Better Utilization of SCR Capability with AC Inductive Load

AN ARTICLE BY
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BETTER UTILIZATION OF SCR CAPABILITY WITH A-C INDUCTIVE LOADS

Designing a small amount of inductive reactance into your load will substantially increase the average-current-handling capability of an SCR at large retard angles, i.e., short conduction time. Some examples are cited.

Today, average-current capability of an SCR is given by one rating to be applied to all power-factor loads from zero (pure reactive) to unity (resistive). Of necessity, this rating must be for the one power factor placing the greatest strain on the SCR; the most strenuous case is that of unity power factor or that of a purely resistive load. For any lagging power factor, this rating is conservative and as such the specification-sheet rating curves can be labeled "for resistive and inductive load".

AVERAGE-CURRENT RATINGS

Fig. 1 shows inverse parallel SCR's controlling a resistive load. Also shown are the associated current and voltage waveforms. The average current through either SCR is the average of that portion of the load-current waveform either above or below zero. It is on this waveform of current that the SCR rating is based.

Fig. 2 shows such a rating. This is a curve of the average current versus maximum case temperature for a 235-amp (rms), C180-type SCR. Note that for different retard angles (nonconducting portion of the cycle) the maximum-allowable average current differs. This is due to the form factor (rms/avg) changing with retard angle. **Fig. 3** shows how form factor changes with retard angle for a resistive load. Let's coordinate **Figs. 2 and 3**. Note from **Fig. 3** that at 0-deg retard angle (full-cycle conduction) the form factor is 1.57. In order to maintain the maximum rated 235 amps (rms), the average current must be limited to 150 amps average (235/1.57 = 150). At 150-deg retard angle, the form factor is

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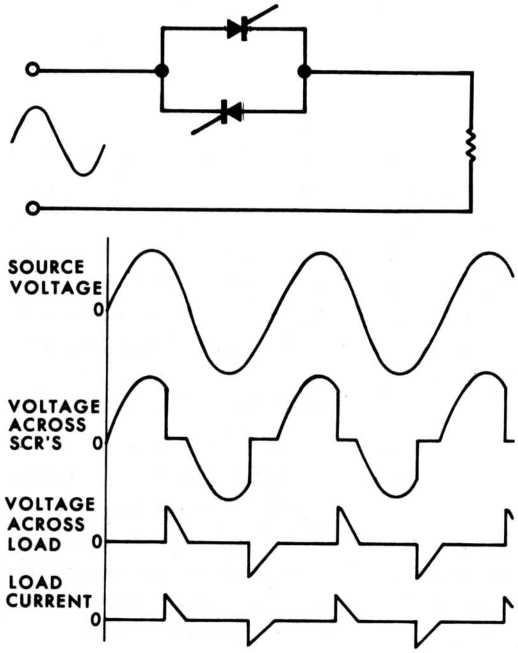

Fig. 1 — Full-wave phase control of resistive load.

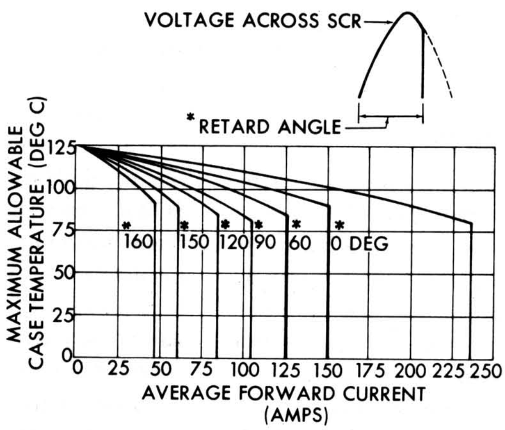

Fig. 2 — Average forward current versus case temperature for Type C180 SCR.

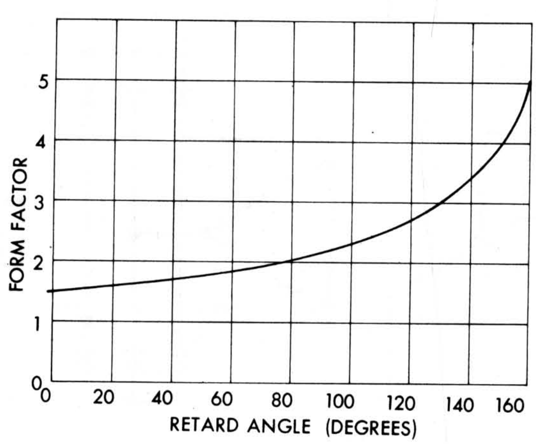

Fig. 3 — Form factor versus retard angle for phase-controlled resistive load.

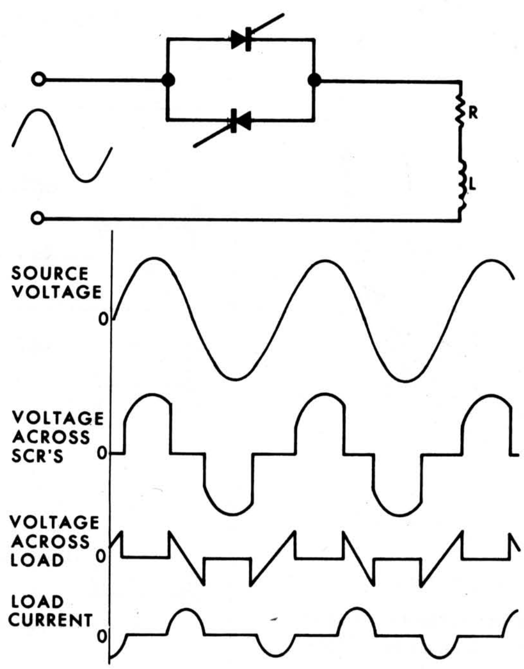

Fig. 4 — Full-wave phase control of inductive load.

SCR Loads (Cont'd)

approximately 4, thus dictating a maximum average current of approximately 60 amps.

What a Little Inductance Can Do

If the load is slightly inductive, as in **Fig. 4**, the waveforms change as shown. Note that the current waveform has been "softened" considerably. As expected, this softening improves (lowers) the form factor because the peak of the current waveform is reduced and its duration extended. **Fig. 5** shows the variation of form factor with retard angle for loads of different lagging power factor. Note the significant improvement in form factor at large retard angles with a slightly inductive load. At a retard angle of 150 deg, a 25-percent reduction (improvement) in form factor is realized by changing the load power factor from unity to 0.9 inductive; better than 15-percent reduction in form factor is realized from a 0.98 power-factor load. Form factor decreases even more for power factors less than 0.9. This improvement in average-current capability at large retard angles can be quite significant. This is particularly true when using high-current SCR's, where 10, 20 or 40 amps of additional capability can be a substantial economic factor. With the introduction of high-voltage (1000v to 1300v) SCR's, this additional current capability represents a substantial amount of additional kva handling capability.

Now the clincher! The unity-power-factor load is rarely found in practical equipment. Note, again, that we show a form-factor curve for a lagging power factor of 0.98 in **Fig. 5**.

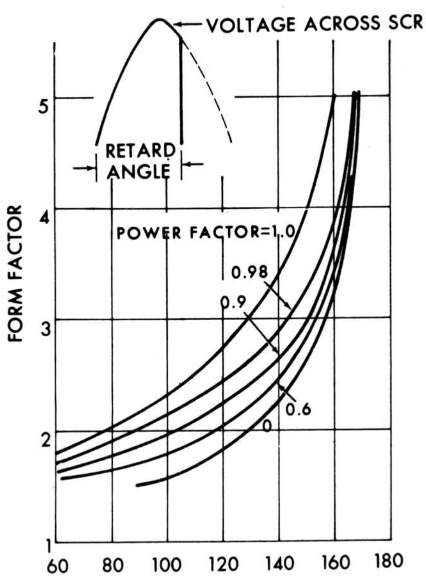

Fig 5—Form factor versus retard angle for phase-controlled loads of different power factors.

EXAMPLE—10,000-AMP POWER SUPPLY

Fig. 6 depicts a very-high-current, low-voltage power supply feeding a resistive load. It is required to supply 10,000 amps with the output voltage variable from 2 to 20v d-c. It has been decided to locate the control in the primary of a wye-delta transformer, operating from a 480v rms line-to-line, 3-phase source. Primary control has been chosen in order to preclude paralleling of SCR's and to make full use of the inherent high-voltage capabilities of today's industrial SCR's. It is assumed that the input voltage can vary ±10 percent.

Transformer Turns Ratio

The transformer turns ratio must be sufficiently high so as to provide 20v d-c output at minus 10-percent input voltage with the primary SCR's in full conduction. (The ideal transformer model is assumed.)

Input voltage (low line-to-line) = 0.9 × 480 = 432v rms

Primary voltage (low line-to-neutral) = 432 ÷ $\sqrt{3}$ = 249v rms

Secondary-voltage requirement = 14.8v rms

(Secondary line-to-line voltage is equal to d-c output voltage × (0.74) for a 3-phase bridge.)

Required turns ratio $= \frac{249}{14.8} = 16.8 : 1$

Turns ratio chosen = 16 : 1

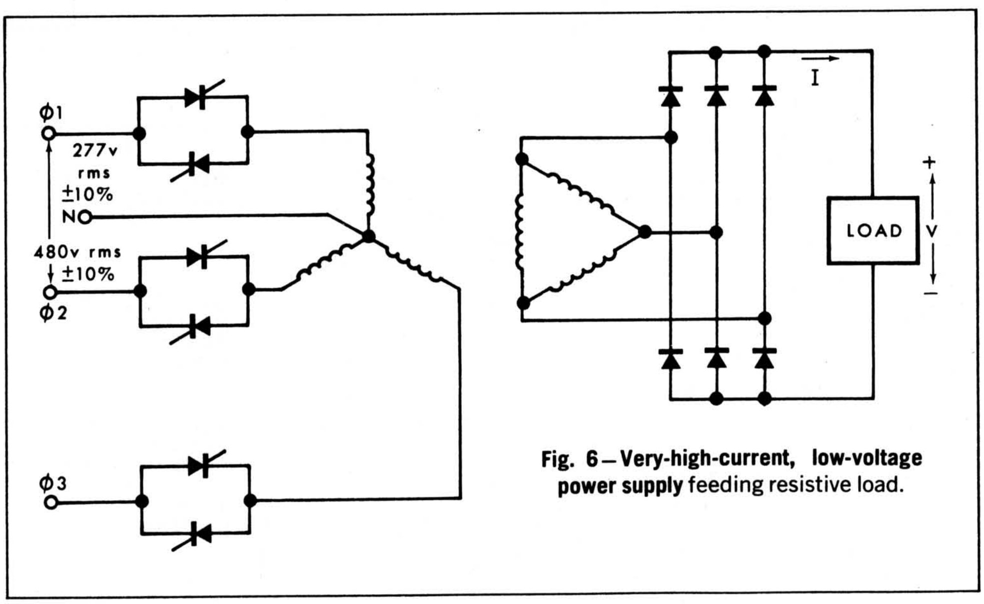

Fig. 6—Very-high-current, low-voltage power supply feeding resistive load.

SCR Loads (Cont'd)

Minimum Required Retard Angle

With a turns ratio of 16:1, the primary line-to-neutral voltage must be 237v rms in order to provide a secondary voltage of 14.8v.

$$\frac{\text{maximum pri (L-N) voltage required}}{\text{minimum pri (L-N) voltage available}} = \frac{237}{249} = 0.95$$

Fig. 7 shows the variation of the rms value of a phase-controlled voltage waveform as a function of retard angle. Checking the 95-percent point, we see that the minimum retard angle will be approximately 40 deg.

Maximum Required Retard Angle

For 2v d-c out of the full-wave bridge, the transformer secondary voltage must be 1.48v rms (again 2 × 0.74). The primary line-to-neutral voltage, at plus 10 percent of nominal line voltage, would be 305v rms if the SCR's were full ON. In order to supply 1.48v rms at the secondary, the SCR's must be phased back so that on the primary side, line-to-neutral voltage is: 1.48 × 16 = 23.7v rms.

$$\frac{\text{minimum pri (L-N) voltage required}}{\text{maximum pri (L-N) voltage available}} = \frac{23.7}{305} = 0.078$$

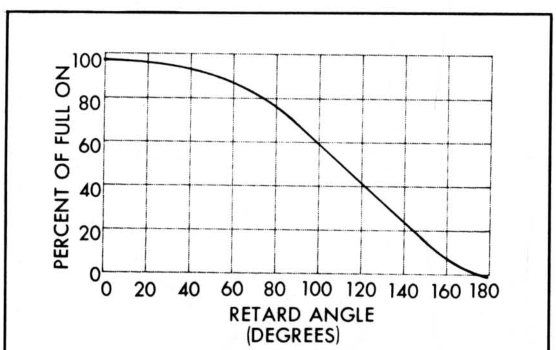

Fig. 7 – RMS voltage versus retard angle as percent of full ON.

By locating the 7.8-percent point on **Fig. 7**, we find that the maximum retard angle is 160 deg.

Primary Line Current

Using the following relationships for a full-wave bridge operating from a delta secondary:

Secondary line current
= 0.816 × d-c output current
Secondary leg current × $\sqrt{3}$
= secondary line current

we have:

$I_{d\text{-}c}$ = 10,000 amps
Secondary line current = (10,000)(0.816)
= 8160 amps (rms)
Secondary leg current = (8160) ÷ $\sqrt{3}$
= 4717 amps (rms)
Primary leg or line current = 4717 ÷ 16
= 295 amps (rms)
Current per SCR = 295 ÷ $\sqrt{2}$ = 209 amps (rms)

LET'S LOOK AT ONE PHASE

Now we know the rms current for the SCR's. For analysis each phase can be examined separately as depicted in **Fig. 8**. We will look again at the case of maximum retard angle. Computing the effective load resistance of **Fig. 8** we have

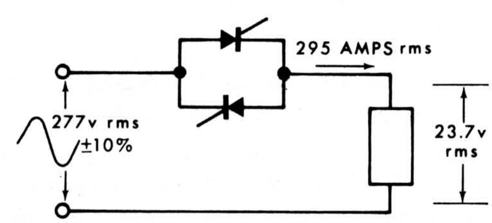

Fig. 8 – Single-phase equivalent of one phase of power supply.

$$R_{eff} = 23.7 \div 295 = 0.08 \text{ ohm}$$

We have shown the load as purely resistive, but in fact we know that this is not so. The very existence of the rectifier transformer and its associated leakage reactance precludes this. Let's look at what a little series inductance will do to the power factor of the load seen by the SCR's. For 0.08-ohm resistance we need add only 100 μh to provide the SCR's with a 0.9 power factor load (at 60 cps, that is); only 40 μh are needed for a 0.98 power factor. Could the rectifier transformer supply this much leakage reactance? Let's see.

(Continued)

SCR Loads (Cont'd)

Estimate of Transformer Leakage Inductance

Assume the use of three each, 85-kva single-phase transformers with 5-percent reactance.

$$\frac{(\text{rated voltage})^2}{\text{rated kva}} = \frac{(277)^2}{8.5 \times 10^4} = 0.9 \text{ ohm}$$

At 5-percent reactance we have:

$(0.05)(0.9) = 0.045$ ohm (inductive reactance)

$0.045 \text{ ohms} = L/\omega$

where: $\omega = 377$ radians/sec at 60 cps

$$L = \frac{0.045}{377} = 119\ \mu\text{h}$$

It is seen that the leakage reactance of our assumed rectifier transformer is enough to show the SCR's a load power factor *less* than 0.9 lagging. In addition, 5-percent reactance is on the low side of that which is generally found in a typical rectifier transformer. Typically, leakage reactance runs from 5 to 8 percent.

SPEC-SHEET BASED ON RESISTIVE LOADS

With SCR's operating into a 0.9 power-factor load, we know from **Fig. 5** that the current form factor at 160-deg retard angle is 3.65. Knowing that the current per SCR is 208 amps rms, we immediately have the average current ($208 \div 3.65 = 57$ amps).

Note that we have worked backward in this example to find the average current per SCR. If an average current of 57 amps at a retard angle of 160 deg had been specified for the application, the C180-type SCR could not be considered if the resistive-load ratings of **Fig. 2** were used. Worse yet, had the SCR been chosen on the basis of 208 amps rms (C180 type) and then the average current measured and found to be 57 amps, according to **Fig. 2** the SCR is being operated out of spec at 160-deg retard angle.

Finally, since the form factor improves with an increasingly lagging power factor for a given retard angle, the average power dissipation for a given average current is less than that shown for a resistive load. The power-dissipation-versus-average-forward-current for the C180-type SCR is shown in **Fig. 9**. This, like **Fig. 2**, is for a resistive load.

HOW TO UTILIZE THE CURVES

Now you might say, "This is all fine, but I'm still saddled with the same old rating curves." This is true, but there's a suggestion on how to use these curves when the load is somewhat inductive. The procedure for determining the approximate amount of increase is as follows:

A. Average Current Versus Case Temperature

1. Locate curve on spec sheet for retard angle in question.
2. Determine new maximum average current from relationship.

$$I_{avg(max)} = \frac{I_{rms(max)}}{F_{PF,\alpha}}$$

where:

$I_{rms(max)}$ = Maximum-rms-current rating of SCR (from spec sheet)

$F_{PF,\alpha}$ = Form factor at given lagging power factor (PF) and retard angle (α)

3. Draw maximum-average-current cutoff line as shown in **Fig. 10**.
4. Plot remainder of curve by determining distance X:

$$X(°\text{C}) = \left(\frac{F_{PF,\alpha}}{F_{1.0,\alpha}}\right)(T_{c(max)} - T_{c(ss)})$$

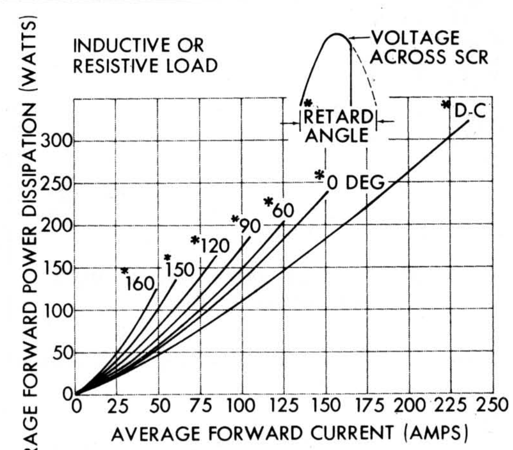

Fig. 9—Average forward current versus average forward power dissipation for type-C180 SCR.

(Continued)

SCR Loads (Cont'd)

$F_{PF,\alpha}$ = Form factor for power factor and retard angle in question

$F_{1.0,\alpha}$ = Form factor for *unity* power factor and retard angle in question

$T_{c(max)}$ = Max allowable case temperature

$T_{c(ss)}$ = Case temperature curve from spec sheet

B. Average Current Versus Average Power Dissipation

1. Locate curve from spec sheet for retard angle in question.
2. Mark maximum average current on curve as previously calculated in A.2. See **Fig. 11**.

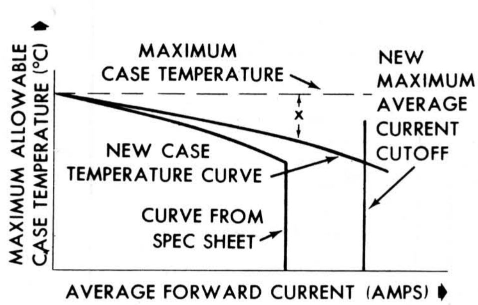

Fig. 10.

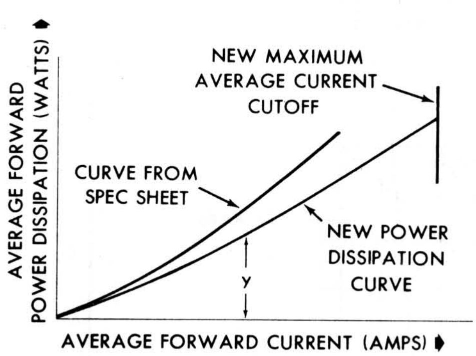

Fig. 11.

3. Plot curve by determining distance Y:

$$Y \text{ (watts)} = \left(\frac{F_{PF,\alpha}}{F_{1.0,\alpha}}\right) P_{ss}$$

where:

P_{ss} = Power dissipation curve from spec sheet

Example Problem

Adjust case temperature and power-dissipation-versus-average-current curves for type-C180 SCR operating under following conditions:

1. Retard angle = 150 deg
2. Power factor = 0.9 (lagging)

- Known:

$I_{rms(max)}$ = 235 amps (from spec)

$F_{0.9,\ 150\ deg}$ = 3.05 } From **Fig. 5**

$F_{1.0,\ 150\ deg}$ = 4.0 }

$T_{c(max)}$ = 125°C (from spec)

- New Maximum Average Current

$$I_{avg(max)} = \frac{I_{rms(max)}}{F_{PF,\alpha}} = \frac{235}{3.05} = 77 \text{ amps}$$

Plot the 77-amp line on **Fig. 12.**

- Computation of Remainder of T_c-Versus-I_{avg} Curve

$$X\ (°C) = \frac{F_{0.9,\ 150\ deg}}{F_{1.0,\ 150\ deg}}(T_{c(max)} - T_{c(ss)})$$

$$= \frac{3.05}{4.0}(125°C - T_{c(ss)})$$

$I_{avg(max)}$ (amps)	$T_{c(ss)}$ (amps)	X (°C)	New Case Temp. ($T_{c(max)} - X$) (°C)
10	121	3	122
20	116	7	118
30	110	11	114
40	104	16	109
50	97	21	104
60	90	27	98

(Continued)

SCR Loads (Cont'd)

• Computation of P_{avg}-Versus I_{avg} Curve

$$Y \text{ (watts)} = \frac{F_{0.9,\ 150\ deg}}{F_{1.0,\ 150\ deg}} P_{ss}$$

$$Y \text{ (watts)} = \frac{3.05}{4.0} P_{ss}$$

I_{avg} (amps)	P_{ss} (watts)	Y (watts)
10	17	13.0
20	32	24.4
30	53	40.4
40	76	58.0
50	104	79.3
60	135	103

Plot new curve on **Fig. 13.**

PLEASE NOTE

It should be carefully noted that what has been described in this design approach does not *increase* the *rating* of a given SCR. It merely shows how to better utilize the built-in capability of the high-power SCR by accurately defining the conditions under which it must operate.

Acknowledgment

The author wishes to acknowledge the work of Chuck Mohler of General Electric Co. in programming, on the GE 225 computer, the problem of SCR's operating into an inductive load. ■

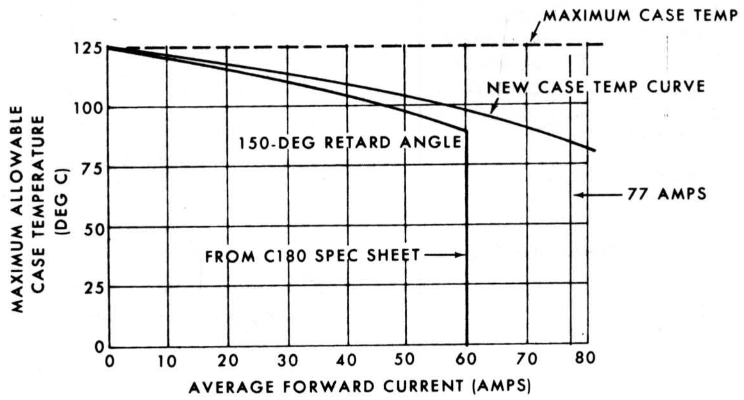

Fig. 12.

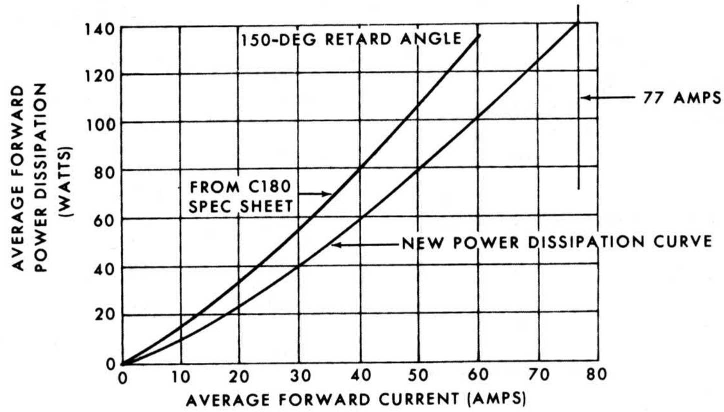

Fig. 13.