THE SILICON CONTROLLED RECTIFIER

Introduction

The silicon controlled rectifier is a high power silicon junction diode, the electrodes of which are in this case called respectively the anode and cathode. To these an additional control electrode, called the gate has been added to produce a new device which can act as a very efficient switch. Provided that the voltage across it is of the correct polarity (but does not exceed the rated value) this switch remains open until a small signal is applied to the gate when it closes and remains so, even if the gate signal is subsequently removed. In normal use the switch only re-opens when the forward voltage across it falls to a very low value. The switch cannot be closed at all when a reverse voltage is applied across it (provided that the rated voltage is not exceeded).

The S.C.R. behaves and rectifies like a large silicon diode but has the added feature that forward conduction does not occur until the instant when a suitable small signal is applied to the gate.

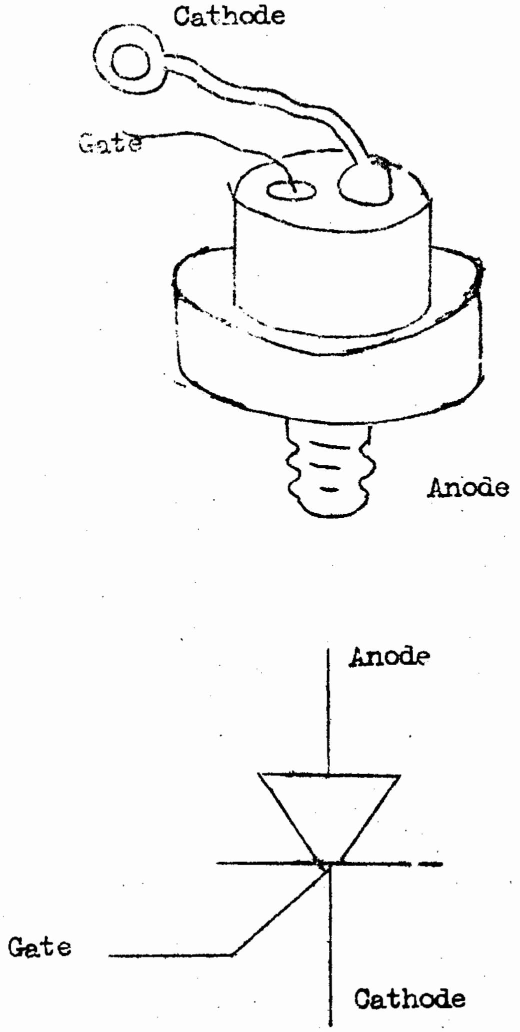

fig. 1

A diagram of one of these devices is shown in Fig. 1. together with the appropriate circuit symbol. Recently produced devices of this type can switch a current of up to 75 amperes with a brief gate current of less than one ampere. When open, the switch might withstand voltages up to about 1,500 volts. A smaller example might have corresponding values of about 8A, 110mA and 200 volts.

Silicon controlled rectifiers are being used to replace mechanical switches, to provide quick overload protection for sensitive circuits, to replace large rectifiers of other types etc. Among some possible applications in the BBC, are the controlled dimming of lights in T.V. studios and the overload protection of transistor power supply units.

Detailed Description of the Behaviour of the S.C.R.

With no signal applied to the gate the current produced by a forward voltage (positive anode voltage) is very small up to the breakdown voltage of the device. This current is due to thermally generated carriers in the semi-conductor material (called I_o in this paper). Once the breakdown voltage is exceeded avalanche conduction occurs and the resistance of the rectifier drops abruptly, permitting a heavy current to flow with only a small anode-cathode voltage. An output characteristic with these effects is shown in Fig. 2.

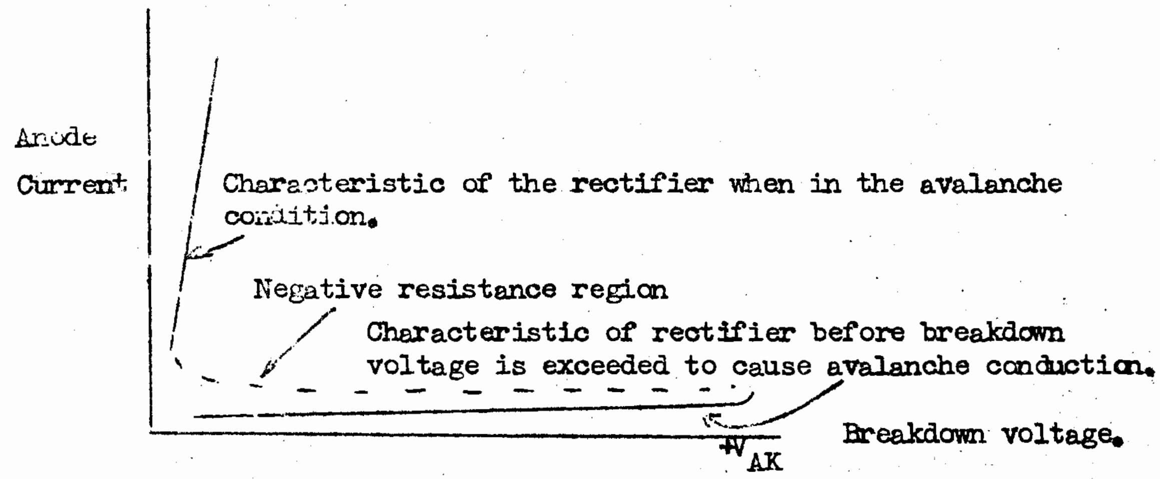

Fig. 2.

The effect of making the gate positive with respect to the cathode and so producing a gate current I_g, is to reduce the breakdown voltage. This effect is illustrated in Fig. 3. The reason for it will be explained later.

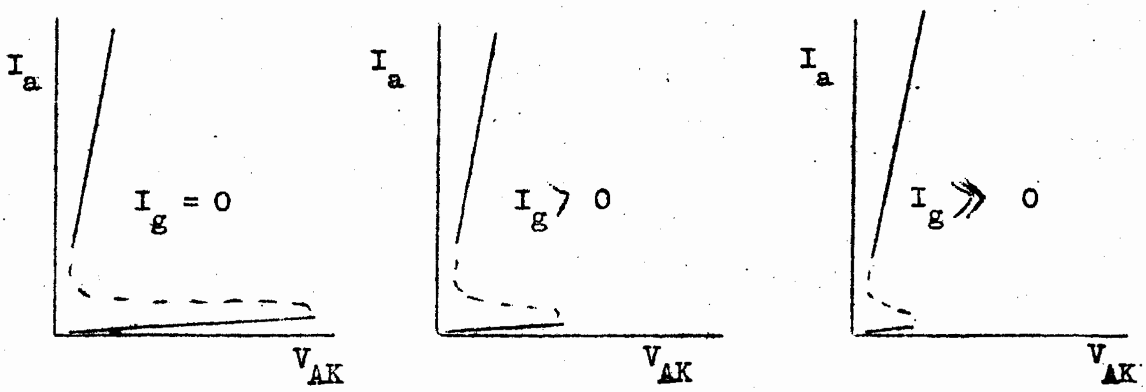

Fig. 3.

The switching action of the S.C.R. may be understood in these terms. Fig. 4 (a) illustrates a S.C.R. in series with a load resistor R_L and Fig. 4 (b) shows the load line for this arrangement superimposed upon the device characteristic.

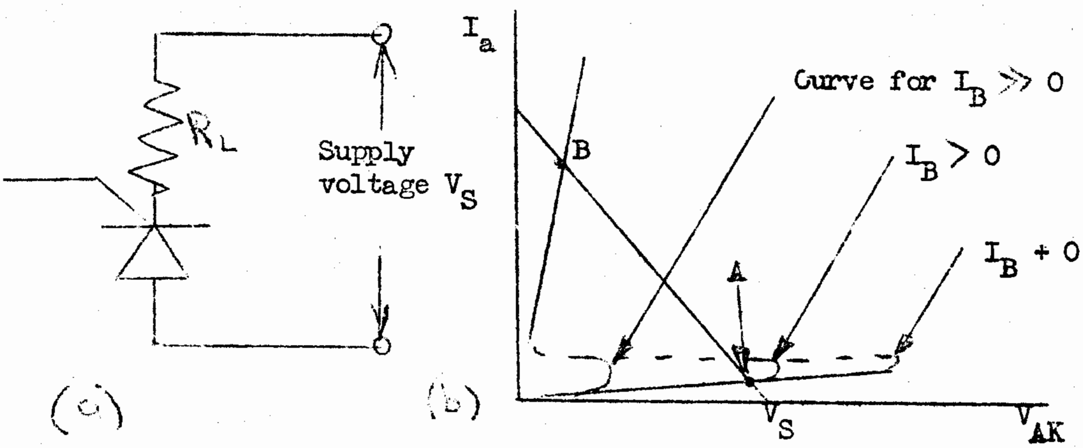

Fig. 4.

Assume for the moment that the supply voltage in the circuit of Fig. 4 is constant, so that the load line is stationary in the position drawn, and that the S.C.R. is initially in the off condition as indicated by the operating point A on the load line. If now a gating signal is applied the breakdown voltage is reduced as was shown in Fig. 3. Imagine the load line remaining still but the characteristic curve collapsing towards the left as the gate signal increases. The breakdown point moves towards, and finally reaches, the operating point A. At this instant avalanche conduction begins and the operating point moves quickly to the only intersection remaining between the load line and the characteristics indicated by point B. The S.C.R. now behaves as a closed switch. Once the operating point reaches B the gate signal can be removed without making further difference. Although the breakdown voltage then returns to its original value the operating point remains at B because avalanche conduction continues.

To open the switch the voltage across the S.C.R. must be reduced to a very low value. This can be done in either of two ways.

(a) The load can be considerably increased. This causes the load line to rotate in an anti-clockwise direction so that the point B slides down the characteristic. Eventually B reaches the bottom of the nearly vertical portion of the characteristic, at which point the avalanche is suppressed (the current at which this occurs is called the sustaining current, I_s). This is shown in Fig. 5.

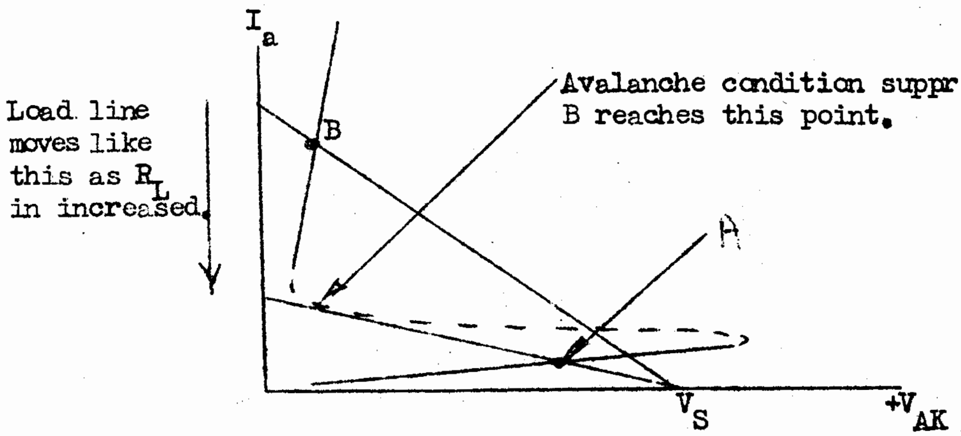

Fig. 5.

Physically this means that the load has become so large that the voltage drop across it, produced by the avalanche current, is about to exceed the supply voltage. The circuit resolves this attempt to contradict Kirchoff's second law by suppressing the avalanche and returning the operating point to A. i.e. the switch re-opens. Once this happens the load can be reduced so that the load line returns to its original position, without reclosing the switch, which then remains open until the next gating signal is applied.

(b) The other method of opening the switch is by reducing the applied voltage V_s. This, for example, is what happens fifty times per second when the applied voltage varies at mains frequency.

When V_s falls the load line retains its slope but moves to the left so that the point B again slides down the vertical portion of the characteristic. The avalanche is then suppressed, the operating point returned to A, and the switch opened in the same way as before, as illustrated in Fig. 6.

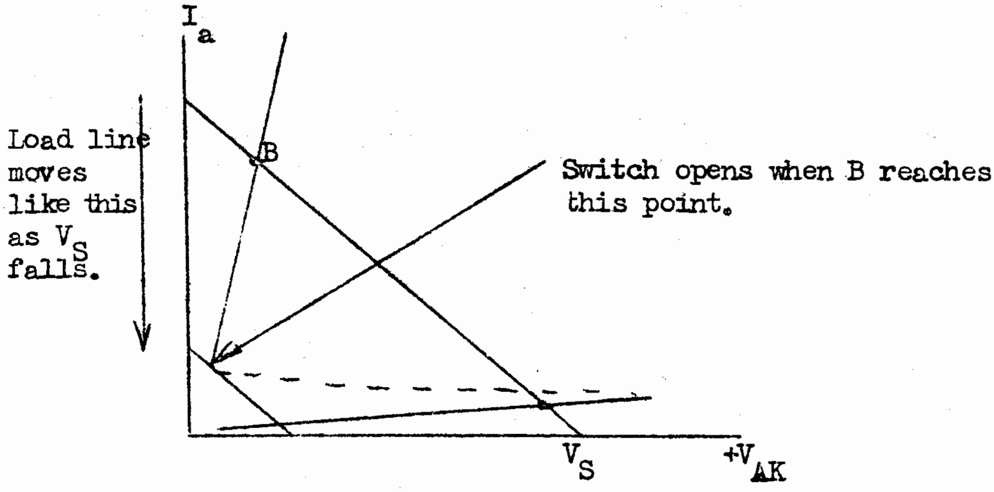

Fig. 6.

If the voltage across the S.C.R. varies sinusoidally the load line makes an excursion along the axis, in the way suggested by Fig. 6, during each positive half cycle of the suuply voltage. If the gate pulse is applied near the beginning of each conducting half cycle the load current consists approximately of a series of half sine waves. If the pulse is delayed with respect to the beginning of the positive half cycle the load current has approximately the form of the subsequent part of that half cycle. A pulse during the negative half cycle produces no load current at all. These points are illustrated in Fig. 7.

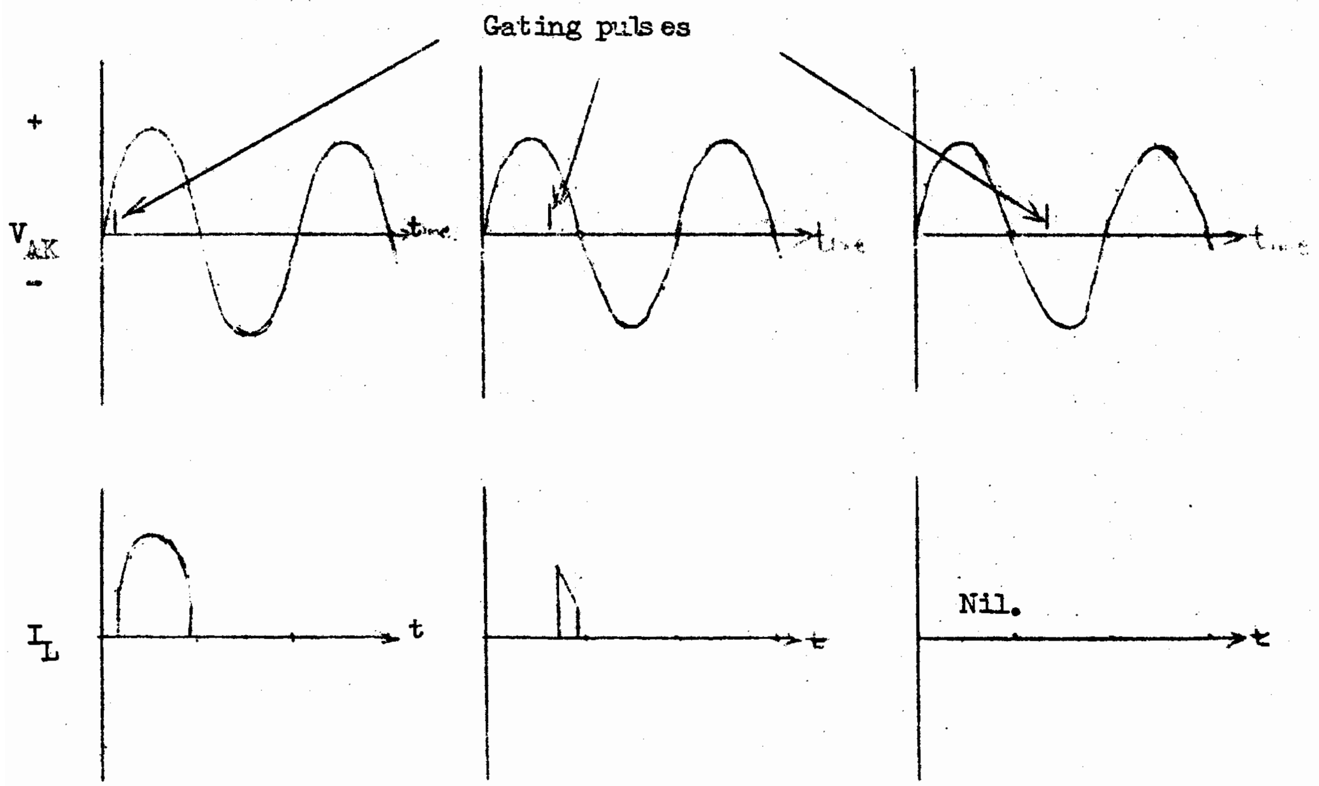

Fig. 7.

From this it is obvious that the r.m.s. value of the current through the load can be controlled by varying the timing of the gating pulses. This is the way in which the S.C.R. could be used as a lighting dimmer in T.V. studios.

Sometimes the S.C.R. is switched using a d.c. rather than a pulsed gating signal. This can be done if the supply voltage varies, as with a.c. supplies.

In this method a controlled but continuous forward bias is applied to the gate so that the breakdown voltage is reduced to some new "constant" value. If the supply voltage is sinusoidal the load line makes regular excursions along the voltage axis and closure occurs each time it moves beyond the breakdown voltage point. This method has the advantage that gating pulses are not required. It is however, infrequently used because the breakdown voltage varies considerably with temperature, and also between particular S.C.R.'s, so that the switching point is badly defined. Variation of the bias current can give some control of the power delivered to a load but this is not very satisfactory and in any case can only produce closure during the first half of each conducting half cycle, instead of at any time during this period, as when gating pulses are used.

Internal Action of the S.C.R.

The S.C.R. consists of four layers of semi-conductor material; P-N-P-N, arranged as in Fig. 8 (a). These can be thought of as consisting of two transistors, one P-N-P and one N-P-N connected together as shown in Fig. 8(b).

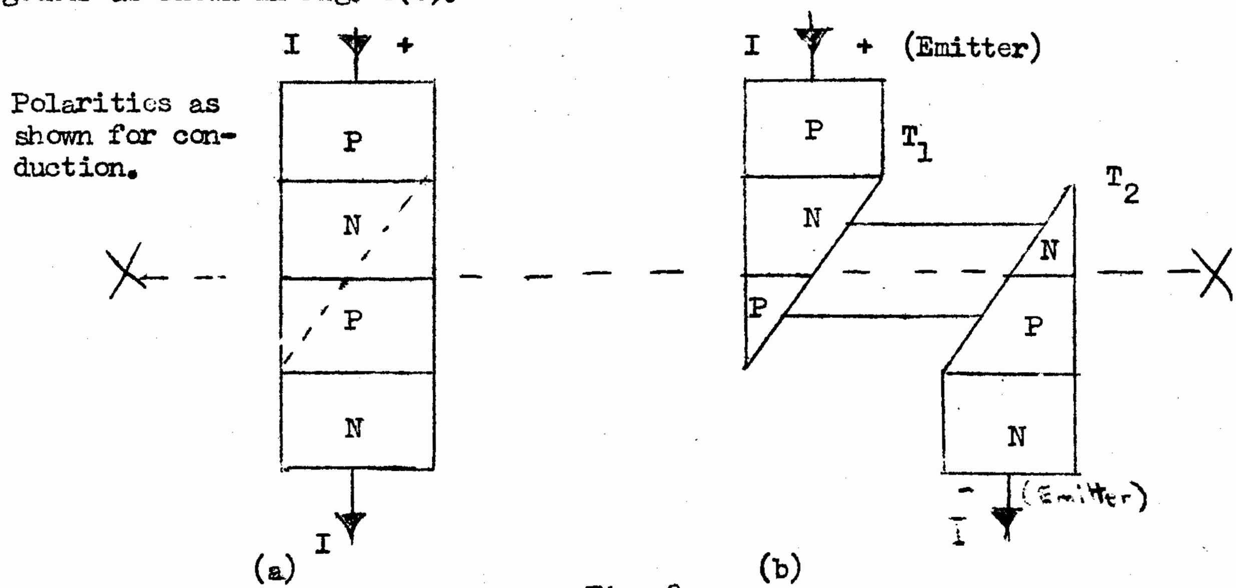

Fig. 8.

Note: The gate electrode is not marked in these diagrams.

Conduction, which in the P.N.P. transistor is by holes and in the N.P.N. transistor is by electrons, can only occur through the S.C.R. when its P end is the most positive. This means that this end is the emitter of the transistor of which it is a part and similarly that the N end of the S.C.R. is the emitter of its transistor.

Now the through current I flows in at the most positive, and out at the most negative end of the S.C.R. and must of course be equalled by that crossing the boundary XX in Fig. 8(a) and (b), Thus, in the absence of a gating current, the following equation must apply to Fig. 8(b).

I = (Current across XX of PNP transistor) +

(Current across XX of NPN transistor) +

(Any thermally produced current, I_o).

These terms can be evaluated as follows:

Consider first the PNP transistor, T_1. The emitter current is I and that across XX into the collector is $h_{FB_1} I$. This hole current crosses the lower PN junction of T_2 without modification as this is forward biased for holes.

Similarly the current into the emitter of T_2 is also I, and that crossing XX into the collector is $h_{FB_2} I$. This electron current crosses the upper NP junction of T_1 without modification as this is forward biased for electrons.

The equation therefore becomes:

$$I = h_{FB_1} I + h_{FB_2} I + I_o$$

Re-arranging gives:

$$I(1 - h_{FB_1} - h_{FB_2}) = I_o$$

$$I = \frac{I_o}{1 - (h_{FB_1} + h_{FB_2})}$$

The S.C.R. is made so that $(h_{FB_1} + h_{FB_2})$ has a value of about 0·9 when the S.C.R. is in the "off" condition. The current I is then only about ten times the thermal current I_o.

i.e. $I = \frac{I_o}{1 - 0{\cdot}9} = 10.I_o$.

(Notice how much the "off" current of the S.C.R. depends on temperature).

To put the S.C.R. into its "on" state a current gating pulse is applied as in Fig. 9.

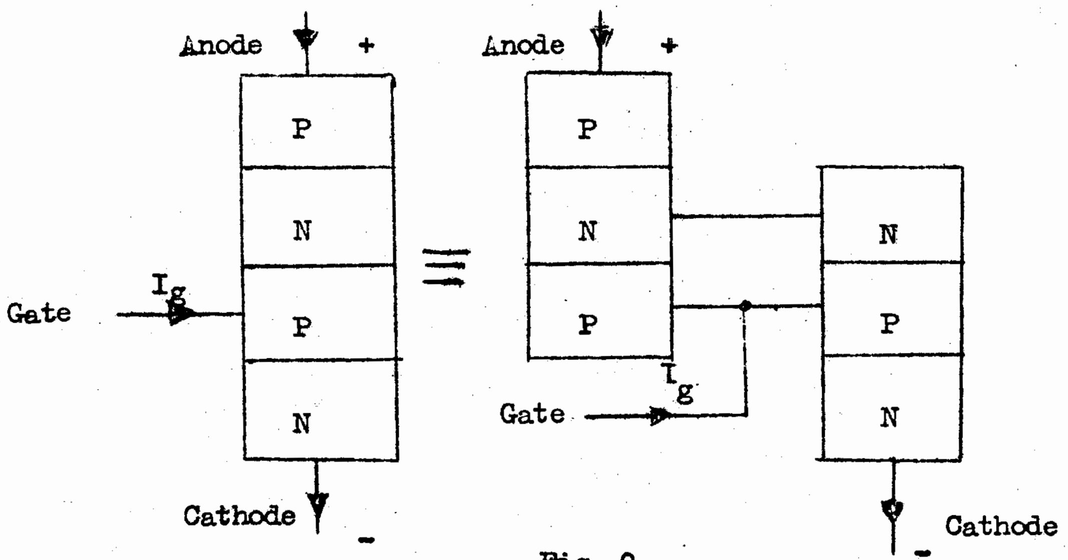

Fig. 9.

This current provides a base signal to T_2 and initiates a chain reaction by increasing the collector current of T_2 which in turn acts as a base current to T_1 to increase its collector current and so on until some new through current I is established. If this is all that happens when the gate signal is applied the switching action described will most certainly not occur. Removal of the gating signal would simply permit the through current to return to its "off" value of $10I_o$. The vital point is that the current gain of a transistor depends upon both the current through and the voltage across the transistor. When the gate signal is applied the increased current through the S.C.R. produces a corresponding increase of the values of the current gain (h_{FB}) of the transistors. If the current reaches a level which causes ($h_{FB1}+h_{FB2}$) to equal unity the through current immediately tends to infinity. i.e. the resistance of the device tends to zero. This is shown by the equation, derived earlier, which becomes

$$I = \frac{I_o}{1-1} \text{ and approaches infinity.}$$

Obviously internal resistances prevent this but the through current can certainly become very large. In fact unless the load is carefully chosen to limit the current the S.C.R. can be easily destroyed. It is this change of current gain which causes the abrupt change in the characteristics from a high to a low resistance form. Now the collector current of each transistor is the base current of the other so that once a heavy current is initiated the transistors tend to hold each other in conduction even if the gate signal is removed.

This conduction can only be interrupted if the voltage across the S.C.R. is reduced to a very low value.

Obviously the gate current and the anode-cathode voltage are complimentary to each other in this action. If the gate current increases the current gain by a certain amount, it is easier for the anode-cathode voltage to complete the job of switching. Thus the "breakdown" voltage is reduced by the gate current.

Some Examples of the Use of the S.C.R.

To replace mechanical switches.

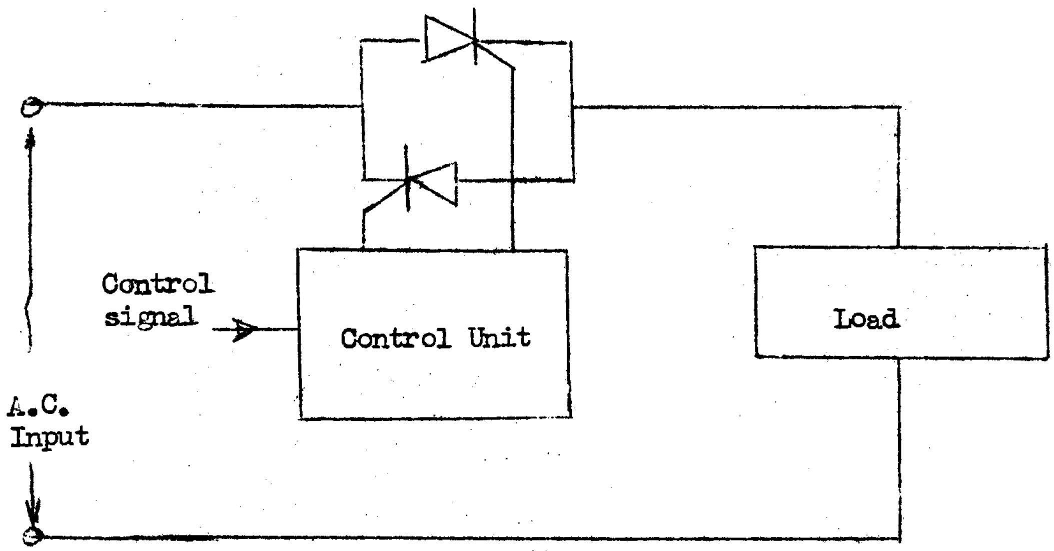

Fig. 10.

The S.C.R. can be used in place of a contactor to switch d.c. or a.c. power. This is very useful when frequent switching is necessary as no contact maintenance is required.

In Fig.10 the control unit responds to the control signal by generating pulses which turn the S.C.R.'s on to conduct for a complete cycle. Such a switch is easily operated by remote control.

The Control of Power Supplied to a Load

The circuit of Fig. 10 could be used provided that the timing of the gating pulses could be controlled. The load current waveform would then vary in the way illustrated by Fig. 7.

The Overload Protection of Transistor Power Supply Units

The difficulty with these units is that fuses and electro-magnetic switches are far too slow in their action to give protection to the transistors used, since these can be destroyed by an overload in a few micro-seconds. The fast switching action of the S.C.R. provides one way of giving such protection.

A possible arrangement to do this is shown in Fig. 11.

The load current of the p.s.u. passes through R_1 to develop a voltage across it which is applied to the gate of the S.C.R. via R_2. Under normal load conditions the resultant gate current is insufficient to close the S.C.R. An increase of the load current produces a consequential increase of the gate current towards the switching level of the S.C.R. The circuit is arranged so that closure occurs if the load current exceeds the permitted value. The voltage applied to the P.S.U. from the unregulated supply is then reduced by the loading of R_3 and R_4. The new voltage developed across R_4 is used to bias the P.S.U. transistors off. After the overload has been removed the S.C.R. is opened by pressing the reset button. This button is usually interlocked so that the P.S.U. does not go "on load" until the button returns to its normally closed state as the circuit is unprotected while the button is depressed.

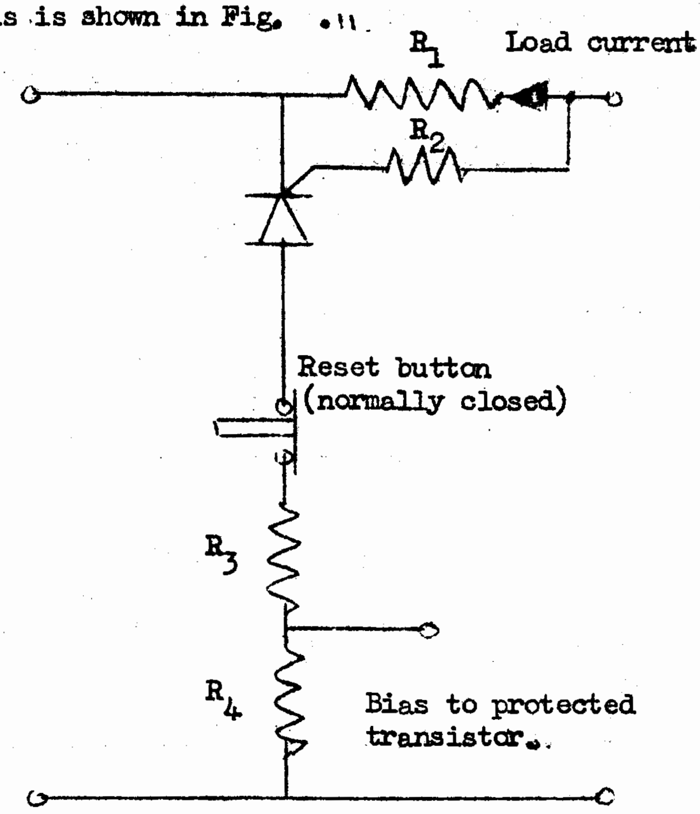

fig 11

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