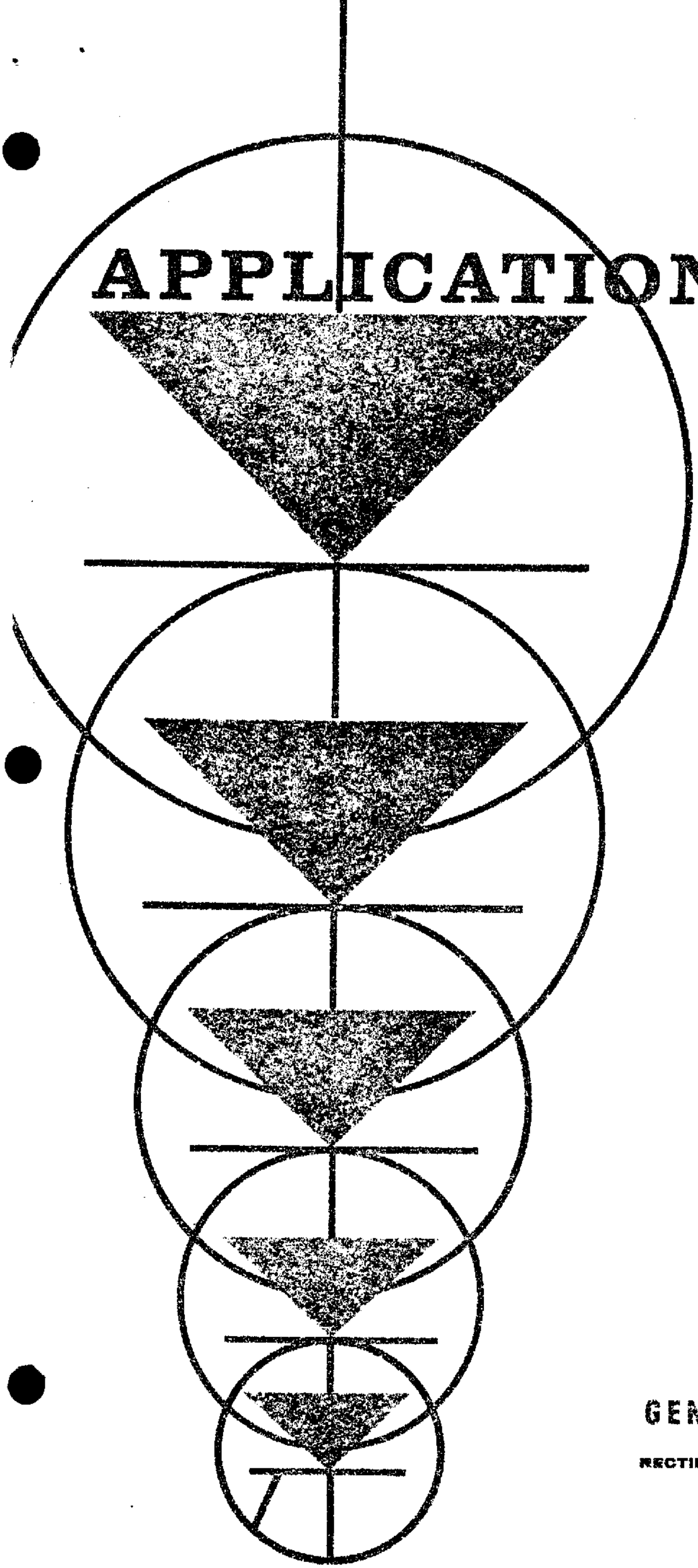
APPLICATION NOTE



THE SERIES CONNECTION OF RECTIFIER DIODES

by

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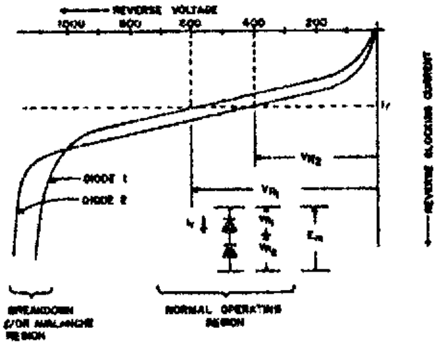
INTRODUCTION

When n_s rectifier diodes are connected in series in order to obtain a greater voltage blocking capability than is available from a single diode, it is usually desirable to have an arrangement whereby each diode assumes $1/n_s$ of the applied voltage transiently as well as in the steady-state. In practice the arrangement should be such that at all times and over the temperature range individual diode voltages are within their capabilities.

Consider the steady-state situation in terms of two diodes connected in series each of which has the hypothetical characteristic at a given junction temperature shown in Figure 1. Since they are in series, the same reverse current i_r flows through each diode. With a voltage $E_m = 1000$ volts applied to the string, a stable condition results at the current i_r such that diode 1 blocks $V_{R1} = 600$ volts and diode 2 blocks $V_{R2} = 400$ volts.

It is clear that the diode having the lowest reverse blocking (or leakage) current for a given voltage (diode 1 in Figure 1) assumes a larger share of the applied voltage. Hence, the reverse voltage a diode assumes in a series string is inversely proportional to its blocking current.



Basic Reverse Voltage Sharing Between
Series-Connected Diodes
FIGURE 1

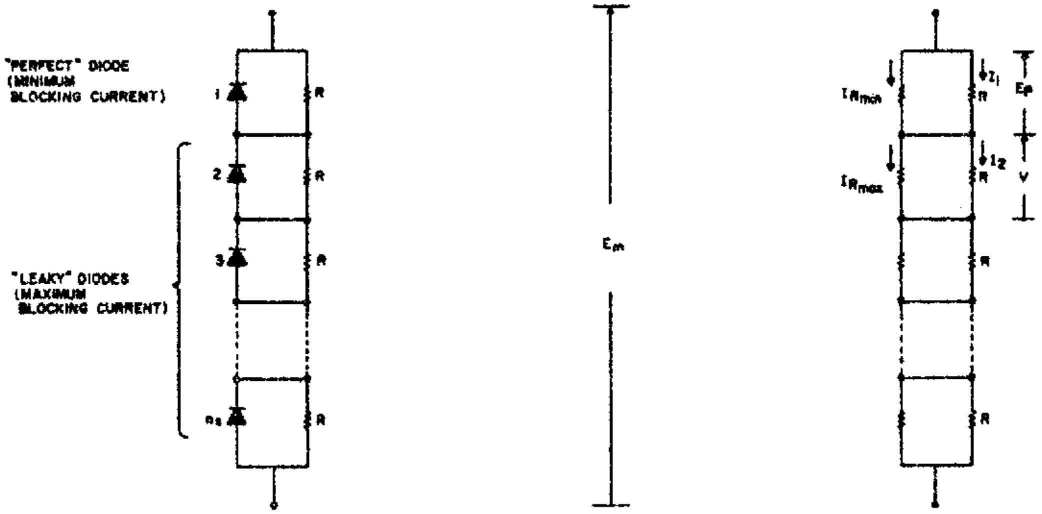
Reverse blocking current versus voltage is a device characteristic. Some diodes exhibit a very "flat" reverse current characteristic; others show a "sloped" current characteristic in the operating region. Generally speaking, it is difficult to obtain a stable reverse voltage sharing condition without the addition of external equalizing circuitry in the case of the "flat" characteristic; often it is possible to operate satisfactorily with diodes of merely the same reverse voltage classification, which sufficiently "matches" them, in the "sloped" case. For example, from the relatively "sloped" case illustrated in Figure 1, additional voltage equalization by means of external circuitry may not be required. Still other diodes, like the controlled avalanche devices, have a rated capability in the reverse avalanche breakdown region; in a series connection such a diode may, therefore, go into avalanche while its current is being limited by the other diodes in the string. For this reason equalizing resistors are usually not required with controlled avalanche diodes.

Generally, reverse current is a strong function of temperature. At the same temperature the diodes may share voltage satisfactorily. However, with a difference of only a few degrees in junction temperature between diodes, one of the diodes' voltage rating may be exceeded. Temperature variations may arise from differences in diode heat dissipation due to forward voltage drop and thermal impedance or from differences in the individual diodes' heatsinking system.

Other factors affecting voltage sharing can be found in the specialized "high voltage" area. Here diode-to-diode and diode-to-ground capacitances as well as corona currents must be considered. These effects are not considered in the following discussion.

A) STEADY-STATE VOLTAGE SHARING BY MEANS OF EQUALIZING RESISTOR

Consider n_s diodes in a series-connected string with equalizing resistors of value R subjected to a peak reverse circuit voltage of E_m volts some time after commutation has been effected, as shown in Figure 2(a). Since each diode under steady-state conditions will block a voltage inversely proportional to its reverse blocking current, a worst case analysis results if it is assumed that one diode in the string is "perfect", that is, exhibits minimum reverse blocking current, and all other (n_s - 1) diodes have their maximum allowable specified value of reverse blocking current. Under these conditions, diode 1 (the "perfect" diode) will assume more than its proportionate share of the total applied circuit voltage.



(a)

Diodes in Series String

(b)

Worst Case Equivalent Circuit

Worst Case Steady-State Voltage Sharing

FIGURE 2

Referring to Figure 2(b), the limiting condition for the voltage across diode 1 is

$$E_p = I_1 R, \text{ where} \tag{1}$$

I_1 = current through resistor R

E_p = peak reverse voltage to which it is desired to stress an individual diode

R = external voltage equalizing resistor

The voltage across each of the other (n_s - 1) diodes in parallel with their respective equalizing resistor of value R is

$$V = \frac{E_m - E_p}{(n_s - 1)}, \text{ where} \tag{2}$$

E_m = peak value of circuit voltage applied to series-connected string

n_s = number of diodes connected in series

Considering the currents assumed in Figure 2(b),

$$I_2 = I_1 + I_{R_{min}} - I_{R_{max}}$$

If we define

$$\Delta I_R = I_{R_{max}} - I_{R_{min}}, \text{ where} \qquad (3)$$

$I_{R_{max}}$ = maximum specified value of diode reverse blocking current under operation voltage and temperature conditions

$I_{R_{min}}$ = minimum specified value of diode reverse blocking current under operating voltage and temperature conditions

we may write

$$I_2 = I_1 - \Delta I_R,$$

or, according to Equation (1),

$$I_2 = \frac{E_p}{R} - \Delta I_R \qquad (4)$$

According to Equation (2), and, since in Figure 2(b) $V = I_2 R$,

$$\frac{E_m - E_p}{(n_s - 1)} = I_2 R,$$

or, with Equation (4),

$$\frac{E_m - E_p}{(n_s - 1)} = R\left(\frac{E_p}{R} - \Delta I_R\right)$$

Solving for R yields the required value of equalizing resistor,

$$R \leq \frac{1}{\Delta I_R} \left[\frac{n_s E_p - E_m}{(n_s - 1)}\right] \qquad (5)$$

A special case of Equation (5) yields the solution for a large number of practical cases for which values of ΔI_R are not readily available for the diode type of interest. Usually, only a value of maximum reverse blocking (or leakage) current $I_{R_{max}}$, at rated voltage $V_{RM(rep)}$ and maximum junction temperature $T_{J_{max}}$, is available from the specification bulletin. For this situation the "perfect" diode, in the worst case equivalent circuit of Figure 2(b), may be assumed as "open" or of infinite resistance; hence, in this case, the current $I_{R_{min}} = 0$, and Equation (3) reduces to

$$\Delta I_R = I_{R_{max}}$$

The general Equation (5) then becomes

$$R \leq \frac{1}{I_{R_{max}}} \left[\frac{n_s E_p - E_m}{(n_s - 1)}\right] \qquad (6)$$

Furthermore, in the practical case, values of $I_{R_{max}}$ (and $I_{R_{min}}$) are rarely available under the specific operating conditions of a particular application as specified in connection with these quantities in Equation (3). Two choices are available. One, is to assume an equivalent resistance value for the "leaky" diodes in the equivalent circuit of Figure 2(b) such that $R_{eq} = \frac{V_{RM(rep)}}{I_{R_{max}}}$, where $V_{RM(rep)}$ = maximum rated repetitive peak reverse blocking voltage of diode at $T_{J_{max}}$. The error of this approach is that the value of R_{eq} under operating conditions is given by the voltage $V < V_{RM(rep)}$ and some other blocking current $I_{R'_{max}}$.

The other approach, taken for Equations (5) and (6), is to use the actual voltage V but to assume negligible change in $I_{R_{max}}$ over the voltage range ΔV which lies such that $V_{RM(rep)} \geq \Delta V \geq V$. In terms of equivalent resistance at the operating voltage V, $R_{eq} = V/I_{R_{max}}$. With assumed $I_{R_{max}} \approx$ constant for both cases in the operating range of interest, $R'_{eq} < R_{eq}$. Hence, the latter approach used here will generally yield more conservative results (lower values of R) since R'_{eq} will draw more current than R_{eq} and thus require a lower value of R across the "perfect" diode to maintain a given value of E_p.

Resistor Tolerance

The tolerance of the resistor should be considered in Equation (5) and Equation (6) by selecting the value of R at the maximum tolerance for a conservative design.

Voltage Rating of Diode

The maximum repetitive peak blocking voltage rating of the diode $V_{RM(rep)}$ may be selected from

$$V_{RM(rep)} \geq \frac{E_p}{U}, \quad \text{where} \tag{7}$$

$$U = \text{voltage utilization factor} = \frac{E_p}{V_{RM(rep)}} \leq 1$$

Power Dissipation of Resistors

The greatest power must be dissipated in the resistor across the "perfect" diode in the circuit of Figure 2(a) since it sees the highest peak voltage E_p in the string. The power dissipation capability required of the resistor R can, therefore, be determined for the general case from

$$P_d = \frac{E_{rms}^2}{R}, \quad \text{where} \tag{8a}$$

E_{rms} = rms value of reverse blocking voltage across "perfect" diode corresponding to the proper circuit waveform of peak value E_p

For conventional rectifier circuits Equation (8a) is more conveniently written as

$$P_d = K\frac{E_p^2}{R}, \quad \text{where} \tag{8b}$$

K = constant relating the peak value of the given circuit waveform to its rms value;
K = 0.25 in half-wave and single phase circuits
K = 0.70 for three phase waveforms

B) TRANSIENT VOLTAGE SHARING BY MEANS OF R_dC NETWORK

In addition to properly sharing steady-state peak repetitive reverse voltage, series-connected diodes must also share voltage on a transient basis within their capabilities. There are basically two situations of concern. One, during the reverse recovery interval, is the sharing of circuit voltage during the time that the series-connected diodes are regaining their reverse voltage blocking capability.[1,2] The other situation, during the time the diodes are blocking voltage, is the sharing of any circuit-imposed voltage transients.

Reverse Recovery

Under action of the circuit commutating voltage E_c the forward current i_F through the diodes shown in Figure 3(a) is reduced to zero at a rate determined by the commutating inductance L_C of the circuit. This circuit-imposed condition, in addition to the characteristics of the diodes used, results in an amount of charge Q_r present in the diode that must be recovered by the circuit before the diode can regain its reverse voltage blocking capability.[1] A worst case equivalent circuit (Figure 3(b)) results if diode 1 is assumed to be a "fast" diode, that is, one having a value of recovered charge $Q_{r_{min}} < Q_{r_{max}}$, where $Q_{r_{max}}$ = charge to be recovered from each of the remaining $(n_s - 1)$ "slow" diodes. Diode 1 will recover and start to assume reverse voltage at a time t_{r1} such that

$$Q_{r_{min}} = \int_0^{t_{r1}} i_{rr}\, dt$$

At time $t = t_{r1}$, the remaining $(n_s - 1)$ diodes will still have a charge

$$\Delta Q_r = Q_{r_{max}} - Q_{r_{min}} \qquad (9)$$

if internal charge recombination during the time t_{r1} is neglected. Since the $(n_s - 1)$ diodes are not blocking voltage at the time t_{r1}, the entire reverse circuit voltage initially appears across the "fastest" diode, and in the absence of a low impedance shunt path around the "fastest" diode, the remaining $(n_s - 1)$ diodes would, therefore, be deprived of additional reverse sweep-out current i_{rr}. They would thus only recover their reverse blocking capability at a rate determined by the internal diode minority carrier lifetime effective under the prevailing conditions. For most rectifier diodes this time is very much greater than the time it would have taken all series-connected diodes to regain their blocking capability if the current i_{rr} had been allowed to continue to flow. In order to have reverse voltage sharing during the reverse recovery interval a low impedance source of recovery current must, therefore, be made available to the "slower" diodes. This function is accomplished by the capacitor C in the circuit of Figure 3(a).

The value of capacitance selected for the capacitor C must:

1. Limit voltage across "fastest" diode in accordance with the circuit commutating conditions.
2. Supply sufficient charge ΔQ_r in order to allow the "slower" diodes to recover quickly.
3. Facilitate circuit-imposed transient voltage sharing within the diodes' rated capability.

The first requirement can be met by the method given in Reference 1 which assumes one diode in the circuit and requires the capacitor C to limit the voltage as though only one diode were present. This is also the situation in the series-connected string of diodes because the circuit is initially controlled by the "fastest" diode in the string since all other diodes are "short" at the time the "fastest" diode recovers.

The second requirement can be shown to be met if

$$C \geq \frac{(n_s - 1)\,\Delta Q_r}{n_s E_p - E_c}\text{, where} \qquad (10)$$

E_c = circuit commutating voltage

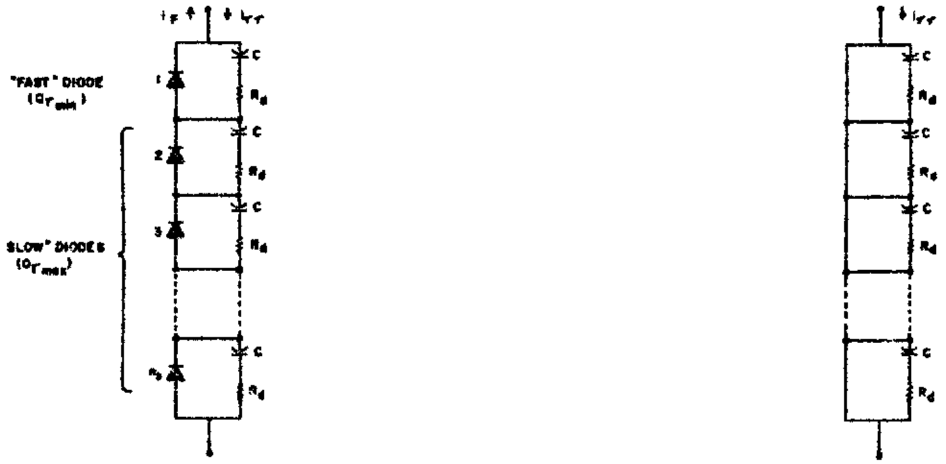
As a first conservative approximation, or for cases where ΔQ_r data are not readily available, the following expression may be used.[3]

$$C = 10 \frac{I_F}{V_{RM(rep)}} \mu f, \text{ where} \tag{11}$$

I_F = current in amperes flowing through diode immediately preceding commutation

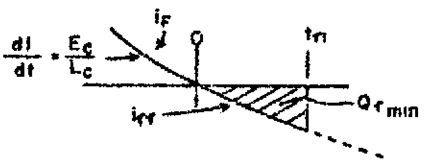
$V_{RM(rep)}$ = repetitive peak reverse voltage rating of diode in volts

The third requirement is generally met by the values of capacitance resulting from the other two considerations. Added external capacitance is usually very large compared to diode self-capacitance and will effectively equalize voltage transients. In many applications a damping resistor R_d is required in series with the capacitor. This is particularly true in higher power circuits in which the energy stored in the supply line at the end of the reverse recovery interval[1] is significant. It cannot be over-emphasized, that the inductance of the RC network, including the capacitor, be held to an absolute minimum.



(a)
Diodes in Series-Connected
String With RC Networks

(b)
Worst Case Equivalent Circuit
at $t = t_{r1}$ + After "Fastest"
Diode Has Recovered



(c)

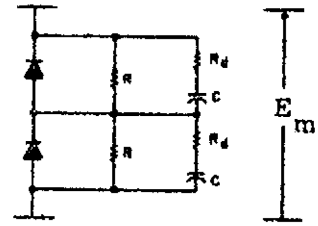
Definition of Variables

Worst Case Transient Voltage Sharing

FIGURE 3

C) ILLUSTRATIVE EXAMPLE

250 ampere/1000 volt A90P with $V_{RM(rep)} = 1000$ volts and $I_{R_{max}} = 18$ ma (per specification sheet); circuit voltage E = 1200 volts rms, single phase. $\Delta Q_r = 100\ \mu$coul. $E_c = 440$ volts, $I_F = 100$ A. For the General Electric A90P diode Chart 1 suggests the use of both R and R_dC networks as follows:



$E_m = \sqrt{2}\ (1200) = 1700$ $\qquad n_s = 2$

a) Select E_p in accordance with Equation (7):

It is decided to stress "best" diode to its full rated capability $V_{RM(rep)}$, or U = 1.0, and

$$E_p = V_{RM(rep)}$$

b) Select equalizing resistor R:

From Equation (6):

$$R \leq \frac{10^3}{18} \left[\frac{2\,(1000) - 1700}{1} \right]$$

$$\leq 16.7 \text{ K ohms, say}$$

$$R = 15 \text{ K ohms}$$

c) Determine power dissipation required in R:

From Equation (8b):

$$P_d = 0.25\ \frac{(1000)^2}{15 \cdot 10^3} = 17 \text{ watts}$$

Therefore, select 20 or 25 watt resistor. (Note: sometimes an application is limited to a given rating of the resistor for reasons of size, heat dissipation, mechanical mounting considerations, etc. Then step (c) determines the minimum possible ohmic value of the resistor. Step (b) must then be solved for $I_{R_{max}}$ or ΔI_R and the diode specified accordingly.)

d) Select R_dC network:

Assume from consideration of commutation conditions[1] a value of C = 0.5 μf and $R_d = 3$ ohms is required. Check per Equation (10).

$$C \geq \frac{(1)\ 100 \cdot 10^{-6}}{(2)\,(1000) - 440} = 0.064\ \mu f$$

Adequate sweep-out current will, therefore, be supplied by the 0.5 μf capacitor since approximately ten times this value had already been selected for adequate protection during commutation. The resistor R does not affect the functioning of the R_dC effective during the reverse recovery interval.

Use of Equation (11) yields:

$$C = 10\ \frac{100}{1000} = 1\ \mu f$$

It is seen that this value is conservative by a factor of two in this case over the value obtained from Reference 1.

SUGGESTED GUIDE CHART

Chart 1 gives a guide to the series operation of General Electric rectifier diodes by product line.

CHART 1: Suggested Guide to the Series-Connection of General Electric Rectifier Diodes

SIZE & PROCESS	BASIC G-E FAMILY	PACKAGE	TYPICAL JEDEC NUMBERS	GUIDE TO SERIES OPERATION(1)
Low Current Alloy	A4	"Top Hat"	1N536-40	Use diodes from same voltage classification. For $n_s \leq 10$: no external equalizing components; $n_s \leq 20$: use capacitor across each diode; $n_s \geq 21$: use capacitor across each diode and equalizing resistor.
	A10	DO-3	-	
	A5	"Stud"	1N253-256	
		DO-4	1N332-349	
	A4	"Top Hat" DO-3	1N1692-97	Same as above, only also equalizing resistors for all series-connected diodes.
Low Current Diffused	A6	Sub-Min Glass	1N645-649	Use diodes from same voltage classification. Place equalizing resistor and a capacitor across each diode.
	A13	Sub-Min Glass Encap	-	
	A16	"Flangeless" DO-13	1N3189-91	
Medium Current Alloy	A20	DO-4	1N1612-16 1N1341A-48A	Use diodes from same voltage classification. Use equalizing resistors across each diode when very close voltage sharing is required.
	A25	DO-4	1N1199-1206	
	A36	DO-5	1N2154-60	
Medium Current Diffused	A18	"Stud" DO-4	1N1124-28 1N1124A-28A	Use diodes from same voltage classification. Use equalizing resistors and R_dC networks across each diode.
	A40	-	-	
	A44/A45	"Press Fit"	-	
	A125	DO-4	1N1199-1206	
	A135	DO-5	1N2154-60	
High Current Diffused	A70	DO-8	1N3289-96	
	A90	DO-9	1N3736-42	
Controlled Avalanche and Derivatives	A7	Sub-Min Glass	-	Use diodes from same voltage classification. Use capacitors across each diode.
	A22	"Flangeless" DO-13	-	
	A23	"Stud" DO-4	-	
	A27..1,2	DO-4	-	Use diodes from same voltage classification. Use R_dC networks across each diode.
	A27..3,4	DO-4	1N3670A-73A	
	A38..1,2	DO-5	-	
	A38..3.4	DO-5	1N3765-68 1N1183-90	
	A76	DO-8	-	
	A92	DO-9	-	

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(1) The need for capacitors and/or RC networks across each series-connected diode is often determined by the characteristics of the total circuit including the supply. The suggestions given above are general and should be modified as required in specific applications.

ACKNOWLEDGEMENT

The author wishes to thank Messrs. B. W. Jalbert, R. R. Schall, and J. C. Hey for their cooperation, helpful suggestions, and assistance in the formulation of the suggested guide for the series-operation of General Electric rectifier diodes.

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3. SCR Manual, 3rd Edition, General Electric Company, Auburn, New York, p 257