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A SOLID STATE CIRCUIT BREAKER

Technological Spinoff Report

Prepared by:
E. R. Elmer

Published February 1974

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**Kansas City
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Department 863

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A SOLID STATE CIRCUIT BREAKER

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Published February 1974

Prepared by E. R. Elmer, D/863

A solid state circuit breaker was designed using the SCEPTRE circuit analysis program. The experimental circuit assembled worked satisfactorily for overloads up to 200 percent. This device would be useful in some special applications where fast operation in the microsecond range would be an advantage.

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SUMMARY

As part of a post-graduate course in electrical engineering, the concept of a solid state circuit breaker was chosen as a topic for study. The SCEPTRE circuit analysis program, with previously developed silicon controlled rectifier (SCR) models and an available diode model, was used in developing the circuit.

The method of operation selected for the breaker was to use one or more diodes between a sensing resistor and a turn-off SCR so that the drop of the diode(s) will have to be overcome before the turn-off SCR will operate. An experimental circuit breaker assembled operated satisfactorily for overloads up to 200 percent; however, additional development and testing is needed.

The disadvantages of this type of circuit breaker for practical industrial use are the number of components needed, and the necessity of putting the starting SCR on the low end of the load, with a consequent lack of protection against shorting of the load to ground. The circuit could, however, be useful in special applications where operation in the microsecond range is needed.

DISCUSSION

SCOPE AND PURPOSE

This work was performed as part of a post-graduate course in electrical engineering. The topic of a solid state circuit breaker was of particular interest because of experience modeling SCR's using SCEPTRE¹ and, also, the availability of a diode model.

PRIOR WORK

Prior to this project, the author had had some experience modeling SCR's using SCEPTRE.

ACTIVITY

Preliminary Investigation

A literature review led to a circuit in a General Electric manual,² and this was selected as the starting circuit. Consideration was given to the following ways to detect an overload and operate the turn-off SCR.

- Use an unijunction transistor that would operate when a parallel capacitor reached a certain voltage to supply gate current to the turn-off SCR.
- Use a transistor amplifier between the sensing resistor and the turn-off SCR.
- Use a very sensitive SCR between the sensing resistor and the turn-off SCR.
- Use one or more diodes between the sensing resistor and the turn-off SCR so that the drop of the diode would have to be overcome before the turn-off SCR operated.

The diode detection method was selected as being the simplest and most direct. Another criterion was that a diode model was available.

SCEPTRE Model

Figure 1 shows the circuit as modeled using SCR's and diodes previously modeled on SCEPTRE. Part descriptions are as follows:

- SCR1--The W1890 is a 35-volt silicon device in a TO-5 can. The gate of this device is desensitized with gate-cathode

R1 = 1 OHM	R10 = 1 MEGOHM	SCR1 = W1890
R2 = 40 OHMS	R28 = 2.5 OHMS	SCR2 = 2N3001
R4 = 10,000 OHMS	RL = 25 OHMS	ALL DIODES = 1N4003
		(D3 MOVED TO D3' IN LATER MODEL)
R6 = 1000 OHMS	C1 = 0.94 μ F	J21, J31 = DUMMY DIODES USED
R7 = 680 OHMS		TO MEASURE VOLTAGES

Figure 1. Schematic of Circuit Modeled

resistance diffused into the semiconductor structure. Important typical dc parameters at room ambient temperature are gate trigger current of 12 milliamperes, gate trigger voltage of 0.67 volt, holding current of 16.5 milliamperes, forward voltage drop of 0.84 volt at 1 ampere, and continuous current rating of 0.75 ampere. SCR1 controls initial current to the load RL and is turned on with a signal at the gate (ESS voltage).

- SCR2--The 2N3001 is a 50-volt sensitive silicon device in a TO-18 can. Important typical dc parameters at room ambient temperature are switching time of 0.5 microsecond, gate trigger current of 1 microampere, gate trigger voltage of 0.6 volt, holding current of 5 milliamperes (with a 40 ohm gate-cathode resistor), and forward voltage drop of 1 volt at 350 milliamperes. SCR2 is the "off" switch and serves to initiate the discharge of C1 in a reverse direction into SCR1. Action is initiated by applying a signal at the gate (ESP voltage), or by automatic circuit action from an overload through R1 which develops a triggering voltage.
- D1, D3, D4, D5, D6--The 1N4003 is a general purpose silicon diode in a DO41 case. Rated dc parameters are 200-volt peak inverse, 1-ampere maximum forward current, and forward voltage drop of 1.6 volts at 1 ampere. D1 and D6 serve to introduce voltage drops into the gate of SCR2 which must be overcome before SCR2 operates. D4 and D5 are gate isolating diodes and are used mainly to facilitate the SCEPTRE model which grounds the gate nodes (ESS and ESP) when no voltage is applied. D3 bypasses the load to negative currents, and was found to be unnecessary to the circuit operation.
- R1--This resistor senses an overload condition in the form of a voltage drop that is passed along to SCR2. The resistor should be noninductive and low in value to minimize the power lost. Its value should be calculated to give a triggering voltage at the desired overload current.
- RL--This resistor simulates a load for the circuit.
- R2--This resistor stabilizes the gate of SCR2 so that it is voltage operated.
- R4--This resistor charges C1 when SCR2 is off and determines the final current that could be supplied to SCR2 when it is on. The resistance should be such that this current is less than the holding current of SCR2 to permit turn-off after SCR2 discharges C1.
- R6, R7--These resistors limit the gate current to the SCR's and are not critical. The values should assure enough gate

current to fire the SCR's. In addition, R6 acts as a voltage divider with R2, so that the value of R6 should assure a minimum firing voltage at R2 when voltage is applied to ESP.

- R10--This high resistance has no circuit function but is necessary in the SCEPTRE program when two diodes are used in series.
- R28--This resistor limits the current from C1 and determines the C1-R28 time constant. It is important that the time constant be short so that an overload is stopped quickly. The resistor should be non-inductive to reduce current lag.
- C1--This capacitor should be a type with a good surge current rating and relatively non-inductive. If R28 is 1 ohm, the current may be in the order of 10 amperes for a short period. The capacitance should be large enough so that the coulomb charge stored is enough to overcome and reverse the current in SCR1.
- J21, J31--These are dummy current sources (current equals zero) used with the SCEPTRE program as a stratagem to read voltage at the points where they are located.

Figures 2, 3, and 4 show the SCEPTRE models of the SCR1, SCR2, and the 1N4003 diode respectively. Figures 5, 6, and 7 show the SCEPTRE program of the circuit with Figure 5 listing the control information, Figure 6 listing the model descriptions, and Figure 7 listing the circuit description with inputs and outputs, and the closing control information. It should be noted that values in the program are given in volts, milliamperes, kilohms, and picofarads.

Model Circuit Runs

Figures 8, 9, and 10 and Table 1 detail the results of the model circuit run with SCR1 on initially and a stopping voltage applied to SCR2. Figures 8 and 9 are graphs of the resulting currents and voltages; Figure 10 shows the circuit with variables data added for the period just after the starting voltage is removed; Table 1 gives variables data for other times of Figures 8 and 9. It was found necessary to add a diode from ground to point (2) in order to clamp the point near ground; otherwise, the point went to an abnormally high negative voltage. At the end of twenty microseconds, SCR2 is still on and the current through it and C1 is being supplied by the current in the load. Thus the time constant of the discharging capacitor has been increased by the load resistance.

Text continued on page 20.

Figure 2. SCEPTRE Model of SCR1 (W1890)

Figure 3. SCEPTRE Model of SCR2 (2N3001)

Figure 4. SCEPTRE Model of Diode (1N4003)

```

EE863-0863-07528-31-04061000. FLMR CIRC BKR MODEL. CM104000, T400.
ATTACH(TAPE10-LIBMOD)
ATTACH(SCEPTR-SCEPTR1)
SCEPTR.
REWIND-TAPE8.
REL.70000.
NOREDUCE.
EUN(S...TAPE8-NULI.)
REWIND-TAPE8.
SKIP(TAPE8.1.17.C)
ATTACH(SCEPTR2-SCEPTR2)
REL.135000.
LOAD.SCEPTR2.
LOAD.LGO.
EXECUTE.
000000020000001000000000

```

Figure 5. SCEPTRE Program Control Information


```

MODEL DESCRIPTION
MODEL 2N2906 (TEMP)(B-E-C)
ELEMENTS
R1, E-R = 1. E3
R2, R-2 = 1. E3
RC, C-2 = 114. E-6
JE, E-R = DIODE 0 (.244E-6, 38.9)
JN, R-2 = TABLE 2(JE)*JE
JC, C-2 = DIODE 0 (.17E-4, 35.8)
JI, E-F = TABLE 1(JC)*JC
CED, E-R = QD(900., 7., VCE0)
CCD, C-2 = QE(900., 7., VCC0)
FUNCTIONS
QD(A,R,C) = (AMAX1(A*(EXP(SIGN(AMIN1(ABS(R*C),4.),C))-1.),100.))
QE(A,R,C) = (AMAX1(A*(EXP(SIGN(AMIN1(ABS(R*C),20.),C))-1.),20.))
TABLE 1
0.0, .1.0, 1..6, 10..6, 11..97, 1.E5..97
TABLE 2
0.0, 5.0, 6..5, 1.E5..5
MODEL 2N2222 (TEMP)(B-E-C)
ELEMENTS
R1, E-F = 1. E3
R2, C-1 = 1. E3
RB, B-1 = .001
RC, C-2 = 570. E-6
CED, E-F = QD(1300..10., VCE0, 2.5)
CCD, C-2 = 20
JE, E-F = DIODE 0 (.284E-07, 40)
JN, C-1 = TABLE 2(JE)*JE
JC, C-2 = DIODE 0 (2.013E-6, 35.2)
JI, E-1 = TABLE 1(JC)*JC
FUNCTIONS
QD(A,R,C,D) = (AMAX1(A*(EXP(SIGN(AMIN1(ABS(R*C),D),C))-1.),100.))
TABLE 1
0.0, .1.0, .5..333, 1.E5..333
TABLE 2
0.0, .4.0, .5..97, 1.E5..97
MODEL 2N5154 (TEMP)(B-E-C)
ELEMENTS
R1, E-E = .100
R2, C-1 = 1.0E3
RB, B-1 = 500. E-6
RC, C-2 = 80. E-6
CED, E-E = QD(650., 7., VCE0)
CCD, C-2 = QE(4.284E-5, 35.8, VCC0)
JE, E-E = DIODE 0 (.3E-6, 38.9)
JN, C-1 = TABLE 2(JE)*JE
JC, C-2 = DIODE 0 (.17E-4, 35.8)
JI, E-1 = TABLE 1(JC)*JC
FUNCTIONS
QD(A,R,C) = (AMAX1(A*(EXP(SIGN(AMIN1(ABS(R*C),4.),C))-1.),100.))
QE(A,R,C) = (AMAX1(A*(EXP(SIGN(AMIN1(ABS(R*C),20.),C))-1.),20.))
TABLE 1
0.0, .1.0, 1..6, 10..6, 11..97, 1.E5..97
TABLE 2
0.0, 5.0, 6..333, 11..333, 16..97, 1.E5..97
MODEL 1N4003 (TEMP)(A-K)
ELEMENTS
RB, A-1 = .5 E-3
RC, A-K = 1. E3
CD, A-K = 230.
JD, A-K = DIODE EQUATION (.42 E-5, 22.)

```

Figure 6. SCEPTRE Program Model Descriptions

```

CIRCUIT DESCRIPTION
ELEMENTS
T1. 9-7-16 = MODEL 2N5154 (TEMP)
T2. 16-2-8 = MODEL 2N2906 (TEMP)
T3. 5-11-15 = MODEL 2N2222 (TEMP)
T4. 15-3-5 = MODEL 2N2906 (TEMP)
D1. 7-14 = MODEL 1N4003 (TEMP)
D3. 11-2 = MODEL 1N4003 (TEMP)
D4. 12-13 = MODEL 1N4003 (TEMP)
D5. 10-9 = MODEL 1N4003 (TEMP)
D6. 14-5 = MODEL 1N4003 (TEMP)
J21. 2-11 = 0
J31. 3-11 = 0
R1. 7-11 = .001
R2. 5-11 = .04
R4. 1-3 = 10
R6. 13-5 = 1
R7. 9-8 = .68
R10. 14-11 = 1.F3
R28. 4-3 = .0025
RL. 1-2 = .025
C1. 2-4 = .94 E6
FDC. 11-1 = TABLE 1
ESS. 11-10 = TABLE 2
FSP. 11-12 = TABLE 3
FUNCTIONS
TABLE 1
0.35. 100000.35
TABLE 2
0.35. 10.35. 20.0.100000.0
TABLE 3
0.0. 100.0. 110.35. 1000.35. 1010.0. 100000.0
OUTPUTS
FDC. ESS. FSP. VJ21. VJ31. PIOT A
IRL. IR1. IR28. IRBD3. PIOT B
VR1. VR2. VJET1. VJCT1. VJET2. VJCT2
IRRT1. IPCT1. IRRT3. IRCT3
CEDT1. CCDT1. CEDT2. CCDT2
INITIAL CONDITIONS
VJET1 = .6. VJCT1 = .6. VJET2 = .6. VJCT2 = .6. VJDD5 = .6.
VJDD1 = .6. VJDD6 = .6
RUN CONTROLS
N-P PASS LIMIT = 4000
RELATIVE CONVERGENCE = 1.
ABSOLUTE CONVERGENCE = .1
MINIMUM ABSOLUTE ERROR = .01
MAXIMUM PRINT POINTS = 112
STOP TIME = 100000
COMPUTER TIME LIMIT = 20
RUN INITIAL CONDITIONS
MAX INTEGRATION PASSES = 500000
INTEGRATION ROUTINE=IMPLICIT
MINIMUM STEP SIZE = 1.E-30
NO OVERFLOW PRINTOUTS
END
00000000000000000000000000000000
R
&DBEND
00000000000000000000000000000000

```

Figure 7. SCEPTRE Program Circuit Description

Figure 8. Voltages Versus Time With SCR1 On With ESS Starting Pulse at Zero Time and With ESP Stopping Pulse Applied at 100 Nanoseconds

Figure 9. Currents Versus Time With SCR1 On With ESS Starting Pulse at Zero Time and With ESP Stopping Pulse Applied at 100 Nanoseconds

R1 = 1 OHM	R10 = 1 MEGOHM	SCR1 = W1890
R2 = 40 OHMS	R28 = 2.5 OHMS	SCR2 = 2N3001
R4 = 10,000 OHMS	RL = 25 OHMS	ALL DIODES = 1N4003
		(D3 MOVED TO D3' IN LATER MODEL)
R6 = 1000 OHMS	C1 = 0.94 μ F	J21, J31 = DUMMY DIODES USED
		TO MEASURE VOLTAGES
R7 = 680 OHMS		

Figure 10. Circuit Operation Following ESS Pulse With SCR1 On and SCR2 Off

Table 1. Data Obtained With SCR1 On Initially and Stopping Pulse ESP Applied From 110 to 1000 Nanoseconds

Variable	Time (Nanoseconds)				
	96	346	356	19065	100668
EDC (Volts)	35	35	35	35	35
ESS (Volts)	0	0	0	0	0
ESP (Volts)	0	35	35	0	0
VJ21 (Volts)	2.1	1.8	-4.4	12.9	34.0
VJ31 (Volts)	34.3	33.4	4.4	1.0	0.64
VR1 (Volts)	1.3	1.1	-1.5	≈0	≈0
VR2 (Volts)	0.11	0.62	3.9	0.86	0.52
IRL (Amperes)	1.32	1.33	1.57	0.88	0.04
IR1 (Amperes)	1.31	1.1	-1.52	≈0	≈0
IR28 (Amperes)	≈0	0.26	9.34	0.88	0.04
ID3 (Amperes)	≈0	0.01	6.81	≈0	≈0

Notes:

1. At 96 nanoseconds, SCR1 on from ESS pulse.
2. At 346 nanoseconds, SCR2 starting on from ESP pulse.
3. At 356 nanoseconds, SCR2 current at maximum.
4. At 19065 nanoseconds, SCR1 off, SCR2 still on, load current decreasing.
5. At 100668 nanoseconds, SCR1 off, SCR2 still on, load current still decreasing.

Figures 11 and 12 and Table 2 detail the results of the model circuit run with SCR1 on initially and with a simulated short in the load resistance. Figures 11 and 12 are graphs of the resulting currents and voltages; Table 2 gives variables data for some time points of Figures 11 and 12. It will be noted that SCR2 goes on after the short is introduced but a negative current is not developed in SCR1, so that the short circuit current is not interrupted. A considerable part of the load short circuit is shunted through the gate of SCR2 via the dropping diodes.

Considerable time was spent with the model before it could be made to run at all. One of the major difficulties concerned the large amount of core space necessary to run the program, involving delays waiting for enough computer time to become available.

Experimental Circuit

A circuit similar to the model was built up using the parts listed in Table 3. Figure 13 is a photograph of the experimental circuit.

Experimental Circuit Test Results

DC Operation

With momentary push-buttons in the starting and stopping gates, and with a variable voltage supply, operation was attempted with different values of C1 and R28. When SCR1 was turned on and the voltage supply was increased until SCR2 fired, VR1 read 2.1 volts and VR2 read 0.68 volts at the firing point. Thus firing occurred with 2.1 amperes in R1. With C1 = 0.3 microfarads, SCR2 would not turn off. With C1 = 1 microfarad or greater, turn-off was successful. Reference 2 recommends a C1 equal to 0.4 times the tripping current with this value to be in microfarads. Thus in this circuit, C1 should be 0.4 times 2.1 or 0.84 microfarads or larger. A C1 of 0.94 microfarad was used in the final circuit.

One circuit anomaly was noted during the testing. If SCR1 is started with the voltage high enough to give a trip current, then SCR1 and SCR2 fire simultaneously before C1 charges. Then both SCR's stay on. Thus, the device is deficient when turned on into an overload. This might be rectified by delaying the pulse reaching SCR2 in order to give time for C1 to charge.

With the circuit operating, a sudden increase in load current was simulated by adding a 10 ohm resistor in parallel with the load. (R1 changed from 13.3 ohms to 5.7 ohms.) The circuit operated successfully.

Text continued on page 25.

Figure 11. Voltages Versus Time With SCR1 On With ESS Starting Pulse at Zero Time and With RL Changed From 25 Ohms to 1 Ohm at 100 Nanoseconds

Figure 12. Currents Versus Time With SCR1 On With ESS Starting Pulse at Zero Time and RL Changed From 25 Ohms to 1 Ohm at 100 Nanoseconds

Table 2. Data Obtained With SCR1 On Initially and RL Changed From 25 Ohms to 1 Ohm at 100 Nanoseconds

Variable	Time (Nanoseconds)			
	95	100.8	10359	19959
EDC (Volts)	35	35	35	35
ESS (Volts)	0	0	0	0
ESP (Volts)	0	0	0	0
VJ21 (Volts)	2.1	15.5	14.8	14.9
VJ31 (Volts)	34.3	47.7	3.2	3.1
VR1 (Volts)	1.3	13.4	12.7	12.8
VR2 (Volts)	0.11	5.9	3.6	3.6
IRL (Amperes)	1.32	19.5	20.2	20.1
IR1 (Amperes)	13	13.4	12.7	12.8
IR28 (Amperes)	~0	0.03	0.4	0.02
ID3 (Amperes)	~0	-0.34	~0	~0

Notes:

1. At 95 nanoseconds, SCR1 on from ESS pulse.
2. At 100.8 nanoseconds, VR2 maximum.
3. At 10359 nanoseconds, both SCR's on.
4. At 19959 nanoseconds, both SCR's still on.

Table 3. Experimental Circuit Parts List

Component	Specifications	Other Requirements	Manufacturers Part
SCR1	35 V, 0.75 A	Medium Power, TO-5 Can	Texas Instruments W1890
SCR2	50 V, 0.35 A	Low Power, Sensitive, TO-18 Can	Unitrode 2N3001
D1, D3, D4, D5, D6	80 V	Zener, Used in Forward Direction	Unitrode UZ 5880
R1	1 $\pm 1\Omega$, 5 W	Wirewound, Non-Inductive	Dale Type NS-5
R2	40 Ω ± 1 percent, 3 W	Wirewound	Dale Type RS-2B
R4	10000 Ω ± 1 percent, 2 W	Wirewound	Dale Type RS-2A
R6	1000 Ω ± 1 percent, 3 W	Wirewound	Dale Type RS-2B
R7	680 Ω ± 1 percent, 1/8 W	Metal Film	Dale Type MF 1/8
R28	2.5 Ω ± 1 percent, 1 W	Wirewound, Non-Inductive	Dale Type NS-1A
RL	40 Ω ± 1 percent, 50 W	Wirewound	Dale Type RH-50-22* /
C1	0.47 μ F ± 10 percent	Dipped Mylar	Cornell-Dubilier Type 1P47**
Pushbutton Switches (2)	SPST	Normally Open	Burstein-Appleby Stock 19A7210
Perforated Insulating Board	6 x 6 In. (15 x 15 cm)		
Board Terminals			Vector Type T9-4
Binding Posts			H. H. Smith No. 386
<p>*Three used in parallel. **Two used in parallel.</p>

Figure 13. Experimental Circuit

Transient Operation

Attempts were made to operate the circuit with two pulse generators, one for the start and one for the stop. However, in the framework of the time and equipment available, operation was not successful in that the two pulse generators, the oscilloscope, and the camera could not be synchronized to get a picture. Finally, only one pulse generator was used and applied to SCR2 as a stopping pulse. SCR1 was gated on all the time. The sequence was that SCR1 was on until SCR2 received its gate pulse. When the SCR2 gate pulse was received, SCR1 immediately turned off, but returned to the "on" condition when the anode voltage was high enough to supply the holding current. Figure 14 is a drawing of one of the oscilloscope displays illustrating this operation. The oscilloscope sweep was made to trigger on ESP. VJ21 rises exponentially after turn-off, showing the load current discharging through C1. It will be noted that VJ21 goes slightly negative in the first few microseconds of the off pulse. This figure illustrates the fast turn-on and turn-off of the

Figure 14. Oscilloscope Trace of Experimental Circuit Transient Operation

SCR's. The power supply used in this experiment was a constant current device set at 0.5 ampere. The off-current voltage of 30 dropped to approximately 10 under load.

Comparison of Model and Experimental Circuits

Table 4 compares some model and circuit values.

The model had trouble with the VJ21 point going negative at turn-off. The addition of the diode D3 helped to clamp this point and provided a parallel path for reverse current. In the actual circuit, the VJ21 point went negative about the same amount as it was positive.

The circuit worked successfully when the load was reduced by 50 percent. The model, when short-circuited by a reduction of the load by 96 percent, did not work successfully because both SCR's turned on. The circuit was not tried with a short circuit, nor was the model tried with a 50 percent reduction in load.

Table 4. Comparison of Model and Circuit Values

Parameter	Value (Volts)	
	Model	Circuit
Forward Voltage Drop of SCR1 (IRL $\approx$ 1.3A)	0.8	0.9
Gate Firing Voltage SCR2	0.62	0.68
Voltage Drop of Diodes D1 and D6 in Series	1.2	1.4
Negative Swing of VJ21 at Turn-Off	-4.4 (IRL = 1.3A)	-1.0 (IRL = 0.5A)

ACCOMPLISHMENTS

A solid state circuit breaker was modeled using the SCEPTRE program. The circuit assembled worked satisfactorily for overloads up to 200 percent (limit of testing). The disadvantages for practical industrial use are the number of components needed, with the attendant costs, and the necessity of placing the starting SCR on the low end of the load with a consequent lack of protection against shorting of the load to ground. The circuit might be useful for special applications where fast operation in the microsecond range would be an advantage.

FUTURE WORK

Only basic tests were run on the circuit, and additional testing might be conducted under various loads and overloads to study the circuit characteristics more fully. Also, additional work might be done with the model to study its short- and long-time characteristics and to adjust its internal parameters to simulate more closely the actual operation.

REFERENCES

¹James C. Bowers and Stephen R. Sedore, *SCEPTRE: A Computer Program for Circuit and Systems Analysis*. Prentice-Hall, 1971.

²*SCR Manual, Including Triacs and Other Thyristors*. Fifth Edition. General Electric, 1972.