.--Shunt Resistance Equivalent Circuit for Rate Effect Suppression.

leads, and it should be possible to easily reduce the total resistance in this stacking manner. This then allows very high values of overload current to be used without excessive device power loss.

Finally, the savings in both size and weight makes a consolidated packaging technique very desirable. This saving becomes extremely important in any application such as space work, where size and weight are at a premium.

B. Multiple Gate Improvement

In a large area controlled rectifier, there exists a problem of uniform spread of conduction across the base layer when a gate pulse is applied. The gate electrode is usually attached to the side of the silicon wafer, and it often takes over 50 microseconds for the conducting area that initiates at the gate electrode to spread over the complete wafer area. It has also been shown[5] that positioning the gate lead in the center of the wafer does not significantly help this situation. The propagation rate of the conducting area is approximately .1 millimeters per microsecond, depending on the magnitude of the load current.[17]

Attaching several gate leads to the wafer helps to spread the turned on area.[12, 17] These multiple gate electrodes are paralleled, and all gates are usually fired in unison. The improvement in conducting area increase for a typical SCR with multiple leads is shown in Figure 27, referenced to the same type unit with only one gate electrode. It is conceivable that more than two gate leads could be connected to the unit to further increase the ability of the SCR to get a large area conducting quickly.

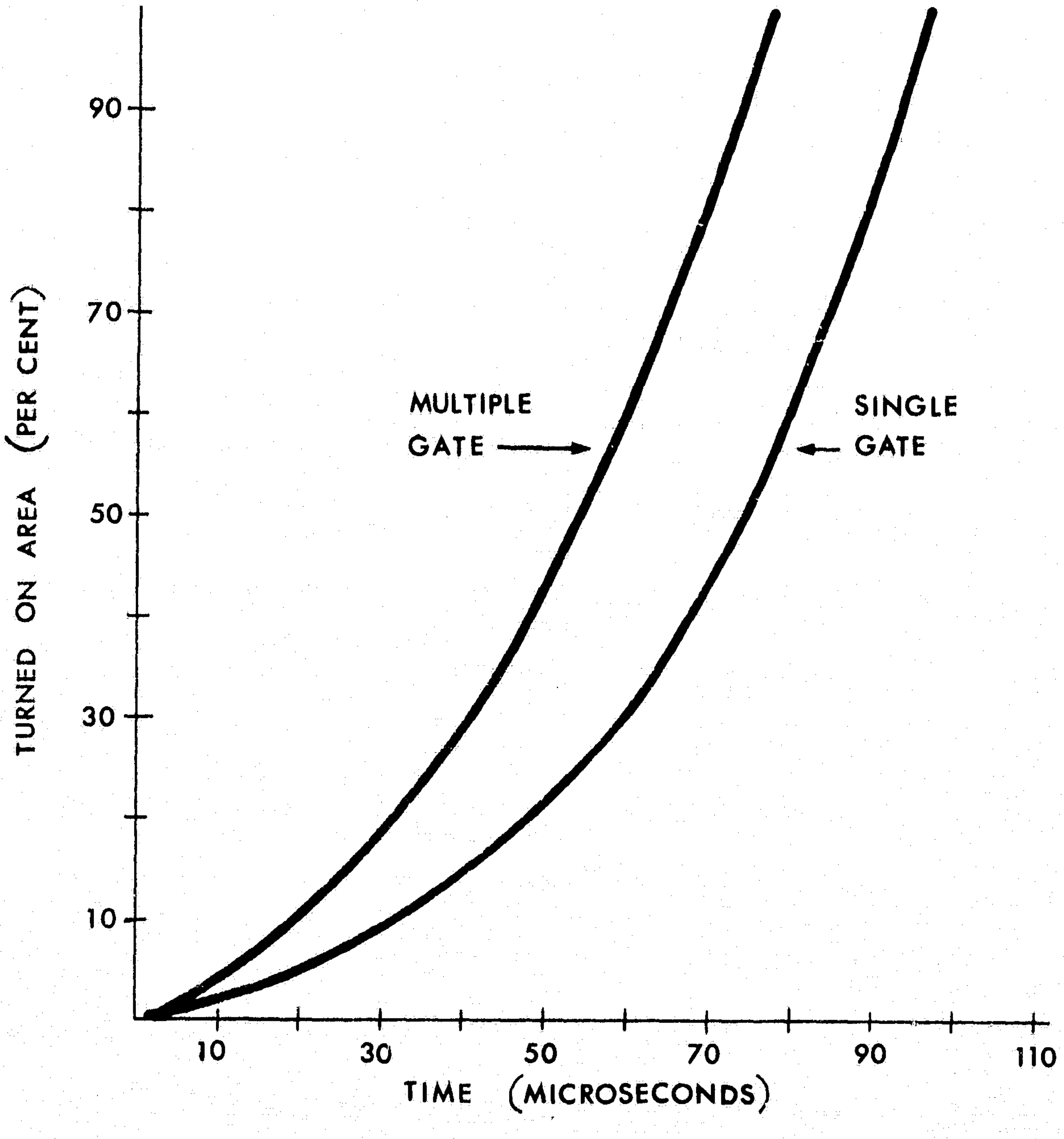


Figure 27.--Circuit Showing Multiple Gate Improvement.

The net effect of the use of multiple gates to the switch designer is the improvement of the di/dt ratings for presently available SCRs. In fact one manufacturer* has predicted that a rate of rise of 1000 Amps per microsecond could be handled by using two 150 ampere units each having 4 gates. There appears to be a maximum number of gates that can be put on a given size SCR with turn on improvement, and much work is currently being done in this area by manufacturers.

The use of multiple gates on the larger model SCRs to improve the di/dt capability greatly enhances the chance that the SCR could compete with other devices in high power static switching. For instance, for the switch designed in this report it may be possible to put 8 or 10 gates on the model 350RA or equivalent and then allow the di/dt values that exist in the circuit. This would then often permit the replacement of large mercury pool switches with SCRs. The design and construction of a large line of SCRs having multiple gates should be persued by anyone interested in the types of applications discussed above.

C. Radiation Triggering

Controlled Rectifiers can be triggered to the conduction state if they are bathed in radiation of the proper wavelength. This radiation creates hole-electron pairs which are accelerated under the field created by the potential across the SCR in the forward blocking state.[3]

The exact proper frequency of radiation to induce triggering is

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*Unpublished correspondence with Mr. D. W. Borst of International Rectifier Inc.

difficult to obtain analytically, because the absorption of silicon is altered significantly by the presence of doping atoms and by other materials diffused into the silicon to create good electrical characteristics. However, an approximation to the proper radiation can be found by assuming that the majority of the absorption of radiation in silicon is utilized in transferring electrons to the conduction band from the valence band. The amount of energy required to do this is called the band gap energy, and this gap energy for silicon is 1.11 electron volts.[14] The wavelength of radiation corresponding to an erergy difference of 1.11 electron volts can be found by the de Broglie equation as;

$$\lambda = \frac{hc}{\Delta E} \tag{26}$$

where $h = 6.62 \times 10^{-27}$ erg seconds (Planck's Constant)

$c = 3 \times 10^{18}$ Å/second, (the velocity of light)

For our case, using $1 \text{ e.v.} = 1.6 \times 10^{-12}$ erg,

$$\lambda = \frac{6.62 \times 10^{-27} \text{ erg seconds}) \, (3 \times 10^{18} \text{ Å/second})}{(1.11 \text{e.v.}) \, (1.6 \times 10^{-12} \text{ erg/e.v.})}$$

$$= 11{,}200 \text{ Angstroms} \tag{27}$$

From this, if the interaction of the doping atoms and other impurities are neglected, radiation of wavelengths longer than 11,200 Angstroms will not contain sufficient energy to create hole electron pairs in the silicon. It now remains to determine the effect of radiation of shorter wavelengths.

Hole-electron pairs that are created on a surface by the absorption of radiation decay exponentially as they penetrate into the silicon wafer. If all photons that strike a surface are absorbed, the number of electron-hole pairs created per unit time in a layer of silicon of thickness dx at a distance x below the surface is given by Lamberts Law of Absorption[3];

$$g(x)\ dx = N(\lambda)\ \alpha\ (\lambda) e^{-\ \alpha(\lambda)\ x}\ dx \tag{28}$$

where $N(\lambda)$ = number of incident photons

$\alpha(\lambda)$ = intrinsic absorption coefficient of silicon

The importance of this equation in determining the proper radiation wavelength is shown by figure 28, which shows the intrinsic absorption coefficient of silicon as a function of wavelength. The large increase in $\alpha(\lambda)$ with decreasing wavelengths, when inserted in equation 28, shows that the net effect of decreasing the wavelength is to cause fewer hole-electron pairs from reaching the interior of the silicon material. In reality, as λ decreases, more minority carriers are combining on the surface of the material, instead of penetrating the silicon and being collected at a junction. Therefore the intensity of the radiation must be increased if λ is decreased, in order to yield the same number of minority carriers at a given junction.[3]

The measured frequency response of a P-N-P-N device to light of visible and infrared frequencies is shown in figure 29. The peak response of this curve occurs very close to the 11,200 Angstrom value calculated above.[3] It is now necessary to determine what type of

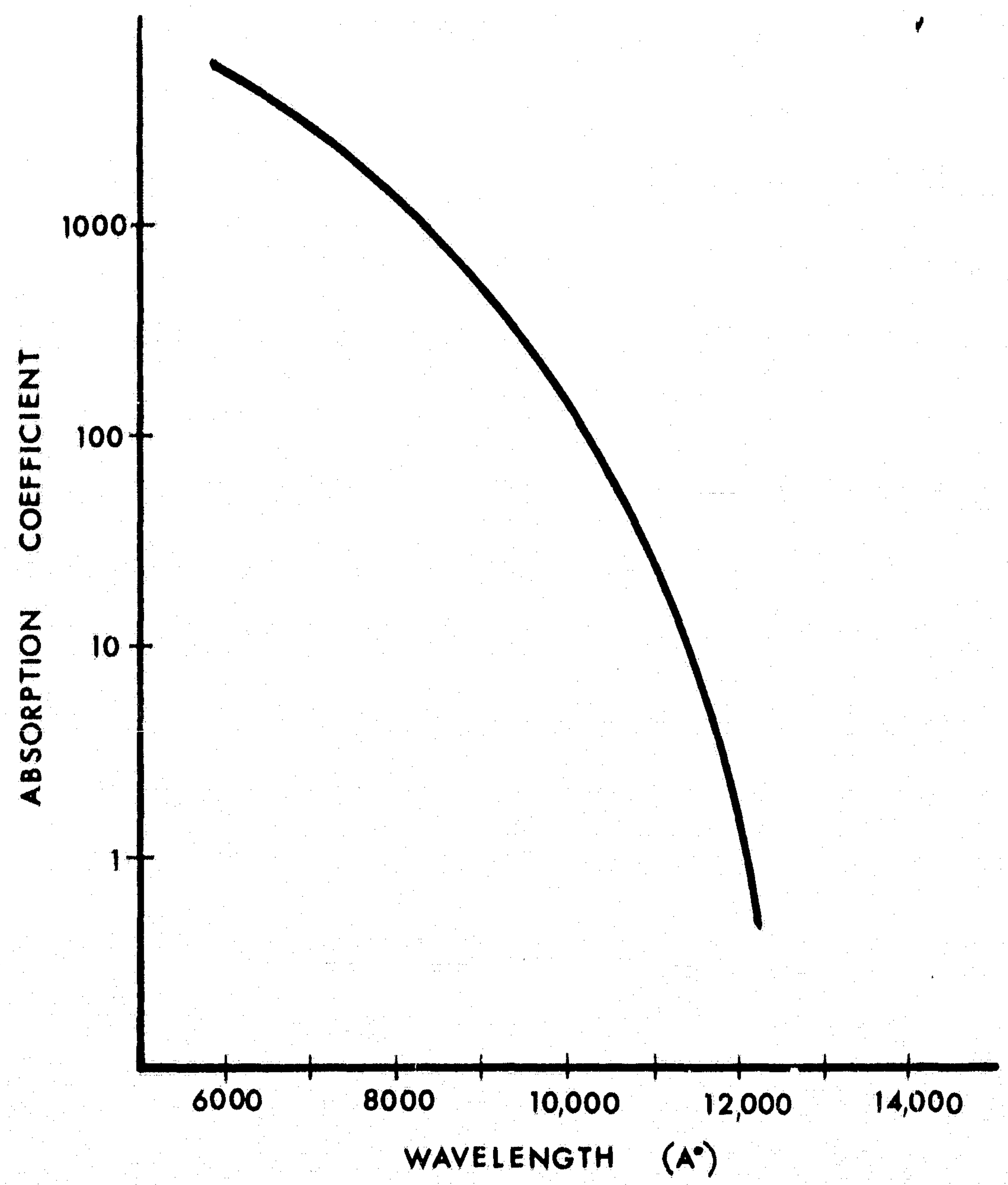

Figure 28.--Silicon Absorption Spectrum.

lamp to possibly use as a triggering source.

For SCR triggering, there are two major requirements that the triggering lamp must satisfy. First, the lamp must be able to emit large quantities of radiation in the wavelength region of the spectral response shown in figure 29, (12,000 Å to 6,000 Å). Secondly, the lamp must be able to reach a large value of intensity in a very short period of time, in order to prevent misfirings and partial triggering.

Typical spectral response curves for several popular light sources are shown in figure 30. This curve is somewhat misleading, however, since it is impossible to compare the relative magnitudes of the radiated energy on the same graph. Therefore, even though neon has its peak value in the proper region for the controlled rectifiers spectral response, the tungsten and Xenon flash lamps are capable of much higher output intensities. In fact, Xenon flash tubes emit such large quantities of light in the spectral region of the SCR that it may be necessary to filter and attenuate the light with optical devices. This factor, coupled with the fact that both tungsten and Xenon can be flash operated, and therefore reach a large light intensity value in a short period of time, makes the most desirable SCR light source either Xenon or tungsten.[3]

This area of light triggering is relatively untried, and all experimental work has been done on the smaller types of controlled rectifiers. However, this author feels that extensive investigation should be conducted in the area of light triggering in static switching, for the following reasons.

First, the degree of isolation that can be obtained by light

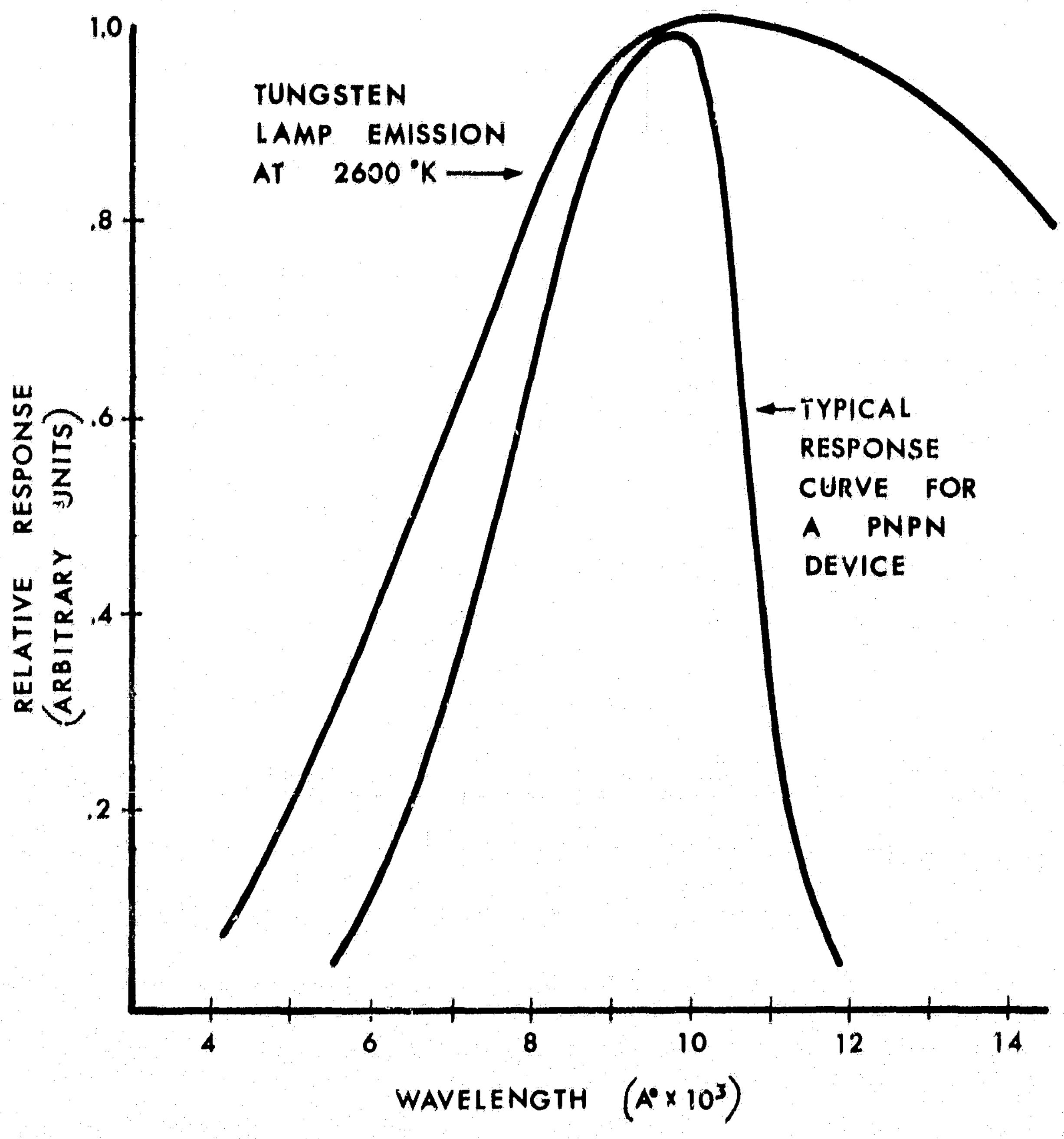

Figure 29.--Response Curve for Typical SCR

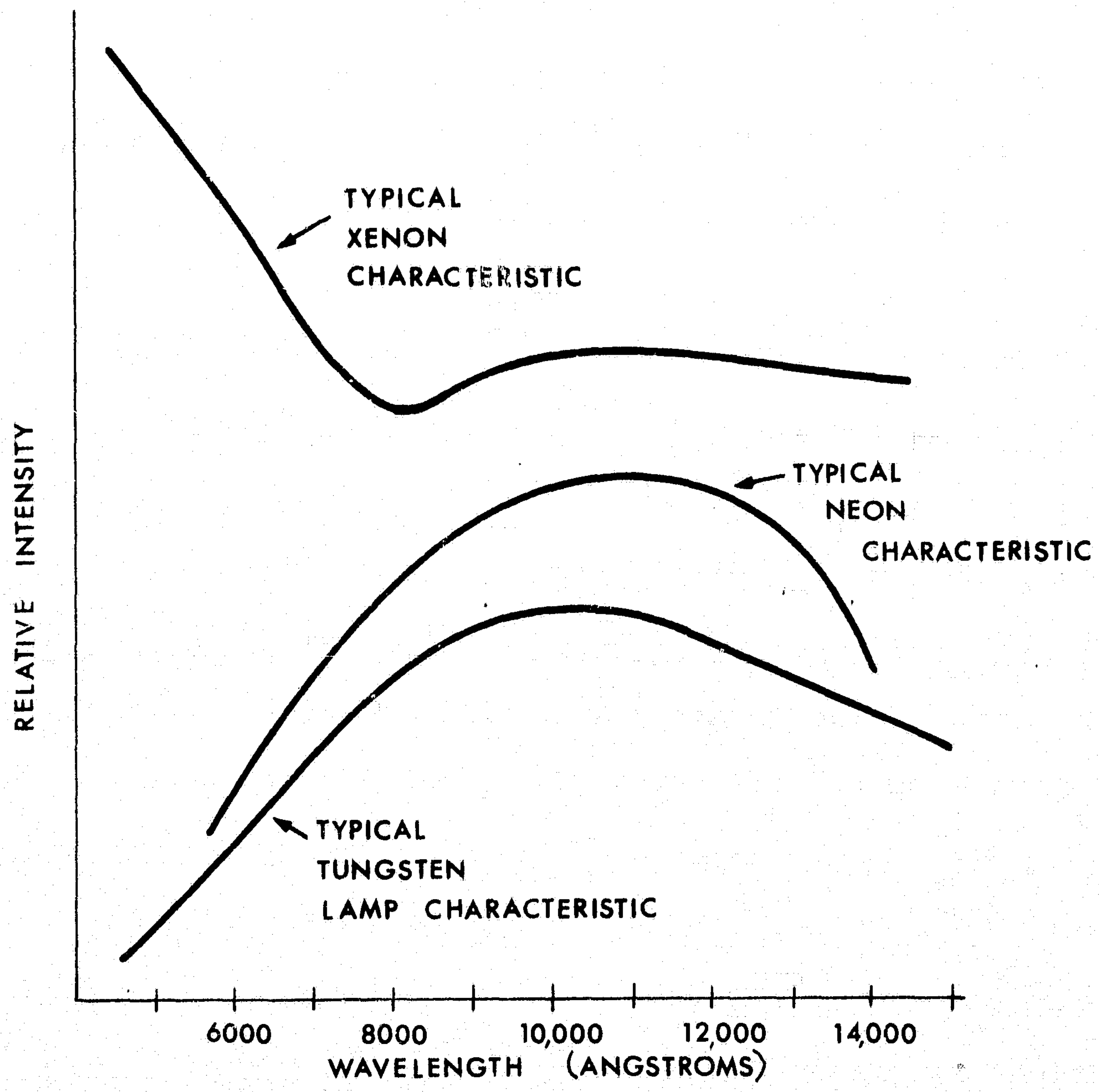

Figure 30.--Typical Lamp Characteristics.

triggering is many times that available by any other technique. If series operation of controlled rectifiers is necessary, the gates can be fired independently by separate pulse transformers, or can be slave fired as discussed earlier. However, light triggering eliminates both the severe isolation requirements put on a pulse transformer in the first case, and the number of parasitic elements such as diodes, resistors, and capacitors required in the second case. Light triggering also eliminates the fairly stringent power requirements and rating requirements put on the voltage equalizing components in the chain, since these components now could serve only the function of voltage equalization instead of also being the triggering means.

Secondly, there is no practical reason why turn on times for light triggering could not be at least as good as the turn on times for gate or anode triggering. Preliminary investigations have indicated that making the junctions light sensitive greatly increases the controlled rectifier's sensitivity to transients and other related phenomena, but if the light source and controlled rectifier were encased in the same reflective housing, which in turn was coated to prevent outside radiation from entering the shell, a good deal of this sensitivity should be eliminated. Also, it may be entirely possible to eliminate this sensitivity by putting an electrical bias on the gates, and then letting the light source serve as the final triggering mechanism.

Thirdly, light triggering would eliminate many problems associated with gate triggering under varied load conditions. As was stressed earlier, the use of inductive loads puts severe requirements on the gate pulse duration. Light triggering eliminates this problem, since light flashes of a millisecond in length are not difficult to obtain and would provide as large a safety factor in turn on as required.

Finally, in a series application of SCRs, where the load cycles where short enough that large heat sinks were not needed, the total static switch and light source could be incorporated into a single housing. This technique would create a large size and weight savings. Also, the problems associated with stray inductance and capacitance and their degradation of device performance could be greatly reduced by this method.

D. PNPN Device Changes

The controlled rectifiers on the market today are designed and built to satisfy a number of applications simultaneously, and it is logical to investigate the probability of improving the PNPN device for applications that would involve only static switching. Indeed, this area must be investigated if controlled rectifiers are to make any large gains over other static switching devices such as spark gaps, especially in applications involving the switching of thousands of volts and thousand of amperes in microsecond time periods.

This type of research effort must be conducted by an organization that has the ability to manufacture and test semiconductor devices. Only the manufacturers of semiconductor devices can predict whether or not a suggested improvement can be implemented, since there are many problems associated with such things as the degree of doping possible for a given silicon wafer and the conduction of heat from the wafer to the metal case. This organization should have the facilities to grow silicon crystals, control doping processes, and measure all of the parameters of the controlled rectifier.

The primary concern in using controlled rectifiers in static switching with short load cycles is that of turn on time, and the general factors that influence turn on are given in this section, with suggestions as to possible future improvements.

Figure 31 shows the cross section of a common high power controlled rectifier. The wafer begins as a single crystal doped with N-type impurities, and the other impurities are selectively diffused into the wafer to form the 4 regions shown in Figure 31. Once the PNPN wafer is formed, leads are attached in the manner shown, with the gate being connected off to the side of the wafer. This gives a good direct path for the load current, although it does not permit complete use of the total area of the wafer at all stages of the turn on period. The controlled rectifier can be thought of as two circuits, the anode-cathode load circuit, and the gate-cathode triggering circuit. The dimensions of the wafer are not drawn to scale with the case, since then the wafer would be so small that it would be impossible to ascertain the different layers.

The resulting net impurity concentration created by selective diffusion are shown in Figure 32. The layer of P-type material closest to the anode is called the anode layer, and is characterized by a very high number of holes next to the anode that decreases quickly with distance into the wafer. This layer is usually only moderately doped and is the second thickest layer. Next into the wafer is the

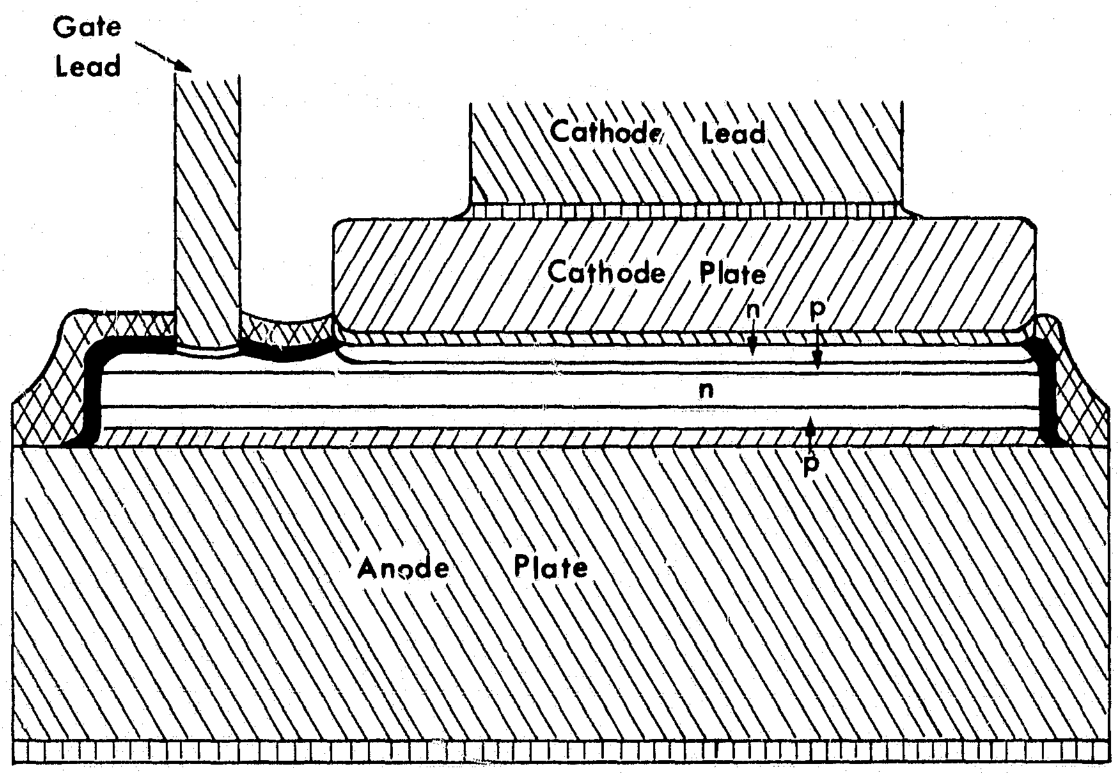

Figure 31.--Cross Section of Typical SCR.

blocking layer, which was the original N-type silicon before the selective diffusing took place. The blocking layer is the thickest layer, and is characterized by a low content of minority carriers. The third layer is called the control layer, and is a moderately doped p-type region with the gate electrode connected to it. The last layer is called the cathode layer, and is the thinnest layer of the wafer. The cathode layer is very heavily doped with N type impurity atoms, and is connected directly to the cathode of the SCR.[5]

After a study of the construction of the doping levels in the PNPN structure, it would seem possible to increase the speed of response of the SCR by altering the doping levels or by changing the width of a doped region, but care must be taken in this attempt. The slope and width of each impurity curve, as well as the magnitude of the impurity concentration, have been carefully selected to given high forward and reverse blocking voltages, and low leakage current in the blocking state. Therefore any change in one of the form layers to improve turn on could drastically effect another property of the device.

For instance, assume that one would attempt to lower the turn on time by widening or increasing the slope of the P-type impurity concentration in the anode layer of Figure 32. However, the anode junction, which is formed by the blocking and anode layers, is the portion of the SCR that blocks reverse voltage across the device. This is true because the control junction, which is formed by the blocking and control layers, is forward biased, and conducts freely. The cathode junction is reverse biased, but since it is very highly doped, it does not

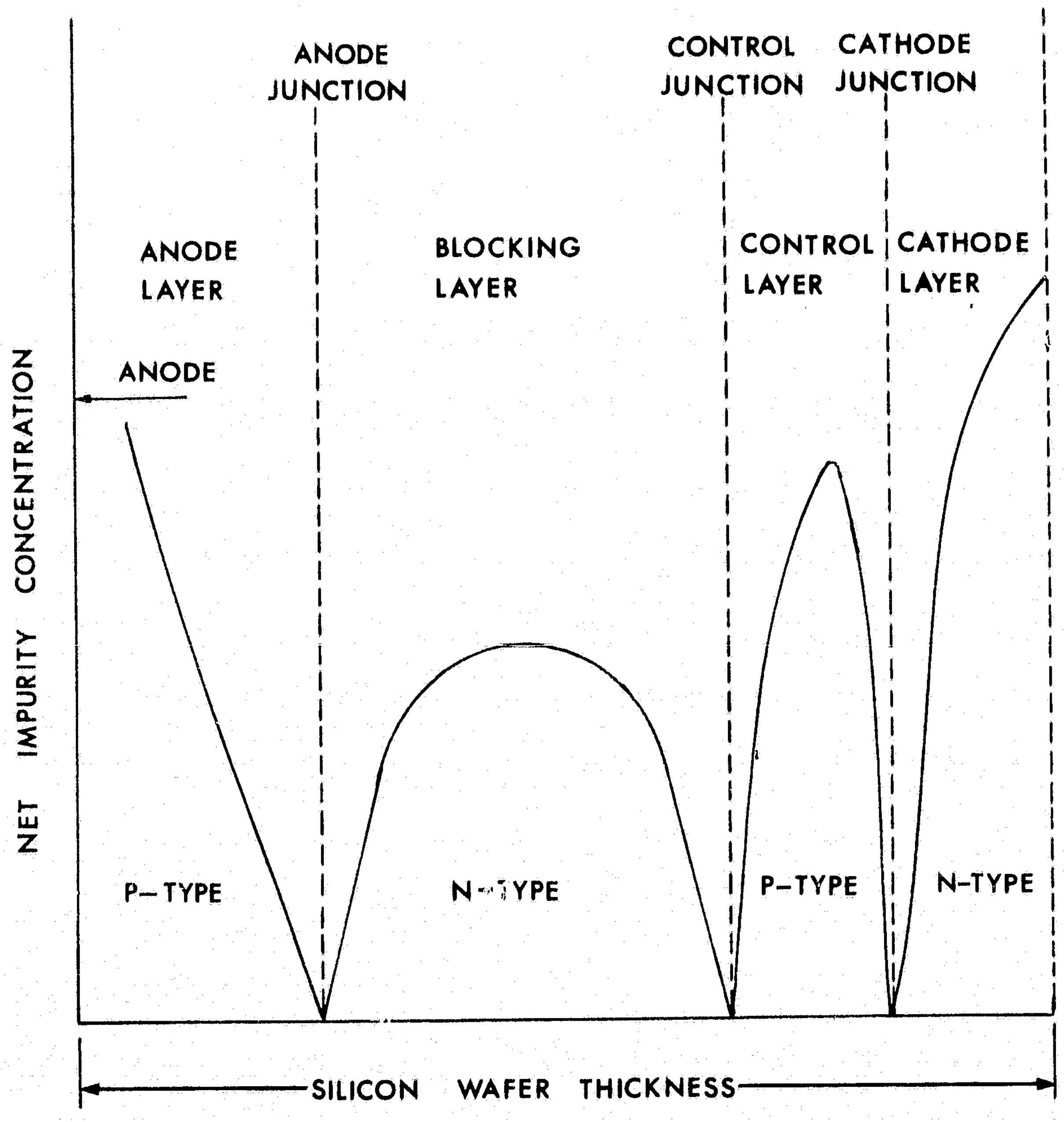

Figure 32.--Impurity Concentration Diagram for a Typical SCR.

have the ability to block large reverse voltages. Therefore the slope and relative doping levels in the region of the anode junction determine the reverse blocking ability of the SCR. Obviously, an increase in the slope of the P region in the anode layer would lead to a lower ability of the SCR to block reverse voltages.[5]

While this example points out the many problems associated with attempting to alter the SCR in order to gain turn on time improvement, it is not meant to imply that this task is impossible. This example does point out that any change in the basic impurity levels of the SCR will have to be done by a physicist or similar person in position to readily evaluate any change. In the above case, for instance, it may be possible to decrease the turn on time by a large factor and only reduce the reverse blocking ability by a few percent, but only the validation of these predictions by lab experiments can be trusted.

While it may not be possible at this point to satisfactorily predict the complete outcome of a basic change in the doping levels in controlled rectifiers, there is a modification that could be made that would greatly enhance the use of controlled rectifiers in static switching. This change involves the conversion of the gate fired SCR to a 4 layer diode and the subsequent use of anode firing.

E. 4 Layer Diodes

The major advantages of anode triggering have already been pointed out, and will not be repeated at this point. However, to fully appreciate the previous discussion on anode firing, and to understand the basis for the forthcoming suggested changes, a comparison with conventional gate triggering should be given using Figures 31 and 32.

Gate firing the SCR can be broken up into separate stages. The first stage occurs when the controlled rectifier is in the forward blocking state, and a fast rising positive gate pulse is applied. This gate pulse injects holes into the control layer, causing a very localized, high density current flow in a very small area around the gate. This forces the potential that normally exists across the control junction in forward blocking to collapse, forming a very small conducting region in the gate area. Due to carrier concentration gradient the injected holes move laterally towards the cathode.[5]

The second stage of gate turn on occurs when the holes reach the region around the cathode. The positive space charge, along with the now lowered potential wall at the control junction area, attracts a large number of electrons from the cathode layer. This initiates the injection of holes from the anode layer, and conduction of load current in a very small area begins. This load current in turn helps speed the spreading of the conducting area over the complete wafer. However, it often takes 50 microseconds for the conducting area to spread completely, and if large anode currents are applied before this time device destruction is highly probable.[5]

There are several reasons[2] why the spread of the conducting region in the SCR takes such a comparitively long time. First, the PN junctions are not perfect, and the avalanche voltage variations from one spot to another on the wafer causes uneven current distribution. Secondly, there are often traces of impurities such as iron, copper or manganese that lead to localized high electric fields and therefore premature breakdown. This premature breakdown causes the lateral current flow to be selective over the area of the wafer. Finally nonuniform current distribution can be induced by other impurities such as dust or oxides in the junction area.

A much more direct means of turn on, and one that eliminates the difficulties caused by imperfections in the silicon wafer, can be explained with the aid of Figure 32. If a very fast rising positive voltage pulse is applied to the anode, a large displacement in the equilibrium distribution of carriers occurs. This means, considering the slopes of the concentrations in Figure 32, that the distributions do not change, they are "displaced" a short distance. This disrupts the equilibrium charge concentrations over the entire wafer area. Thus at the control junction there is a very quick flow of holes toward the control layer, and a corresponding quick flow of electrons toward the blocking layer. Due to the high slopes of concentration densities in the junction region, there is a net charge displacement, and a potential wall suddenly forms across the junction. This initiates large numbers of minority carrier drifting, and due to resulting carrier multiplication a uniform, large drift current completes the turn on action. Actually the displaced charge creates a current that never stops flowing, and the resulting turn on time is much shorter than that obtained by gate turn on. Also, the turn on effect occurs over the whole junction, and the change is so large that the impurities and imperfections cannot affect turn on.[5]

Anode turn on demands that the voltage rate of rise for the triggering pulse be very high. One author[5] has suggested that the rise time T, of the triggering pulse should be related to the breakover voltage, V_{BO}, of the SCR, and the peak triggering pulse voltage V_P, as;

$$V_P = \frac{V_{BO}\, T^{1/4}}{2} \tag{29}$$

In this equation T is expressed in microseconds. For a V_{BO} of 1200 volts, and a rise time of 1 microsecond, V_P, the magnitude of the anode triggering pulse, can be calculated as 600 volts. This value is not an unreasonable value in light of the pulse generators available today, but if a long series of SCR's were used it can be seen that the magnitude of the triggering voltage pulse would be excessive.

To date, anode firing has been used successfully in triggering medium sized 4 layer diodes. One author[2] reports that with anode triggering it was possible to allow current densities of 55,000 amperes per square centimeter without device failure. This current density is several times larger than the allowed current densities for the controlled rectifiers presently available. This is very promising for applications involving very high anode current rate of rises.

The more direct, and basically simplier, method of turn on by anode triggering makes its use very appealing in high power switching. The anode firing of small area 4-layer diodes has been very successful, and there is no reason to expect any problems in anode firing of larger 4 layer diodes. Since there is no gate electrode, the cathode lead could be placed exactly in the center of the silicon wafer, as is shown in Figure 33 for 4 series connected 4 layer diodes. This yields

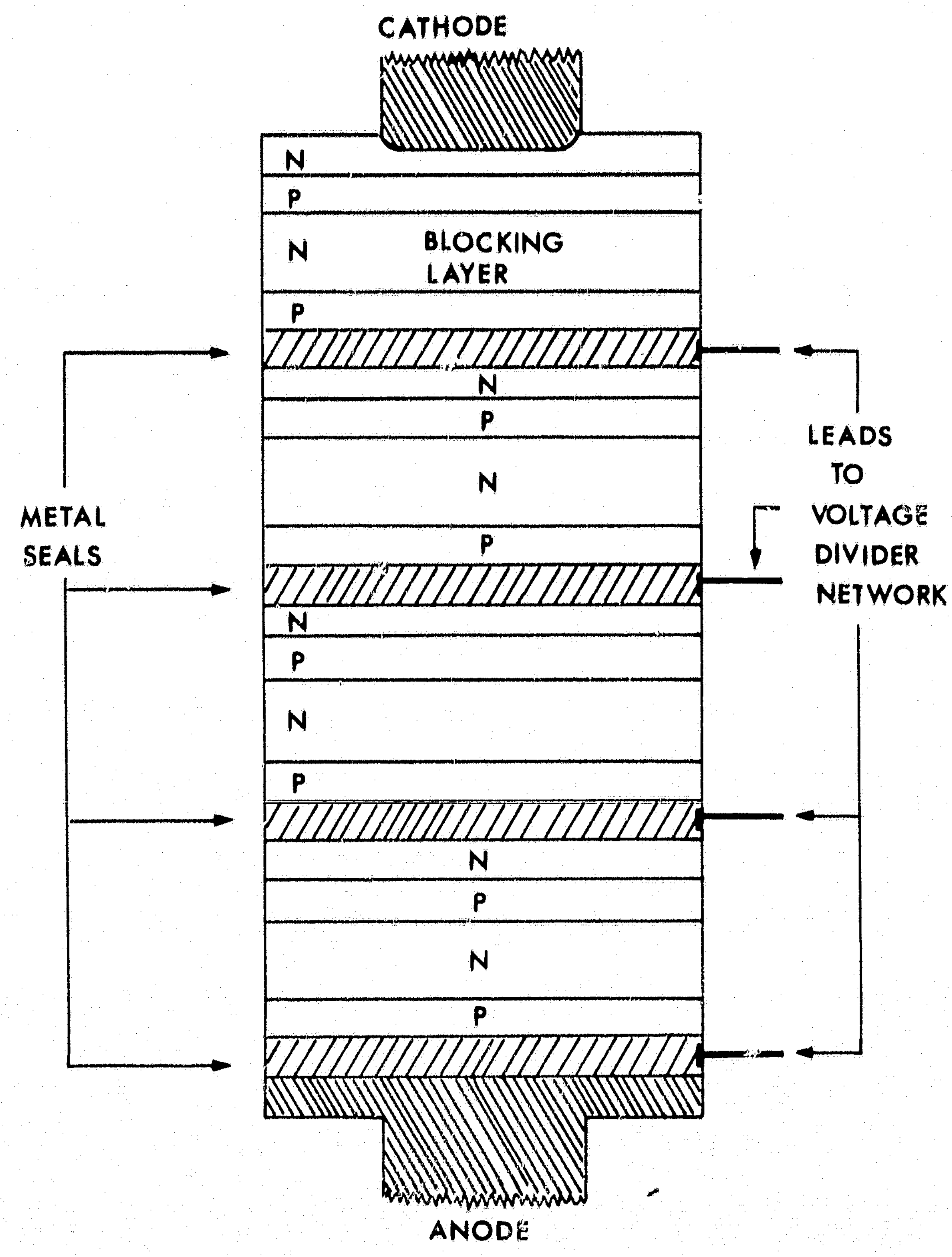

Figure 33.--Typical Packaged Construction for Anode-Fired SCRs.

a more symmetrical configuration that should distribute the load current more evenly that in the gate connected configuration. This could possibly allow still larger current densities and total load current values than obtained before, even by using the same size silicon wafer.[2]

Finally, the use of large 4 layer diodes would greatly enhance the adaptability of most of the improvements previously mentioned in this section. A comparison between Figure 33 and Figure 25 shows that in cases where consolidated packaging is possible, the 4-layer diode configuration yields a basically simplier switch design. The improvement by using light triggering can also still be easily employed for 4 layer diodes, and in cases where long series chains of SCRs are necessary this technique has tremendous possibilities.

V. CONCLUSION

The semiconductor controlled rectifier has several advantages over other types of static power switches. These advantages include high turn-on power gain, mobility, and no warm up time. However, even with these advantages the SCR can replace other static switches like spark gaps or mercury-pool rectifiers in only a limited number of areas.

If the power to be switched is of the order of hundreds of amperes and hundreds of volts, the controlled rectifier usually has very definite advantages. In fact, for overall performance the controlled rectifier has no real competitor in this power range, even if this amount of power must be switched in a very short period of time.

If the power to be switched is of the order of thousands of volts and thousands of amperes, the semiconductor controlled rectifier loses its clear-cut advantages. At the present time, series and parallel operation is inescapable for voltages greater than approximately 1200 volts, and currents greater than a few thousand amperes (depending on the load cycle). If a large number of SCRs have to be put in series, or parallel and series operation must be employed simultaneously, the practicality of the switch becomes questionable. Also, the di/dt rating of the SCR in this power range puts limits on their usefulness in situations involving very fast rising waveforms.

Finally, there are many improvements that can be made on SCRs to better adapt the device for static switching. Integrated packaging, multiple gate triggering, and light triggering are just a few of the areas that should receive careful attention. The manufacture of semi-conductor controlled rectifiers capable of blocking 2000 volts are in the very near future, and the use of these silicon wafers as 4 layer diodes or as multiple gate SCRs has tremendous promise. Finally, in view of the progress made in the short lifetime of the SCR, and the present experimental work being performed, the replacement of even the largest of static electronic switches with SCRs could be in the near future.

BIBLIOGRAPHY

1. Electron Tube Circuits, Samuel Seely, McGraw Hill Book Company, Inc. 1958, New York.

2. Uniform Turn-On in 4 Layer Diodes, K. Hubner, M. Melehy, R. L. Biesele, I. R. E. Transactions on Electron Devices, November, 1961.

3. Semiconductor Controlled Rectifiers-Gentry, Gutzwiller, Holonyak, Von Zastrow. Prentice Hall, Inc. 1964, Englewood Cliffs, New Jersey.

4. Electronics in Industry, George M. Chute, Third Ed., McGraw Hill Book Company, New York, 1965.

5. The Controlled Rectifier, Volume 1., International Rectifier Corporation, El Segundo, California. Edward J. Diebold, Editor.

6. How to Suppress Rate Effect in PNPN Devices, Richard A. Stasior, Application Note 90.21 Semiconductor Products Department, General Electric Company, Syracuse, N. Y.

7. Series and Parallel Operation of Silicon Controlled Rectifiers D. W. Borst and E. J. Diebold, Military Systems Design, January, 1962.

8. How to Ruin SCRs., Keith Sucker, I.E.E.E. Proceedings, August, 1966.

9. International Rectifier, Silicon Controlled Rectifiers, Catalogue A-66, International Rectifier Corporation, El Segurdo, California.

10. Power Semiconductor Ratings Under Transient and Intermittant Loads. F. W. Gutzwiller, T. D. Sylvan, Application Note 200.9, General Electric Company, Syracuse, New York.

11. The Ratings of SCRs when Switching into High Currents, Neville Mapham, Application Note 200.28, General Electric Company Syracuse, New York.

12. Overcoming Turn On Effects in SCRs. Neville Mapham, Electronics, August 17, 1962.

13. Network Analysis, 2nd Edition, M. E. Van Valkenburg, Prentice-Hall Inc. Englewood Cliffs, New Jersey, 1955.

14. Electrons and Holes in Semiconductors, William Shockley, D. Van Nostrand Company, Princeton, New Jersey, 1950.

15. Pulse Current Limits of Silicon Controlled Rectifiers, Kristian Aaland, AIEE Conference Paper, August 1963.

16. International Rectifier, Silicon Controlled Rectifier, Bulletin A-121, Hockey Puk SCRs, International Rectifier Corporation, El Segundo, California.

17. "Turn-On Action in Large Controlled Rectifiers" D. W. Borst, International Rectifier News, Fall, 1966.