MOTOROLA

SILICON RECTIFIER HANDBOOK

ENGINEERS' GUIDE TO SILICON RECTIFIER APPLICATIONS

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TEST DEPARTMENT.

SILICON RECTIFIER HANDBOOK

Technical Editor

Bob Dale
Applications Engineering

Associate Editor

William Max Ivey
Technical Information Center

Contributors

Bob Dale
Applications Engineering

Rex Ivins
Applications Engineering

Technical Editorial Assistance

Ralph Greenburg
Applications Engineering

Art Supervisor

Stan Bennett
Technical Information Center

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Motorola Multi-cell rectifier fabrication process — patents pending.

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INTRODUCTION

The rapid progress of semiconductor technology in the last decade has made it increasingly difficult for electronic workers to remain well informed. Motorola's series of semiconductor device handbooks, each dealing with a unique field of fundamental importance, places within the grasp of every engineer and technician up-to-date knowhow in his field of interest.

This rectifier handbook satisfies a growing need to have conveniently assembled in one handy reference volume, design information on recently expanded silicon rectifier capabilities. Silicon rectifiers may now be used in many applications, impossible only a few years ago — yet, a comprehensive rectifier handbook has not been published in recent years.

Also, there exists an ever-present need to inform the uninitiated engineer or technician. True, the rectifier is not an "exotic" device, requiring daily study to keep up-to-date. Nevertheless, new engineers enter the power-control field constantly without the practical experience useful for designing circuits. This rectifier handbook has been compiled by engineers with years of industrial experience. New technical men, by reading the Motorola Silicon Rectifier Handbook, may "cash-in" on this practical knowledge.

Finally, Motorola's rectifier line represents the most complete range of capabilities in the industry. The Motorola Silicon Rectifier Handbook attempts to introduce these capabilities — pointing out where each may be used to the greatest advantage.

ACKNOWLEDGEMENT

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Bob Dale

William Max Ivey

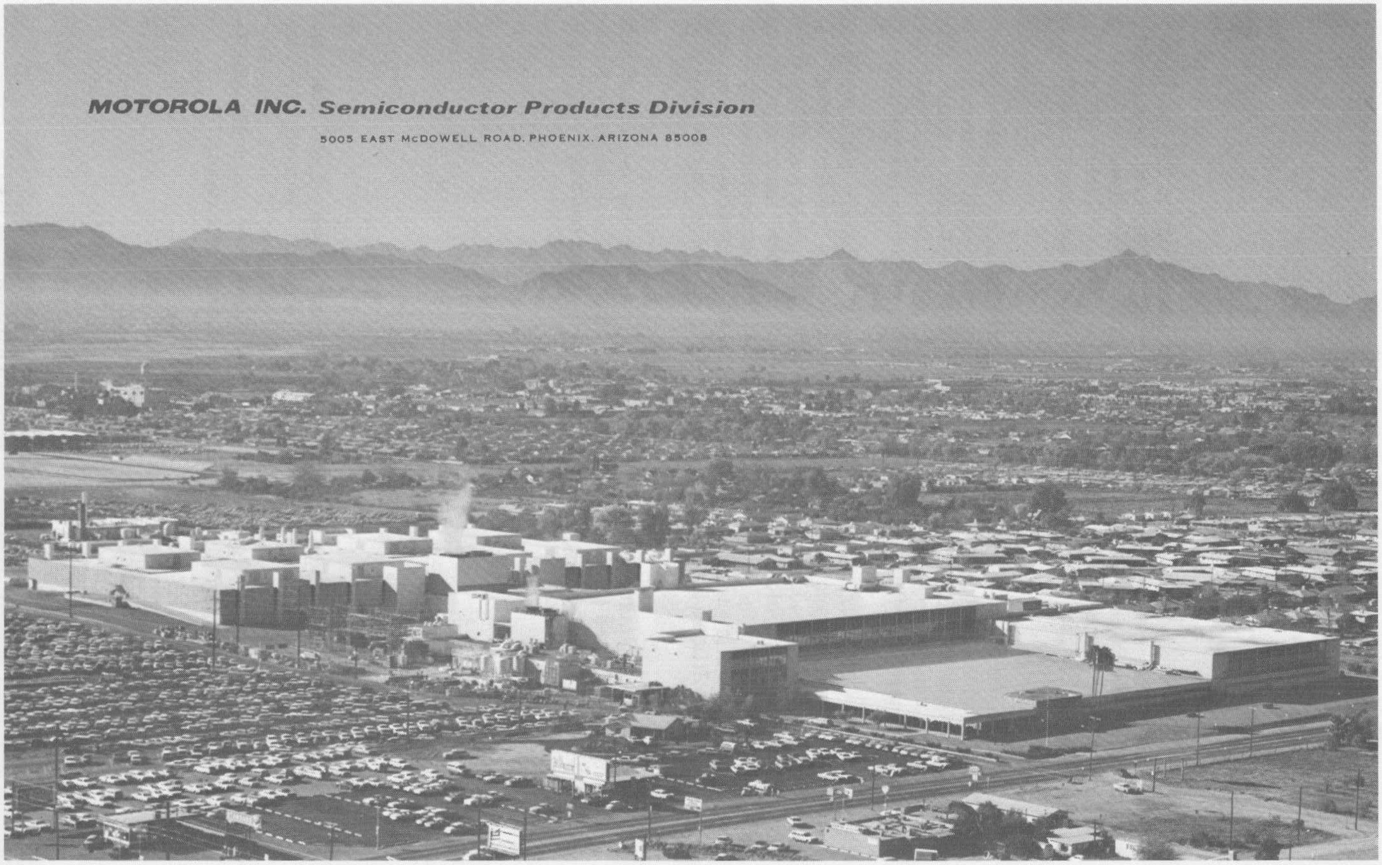
MOTOROLA INC. Semiconductor Products Division
5005 EAST McDOWELL ROAD, PHOENIX, ARIZONA 85008

TABLE OF CONTENTS

Page

CHAPTER 1

Semiconductor Theory

Introduction

The phenomenon of rectification in a two-terminal device, i.e., greater conductance in one direction than in the other, occurs at the junction of two dissimilar conductors. This rectification effect was first noticed in the junction of copper sulfide and magnesium and later in the junctions of copper/cuprous oxide, selenium/iron, and selenium/aluminum. Rectifiers using these junctions have all been quite popular as a result of their relative high efficiency and their low cost when compared to tube-type devices. As a group, they are known as polycrystalline devices since they are actually formed of millions of individual crystal junctions in parallel. More recently, junctions in single-crystal semiconductor materials, such as germanium and silicon (monocrystalline devices) have replaced the polycrystalline junctions in most rectifier applications.

The polycrystalline devices as a group are characterized by moderate forward voltage drops per cell (100 millivolts for copper oxide to about 1 volt for selenium types), fairly low reverse breakdown voltages (63 volts for the best selenium) and a forward-to-reverse current ratio of about 10. In order to obtain higher reverse voltage capability, cells commonly are connected in series. This also increases the forward voltage drop of the rectifier system and reduces rectification efficiency. These rectifiers are limited, in general, to cell temperatures of 85°C to obtain a reasonable device life.

Forward voltage drops in monocrystalline devices are about the same as for polycrystalline junctions, but the reverse voltages are more than an order of magnitude higher. In addition, the forward-to-reverse current ratios reach 10,000 in germanium and approach 1 million in some silicon cells. It can readily be seen that the monocrystalline rectifier offers far greater rectification efficiency and, as a result of the reduction of heat generated in the rectification process, the rectifier system size may be considerably reduced compared with an equivalent polycrystalline system.

Within the monocrystalline group, the two most common types of cells are silicon and germanium. The low forward drop of germanium is at times a decided advantage; however, the relatively low temperature limit of 100°C and the inherent sensitivity to transient voltage and current peaks seriously limit the usability of this material. All these limitations make the silicon rectifier the most practical of the presently manufactured rectifiers for most circuits. Its high reverse-voltage capability (up to 1500 volts in a single junction), its low reverse current, and its high operating temperature (175° to 200°C) more than compensate for its slightly higher forward-voltage drop compared with germanium. This handbook, therefore, will be devoted primarily to the discussion of silicon rectifiers in theory and practice.

To understand the operation of silicon rectifiers, some knowledge of basic semiconductor theory is necessary. In the following sections, the most important properties of this semiconductor material are discussed. A qualitative discussion of the p-n junction follows, with emphasis on factors which affect various rectifier parameters.

Electrical Properties of Semiconductor Materials

The crystal structure of silicon and germanium consists of a regular repetition in three dimensions of a unit cell in the form of a tetrahedron with an atom at each corner. This configuration is shown for two dimensions in Figure 1-1.

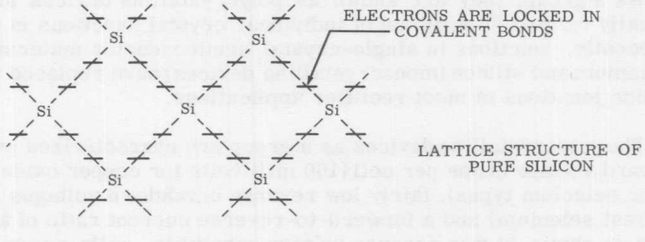

Figure 1-1. Two-Dimensional Representation of Silicon Lattice

The atomic structure of germanium (atomic number, 32) and silicon (atomic number, 14) is such that both of these elements have four valence electrons in the outer shells; that is, the atoms are tetravalent. These elements are found in Group IV of the periodic table. From basic chemistry, we know that the number of electrons in the outer shell of the atom determine its chemical and electrical properties, and that an atom with eight electrons in its outermost shell is relatively stable. This stability is attained in a pure germanium or silicon crystal by sharing electrons; that is, each electron in the valence shell of one atom is shared by a neighboring atom in the tetrahedral structure. As a result, each atom claims not only its own valence electrons, but an additional electron from each of four neighboring atoms. This electron sharing stabilizes each atom and imparts to the pure semiconductor crystal a low conductivity despite the fact that there are only four electrons in the valence shell of each individual atom. Moreover, the covalent bond serves to keep each atom tightly bound within a crystal lattice structure, as shown in Figure 1-1. Ideally, at very low temperatures, this crystal structure contains very few free electrons and behaves as an insulator.

The electrons within the crystal lattice possess energy, since they are constantly in motion. From solid-state physics and quantum mechanics, we know that each electron exhibits a definite and discrete energy level.

This energy level is dependent upon the momentum of the electron and the radius of the electron from the nucleus of the atom. This concept leads to the energy-band theory of solids. Although the concept of energy bands is complex, a brief explanation can be given with the aid of the simplified diagram of Figure 1-2.

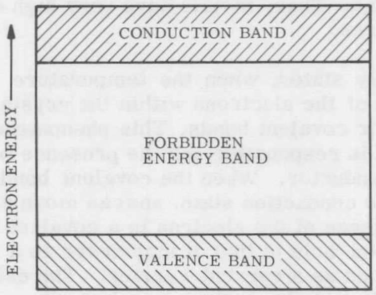

Figure 1-2. Simplified Energy Bands in Solids

Here the innermost energy bands are neglected because electrons in these bands are tightly bound to the nucleus of the atom and contribute nothing to the electrical conductivity of the solid. It is the valence band and those bands directly above the valence band which determine the electrical properties of the materials. In Figure 1-2, the valence band is separated from the conduction band by an energy-band gap. This gap is called the forbidden-energy band because electrons do not exist in the crystal at these energy levels. This is because of the discrete energy levels associated with electrons in solids. The conduction band receives its name from the fact that the energies associated with electrons in this band permit electrical conduction through the solid. In intrinsic semiconductors and insulators, the valence band is completely filled and the conduction band is empty at the temperature of absolute zero. At room temperature, some electrons in the valence band will acquire enough energy to break their covalent bonds and move into the unfilled energy states in the upper (conduction) energy band. The primary difference between an intrinsic semiconductor, an insulator, and a good conductor is the size of the energy-band gap. This difference is illustrated in Figure 1-3. In the case of the

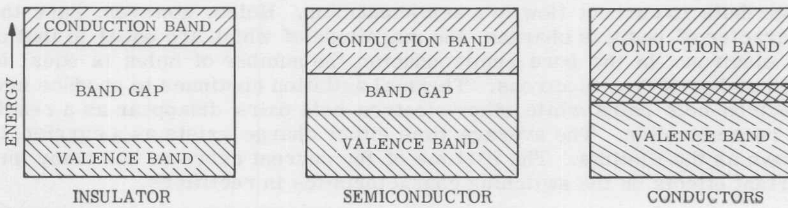

Figure 1-3. Energy-Band Gaps of Insulators, Semiconductors, and Conductors

insulator, the forbidden band is so large that, at room temperature, very few electrons acquire sufficient energy to raise them into the energy levels of the empty conduction band. In semiconductors, the forbidden band is much narrower, so that, at room temperature, a large number of electrons may be excited into the conduction band. In conductors, such as metals, the energy bands overlap, leaving many unfilled energy states in or very near the valence band. Thus, metals have very high conductivities even at very low temperatures.

As previously stated, when the temperature of the semiconductor is increased, some of the electrons within the crystal will acquire enough energy to break their covalent bonds. This phenomenon is called electron-hole generation. It is responsible for the presence of current carriers in the intrinsic semiconductor. When the covalent bond is broken, the electron is excited to the conduction state, and can move about within the semiconductor. The absence of the electron in a covalent bond is called a hole. The importance of the hole is that it may serve as a current carrier, just as an electron serves as a current carrier. The existence of the incomplete covalent bond, or hole, makes it relatively easy for a neighboring electron to leave its covalent bond to fill this hole. An electron moving from a bond to fill a hole leaves a hole in its initial position. Thus, the hole appears to move in a direction opposite to that of the electron. This is illustrated in Figure 1-4, where [in 4(a)] the hole exists in the sixth position. The electron moves from position 7(a) to fill the hole at position 6(a). The hole now appears in position 7(b) and has effectively moved to the right.

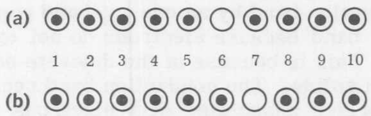

Figure 1-4. Mechanism by which a Hole Contributes to Conductivity

The concept of conduction by holes in semiconductors does not involve the free electron since hole flow takes place within the valence band, while the electron flow occurs within the conduction band. Thus, we can see that a hole can move through the semiconductor crystal and act as a current carrier just as the electron does, and that both electrons and holes contribute to current flow in a semiconductor. Holes, however, have the character of positive charges, the magnitude of which are equal to that of an electron. In the pure semiconductor, the number of holes is equal to the number of free electrons. Thermal agitation continues to produce new electron-hole pairs while other electron-hole pairs disappear as a result of recombination. The average time either charge exists as a carrier is known as the lifetime. The lifetime of the current carriers has many important effects on the switching characteristics in rectifiers.

With each electron-hole pair generated, two current carriers are created – the electron and the hole. These carriers move in opposite directions when under the influence of an electric field, however, since the charges they carry are opposite in sign, the net current contributed by each is in the same direction. With increasing temperature, the density of the electron-hole pairs increases and, correspondingly, the conductivity increases. The intrinsic concentration of current carriers in the semiconductor is given by the following expression:[1]

$$n_i^2 = np = A_0 T^3 e^{-(E_g/kT)} \tag{1-1}$$

where n_i = intrinsic carrier concentration
n = number of free electrons/cm^3
p = number of holes/cm^3
k = Boltzman's constant
E_g = forbidden-band energy
A_0 = proportionality constant
T = temperature in °K

From Equation (1-1), it can be seen that the number of free carriers increases quite rapidly with increases in temperature. It will be shown later in this paper that this is not desirable with most semiconductor devices, since it drastically limits the uses of these devices.

Impurities in Semiconductors

Semiconductor materials have no practical application in their intrinsic form. To obtain useful semiconductor devices, controlled amounts of impurities are introduced into a crystal. Precise control of these impurities is the most important requirement of fabricating semiconductor materials. The process of adding impurities to silicon or germanium is called doping. Doping may be accomplished by several different methods. Alloying and diffusion are two common methods currently in use. In doping a semiconductor crystal, elements from Group III or Group V of the periodic table are introduced into a silicon or germanium crystal. The electrical conductivity that results from impurity doping is referred to as extrinsic conduction.

If pentavalent elements such as antimony, phosphorus, or arsenic are introduced into the intrinsic semiconductor crystal, some of the silicon or germanium atoms will be displaced by the impurity atoms. This is illustrated in Figure 1-5(a). The ratio of impurity atoms to parent atoms can be as small as one impurity atom to 10^{18} parent atoms. Thus, it is most probable that the impurity atoms will be completely surrounded by parent atoms. Four electrons of the impurity atom will form covalent

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[1] Phillips, Transistor Engineering, p. 51, McGraw-Hill, 1962.
Millman, Vacuum Tube and Semiconductor Electronics, p. 82, McGraw-Hill, 1958.

bonds with the four surrounding atoms and the fifth electron will be free to act as a current carrier [Figure 1-5(a)]. The pentavalent impurity is called a "donor", because it gives up electrons, and the material is said to be n type because it has free electrons (negative charges).

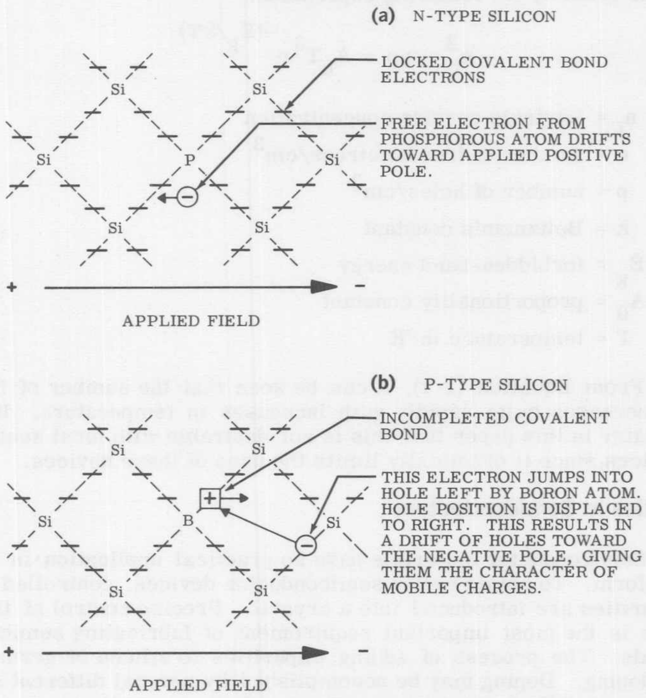


Figure 1-5. Impurity Atoms in the Semiconductor Crystal

If a trivalent impurity atom, such as boron or indium, is added to the semiconductor crystal, parent atoms will again be displaced. Now, however, the electrons surrounding the impurity atom cannot form a stable set of covalent bonds. There will be one incomplete bond due to the 3-electron structure of the impurity atom, and this incomplete bond constitutes a hole. This condition is shown in Figure 1-5(b). The hole formed by the trivalent atom easily accepts neighboring electrons (as described previously). This type of impurity is called an acceptor impurity and forms a p-type semiconductor material. The p-type refers to the fact that the current carriers act as positive charges. Although the impurity atoms exist in the extrinsic materials as positive and negative ions, the material is still electrically neutral.

Electron-hole generation due to thermal excitation occurs whether the semiconductor is intrinsic or extrinsic. However, the doping of silicon or germanium with n-type impurities decreases the number of holes available in the extrinsic semiconductor. The decrease is brought about because the large number of electrons present increases the rate of recombination of holes with electrons. By a similar argument, the number of electrons in the semiconductor is reduced by doping with p-type impurities. The doping of semiconductors has two important effects. It increases the conductivity of the intrinsic material while, at the same time, producing current carriers which are predominantly holes or electrons. In the n-type semiconductor, the electrons are the majority carriers and the holes are minority carriers. In p-type materials, the holes are majority carriers and the electrons are minority carriers.

Figure 1-6 shows the simplified energy diagrams for extrinsic semiconductors. For an n-type material, Figure 1-6(a), the positive impurity ion is less than 0.05 electron volt below the conduction band. At this energy level, the free electron is readily excited into the conduction band. It requires less than 1.1 electron volts to raise an electron from the valence band to the conduction band. For the p-type material, Figure 1-6(b), the negative impurity ions are less than 0.02 electron volt above the valence band of energies. Thus, electrons from the valence band will become bound to the acceptor atoms leaving holes in the conduction band available for conduction. Therefore, conduction by holes occurs in the valence band for p-type material and conduction by electrons occurs in the conduction band.

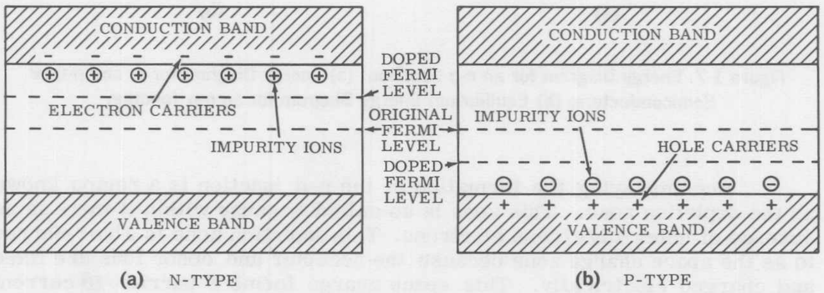


Figure 1-6. Energy Diagrams for Extrinsic Semiconductors

At this point it is best to introduce a term known as the Fermi level. The Fermi level is a reference energy level above and below which all energies may be conveniently measured. The Fermi level is defined as that energy level at which the probability of finding an electron N energy units above the level is equal to the probability of finding an absence of an electron N energy units below the level. The Fermi level for intrinsic crystals is midway between the valence band and the conduction band. The importance of the Fermi level becomes apparent in the discussion of the basic p-n junction.

The P-N Junction

When a p-n junction is formed, an equilibrium condition results; the Fermi levels of the two materials have aligned. This then may be stated as a fundamental law; the Fermi levels align when the junction is formed in a single crystal. A simple analogy of this could be considered with two volumes of water, one being higher than the other. Upon joining of the two volumes, the level of both reaches the same height. A p-n junction energy level diagram is shown in Figure 1-7. A p-n junction can be formed only by a chemical process within a single crystal. If separate p- and n-type crystals were joined mechanically, a polycrystalline semiconductor would be the subsequent result. This type device will not give rectification.

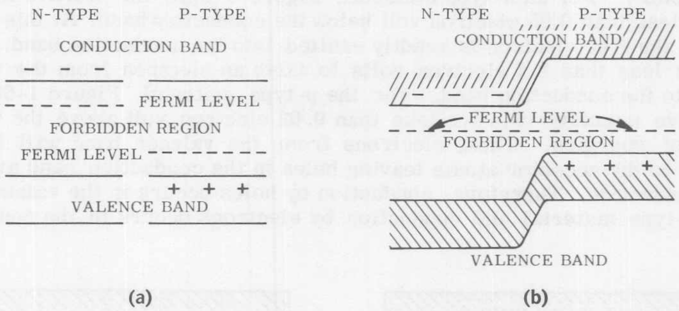


Figure 1-7. Energy Diagram for an n-p Junction: (a) Energy Diagram for n- and p-type Semiconductors; (b) Equilibrium Energy Diagram for an n-p Junction

Accompanying the formation of the p-n junction is a region known as the depletion zone. This zone is so called because within it there is an absence of holes and excess electrons. This depletion zone is also referred to as the space charge zone because the acceptor and donor ions are fixed and charged electrically. This space charge forms a barrier to current flow.

When an external battery is applied with the positive output attached to the p layer, the junction is in the forward-biased state. The external voltage source causes the holes in the p region to move from the positive source potential to the negative potential. An opposite action occurs in the n material. These two actions cause the depletion zone to shrink, thereby causing less resistance to majority carrier current flow.

When the applied battery or source potential is placed with the negative potential attached to the p layer, the junction is in the reverse-biased state. The holes in the p region are drawn toward the negative terminal while the electrons in the n region are drawn to the positive terminal. This resultant action causes the depletion zone to increase in thickness, subsequently creating a large resistance for majority carrier flow.

The reverse current tends to maintain a relatively constant value at all voltages up to a voltage called the junction breakdown voltage. In this voltage region, current conduction across the junction interface increases rapidly and the diode is often destroyed by heating. There are two causes of voltage breakdown in semiconductor diodes. One is called avalanche breakdown, and the other zener breakdown.

Avalanche voltage breakdown can be thought of as an electrical multiplication process. A schematic representation of this process is shown in Figure 1-8.

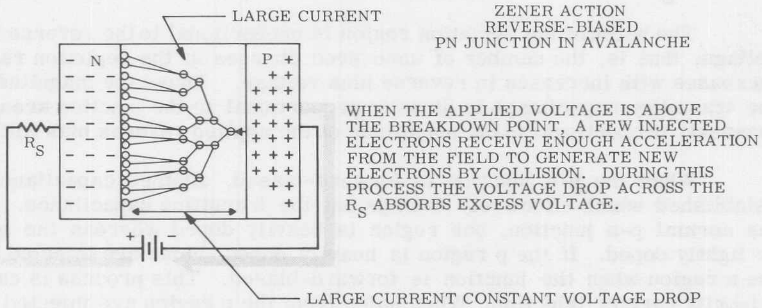


Figure 1-8. Avalanche Breakdown in the p-n Junction

In the avalanche process, a free electron acquires enough energy from the applied voltage (which exists across the very narrow junction interface) to accelerate it sufficiently such that when it collides with a fixed electron, it knocks it free. These electrons are again accelerated until each suffers a second collision, resulting in further electron multiplication. The higher the applied voltage the more rapid the electron multiplication. The voltage across the junction does not increase substantially, since the energy of the avalanche electron is limited by the critical impact velocity.

Under zener breakdown, the actual breakdown of the semiconductor is initiated through the direct rupture of the covalent bonds due to an exceptionally strong electric field which is developed across the junction. Zener breakdown is more prevalent in very narrow junctions where the field intensity becomes very high. In wider junctions, avalanche breakdown is more prevalent, since the impressed voltage is not confined to such a narrow region. In junction diodes, the junction will recover when the magnitude of the reverse voltage is reduced below the breakdown voltage provided the diode junction has not been damaged by excessive temperatures while operating in the breakdown region.

Diode Capacitance

The uncovered ions in the depletion region of the p-n junction create a capacitive effect within the diode. This capacitance is called the transition or space-charge capacitance. The boundaries of the depletion region may be thought of as the parallel plates of a capacitor and the value of this capacitance is given by the following expression:

$$C_T = \frac{\epsilon A}{W_D} \tag{1-2}$$

where ϵ = dielectric constant of the material

A = area of the junction

W_D = width of the depletion region

The width of the depletion region is proportional to the reverse bias voltage, that is, the number of uncovered charges in the depletion region increases with increases in reverse bias voltage. Thus, the magnitude of the transition capacitance is directly proportional to the junction area and inversely proportional to the magnitude of the applied reverse bias voltage.

When the p-n junction is forward-biased, another capacitance is established which effectively swamps out the transition capacitance. For the normal p-n junction, one region is heavily doped whereas the other is lightly doped. If the p region is heavily doped, holes are injected into the n region when the junction is forward-biased. This process is called minority carrier injection. When holes from the p region are injected into the n region, they become minority carriers and will diffuse away from the junction and recombine with electrons. As a result of this recombination, the hole density falls off exponentially with distance from the junction. The rate of change of charge with applied voltage is the diffusion capacitance or the storage capacitance. The diffusion capacitance is directly proportional to the mean lifetime of the holes in the n region and inversely proportional to the forward dynamic resistance of the diode. This relationship is given by the equation:

$$C_D = \frac{\tau_P}{\gamma} \tag{1-3}$$

where C_D = diffusion capacitance

τ_P = mean lifetime of holes

γ = dynamic resistance of the diode

The time constant γC_D limits the usefulness of the diode at high frequencies. When a reverse bias is applied to the diode (after conducting in the forward direction) a large current flows in the rectifier. The reverse bias voltage is in the direction which forces the stored charge carriers across the junction. Thus, the large reverse current flows until the minority carriers stored in the n region are either swept across the junction or recombined with electrons. The time required to remove the stored charge and to raise the back resistance to a high value is called the reverse or back recovery time. The back recovery time of the diode is not only a function of the time constant, γC_D, but is also a function of the external circuit.

Diode Voltage-Current Relationship

The ideal p-n junction follows the voltage-current relationship as predicted by the simple first-order theory as developed by Shockley. This relationship is expressed by the following equations:

$$I_F = I_R(e^{qV/kT} - 1) \qquad (1\text{-}4)$$

or $$V = \frac{kT}{q} \ln \left(1 + \frac{I_F}{I_R}\right) \qquad (1\text{-}5)$$

where I_F = forward junction current

I_R = reverse junction current

k = Boltzman's constant

T = absolute temperature

q = electronic charge

V = voltage across the junction

A plot of the ideal diode characteristics is shown in Figure 1-9. This shows that for any reverse voltage, in excess of a few tenths of a volt, a small reverse current is produced which remains essentially constant. When a forward voltage is applied, the forward current increases exponentially.

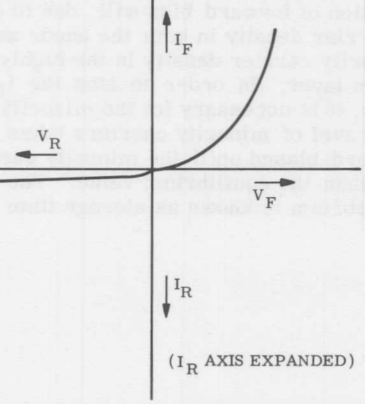


Figure 1-9. Ideal Diode Characteristics

An ideal rectifier diode has very low forward resistance and a very high reverse resistance. To create a diode with a low forward drop and a high reverse voltage capability, it is necessary for the semiconductor layer on one side of the junction to be highly doped with impurities (low resistivity) and the opposite layer to have a low doping level (high resistivity). If the p region is more heavily doped with impurities than the n region, it will have a greater number of current carriers and becomes the emitter.

P-N Junction Turn-Off Theory

The characteristics of a diode under turn-off conditions may be explained by using a turn-off test circuit such as the one shown in Figure 1-10. Figure 1-10 consists of a diode in series with a resistor placed across some fixed power supply. The polarity of the power supply may be reversed with the aid of a double-pole double-throw switch. Assume initially that the switch is connected so that the diode is biased in the forward direction. The induced voltage causes a steady-state current flow I_F in the diode and load as shown in Figure 1-10. The $I_F = (V - V_D)/R_L$.

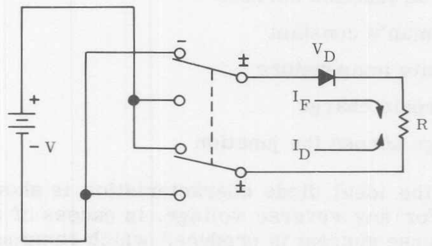


Figure 1-10. Diode Turn-Off Time Test Circuit

When the p-n junction is biased in the reverse direction for the majority carriers, it is biased in the forward direction for the minority carriers. The application of forward bias will, due to carrier action, increase the minority carrier density in both the anode and cathode sides of the junction. The minority carrier density in the highly doped p layer will be greater than in the n layer. In order to stop the I_F by reversing the external source voltage, it is necessary for the minority carriers to return to the junction. This travel of minority carriers takes a finite time. The diode will remain forward-biased until the minority carrier density at the junction becomes less than the equilibrium value. The finite time that it takes to return to equilibrium is known as storage time t_s.

CHAPTER 2

Rectifier Production Techniques

Introduction

A brief familiarity with the techniques used in rectifier fabrication and testing can provide the engineer additional insight when he is faced with rectifier application problems. By better understanding the rectifier's capabilities and limitations he can more effectively utilize the device. This chapter discusses the various stages of the rectifier fabrication and testing process without belaboring the reader with unnecessary details concerning each specific step. The process described here is actually employed by Motorola in the construction of high-voltage power rectifiers, and differs only slightly for other types.

P-N Junction Fabrication

CRYSTAL GROWING

Crystals for Motorola rectifiers are grown by the Czochralski technique, a widely used process which begins with ultra-pure polycrystalline silicon. The polycrystalline silicon is melted down, and then allowed to slowly solidify into a single large crystal of silicon (monocrystalline). This large crystal is then sliced into many thin silver-dollar shaped sections, called wafers. After further processing, these wafers will become the rectifier die.

The crystal growing process begins by loading chunks of polycrystalline silicon, along with carefully controlled quantities of certain impurities, into a quartz crucible. Although the impurities amount to only several parts per billion of silicon, they can greatly change the electrical characteristics of the semiconductor crystal. Consequently, their concentration must be carefully controlled. The crucible, supported by a carbon holder, is placed in an induction heating furnace. Next, a monocrystalline seed of silicon, possessing the same lattice structure and impurity concentration as the desired crystal, is lowered into the molten misture. Only a minute quantity of the seed crystal is allowed to melt, before the mixture temperature is lowered sufficiently for recrystallization to begin. The seed crystal is now withdrawn from the molten mixture at such a rate that the crystal grows uniformly. When the crystal is completely grown it undergoes testing for net impurity polarity, resistivity, and minority carrier lifetime, as well as several mechanical parameters. It is then sliced into wafers for further processing.

THE PROCESSING OF THE WAFER

After the basic intrinsic wafers have been prepared they are sent to the wafer preparation station (see Figure 2-1). At this station the wafers are coated on one side with a boron dopant and on the other side with a phosphorus dopant. The wafer is then placed in a furnace, the elevated temperature diffusing the dopants into the silicon wafer in precisely controlled amounts. Thus, this diffusion process produces a p-n junction within each wafer.

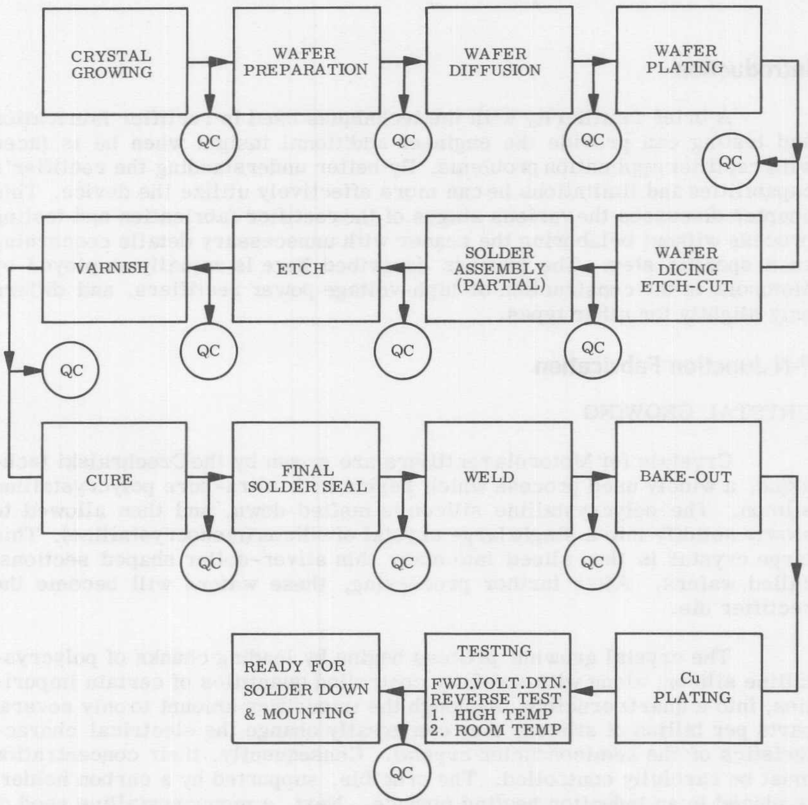


Figure 2-1. Flow Chart Illustrating the Major Steps of Wafer Preparation and Cell Assembly

An important step immediately follows the diffusion. When the wafers have adequately cooled, they are immersed in etchants. The etchants perform a number of important functions such as the separation of the wafers and removal of surface stresses. After the wafer separation is complete, they are rinsed and dried prior to a controlled sand blast pattern. Once again, the wafers are subjected to a cleaning solution for surface preparation. Gold makes an excellent soldering media, however, unfortunately, gold will not electrolytically deposit on silicon. Consequently, a nickel plate deposit is first deposited on the silicon, in order to provide a gold interface. The nickel is deposited on both faces of the silicon wafer.

The next process takes place at the dicing etch-cut station. At this station the nickeled wafer is masked and sprayed with an acid resistant material. The mask is so patterned so that the etch will produce a contoured edge around the periphery of the die. This contour helps create high-voltage devices, by producing a longer voltage path and, consequently, reducing surface breakdown. If no surface breakdown is possible, then the rectifier voltage maximum rating will be limited by bulk breakdown only. The masked wafer is now placed in an etch-out which removes all the uncovered silicon, leaving only the required die size. Consequently, from one large wafer, many individual p-n junctions are obtained. The die are then thoroughly cleaned and made ready for actual rectifier assembly. Between each of these stations a quality control department performs many tests to insure that the die has the desired electrical and mechanical characteristics.

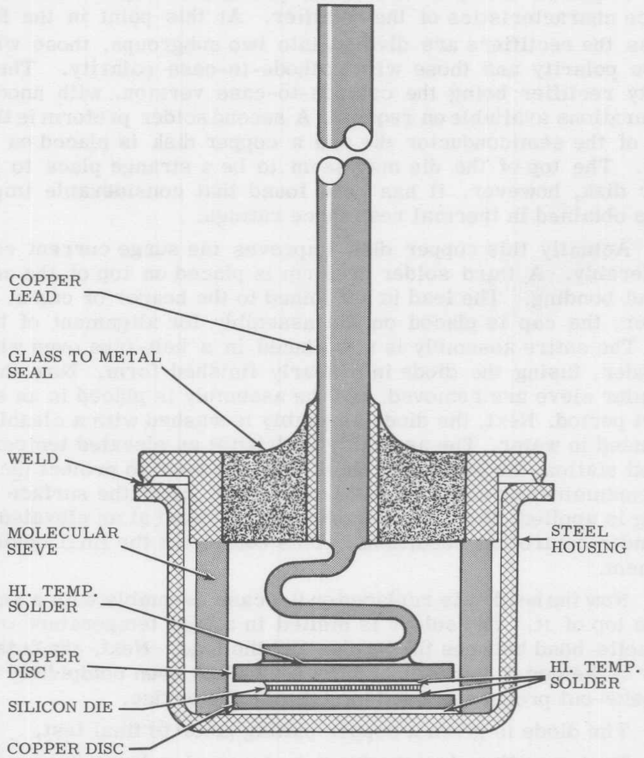


Figure 2-2. Cut-Away View of Basic Rectifier Cell Illustrating Mechanical Assembly Details

A new phase of rectifier assembly now begins, the semiconductor die having been properly formed must now be integrated into the proper mechanical assembly to produce the finished rectifier. The die first goes to the solder assembly station. This phase of rectifier assembly may be more easily explained by referring to the mechanical cut-away view (Figure 2-2). The first step is the insertion of the molecular sieve into the steel housing. This sieve serves two purposes. One, it centers the components inside the case. This centering is very important in the prevention of high-voltage arc-over, electrical shorts, and thermal fatigue failures. The molecular sieve also serves the function of collecting contaminates which sometimes cause surface malfunction. This contaminate reduction is especially effective in reducing low-voltage rectifier failure, since the low-voltage type cell never reaches surface breakdown in ordinary use. The lower voltage cells do not receive any elaborate surface coatings, such as those that the higher voltage rectifiers receive at a later state. (Due to this highly effective surface preparation, the molecular sieve is removed from the higher voltage rectifiers after component alignment is complete.) After the molecular sieve is placed in the case, a solder preform is in-inserted with it. This solder preform is simply a thin leaf of solder with a very high melting point (sometimes known as hard solder). A disk of copper is placed on top of this solder preform to improve the thermal resistance characteristics of the rectifier. At this point in the fabrication process the rectifiers are divided into two subgroups, those with anode-to-case polarity and those with cathode-to-case polarity. The standard polarity rectifier being the cathode-to-case version, with anode-to-case configurations available on request. A second solder preform is then placed on top of the semiconductor die and a copper disk is placed on top of the solder. The top of the die may seem to be a strange place to place this copper disk, however, it has been found that considerable improvement may be obtained in thermal resistance ratings.

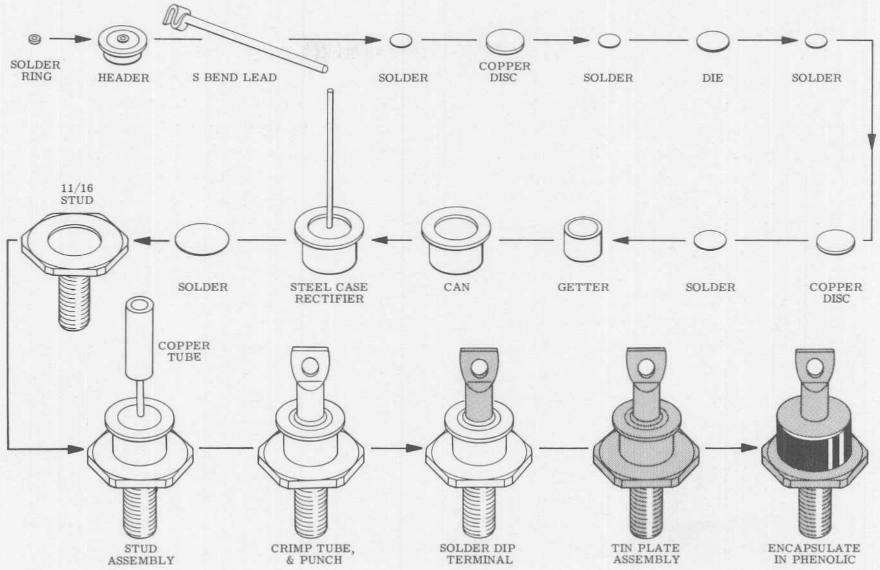
Actually this copper disk improves the surge current capabilities considerably. A third solder preform is placed on top of the copper disk for lead bonding. The lead is not joined to the header or cap at this time, however, the cap is placed on the assembly for alignment of the S bend lead. The entire assembly is now placed in a belt-type oven which melts the solder, fusing the diode into nearly finished form. Now the cap and molecular sieve are removed, and the assembly is placed in an etchant for a short period. Next, the diode assembly is washed with a cleaning solvent and rinsed in water. The assembly is dried at an elevated temperature. At the next station, the surface of the diodes is coated to protect the assembly from contaminating environmental conditions. After the surface protective coating is applied, the diode is covered and baked at an elevated temperature under controlled conditions. This completes the final device surface treatment.

Now the header is replaced on the case assembly with a small solder ring on top of it. The solder is melted in a high temperature oven creating a solid bond between the header and the lead. Next, the outside of the header is welded to the case and the device has been completely sealed. A final bake-out process is used to stabilize the device.

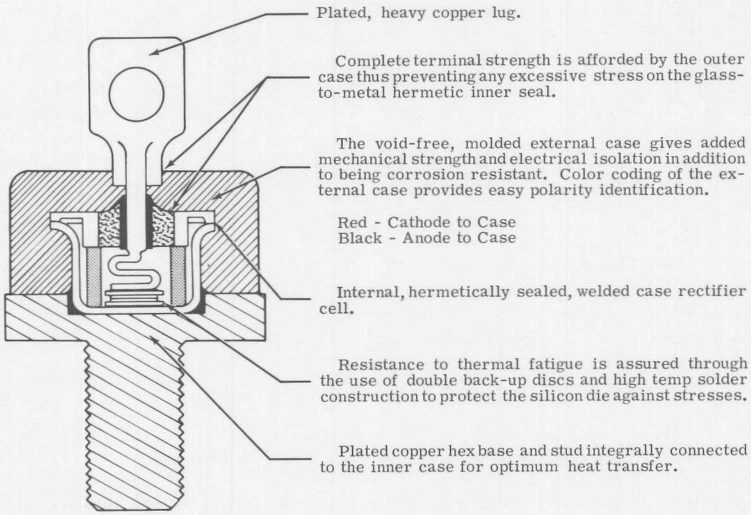
The diode is given a copper plating prior to final test.

Each rectifier has its dynamic forward voltage drop measured at about five times its rated current. During this phase of the testing, the devices are grouped according to forward voltage drop characteristics. All other tests are conducted with one group of matched devices: the reverse voltage is measured at a maximum leakage, both at room temperature and at 150°C case temperature.

From this point in the production many varieties may be designed from the one basic rectifier. Figure 2-3 shows the construction of the 1N249B, 1N250B, 1N2135A, and the 1N1198A. The higher current diodes are then constructed by paralleling as many as 48 diodes (1,000 amps).



(a)



(b)

Figure 2-3. (a) Flow Chart Illustrating Construction Sequence for "Typical" Rectifier such as the 1N249B
(b) Cut-away View of "Typical" Rectifier such as the 1N249B

Figure 2-3. (a) Flow Chart Illustrating Construction Sequence for "Typical" Rectifier Used in the 1N3493
(b) Cut-Away View of "Typical" Rectifier Used in the 1N3493

CHAPTER 3

Silicon Rectifier Ratings and Characteristics

Introduction

A thorough understanding of rectifier ratings and characteristics is one of the absolutely essential ingredients in the preparation of the design engineer. A fair question might be: What are ratings and characteristics. Well, a rating is a value assigned under specified test conditions to the device by its manufacturer which the manufacturer assets will enable the device to operate safely and satisfactorily. Operation of a device beyond its rating may cause immediate failure or gradual degradation of the device. A characteristic may be defined as a measurable value obtained under specified test conditions which is inherent on any given device.

This chapter attempts to explain those ratings and characteristics which are found on manufacturers data sheets. Each term will be fully defined. A short explanation will follow each definition.

Maximum Ratings

$V_{RM(rep)}$: MAXIMUM REPETITIVE PEAK-REVERSE VOLTAGE

The maximum repetitive peak-reverse voltage is defined as the maximum allowable instantaneous value of the reverse voltage, including all repetitive transient voltages, but excluding all nonrepetitive transient voltages which occur across a rectifier or rectifier stack (Figure 3-1).

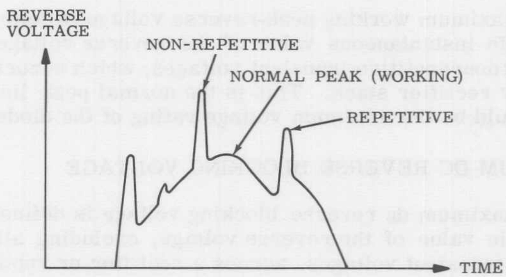


Figure 3-1. Reverse Voltage Waveform

The maximum reverse voltage rating is limited by the amount of reverse power being dissipated. Therefore, $V_{RM(rep)}$ is primarily dependent on two rectifier properties: one is the p-n junction itself, and the other is the case design. The reverse heating is proportional to the reverse power which is given by the product of the reverse voltage and the reverse leakage current [Equation (3-1)]. As the reverse voltage is increased, reverse leakage current will increase according to the V-I characteristics of each device. Unless the heat can be dissipated by the case, the junction temperature will rise rapidly. Increased junction temperature will cause a further increase in the reverse leakage current, which will further increase the junction temperature, etc. The mutual effects of the junction temperature and the reverse leakage current can lead to a condition called thermal runaway, in which the temperature increase is too high, causing device destruction.

The $V_{RM(rep)}$ rating is obtained at the worst-case conditions for each registration-number rectifier, thus assuring that the device will not suffer thermal runaway as long as $V_{RM(rep)}$ is not exceeded. The diode is rated in the following manner: It is placed in a controlled elevated-temperature environment, precisely set to the maximum hot junction operating temperature, and then subjected to either a reverse dc voltage or a half sine-wave of voltage. Its reverse leakage current is simultaneously recorded. If this leakage current is below the rated leakage for this type-number device, the voltage is increased until the maximum rated leakage current is actually obtained. In this manner, each device is actually tested at its maximum rated leakage current. Many manufacturers will test for $V_{RM(rep)}$ under dc conditions, since that test procedure can be easily reproduced by the user. The $V_{RM(rep)}$ value should never be exceeded under steady-state conditions. For most applications a rectifier with a $V_{RM(rep)}$ of about 2.5 times the maximum expected peak repetitive voltage should be used.

$$P_{rev} = V_{RM(rep)} \times I_{RM} \text{ or } \bar{P} = V_{DC} \times I_{DC} \tag{3-1}$$

$V_{RM(wkg)}$: MAXIMUM WORKING PEAK-REVERSE VOLTAGE

The maximum working peak-reverse voltage is defined as the maximum allowable instantaneous value of the reverse voltage, excluding all repetitive and nonrepetitive transient voltages, which occurs across a rectifier diode or rectifier stack. This is the normal peak line voltage. The $V_{RM(wkg)}$ would be the minimum voltage rating of the diode.

V_r : MAXIMUM DC REVERSE BLOCKING VOLTAGE

The maximum dc reverse blocking voltage is defined as the maximum allowable value of the reverse voltage, excluding all repetitive and nonrepetitive transient voltages, across a rectifier or rectifier stack.

$V_{RM(nonrep)}$: MAXIMUM NONREPETITIVE PEAK-REVERSE VOLTAGE

The maximum nonrepetitive peak-reverse voltage is the maximum allowable instantaneous value of the reverse voltage including all nonrepetitive transient voltages, but excluding all repetitive transient voltages, across a rectifier stack. Most Motorola rectifiers are tested under reverse voltage conditions of half-wave, single-phase, 60-cycle peak.

$$\frac{V_{RM(rep)}}{\sqrt{2}} \tag{3-2}$$

I_0: MAXIMUM AVERAGE FORWARD CURRENT

The maximum average forward current is defined as the maximum allowable value of the average forward current (averaged over full cycles under stated conditions). The test conditions used for most Motorola rectifiers are 60 Hz, single phase, with a resistive load, and case temperature at some elevated value. I_0 is measured by a dc ammeter which integrates the current over a full cycle. Note that most rectifier data sheets have a thermal derating curve. It is a plot of the allowable average forward current versus case temperature. The average current is always a calculated current based on the RMS rating of the device.

Any semiconductor rectifier contains a certain amount of inherent resistance. Although these resistance values are usually quite small at high currents they can produce significant heating. For this reason, RMS current rating is the limiting power dissipation factor. The maximum RMS current is independent of the case temperature. Ohmic heating is thermal effect completely distinct from average power junction heating, consequently, in most cases, due to cooling techniques (especially when the diode has natural convection cooling) its RMS limit is not reached. In some exceptional cases where excellent diode cooling exists, the RMS current limit can be reached and this is the reason for the sharp cutoff of the average current in the derating curves.

$I_{FM(rep)}$: MAXIMUM REPETITIVE PEAK-FORWARD CURRENT

The maximum repetitive peak-forward current is defined as the maximum allowable repetitive instantaneous peak-forward current permitted under static conditions of case temperature and $V_{RM(rep)}$ following each peak current. It is important to note that the RMS device limit may still not be exceeded. This type of rating is especially effective in applications possessing large capacitive loads where the peak-to-average ratios can be quite high.

$I_{FM(surge)}$: MAXIMUM NONREPETITIVE SURGE CURRENT

The maximum nonrepetitive peak surge current is defined as the maximum allowable nonrepetitive peak-forward current under the prescribed conditions of $V_{RM(rep)}$ (following surge), forward load current, peak surge current, case temperature (prior to surge current), and the frequency.

The rectifier must be capable of blocking $V_{RM(rep)}$ immediately after the surge current for at least 100 surges without degradation. The surge rating implies that the rectifier is operating at its rated $V_{RM(rep)}$, maximum average current I_0, and at its corresponding case temperature. Successive surges may not be applied until the rectifier has returned to its normal operating conditions. This normally requires 5 to 10 seconds. The surge current is a single-phase 60 Hz sinusoidal. The total waveform is composed of the normal load current and the superimposed surge current. Surge rating for test conditions other than those specified would, naturally, vary. It is evident upon examining the surge specifications for a given device, that the RMS rating and the maximum junction temperature have both, in all likelihood, been exceeded. Consequently, these conditions should be avoided in applications whenever possible. In an ideal circuit design, the circuit's short-circuit capabilities should be equal to or less than $I_{FM(rep)}$. This, of course, is not always economical and should not limit the designer from using $I_{FM(surge)}$ when necessary.

I^2t: (MAXIMUM RMS CURRENT)^2 SECONDS

The (maximum current)^2 seconds is defined as that maximum value of the forward nonrecurring overcurrent capability for 8.3 milliseconds or less. This value should never be exceeded – the protective fusing element should have an I^2t value less than the rectifier, so that the circuit "opens" before the rectifier can be damaged. It is important to note that this value is dependent on the number of surges. Calculations may be made using Equation (3-3). For further information, see the overcurrent protection chapter.

$$I^2t = (\text{RMS})^2 t$$
$$= (\text{Peak one cycle surge} \times 0.707)^2 \; 8.3 \text{ ms for one cycle} \qquad (3\text{-}3)$$

T_J: MAXIMUM AND MINIMUM INSTANTANEOUS OR CONTINUOUS JUNCTION OPERATION TEMPERATURE

The maximum and minimum instantaneous or continuous junction operating temperature is defined as the allowable value of temperature that exists at any instant of time without causing failure. The maximum value cannot exceed the temperature at which the device was classified for $V_{RM(rep)}$. In general, the cooler any semiconductor is operated the better it will function, but cracking of the crystal structure may occur below the rated minimum temperature. For further information, see the thermal characteristics chapter.

T_{stg}: MAXIMUM AND MINIMUM STORAGE JUNCTION TEMPERATURE

The maximum and minimum storage junction temperature is defined as the allowable value of temperature that exists during device storage. Note that either excessively hot or excessively cold temperatures can damage the device even though the device is not operating. Temperatures below −65°C can cause cracking of the crystal lattice with subsequent voltage degradation or catastrophic failure.

Electrical Characteristics

$V_{F(av)}$: AVERAGE FORWARD VOLTAGE DROP

The average forward voltage drop is defined as the average voltage which appears across the device over one complete cycle under the stated conditions of frequency, average forward current, single-phase operation, resistive load, case temperature, and rated reverse voltage.

V_F: DC FORWARD VOLTAGE DROP

The dc forward voltage drop is defined as that voltage which appears across the rectifier under the stated conditions of dc current and case temperature. This specification has gained widespread popularity since it is not difficult to accurately measure these small voltages.

$I_{R(av)}$: AVERAGE REVERSE LEAKAGE CURRENT

The average reverse leakage current is defined as the average value of the reverse leakage current over one complete cycle under the stated conditions of forward current, reverse voltage, 60 Hz sinusoidal, single-phase operation, resistive load, and case temperature. This specification serves as a comparison of the rectifier and an ideal switch of zero leakage in open position.

I_R: DC REVERSE LEAKAGE CURRENT

The dc reverse leakage current is defined as that leakage current through the rectifier in the reverse direction under the stated conditions of reverse voltage and case temperature. This value is often used in practice since it is easy to measure.

Thermal Characteristics

θ_{jc}: STEADY-STATE DC THERMAL RESISTANCE JUNCTION-TO-CASE

The steady-state dc thermal resistance junction-to-case is defined as the effective thermal resistance from junction-to-case. The effective thermal resistance is responsible for the temperature rise per unit power dissipation above the temperature of the external reference point. Since there are no transient temperature excursions, the equation $\Delta T = P\theta_{jc}$ may be used. For further information, refer to the next section.

Data Sheet Curves

FORWARD DROP CHARACTERISTICS

The forward drop characteristics curve is a plot of the instantaneous forward voltage in volts versus the instantaneous forward current in amperes at a constant junction temperature. From this one curve, nearly all of the important rectifier operating curves may be generated. There are usually at least two curves on the graph – which illustrate the effect of temperature on the forward voltage drop. These two curves will intersect at some elevated temperature, the point of intersection approximately equal to or greater than the peak surge current rating of the device. The curves are maximized so that all devices with this specification would have less power dissipation than would be given by V_F and I_F using this curve to estimate the values. Since rectifiers usually operate at a junction temperature above the room temperature, it is desirable to use the maximum allowable operating junction temperature to calculate the average power dissipation.

FORWARD POWER DISSIPATION

The forward power dissipation curve is a plot of the average forward power dissipation in watts versus the average forward current in amperes at a constant junction temperature. There are many different methods used to calculate the power dissipation in a rectifier. The easiest method makes the assumption that the power dissipation curve is sinusoidal as used in Equations (3-4) and (3-5).

$$\overline{P} = \frac{1}{2\pi} \int_0^{\pi} P_{peak} \sin\theta d\theta \tag{3-4}$$

where $P_{peak} = I_{peak} \times V_{peak}$.

$$I_{av} = \frac{1}{2\pi} \int_0^{\pi} I_{peak} \sin\theta d\theta \tag{3-5}$$

A power dissipation example: Find $\overline{P}$ dissipated when 12 amperes is flowing through an MR1120 (refer to MR1120 data sheet)

$$I_{av} = \frac{I_p}{2\pi} \int_0^{\pi} \sin\theta d\theta = \frac{I_{peak}}{\pi}$$

Therefore, 12 amperes $\times \pi = I_{peak} = 37.8$ amperes

V_F at 37.8 amperes peak = 0.99 volts when $T_j = 150°C$

$P_{peak} = I_{peak} \times V_{peak} = 37.8 \times 0.99 = 37.4$ watts

Assuming power waveform is sinusoidal

$$\frac{P_{av}}{P_{peak}} = 0.318 \qquad P_{av} = 37.4 \times 0.318 = 11.9 \text{ watts}$$

Note that at 12 amperes average current (single phase), the forward power dissipation is 12 watts. This method does not yield an exact solution since the power waveform is not sinusoidal, however, it is extremely rare for any device to exceed the values calculated by this method. Values for other devices may be obtained by using the same procedure as illustrated here—only changing the limits of integration.

Two other power estimation methods might be mentioned. One uses graphical integration to average the power waveform over the 2π time interval. The second method makes the assumption that the V_F versus I_F square plot is linear out to four times the RMS rating of the device, and then uses Equation (3-6).

$$P = \left(\frac{I_{av}}{S}\right)^{3/2} A + I_{av} V_0 \quad (3\text{-}6)$$

where V_0 = the voltage intercept

A = constant 1.55

S = the square function slope

A useful method of measuring the power dissipation is the following. First the rectifier is mounted on a heat sink, capable of holding the junction temperature below its maximum rated value when its rectifier is carrying full average current. A thermocouple is used to measure the heat sink temperature. The terminals of the rectifier are connected to an appropriate low-voltage high-current dc supply. The rectifier current, forward voltage, ambient temperature, and the heat sink temperature are all recorded. Using this data, a plot of the curve ΔT-versus-power, where $\Delta T = T_{heat\ sink} - T_{ambient}$ and power = VI. Next, the circuit is connected as shown in Figure 3-2(b).

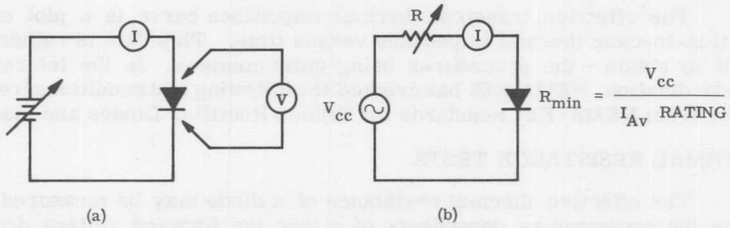


Figure 3-2. Empirical P Schematic

R or V_{CC} is varied such that the average current is caused to vary from a low value to its maximum average current rating. As R or V_{CC} is varied, the data is recorded as indicated before. The set of such readings forms a graph as shown in Figure 3-3.

From Figure 3-3 it can be seen that the curve of the actual power versus I_{av} can be obtained by interconnecting the dotted lines.

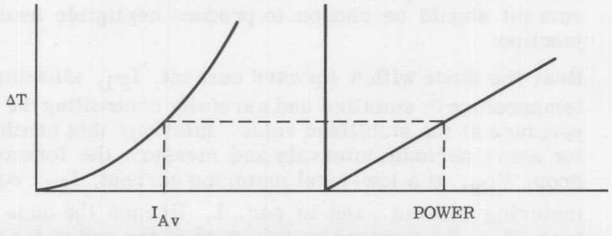


Figure 3-3. Actual Power vs. I_{av}

From the average power curves, all power data necessary to calculate the needed thermal cooling media may be obtained. Also, note that no additional calculations have been performed to account for such losses as blocking-loss and switching-loss. This is because the relative power-loss in these modes is insignificant when compared to the current-produced losses. Should these effects become significant for any particular application, then the manufacturer will always provide this information.

MAXIMUM ALLOWABLE SURGE CURRENT

The maximum allowable surge current is a plot of $I_{FM(surge)}$ versus the number of cycles at a 60 cps rate. This is a non-recurrent condition, and shows the allowable surge rating is dependent on the number of cycles. This is strictly an empirical test, consequently, many devices should be tested in order to insure a statistically significant result. After this failure data has been obtained, a safety-factor derating is added to enable the manufacturer to guarantee all devices under these conditions.

EFFECTIVE TRANSIENT THERMAL IMPEDANCE

The effective transient thermal impedance curve is a plot of the junction-to-case thermal impedance versus time. This data is rather difficult to obtain – the procedures being quite complex. In the interest of standardization, NEMA-EIA has created the following test conditions (reproduced from NEMA-EIA Standards for Silicon Rectifier Diodes and Stacks).

THERMAL RESISTANCE TESTS

The effective thermal resistance of a diode may be measured utilizing the temperature dependence of either the forward voltage drop or reverse current. However, the forward voltage drop has been demonstrated to have a more linear dependence on temperature and is, in general, more readily reproducible as shown in Figure 3-4 if a low-level metering current is used.

An effective thermal resistance measurement utilizing the temperature dependence of the forward voltage drop should be performed as follows:

1. Obtain a curve similar to Figure 3-4 by measuring the forward voltage drop as a function of junction temperature with the diode conducting a low-level metering current. This metering current should be chosen to produce negligible heating of the junction.

2. Heat the diode with a forward current, I_{F1}, allowing the case temperature to stabilize and carefully controlling the case temperature at the stabilized value. Interrupt this heating current for short periodic intervals and measure the forward voltage drop, V_{F2}, at a low-level metering current, I_{F2}, equal to the metering current used in par. 1. Record the case temperature, T_{C1}, the forward voltage drop at the end of the conduction period, V_{F2}, and the power dissipated, P_{F1} ($P_{F1} \approx V_{F1} \times I_{F1}$).

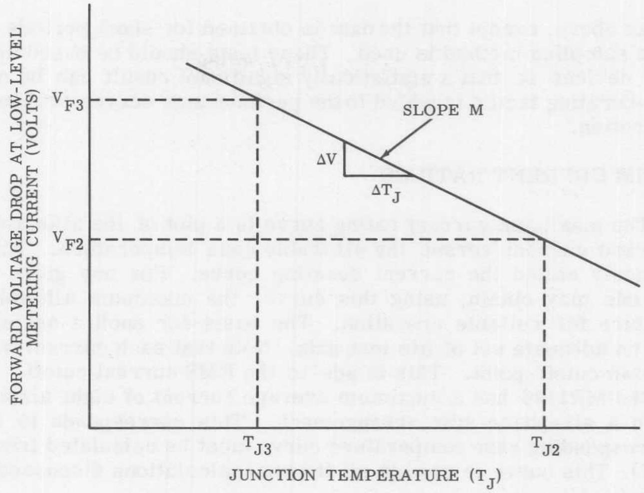


Figure 3-4. Linear Dependence of V_F on T_J

3. From the curve obtained in par. 1 a value of junction temperature at the end of the conduction period, T_{J2}, may be obtained for the forward voltage drop, V_{F2}, recorded in par. 2. The effective thermal resistance is then calculated from:

$$\theta_{jc} = \frac{T_{J2} - T_{C1}}{P_{F1}}$$

4. If it is not practical or convenient to obtain individual calibration curves, and it has been shown that the slope (M) of Figure 3-4 is uniform for a given group of devices, the value of T_{J2} may be obtained from:

$$T_{J2} = \frac{V_{F2} - V_{F3}}{M} + T_{J3}$$

where V_{F3} is measured at a convenient value of T_{J3} with the low-level metering current. Then,

$$\theta_{jc} = \frac{(V_{F2} - V_{F3})/M + T_{J3} - T_{C1}}{P_{F1}}$$

Then, because junction temperature even at steady-state conditions oscillates above and below the average junction temperature (due to pulsating current), an additional thermal impedance must be added to the dc thermal impedance. This additional term is known as the transient thermal impedance. This resultant additional thermal impedance is obtained by the same method as above, except that the data is obtained for short periods of time. The time sampling method is used. These tests should be based upon hundreds of devices so that a statistically significant result can be obtained. A safety-derating factor is added to the performance curves to insure reliable operation.

MAXIMUM CURRENT RATINGS

The maximum current rating curve is a plot of the allowable average forward current versus the allowable case temperature. This curve is commonly called the current derating curve. For any given average current one may obtain, using this curve, the maximum allowable case temperature for reliable operation. The basis for such a set of curves must be an adequate set of life test data. Note that each current waveform has its own cutoff point. This is ude to the RMS current cutoff. For example, the MR1126 has a maximum average current of eight amperes per device in a six-phase star arrangement. This corresponds to 19 RMS. The corresponding case temperature curve must be calculated from Equation (3-7). This curve is used in all thermal calculations discussed in later chapters.

$$T_J - T_C = \theta_{jc} \bar{P} \qquad (3\text{-}7)$$

$$T_C = T_J - \theta_{jc} \bar{P}$$

where T_J is the maximum operating temperature

θ_{jc} is the steady-state value for the specified current waveform

$\bar{P}$ is at the average power of the given current waveform.

There are other techniques of calculating the case temperature. Many are quite complex and require access to a large-scale computing machine. Also, devices which may employ forced air or water cooling may require an improvement factor in order to accurately estimate the case temperature.

MAXIMUM STUD TORQUE

The maximum stud torque limit is defined as the allowable torque which may be applied to the threaded portion of the stud in a dry-friction condition without damage to either the p-n junction or the case. By using this torque, the rectifier can be seated adequately for thermal impedance. This parameter will be discussed more fully in the section on heat sink applications.

CHAPTER 4

Single-Phase Rectifier Circuits

Introduction

Silicon rectifiers are often used in applications converting ac power to dc power. This function is usually accomplished by rectifying the ac waveform and removing the undesirable ripple with filters.

In the design and fabrication of practical ac-to-dc converters, it is necessary to employ considerable auxiliary equipment in addition to the basic rectifiers. Transformers, protective devices, and cooling apparatus are typical of the auxiliary equipment commonly used in such applications.

The transformer is usually used to change the supply voltage to the required dc output voltage. The rated current-handling capabilities of these power circuit transformers may usually be up-graded somewhat, for the following reason: transformers are usually rated for current-handling capabilities under sinusoidal test conditions. However, for many power circuits, the transformers carry nonsinusoidal currents – with the winding not carrying current continuously, but only intermittently, with lower transformer power dissipation being the result. Consequently, transformer current-handling ratings may be considered to be conservative estimates of their actual capabilities in most applications.

Rectifier Circuit Performance Characteristics

Listed below are the terms frequently used in rectifier circuit design. Brief definitions are provided.

I_{ac} = Effective value of all alternating components of the load current (ac meter current)

I_0 = Average value of load current (dc meter current)

I_{RMS} = Effective value of the total load current

$$I_{RMS} = \left(I_{ac}^2 + I_0^2\right)^{1/2}$$

F = Form factor = (I_{RMS}/I_0)

γ = Ripple factor

$$\gamma = \left[\left(\frac{I_{ac}}{I_0}\right)^2 - 1\right]^{1/2} = \left[F^2 - 1\right]^{1/2}$$

η_R = Rectification efficiency = $(P_0/P_{ac})(100)$

PIV = Peak inverse voltage of rectifier

R_S = Total equivalent series resistance (source resistance plus diode resistance)

$\omega = 2\pi f$ where f is the supply line frequency

R_L = Load resistance

V_0 = dc output voltage

V_m = Peak voltage

P_0 = Average power

I_s = Secondary RMS line current

V_s = Secondary RMS line voltage

I_p = Primary RMS line current

V_p = Primary RMS line voltage

Single-Phase Half-Wave Rectifier Circuit With Resistive Load

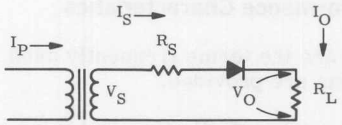


Figure 4-1. Half-Wave Rectifier.

The single-phase half-wave rectifier circuit with resistive load is shown in Figure 4-1. The waveform of the load voltage is illustrated in Figure 4-2. The current waveform, illustrated in Figure 4-2, is in phase with the load voltage.

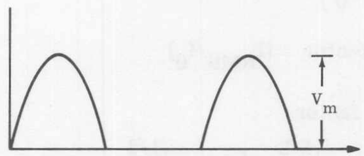


Figure 4-2. Half-Wave Rectified Sine Wave.

The characteristics of the half-wave rectifier circuit may be obtained by analyzing the waveform of Figure 4-2. These characteristics may be calculated from the following expressions:

(1) Peak current through rectifier and load

$$I_m = \frac{V_m}{R_s + R_L}$$

(2) Peak inverse voltage

$$PIV = V_m = \sqrt{2}\,V_s$$

(3) Average load current

$$I_0 = \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin\theta d\theta + \int_{\pi}^{2\pi} \theta d\theta\right]$$

$$I_0 = \frac{I_m}{\pi} = \frac{1}{\pi}\,\frac{V_m}{R_s + R_L}$$

(4)
$$I_{RMS} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} (I_m \sin\theta)^2 d\theta + \int_{\pi}^{2\pi} \theta d\theta\right]}$$

(5)
$$V_{RMS} = \frac{V_m}{2}$$

(6) Average load voltage

$$V_0 = I_0 R_L = \frac{I_m R_L}{\pi} = \frac{V_m}{\pi}\left(\frac{R_L}{R_s + R_L}\right)$$

(7) Average power

$$P_0 = I_0 V_0 = \left[\frac{V_m}{\pi(R_s + R_L)}\right]\left[\frac{V_m R_L}{\pi(R_s + R_L)}\right] = \frac{V_m^2 R_L}{\pi^2 (R_s + R_L)^2}$$

(8) Efficiency

$$\eta_R = \frac{P_0}{P_{ac}}(100) = \frac{V_0 I_0}{V_{RMS} I_{RMS}}(100) = \frac{\left[V_m^2 R_L/\pi^2 (R_s + R_L)^2\right]}{\left[V_m^2/4(R_s + R_L)\right]}(100) = \frac{40.6\%}{(1 + R_s/R_L)}$$

(9) Ripple factor

$$\gamma = \left[\left(\frac{I_{RMS}}{I_0}\right)^2 - 1\right]^{1/2} = \left[\frac{\pi^2}{4} - 1\right]^{1/2} = 1.21 \text{ or } 121\%$$

Transformer construction characteristics:

(1) Secondary RMS voltage

$$V_s = \frac{V_m}{\sqrt{2}} = \frac{\pi V_0}{\sqrt{2}\,\sin \pi/2} = 2.22\,V_0$$

(2) Secondary RMS line current

$$I_s = \frac{\pi\sqrt{(1/2\pi)(\pi/2 + \sin \pi/2)}}{\sin(\pi/2)}\,I_0 = \frac{\pi I_0}{2} = 1.57 I_0$$

(3) Maximum transformer current (secondary)

$$I_m = \pi I_0 = 3.14 I_0$$

$$I_m = 2\,I_s$$

(4) Primary RMS current

$$I_{0(RMS)} = \sqrt{I_s^2 - I_0^2} = \sqrt{(1.57\,I_0)^2 - I_0^2} = 1.21\,I_0$$

Therefore, $I_p = 1.21\,(N_s/N_p)I_0$

(5) Secondary rating

$$V_s I_s = (2.22\,V_0)(1.57\,I_0) = 3.49\,V_0 I_0$$

(6) Primary rating

$$V_p I_p = (N_p/N_s)V_s(1.21)(N_s/N_p)I_0 = (2.22\,V_0)(1.21 I_0) = 2.7\,V_0 I_0$$

The above equations apply to a half-wave rectifier with a resistive load only. Although the dc resistance of the transformer is included in R_S, the reactance of the transformer has been neglected. The maximum theoretical rectification efficiency of the circuit is 40.6 per cent.

The ripple factor of the half-wave rectifier is 121 per cent—a rather large ripple. For this reason, filters are usually employed to reduce the ripple voltage. Reactive elements may also be used to filter the undesired ac sources.

Single-Phase Half-Wave Rectifier Circuit With Capacitive Filter

Capacitive load filtering (as shown in Figure 4-3) is frequently used to reduce ripple current. The filtering action of this circuit depends on the basic fact that a capacitor stores energy. Therefore, we have a two energy-source system: the "charging" current through the diode, and the capacitor discharge current. Figure 4-4 shows the voltage and current waveforms for the half-wave rectifier.

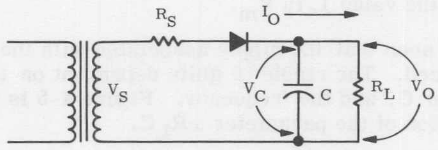


Figure 4-3. Half-Wave Rectifier Circuit with Capacitive Filter.

The change in voltage is given by the expressions, where T_1 is the capacitor discharge time.

$$E_R = \frac{I_0 T_1}{C}$$

$$E_R = \frac{I_0 V_0}{2fCV_m}$$

The output voltage is given by the expression

$$V_0 = \frac{V_m - I_0/4fC}{1 + I_0/4fCV_m} \qquad (4\text{-}1)$$

The output ripple is calculated from

$$\gamma = \frac{I_0}{4fC\sqrt{3}}\left(\frac{1}{V_m} + \frac{1}{V_0}\right) \qquad (4\text{-}2)$$

The diode peak voltage is

$$PIV \cong 2\,V_m \qquad (4\text{-}3)$$

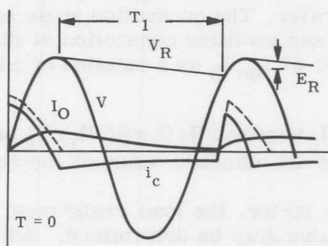


Figure 4-4. Voltage and Current Waveforms for the Half-Wave Rectifier with Capacitive Input Filter.

This expression is highly accurate for high load impedances. If the forward current is large, the PIV may drop slightly below the value 2 V_m, but never below the value 1.75 V_m.

It can be seen that the ripple associated with the output voltage can be greatly reduced. The ripple is quite dependent on the load resistance R_L, the capacitor C, and the frequency. Figure 4-5 is a plot of the ripple factor as a function of the parameter $\omega R_L C$.

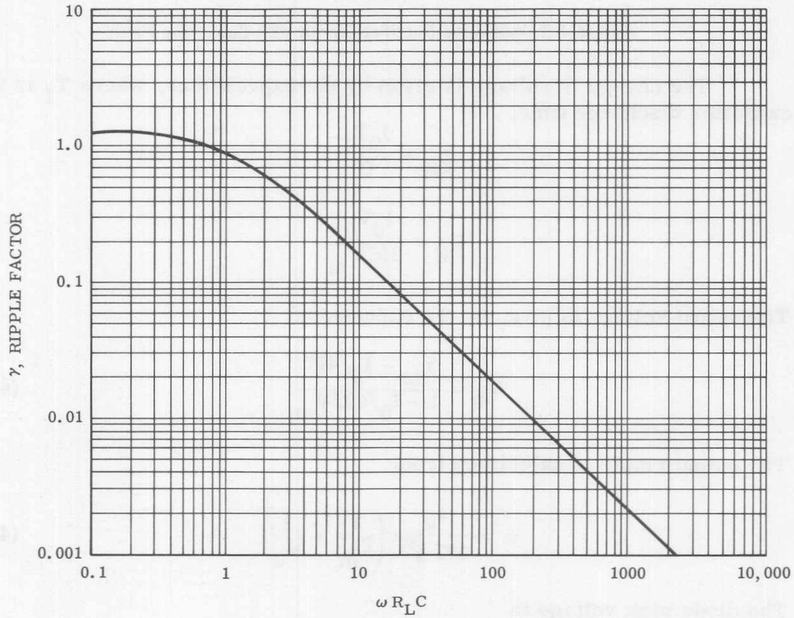


Figure 4-5. Ripple Factor versus $\omega R_L C$.

By using capacitive filtering, highly repetitive peak current may be passed through the rectifier. The conduction angle is changed by capacitor charge and discharge, and rectifier conduction at different voltage levels. Figure 4-6 shows a plot of I_m/I_0 as a function of $\omega R_L C$ with R_S/R_L as a parameter.

A plot of I_{RMS}/I_0 versus $\omega R_L C$ with R_S/R_L as a parameter is given by Figure 4-7. I_{RMS} is the effective value of the current in the rectifier.

When the ripple factor, the load resistance, and ω are known, the required capacitance value may be determined. Additional series resistance may be required to limit the turn-on surge current to a safe value when the circuit is turned on. Occasionally, the initial surge current will be the primary determining factor in the selection of a rectifier for a given application. However, in general, the surge current, the peak repetitive current, and the RMS current must be known for proper device selection.

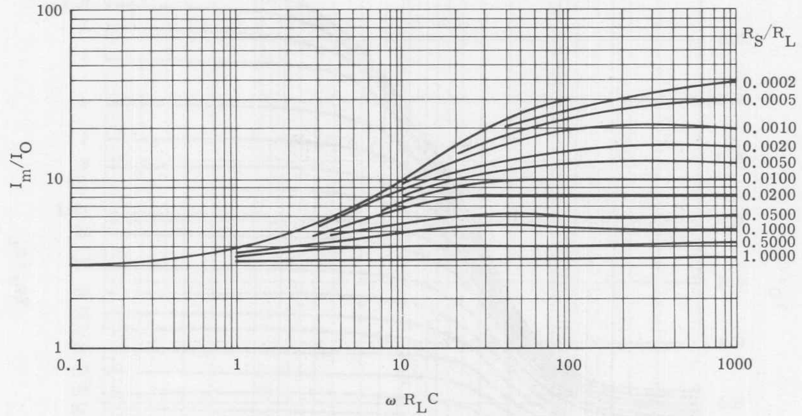


Figure 4-6. I_m/I_O versus $\omega R_L C$.

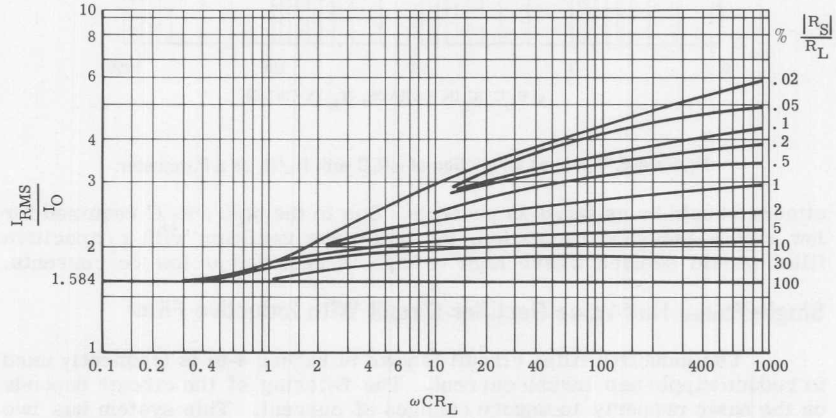


Figure 4-7. I_{RMS} versus $\omega R_L C$.

The charging rate of a capacitor is controlled by the $R_S C$ time constant. If this value is small compared to the half-cycle period of the ac supply, the capacitor will charge in the first cycle of the line voltage. If not, the charging current will consist of several successive surges, the peak value of each surge decreasing exponentially in amplitude. Thus, the time constant of the charging current must be considered when selecting the rectifier element, if the initial surge current is the controlling factor.

It can be seen that the ratio of V_0/V_m approaches unity when $\omega R_L C$ is large and R_s is small. For good regulation with varying load, the capa-

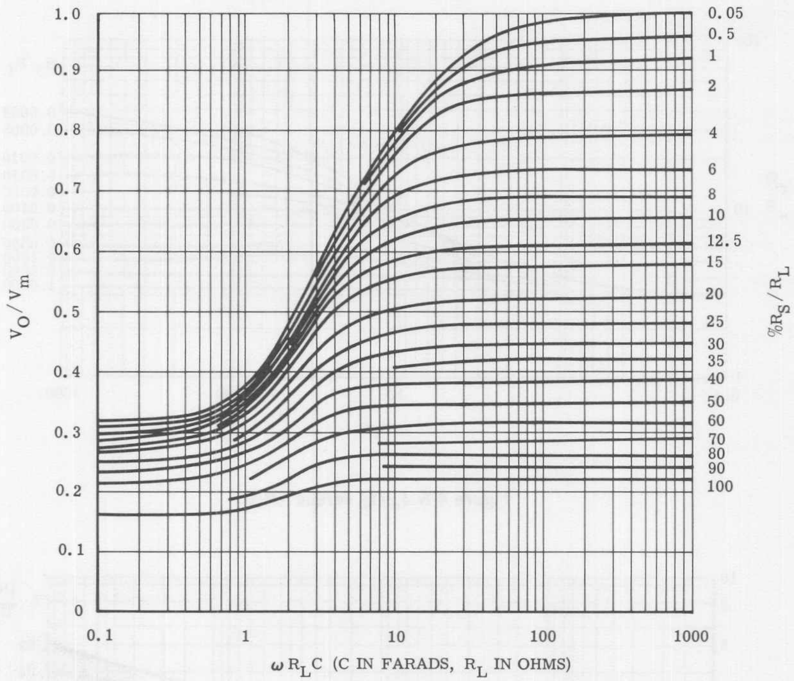


Figure 4-8. V_O/V_m as a Function of $\omega R_L C$ with R_S/R_L as a Parameter.

citance should be as large as possible. Due to the high $\omega R_L C$ required for low ripple and good regulation, the half-wave rectifier with a capacitive filter should be used where high voltage is required at low dc currents.

Single-Phase Half-Wave Rectifier Circuit With Inductive Filter

The inductive filter circuit (shown in Figure 4-9) is frequently used to reduce ripple and inrush current. The filtering of the circuit depends on the basic property to oppose changes of current. This system has two energy sources, much like the capacitively filtered system with the series inductor replacing the discharging capacitor. The simple inductive filter is seldom used with a half-wave circuit, since it is a current operated filter. Figure 4-10 shows the effect of the inductance on the waveform of the output current.

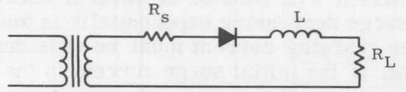


Figure 4-9. Half-Wave Rectifier with Series Inductor.

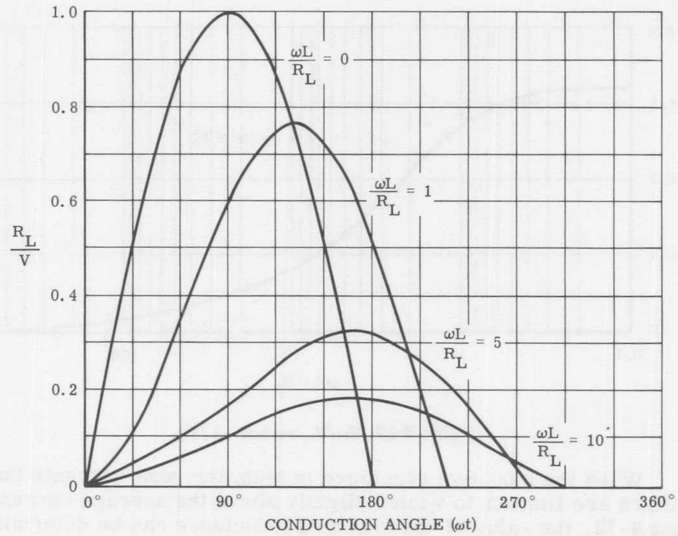


Figure 4-10. The Effect of Changing the Inductance on the Waveform of the Output Current in a Half-Wave Rectifier with an Inductor Filter. The Load Resistance R is Assumed Constant.

The inductor acts as a high impedance to the harmonic components of the load current. When the current is above its average value, energy is stored in the inductor; when the current is below the average value, the stored energy is released. Figure 4-11 is a plot of the ripple factor as a function of $\omega L/R_L$.

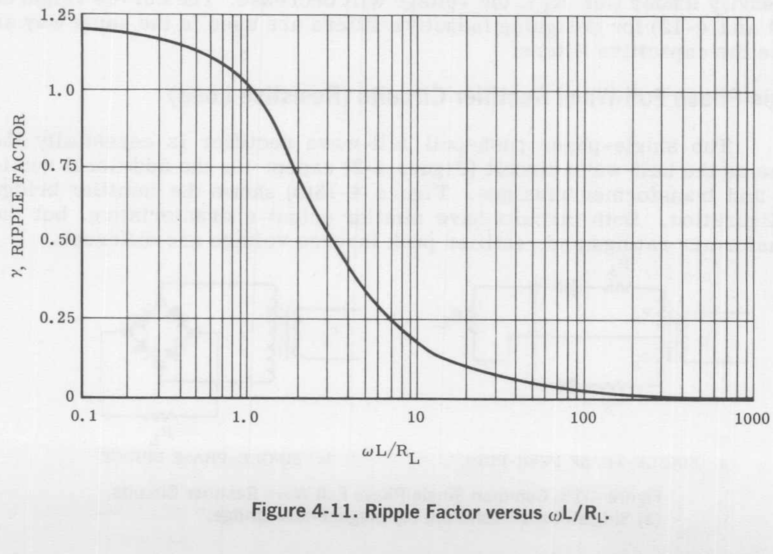


Figure 4-11. Ripple Factor versus $\omega L/R_L$.

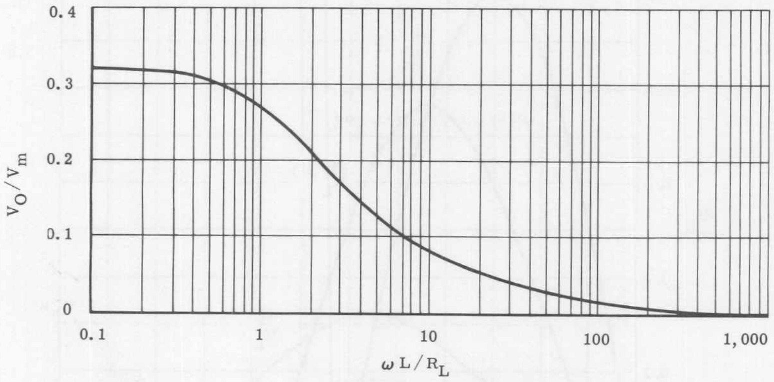


Figure 4-12. V_O/V_m **versus** $\omega L/R_L$**.**

When the inductive reactance is high, the peak currents through the rectifiers are limited to values slightly above the average current. From Figure 4-12, the value of the required inductance can be determined when the ripple factor, the load resistance, and the supply frequency are known.

The series inductor circuit has the advantages of lower peak currents through the rectifier and better voltage regulation. The maximum peak inverse voltage is V_m, the peak value of the input voltage.

Since the effect of adding inductance to the circuit is an increase in the lag between voltage and current, it also results in a decrease in average load voltage. When the load resistance is large, the output voltage is the highest. When the output of a half-wave rectifier with series inductor is heavily loaded (low R_L), the voltage will decrease. The curves (Figures 4-11 and 4-12) for designing inductive filters are used in the same way as those for capacitive filters.

Single-Phase Full-Wave Rectifier Circuits (Resistive Load)

The single-phase push-pull full-wave rectifier is essentially the same as the half-wave circuit (Figure 4-2) except for the additional rectifier and transformer windings. Figure 4-13(b) shows the familiar bridge configuration. Both circuits have similar output characteristics, but the transformer ratings and rectifier peak inverse voltage are different.

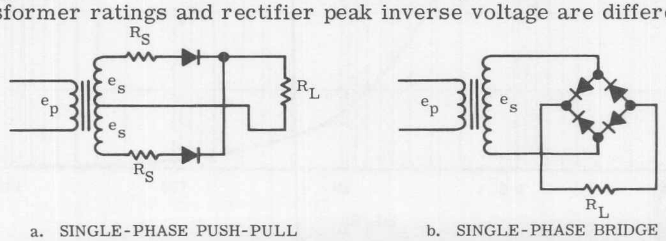


Figure 4-13. Common Single-Phase Full-Wave Rectifier Circuits. (a) Single-Phase Push-Pull; (b) Single-Phase Bridge.

The output voltage waveforms of the push-pull rectifier and the full-wave bridge rectifier are shown in Figure 4-14. If the transformer reactance is neglected, the current and voltage curves will be in phase and have the same waveform characteristics.

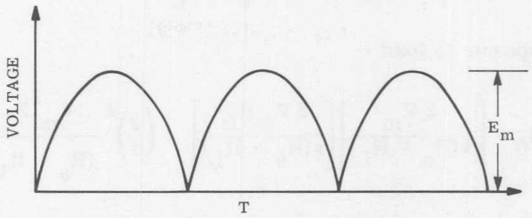


Figure 4-14. Full-Wave Rectified Sine Wave.

The full-wave push-pull rectifier with resistive load will have characteristics given by the following equations:

(1) Peak current through the load and rectifier

$$I_m = \frac{V_m}{R_s + R_L}$$

(2) Average load current

$$I_0 = \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin\theta d\theta + \int_{\pi}^{2\pi} (I_m \sin\theta)^2 d\theta\right]$$

$$I_0 = \frac{2 I_0}{\pi} = \frac{2 V_m}{\pi(R_s + R_L)}$$

(3) Effective load current

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} (I_m \sin\theta)^2 d\theta + \int_{\pi}^{2\pi} (I_m \sin\theta)^2 d\theta\right]}$$

$$I_{RMS} = \frac{I_m}{\sqrt{2}} = \frac{V_m}{\sqrt{2}\,(R_s + R_L)}$$

(4) Effective transformer voltage

$$V_{RMS} = \frac{V_m}{\sqrt{2}}$$

(5) Average load voltage

$$V_0 = I_0 R_L = \frac{2 V_m R_L}{\pi (R_s + R_L)}$$

(6) Average power to load

$$P_0 = V_0 I_0 = \left[\frac{2 V_m}{\pi (R_s + R_L)}\right]\left[\frac{2 V_m R_L}{\pi (R_s + R_L)}\right] = \left(\frac{2}{\pi}\right)^2 \frac{V_m{}^2 R_L}{(R_s + R_L)^2}$$

(7) Efficiency

$$\eta = \frac{P_0}{P_{ac}} (100) = \frac{(2/\pi)^2 V_m{}^2 R_L/(R_s + R_L)^2}{(V_m/\sqrt{2})(V_m/\sqrt{2}\,(R_s + R_L)} (100) = \frac{8}{\pi^2}\left(\frac{100}{1 + R_s/R_L}\right)\%$$

(8) Ripple factor

$$\gamma = \left[\left(\frac{I_{RMS}}{I_0}\right)^2 - 1\right]^{1/2} = \left[\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1\right]^{1/2} = 0.48 \text{ or } 48\%$$

Transformer characteristics:

Push-pull rectifier circuits

(1) Secondary RMS voltage

$$V_s = \frac{V_m}{\sqrt{2}} = \frac{\pi V_0}{2\sqrt{2}} = 1.11\ E_0$$

(2) Secondary RMS current per winding

$$I_s = \frac{I_m}{2} = \frac{\pi I_0}{4} = 0.785\ I_0$$

(3) Maximum secondary current

$$I_{ms} = \frac{\pi I_0}{2} = 1.57\ I_0 = 0.23\ I_s$$

(4) Primary RMS current

$$I_p = \sqrt{2}\left(0.785\ I_0\right)\left(\frac{N_s}{N_p}\right) = 1.11\left(\frac{N_s}{N_p}\right) I_0$$

(5) Secondary rating

$$2\,V_sI_s = 2(1.11\,E_0)(0.785\,I_0) = 1.74\,E_0I_0$$

(6) Primary rating

$$V_pI_p = (N_p/N_s)(V_s)(1.11)(N_s/N_p)\,I_0 = 1.23\,E_0I_0$$

Note that the secondary winding is utilized for one-half the cycle. Also, the RMS current is the same as for the half-wave circuit.

From an analysis of the circuit, it can be seen that the peak inverse voltage of the rectifier is twice the maximum value of the applied voltage per winding.

Bridge rectifier circuit characteristics

(1) Secondary RMS voltage

$$V_s = \frac{V_m}{\sqrt{2}} = \frac{\pi V_0}{2\sqrt{2}} = 1.11\,E_0$$

(2) Secondary RMS current

$$I_s = \frac{I_m}{\sqrt{2}} = \frac{\pi I_0}{2\sqrt{2}} = 1.11\,\not{E}_0\,I_0$$

(3) Maximum secondary current

$$I_{ms} = \frac{\pi I_0}{2} = 1.57\,I_0$$

(4) Primary RMS current

$$I_p = \left(\frac{N_s}{N_p}\right)I_s = 1.11\left(\frac{N_s}{N_p}\right)I_0$$

(5) Secondary rating

$$V_sI_s = (1.11\,E_0)(1.11\,I_0) = 1.23\,E_0I_0$$

(6) Primary rating

$$V_sI_s = (1.11\,E_0)(1.11\,I_0) = 1.23\,E_0I_0$$

The peak inverse voltage across the rectifier is equal to the peak value of the transformer secondary voltage.

Both of the circuits have the weak and strong points. In push-pull full-wave rectifiers, two windings are required, and each of these conducts for only half-time. Also, the peak inverse voltage across the rectifier is high. The full-wave bridge circuit requires two additional rectifiers increasing cost and power loss, but reducing the peak inverse voltage across each rectifier by 50 per cent (compared to push-pull rectifier). Also, the full-wave bridge circuit does not require transformers with high ratings.

Both full-wave rectifier circuits are considerably more efficient than half-wave rectifier circuits. The maximum full-wave efficiency is approximately twice the half-wave efficiency, and the ripple factor is reduced from 121 per cent to 48.7 per cent.

Even in view of this significant ripple factor reduction, the ripple associated with full-wave rectifiers is usually too great for most applications without filters.

Single-Phase Full-Wave Rectifier Filters

Either capacitive or inductive filtering may be used in full-wave rectifier circuits. These filters are used in nearly the same manner for full-wave rectifier circuits as for half-wave circuits, but smaller values of L and C are usually sufficient to obtain the same ripple factor. Figure 4-15 shows the ripple factor for both inductive and capacitive filtering. This curve will be accurate only for $R_S << R_L$.

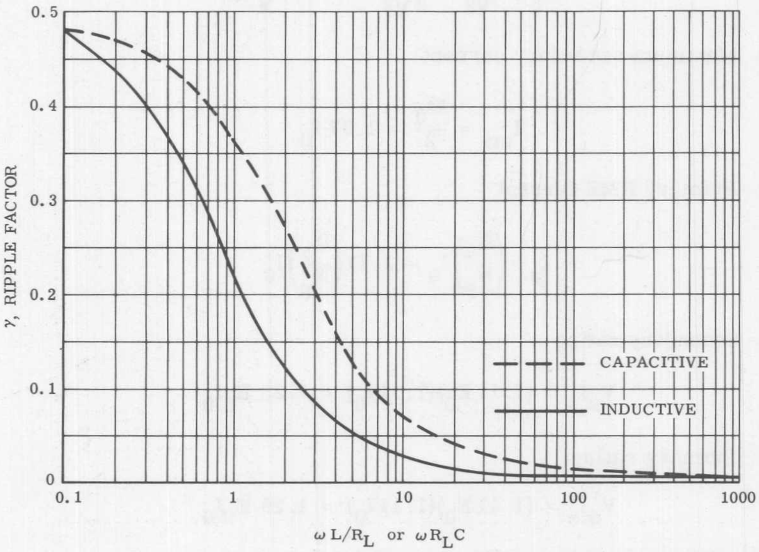


Figure 4-15. Ripple Factor versus $\omega R_L C$ (or $\omega L/R_L$) in the Full-Wave Rectifier

Single-Phase Full-Wave Rectifier Circuit With Capacitive Filter

Using a capacitive filter, the designer can expect high peak currents in the half-wave rectifier circuit. Figure 4-16 illustrates this problem. I_m is the repetitive peak current through the rectifier. Figure 4-17 shows the relationship of the RMS current of the rectifier and the average rectifier current as a function of $\omega R_L C$.

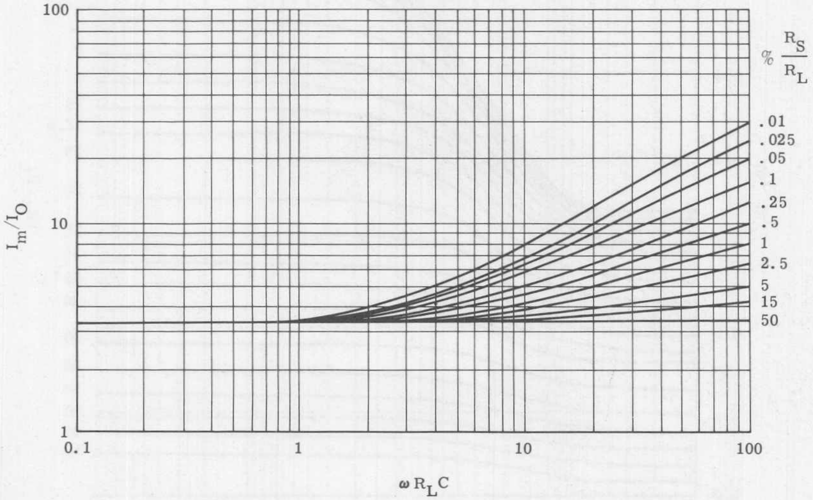


Figure 4-16. I_M/I_O versus $\omega R_L C$ for a Full-Wave Rectifier.

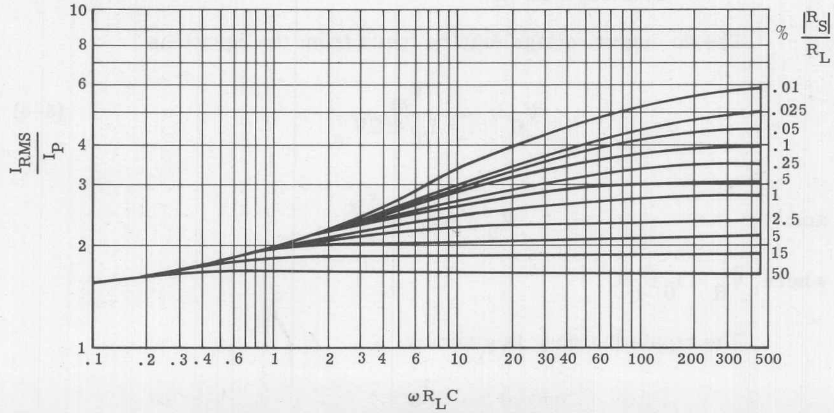


Figure 4-17. I_{RMS}/I_O (per rectifier) versus $\omega R_L C$.

The average value of the peak currents must be kept within the rated average half-wave rectifier current. Since the waveform is nonsinusoidal, a graphical method of determining the average current may be used.

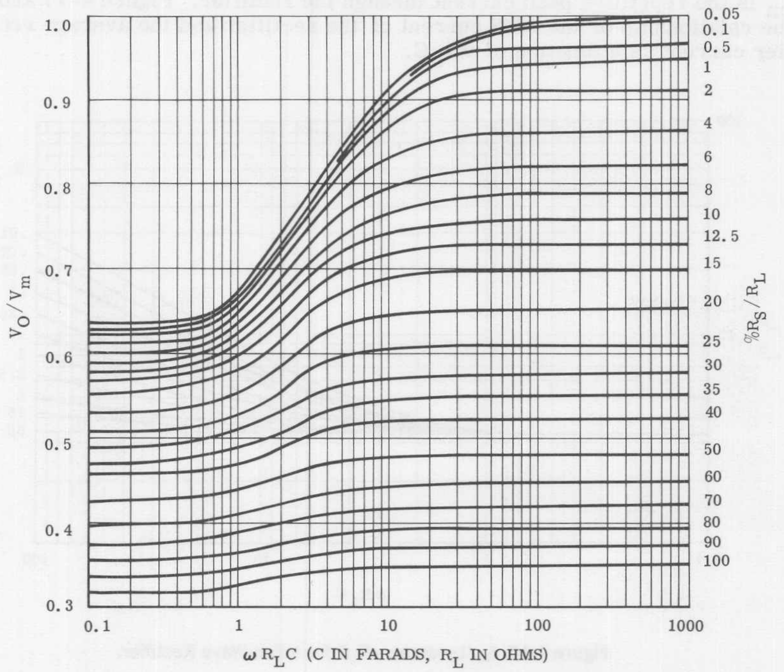


Figure 4-18. V_O/V_M **versus** $\omega R_L C$**. The Output Voltage may be found if** R_L **is Varied.**

The dc output voltage may be found from the equations

$$V_0 = \frac{V_m}{1 + I_0/4fCV_m} \qquad (4\text{-}4)$$

and

$$V_0 = V_m - \frac{V_R}{2}$$

where $V_R = I_0 T_1/C$.

The ripple factor γ is given by

$$\gamma = \frac{I_0}{4\sqrt{3}\, fCV_m} \qquad (4\text{-}5)$$

Single-Phase Full-Wave Rectifier Circuit With Inductive Filter

Several factors contribute to the lack of design equations for the single-phase full-wave rectifier circuit with inductive filter. One, the load current never reaches zero in the inductive load and this makes exact equations impractical for most applications. Second, since L sections and π filters produce better filtering characteristics, little work has been done in this area.

The dc output voltage is given by

$$V_0 = I_0 R_L = \frac{2\,V_m}{\pi} = 0.90\,V_s \qquad (4\text{-}6)$$

From the following equation it may be seen that V_0 decreases as I_0 increases

$$V_0 = \frac{2\,V_m}{\pi} - I_0 R$$

where R is the resistance of the load circuit, excluding the load.

The ripple factor γ is given by

$$\gamma = \frac{R_L}{3\sqrt{2}\,\omega L} \qquad (4\text{-}7)$$

Single-Phase Full-Wave Rectifier Circuit With L-Section Filter

The L-section filter (Figure 4-19) combines the decreasing ripple and increasing load of the series inductor with increasing ripple with increasing load of the shunt capacitor. The inductor appears as a high series impedance and the capacitor as a low shunt impedance to the harmonic terms.

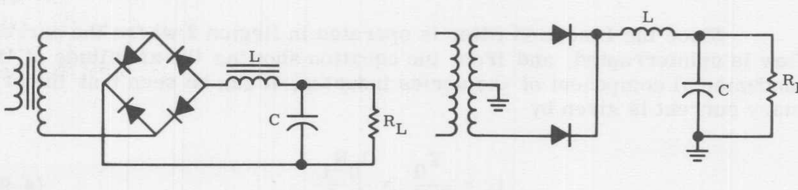


Figure 4-19. The L-Section Filter

The filter circuit operates in the following manner: when $R_L \rightarrow \infty$, that is, under unloaded conditions ($I_0 = 0$), the filter capacitor will charge to V_m, the peak voltage. The output voltage will therefore be equal to the peak value of the input voltage. As the load resistance decreases and the load current increases, the capacitors will charge and discharge at some rate of time. The average value of the output voltage will be less than V_m.

When the load current is small, the energy stored in the inductor will also be small and the inductor essentially out of the circuit. This accounts for the low current region as shown in Figure 4-20.

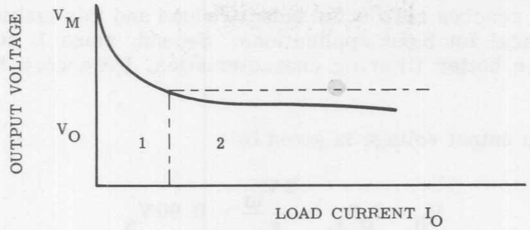


Figure 4-20. Regulation Curve for Full-Wave Rectifier with L-Section Filter.

Region 1 (Figure 4-20) is a discontinuous current operating mode. Region 2 is a continuous operating mode. As the load current is increased, the conduction angle increases until all diodes are operating in Region 2. As more current flows, the energy stored in the series inductor becomes a greater influencing factor.

The ripple components, clearly, are the even harmonics. Therefore, to minimize these terms, L should have a high reactance and C a low reactance at the second frequency. Since C is to have negligible reactance,

$$R_L >> \frac{1}{2\omega C}$$

$$C = \frac{0.0562}{f\gamma R_K} \tag{4-8}$$

where R_K is the bleeder shunt resistance.

Since the L-section filter is operated in Region 2 where the current flow is uninterrupted, and from the equation showing the amplitude of the fundamental component of the series inductor, it can be seen that the primary current is given by

$$i_p = \frac{V_0}{3\omega L} = \frac{I_0 R_L}{3\omega L} \tag{4-9}$$

If the peak negative excursion of current does not exceed I_0, then the coil current will not be interrupted and the operation in Region 2 will be accomplished. Therefore,

$$L = \frac{0.471 + \gamma}{4\omega^2 C\gamma} = \frac{R_K}{3\omega}\left(1 + \frac{\pi}{0.471}\right) \tag{4-10}$$

The critical inductance is

$$L_C = \frac{R_L}{3\omega} \tag{4-11}$$

where R_L is the total resistive load.

The ripple factor is

$$\gamma = \frac{0.471}{4\omega^2 LC - 1}$$

$$\gamma = \frac{0.83}{LC} \quad \text{at 60 cps} \tag{4-12}$$

where L = henrys

C = microfarads.

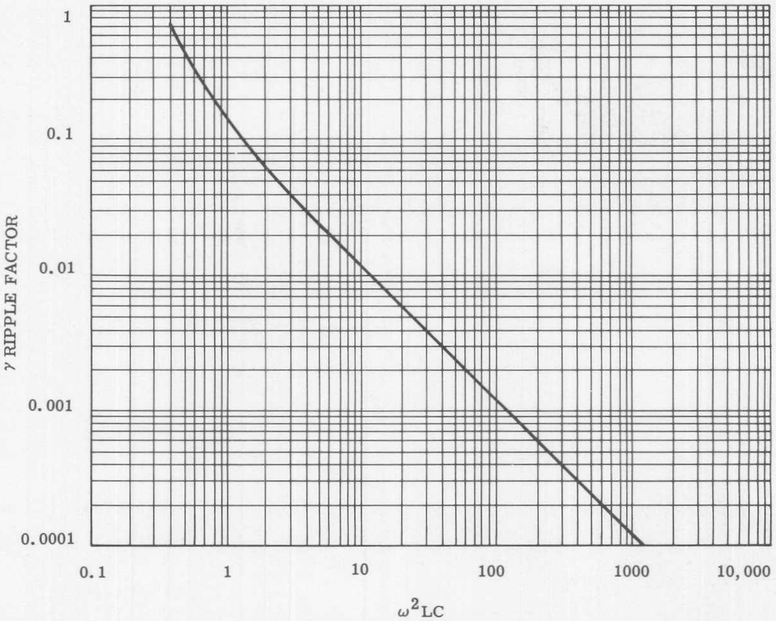


Figure 4-21. Ripple Factor versus ω^2LC for Full-Wave Rectifier Single-Phase Source.

The value of the bleeder resistor placed in shunt with the capacitor becomes obvious when the inductor is not a swinging choke type. R_K may be calculated from the following equation. I_K is assumed to be one-tenth the minimum load current.

$$R_K = \frac{V_0}{I_K} \tag{4-13}$$

Multiple L-sections have as ripple factor

$$\gamma = \frac{0.471}{(4\omega^2 L_1 C_1 - 1)(4\omega^2 L_2 C_2 - 1) \cdots (4\omega^2 L_N C_N - 1)}$$

and

$$LC = 1.76 \left(\frac{0.471}{\gamma}\right)^{1/N} \qquad (4\text{-}14)$$

CHAPTER 5

Multiphase Rectifier Circuits

Introduction

In applications involving very high power control, polyphase rectifier circuits are nearly always used. The basic reason for the selection of polyphase circuits is twofold: One, all large power sources, distributed by the power companies, are three-phase systems; second, semiconductor diodes approach optimum utilization in high polyphase operations. Polyphase circuits have many other desirable features, such as low ripple and high rectification efficiency.

In modern multiphase power systems, transformer design is of fundamental importance. In such applications the primary of the transformers is often connected in a delta configuration with the secondary windings connected as either a wye or delta configuration, or both. While the primary source of power is distributed as a three-phase system, phase transformation (with transformers) can yield six phases, 12 phases, or many other polyphases.

The silicon rectifier has made the use of polyphase circuits much more practical than earlier elements, such as tubes and selenium or copper oxide rectifiers. The reasons for the superiority of the silicon rectifier over all other types will become apparent in later sections of this chapter. The conversion of old systems to compact and efficient silicon rectifiers is a straightforward, uncomplicated procedure. Motorola's Semiconductor Applications Engineering department is always ready to provide assistance on your specific rectifier applications problem.

General Voltage and Current Relationships in Polyphase Rectifiers

The analysis of polyphase rectifier circuits may be greatly simplified, if the transformers and rectifiers are idealized; that is, they are assumed to possess no resistance or leakage reactance. Naturally, in actual practice this is not the case. Losses are incurred due to resistances and reactances in the transformers and rectifiers which affect the output characteristics. However, allowances can be made for these losses, and highly accurate value obtained from such an analysis.

General expressions can be derived for polyphase rectifiers which greatly reduce the computations required in circuit design. Figure 5-1 shows the rectified voltage waveform for the general case of a multiphase rectifier circuit.

Conduction takes place through the rectifier with the highest voltage across it. It should be apparent from Figure 5-1 that neither the voltage nor the current is ever zero in the load, and that the current is relatively constant. The instantaneous load voltage of Figure 5-1 is equal to the voltage of the conducting phase, and is given by

$$V = V_m \sin \theta \qquad (5\text{-}1)$$

where V_m = the peak-to-neutral voltage

m = the number of output pulses per cycle.

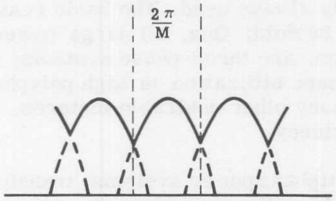


Figure 5-1. Rectified Voltage Waveform For Multiphase Rectifier Circuit

The dc load voltage is given by

$$V_0 = \frac{V_m}{2\pi/m} \int_{(\pi/2) - (\pi/m)}^{(\pi/2) + (\pi/m)} \sin \theta d\theta$$

$$V_0 = V_m \left(\frac{m}{\pi} \sin \frac{\pi}{m} \right) \qquad (5\text{-}2)$$

The necessary line-to-neutral or line-to-line voltage,

$$V_s = \frac{\pi V_0}{\sqrt{2}\, m \sin (\pi/m)} \qquad (5\text{-}3)$$

The average current per phase is given by

$$I_{av} = \frac{I_m}{2\pi} \int_{(\pi/2) - (\pi/m)}^{(\pi/2) + (\pi/m)} \sin \theta d\theta$$

$$I_{av} = \frac{I_m}{\pi} \left[\sin \left(\frac{\pi}{m} \right) \right] \qquad (5\text{-}4)$$

The RMS value of the secondary phase current is

$$I_s = \left[\frac{1}{2\pi}\int_{(\pi/2)-(\pi/m)}^{(\pi/2)+(\pi/m)} I_m^2 \sin^2\theta d\theta\right]^{1/2}$$

$$I_s = I_m\left[\frac{1}{2\pi}\left(\frac{\pi}{m} + \frac{1}{2}\sin\frac{2\pi}{m}\right)\right]^{1/2} \tag{5-6}$$

From Equation (5-5)

$$I_m = \frac{\pi I_0}{m\sin(\pi/m)}$$

Therefore
$$I_s = \frac{I_0\pi\sqrt{(1/2\pi)[\pi/m + (1/2)\sin 2\pi/m]}}{m\sin(\pi/m)} \tag{5-7}$$

For m greater than or equal to 3, Equation (5-7) may be approximated by

$$I_s = \frac{I_0}{\sqrt{m}} \tag{5-8}$$

The utility factor, defined as the ratio of the dc power output to the load to the volt-ampere rating of the transformer bank, is commonly used to compare the quality of rectifier circuits. Thus, the utility factor may be expressed as

$$UF = \frac{V_0 I_0}{mV_s I_s}$$

$$UF = \frac{\sqrt{2}}{\pi}\sin\frac{\pi}{m} \tag{5-9}$$

Equation (5-7) is obtained by direct substitution of Equation (5-1) into Equation (5-5), and using the approximating relationship given in Equation (5-8). It has been found that the maximum utility factor is obtained with a three-phase system; beyond this point the utility factor decreases with increasing phases.

This indicates that a higher secondary kilovolt-ampere rating is required for a given dc power output as the number of phases increases. This is one of the principal disadvantages of high polyphase rectifier circuits. However, there are special six anode secondary winding connections which attain the reduced ripple factor of higher polyphase systems and still have the secondary utilization factor of the three-phase system.

The utility factor is also commonly referred to the primary side of the transformer. In this case, V_s and I_s are replaced by V_p and I_p in Equation (5-9).

A simple expression for the ripple factor can be obtained for the general polyphase rectifier system by applying Fourier analysis to the waveform. The resulting expression is given by

$$\gamma_n = \frac{V_{mn(max)}}{\sqrt{2}\, V_0} = \frac{\sqrt{2}}{\left[(nm)^2 - 1\right]} \qquad (5\text{-}10)$$

where m = the number of output pulses per cycle (number of rectifier anodes)

n = the order of the harmonic

γ_n = the ripple factor due to the n^{th} harmonic

V_{max} = the peak voltage of the n^{th} harmonic.

In Equation (5-10), the only harmonics involved are multiples of m. Thus, for m = 3, only the third, sixth, ninth, etc., harmonics contribute to the ripple voltage. The third harmonic is the fundamental frequency component.

The general expression given above describes any polyphase system with a common neutral where current flows in only one phase at a time. However, the expression is also valid if line-to-line voltages are used, and the current expressions are modified.

Leakage reactance in a transformer causes overlap, a period where current flows in two rectifiers of different branches at one time. Leakage inductance will not allow current in the individual phases to change instantaneously. The overall effects of overlap are to reduce the output of the rectifier circuits. This reduction, along with the voltage drop in the rectifier and transformer, may be used to correct from the idealized case. The expression is given by the following equation:

$$V = V_0 - \left(\frac{mX}{2\pi} I_0 + RI_0 + V_R\right) \qquad (5\text{-}11)$$

where V = actual output voltage

V_0 = idealized output voltage

m = number of phases or elements

X = ωL, the transformer leakage reactance

I_0 = output current

R = transformer resistance per phase relative to secondary

V_R = voltage drop of the rectifier elements at I_0.

In order to determine the current direction one must construct a vector plot of each voltage phase against a vector projection plane. Figure 5-2 is such a plot.

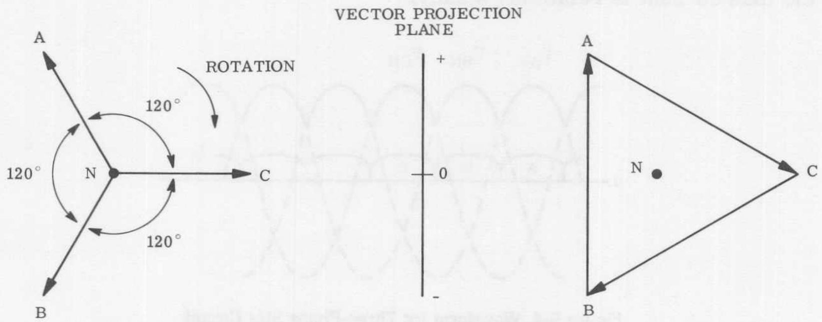


Figure 5-2. Plot of Voltage Phase Versus Vector Projection Plane

The current path is determined by perpendicular lines projected from the vector projection plane to the vector plot. Referring to Figure 5-2, current will flow from A to N when there is a neutral connection, or from A to B when there is no neutral connection. This is a plot of ABC rotation. Studying this type of plot makes natural line commutation readily understood.

Three-Phase Star Rectifier Circuit

The three-phase star rectifier circuit, often referred to as the three-phase half-wave rectifier, is illustrated in Figure 5-3. The load is resistive. The associated voltage and current waveforms are shown in Figure 5-4.

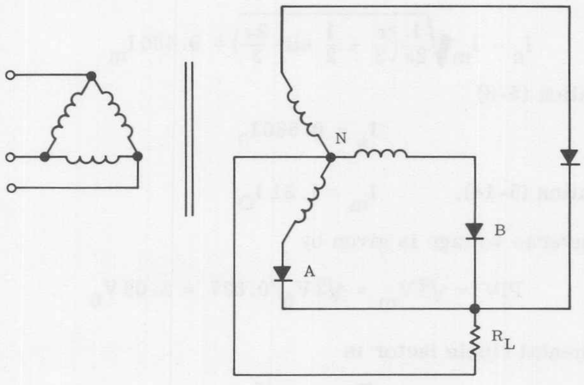


Figure 5-3. Three-Phase Star Rectifier Circuit

The circuit of Figure 5-3 is the simplest three-phase rectifier circuit; it employs only one rectifier per phase. It can be seen from Figure 5-4 that each phase lasts for $2\pi/3$ radians, or 120° of each cycle, and that the load current is relatively steady.

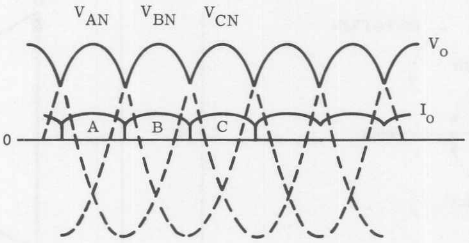


Figure 5-4. Waveform for Three-Phase Star Circuit

General equations have been developed to explain the behavior of this type of circuit. From Equation (5-2),

$$V_0 = \frac{3}{\pi} V_m \sin\frac{\pi}{3} = 0.827 V_m = 0.827\sqrt{2}\, V_s = 1.17 V_s \qquad (5\text{-}12)$$

From Equation (5-12), $V_s = 0.855 V_0$ (5-13)

From Equation (5-5),

$$I_0 = \frac{3 I_m}{\pi} \sin\frac{\pi}{3} = 0.827 I_m \qquad (5\text{-}14)$$

From Equation (5-7),

$$I_s = I_m \sqrt{\frac{1}{2\pi}\left(\frac{\pi}{3} + \frac{1}{2}\sin\frac{2\pi}{3}\right)} = 0.486 I_m \qquad (5\text{-}15)$$

From Equation (5-8)

$$I_s = 0.586 I_0 \qquad (5\text{-}16)$$

From Equation (5-14), $I_m = 1.21 I_O$ (5-17)

The peak inverse voltage is given by

$$PIV = \sqrt{3}\, V_m = \sqrt{3}\, V_0/0.827 = 2.09 V_0 \qquad (5\text{-}18)$$

The fundamental ripple factor is

$$\gamma = \frac{\sqrt{2}}{\left[(3)^2 - 1\right]} = \frac{\sqrt{2}}{8} = 0.177 \qquad (5\text{-}19)$$

The efficiency of the rectifier can be obtained by finding the ratio of the ac power output to the dc power output. This is given by the following expressions:

$$I_{RMS(load)} = \sqrt{3}\, I_s = \sqrt{3}\,(0.586)\, I_0 = 1.015\, I_0$$

$$\eta = \frac{P_0}{P_{ac}}(100) = \frac{I_0^2 R_L}{(1.015\, I_0)^2 R_L}(100) = 97\% \qquad (5\text{-}20)$$

This efficiency value represents the maximum conversion efficiency of the rectifier system, and should not be thought of as an overall efficiency.

The transformer ratings are obtained in a similar manner; the mean value of the secondary phase current is one-third of the dc output current. The RMS value of the ac component of the secondary is

$$\sqrt{I_s^2 + I_{av}^2} = \sqrt{(0.586\, I_0)^2 - \left(\frac{I_0}{3}\right)^2} = 0.484\, I_0$$

Therefore, the primary current is

$$I_p = 0.484\, I_0 \left(\frac{N_s}{N_p}\right) \qquad (5\text{-}21)$$

The secondary rating is

$$3\, V_s I_s = (3)(0.855)\, V_0 (0.586)\, I_0 = 1.50\, V_0 I_0 \qquad (5\text{-}22)$$

and the primary rating is

$$3 V_p I_p = 3\left(\frac{N_p}{N_s}\right) V_s (0.484)\left(\frac{N_s}{N_p}\right) I_0 = 3(0.850) V_0 (0.484) I_0 = 1.24\, V_0 I_0 \qquad (5\text{-}23)$$

It can be seen that the three-phase star rectifier system has a much lower ripple factor than the single-phase systems. The conversion efficiency is also much higher. The principal limitation of the three-phase star rectifier circuit is only one secondary phase conducts at a time, and, consequently, the transformer primary must be delta connected.

Three-Phase Star Rectifier Circuit with Resistance-Inductance Load

The use of an inductive load in the star rectifier circuit smooths the current waveform through the resistive load. The analysis of this circuit is very similar to the preceding one; both the voltage waveform and the average voltage are the same as with the resistive load circuit. The inductor in series with the load resistance decreases the ac component of the load voltage. The smoothing factor is given by

$$\delta = \sqrt{1 + Q^2} \tag{5-24}$$

where Q is the ratio of the reactance X_L to the load resistance R_L. The ripple factor of the load is reduced by

$$\gamma R = \frac{0.177}{\sqrt{1 + Q^2}} \tag{5-25}$$

If the load is highly reactive, the load current becomes nearly constant.

Three-Phase Inter-Star Rectifier Circuit

The three-phase inter-star rectifier circuit does not suffer from many of the limitations of the three-phase star circuit. This circuit is shown in Figure 5-5.

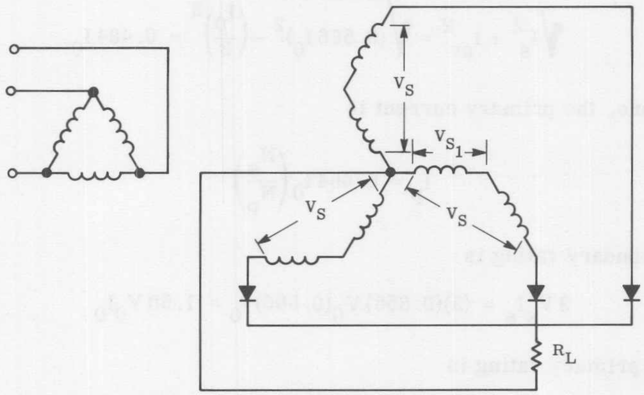


Figure 5-5. The Three-Phase Inter-Star Circuit

The secondary windings consist of identical coils, with any pair of coils forming a phase, located on different branches of the transformer. Thus, two primary phases are carrying equal currents at the same time. Either a delta or a star-connected transformer may be used in this circuit.

The primary rating is reduced, since each primary phase passes current twice per cycle, but the secondary rating is increased due to the inter-star connection. The voltage across two coils of each phase is $\sqrt{3/2}$ as great as that which exists in the three-phase star circuit. The secondary rating is $2/\sqrt{3}$ times as great as the regular star circuit.

For the three-phase inter-star rectifier circuit m is equal to 3, and the same voltage-current values hold as with the three-phase star circuit. The transformer ratings are as follows:

$$V_s = \sqrt{3}\, V_{s1}$$

$$V_{s1} = \frac{V_s}{\sqrt{3}} = \frac{E_0}{2}$$

The primary phase carries current twice per cycle and is given by

$$I_p = \sqrt{2}\left(\frac{N_s}{N_p}\right) I_s = 0.825\left(\frac{N_{s1}}{N_p}\right) I_0 \tag{5-26}$$

The secondary rating is

$$6\, V_{s1} I_s = 6\left(\frac{E_0}{2}\right)(0.586\, I_0) = 1.75\, E_0 I_0 \tag{5-27}$$

The primary rating is then

$$3\, V_p I_p = 3\left(\frac{N_p}{N_{s1}}\right) V_s (0.825)\left(\frac{N_{s1}}{N_p}\right) I_0 = 3\left(\frac{E_0}{2}\right)(0.825\, I_0) = 1.24\, E_0 I_0 \tag{5-28}$$

Three-Phase Full-Wave Bridge Circuit

The three-phase full-wave bridge circuit has a low ripple factor, and a high utility factor. Because of this, it is one of the most common rectifier circuits. A schematic of the circuit is shown in Figure 5-6. The voltage waveforms are shown in Figure 5-7.

Each conduction path through the transformer and load passes through two rectifiers in series; a total of six rectifier elements are required. Commutation in the circuit takes place every 60°, or six times

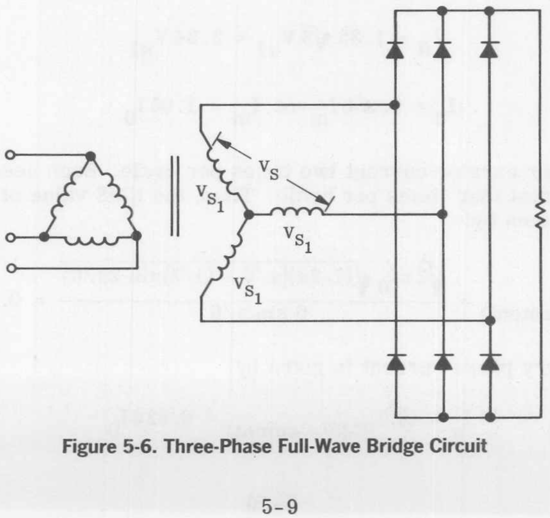


Figure 5-6. Three-Phase Full-Wave Bridge Circuit

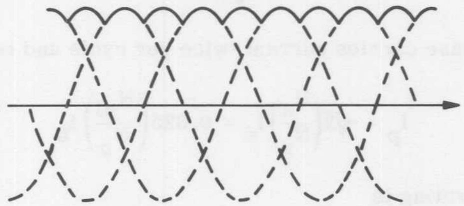


Figure 5-7. Voltage Waveforms Three-Phase Full-Wave Bridge Circuit

per cycle. This reduces the ripple factor and increases the frequency of the fundamental harmonic voltage. Thus, with this circuit the low ripple factor of a six-phase system is achieved while still obtaining the high utility factor of a three-phase system.

For an analysis of this circuit, m is equal to six and V_s is the line-to-line voltage. Using the general expressions

$$V_0 = V_m \frac{6}{\pi} \sin \frac{\pi}{6} = 0.956\, V_m = 0.956\sqrt{2}\, V_s = 1.35\, V_s \tag{5-29}$$

$$V_s = \sqrt{3}\, V_{s1} \tag{5-30}$$

$$V_0 = 1.35\sqrt{3}\, V_{s1} = 2.34\, V_{s1} \tag{5-31}$$

$$I_0 = 0.956\, I_m \quad \text{or} \quad I_m = 1.05\, I_0 \tag{5-32}$$

Each rectifier carries current two times per cycle. Each secondary phase carries current four times per cycle. Thus, the RMS value of the rectifier current is given by:

$$I_{RMS(element)} = \frac{\sqrt{2}\,\pi I_0 \sqrt{(1/2\pi)[\pi/6 + (1/2)\sin 2\pi/6]}}{6 \sin \pi/6} = 0.580\, I_0 \tag{5-33}$$

The secondary phase current is given by

$$I_s = \sqrt{2}\, I_{RMS(element)} = 0.820\, I_0 \tag{5-34}$$

The peak inverse voltage is

$$\text{PIV} = \sqrt{3}\,V_{s1m} = \frac{\sqrt{3} \times \sqrt{2}}{2.34} V_0 = 1.04\,V_0 \qquad (5\text{-}35)$$

The transformer ratings are also easily computed

$$I_p = \left(\frac{N_s}{N_p}\right) I_s = 0.820 \left(\frac{N_s}{N_p}\right) I_0$$

$$3\left(\frac{V_s}{\sqrt{3}}\right) I_s = 3\left(\frac{0.740\,E_0}{\sqrt{3}}\right)(0.820\,I_0) = 1.05\,E_0 I_0 \text{ (star-connected secondary)}$$

Primary rating = secondary rating

A star or a delta-connected primary may be used, since current flows in two phases at one time.

The ripple factor for the fundamental frequency [Equation (5-10)] is equal to 4.2 per cent. The utility factor is 1/1.05, or 0.955, making the three-phase full-wave bridge circuit one of the most desirable rectifying circuits.

The addition of an inductor in series with the load will smooth the load current as it does in the three-phase half-wave rectifier circuit. However, since the load current is already relatively smooth, the load current will not change appreciably.

Three-Phase Double-Wye Rectifier with Interphase Transformer

The three-phase double-wye rectifier circuit is frequently used due to its high utility factor (comparable to the three-phase star circuit) and its low ripple factor (comparable to the six-phase systems). It has advantages over the three-phase full-wave bridge circuit due to more efficient utilization of the rectifier elements.

The circuit (Figure 5-8) consists essentially of two three-phase star circuits with their neutral points interconnected through an interphase transformer or reactor. The purpose of the reactor is to equalize the phase-to-neutral voltages of the two sections. The voltage impressed across the reactor is the difference of the phase groups. One-half of this difference is either added to or subtracted from a group. This permits two phases to carry current at the same time.

The three-phase double-wye rectifier circuit has many characteristics of the three-phase star circuit. The output voltage is the same as the three-phase star system.

$$V_0 = 1.17\,V_s$$

$$V_s = 0.855\, V_0$$

Each group supplies one-half the dc output current. Therefore,

$$I_s = 0.293\, I_0$$

$$I_m = 1.05\left(\frac{I_0}{2}\right) = 0.525\, I_0$$

The transformer ratings are

$$I_p = \sqrt{2}\left(\frac{N_s}{N_p}\right) I_s = 0.414\left(\frac{N_s}{N_p}\right) I_0 \qquad (5\text{-}36)$$

$$6\, V_s I_s = 6(0.855\, V_0)(0.293\, I_0) = 1.50\, E_0 I_0$$

$$3\, V_p I_p = 3(0.855)\left(\frac{N_p}{N_s}\right)(V_0)(0.41)\left(\frac{N_s}{N_p}\right) I_0 = 1.05\, E_0 I_0$$

The peak inverse voltage for this circuit is higher than the three-phase star system due to the interphase reactor. It is approximately

$$\text{PIV} = 2.42\, E_0 \qquad (5\text{-}37)$$

The interphase transformer must withstand the voltage between the two neutral points of the individual groups. To maintain this voltage gradient, some current must flow at all times. If the current becomes small, the circuit will revert to that of a six-phase star. Thus, minimum reactor

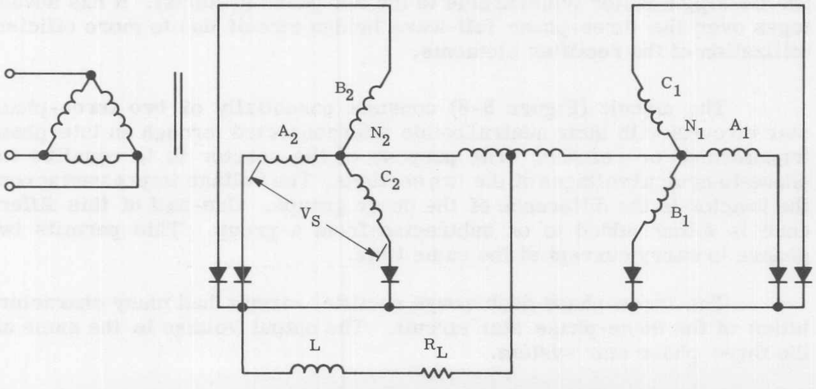


Figure 5-8. The Three-Phase Double-Wye Circuit

inductance is required to assure current flow. The current from groups one and two may be expressed as a Fourier series. The difference between the two series is the magnetizing current of the reactor. This magnetizing current circulates between the two groups. Its major component is the third harmonic. The direct current carried by the reactor (one-half the load current) must be greater than the maximum value of the excitation current. This may be expressed

$$\frac{I_0}{2} \geq I_{3m} = \frac{V_{3m}}{3\omega L} \tag{5-38}$$

The maximum value of the third harmonic voltage is given by

$$V_{3m} = \frac{3\sqrt{3}\, V_{s(max)}}{4\pi} \tag{5-39}$$

and the minimum inductance by

$$L_{min} \geq \frac{\sqrt{3}\, V_{s(max)}}{2\pi\omega I_0} = \frac{0.390\, V_s}{\omega I_0} \tag{5-40}$$

A series inductor, usually employed in the load circuit, decreases the ripple factor by $\sqrt{1 + Q^2}$.

Six-Phase Star Rectifier Circuit

The six-phase star rectifier circuit is often referred to as the three-phase diametric rectifying circuit because it has a center-tapped transformer. The six-phase star circuit is shown in Figure 5-9.

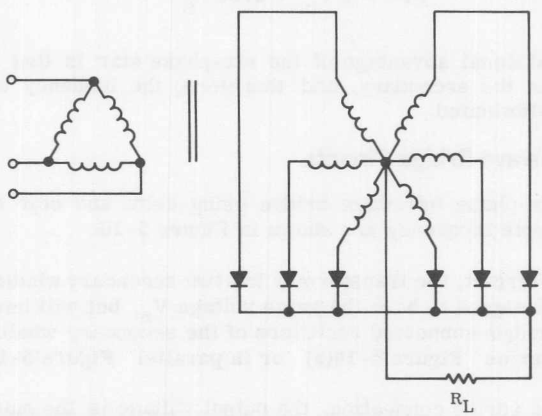


Figure 5-9. The Six-Phase Star Circuit

The six-phase star circuit is used in applications which require a low ripple factor and a common cathode or anode connection. It should be noted that current flows in only one rectifying element at a time. The primary winding, therefore, must be delta connected.

The following circuit characteristics can be easily obtained from the general rectifier equations where m is equal to six. These are as follows:

$$V_s = 0.741\,E_0$$

$$I_s = 0.410\,I_0$$

$$I_m = 1.05\,I_0$$

$$\gamma = 0.042 \text{ (fundamental)}$$

$$\eta = 99.5\%$$

$$I_p = 0.580\left(\frac{N_s}{N_p}\right)I_0$$

$$6\,V_s I_s = 1.82\,E_0 I_0$$

$$3\,V_p I_p = 1.28\,E_0 I_0$$

The peak inverse voltage on the rectifier, twice the peak phase voltage, is given by

$$PIV = 2\,V_m = 2.09\,V_0 \tag{5-41}$$

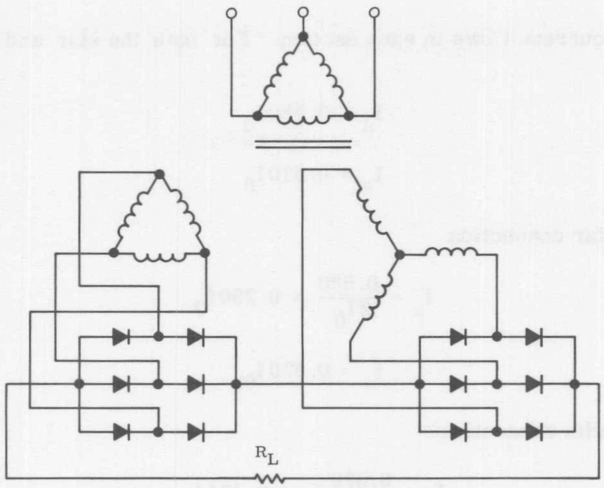
One additional advantage of the six-phase star is that the dc currents cancel in the secondary, and therefore, the tendency toward core saturation is eliminated.

Six-Phase Full-Wave Bridge Circuits

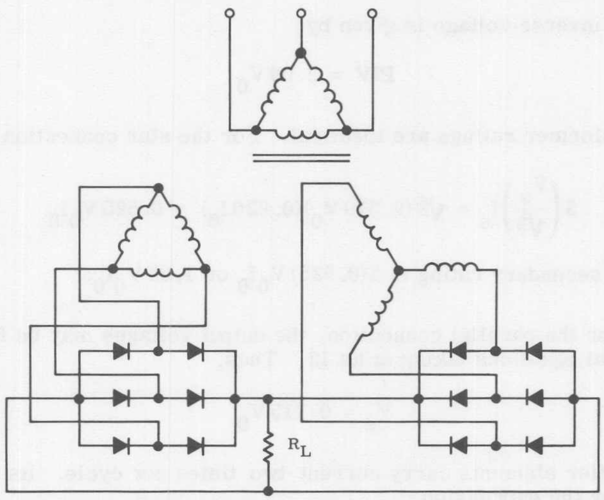
The six-phase full-wave bridge using delta and star secondaries to increase ripple frequency are shown in Figure 5-10.

In this circuit, the transformer has two secondary windings. These windings are designed to have the same voltage V_s, but will have different phase. The bridge-connected rectifiers of the secondary windings may be connected in series Figure 5-10(a) or in parallel Figure 5-10(b) .

For the series connection, the output voltage is the sum of the instantaneous voltages developed in the two sections. The phase voltages of the two sections are displaced 30° (electrical), and the resulting load ripple



(a) SERIES CONNECTED



(b) PARALLEL CONNECTED

Figure 5-10. Six-Phase Full-Wave Bridge Circuit

frequency will be 12 times the supply ripple frequency. The characteristics of the series circuit may be obtained by considering each bridge section separately for transformer considerations. The load should also be considered separately. For each section

$$V_s = \frac{0.740\,V_0}{2} = 0.370\,V_0 \tag{5-42}$$

The load current flows in each section. For both the star and secondary lines,

$$I_a = 0.580\, I_0 \qquad (5\text{-}43)$$

$$I_s = 0.820\, I_0$$

For the star connection

$$I_a = \frac{0.580}{2\, I_0} = 0.290\, I_0 \qquad (5\text{-}44)$$

$$I_s = 0.820\, I_0$$

For the delta connection

$$I_s = \frac{0.820}{\sqrt{3}}\, I_0 = 0.474\, I_0 \qquad (5\text{-}45)$$

The peak inverse voltage is given by

$$PIV = 2.09\, V_0$$

The transformer ratings are identical. For the star connection

$$3\left(\frac{V_s}{\sqrt{3}}\right) I_s = \sqrt{3}\,(0.370\, V_0)(0.820\, I_0) = 0.525\, V_0 I_0$$

The total secondary rating is $2(0.525)\, V_0 I_0$ or $1.05\, V_0 I_0$.

For the parallel connection, the output voltages may be found from the general equations taking m as 12. Thus,

$$V_s = 0.715\, V_0$$

The rectifier elements carry current two times per cycle. Its RMS value is given by the expression

$$I_{RMS(element)} = \sqrt{2}\, I_a = 0.410\, I_0$$

and

$$I_s = \sqrt{2}\,(0.410\, I_0) = 0.577\, I_0$$

The transformer ratings are

$$3\left(\frac{V_s}{\sqrt{3}}\right) I_s = 3\left(\frac{0.715\, V_0}{\sqrt{3}}\right)(0.577\, I_0) = 0.715\, V_0 I_0$$

The total rating of the two sections is twice the transformer rating or

$$1.43\, V_0 I_0$$

A comparison of the series and shunt connections will show the following:

(1) The transformer ratings are greater for the parallel connection than for the series connection.

(2) The current passes through four rectifiers (in series) in the series connection, as compared with only two for the parallel connection.

(3) The output ripple voltage is slightly higher for the parallel circuit.

If an equalizing reactor is used to couple the two bridge sections of Figure 5-10(b), the system reverts to two parallel three-phase bridge circuits, with each section supplying one-half the load current. The ripple frequency is 12 times the supply frequency, since the phase voltages are displaced 30°. The reactor design is the same as for the three-phase double-wye rectifier.

CHAPTER 6

Rectifier Voltage Multiplier Circuits

Introduction

Voltage multiplying power supply circuits are employed when high voltage sources are required, and the current demand is small.

The principle of operation for all multiplying circuits is essentially the same. Capacitors are charged and discharged on alternative cycles of the ac supply voltage. The voltage at the output terminals is the sum of these voltages, plus the supply voltage, in series. Thus, the rectifier loading is necessarily capacitive, and high peak currents flow through the rectifier, much like half-wave rectifier circuits with capacitor input filters.

Although high output voltages can be obtained, voltage multiplying circuits often have poor regulation. Since circuit operation depends on capacitor charge and discharge, large value capacitors with high voltage ratings must be used.

Voltage Doubling Circuits

Conventional Voltage Doubler

The conventional voltage doubler circuit is shown in Figure 6-1. This is the most commonly used voltage doubling circuit.

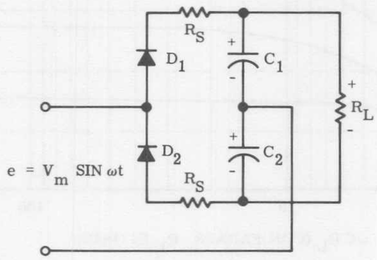


Figure 6-1. Conventional Voltage Doubling Circuit

The circuit operates as follows: C_2 is charged to V_m through D_2 during the negative half-cycle of the supply voltage. During the positive half-cycle, the capacitor C_2 and the supply voltage charge C_1. A voltage of $2\,V_m$ will appear across the output terminals. The capacitors, C_1 and C_2, must be rated greater than V_m, and the peak inverse voltage and voltage rating of the rectifiers must be greater than $2\,V_m$. The ripple frequency will be twice that of the supply.

The conventional voltage doubler circuits can be designed from curves similar to those used for capacitor input filters. These curves are presented in the following pages.

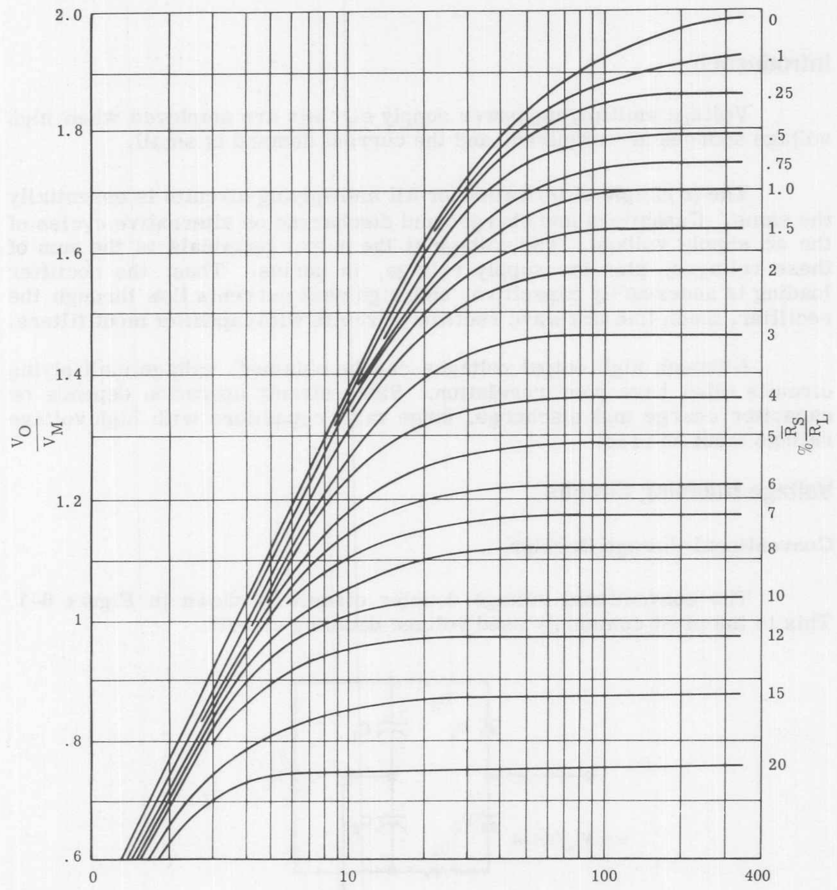


Figure 6-2. V_o/V_m Versus ωCR_L

The voltage doubler will have the high inrush and peak repetitive currents often encountered with capacitive input filters. In Figure 6-3, I_m is the peak repetitive current, not the initial inrush current.

The RMS current through the rectifier may be obtained from Figure 6-4 which shows the ratio I_{RMS}/I_0 plotted against ωCR_L. Figure 6-5 is a plot of the ripple factor versus ωCR_L.

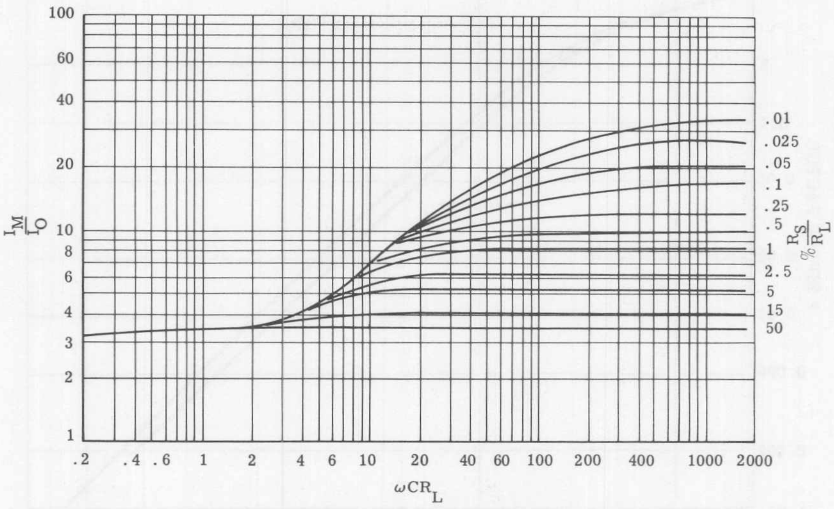


Figure 6-3. I_m/I_o **Versus** ωCR_L

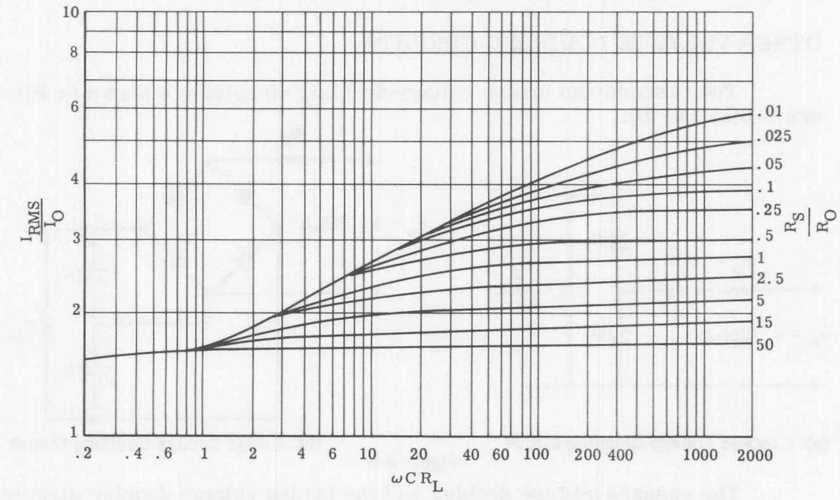


Figure 6-4. I_{RMS}/I_o **Versus** ωCR_L

The curves given in Figures 6-2 through 6-5 provide sufficient information to design a voltage doubling circuit as shown in Figure 6-1, provided the output characteristics have been established.

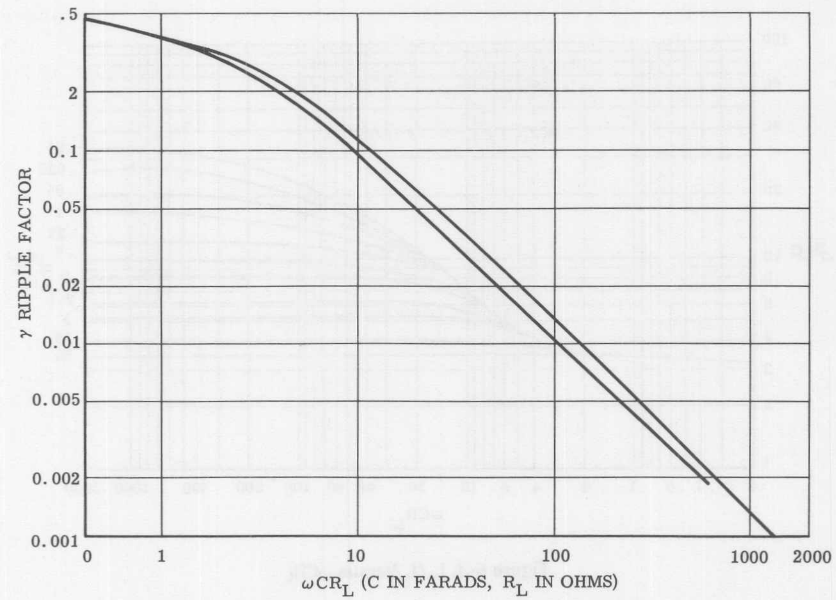
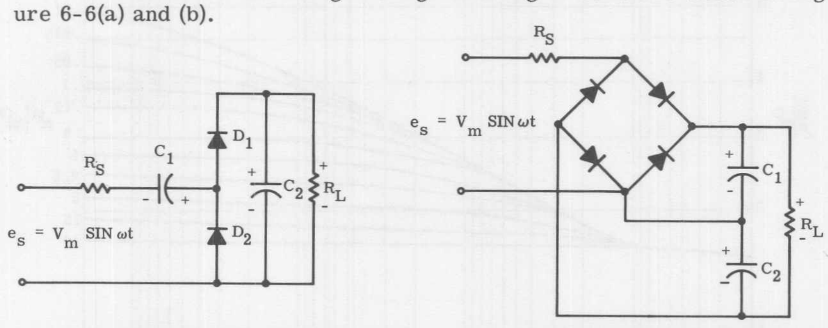


Figure 6-5. γ Versus ωCR$_L$ (Conventional Voltage Doubler)

OTHER VOLTAGE DOUBLING CIRCUITS

The cascade and bridge voltage-doubling circuits are shown in Figure 6-6(a) and (b).



(a). Cascade Voltage-Doubling Circuit **(b). Bridge Voltage-Doubling Circuit**

Figure 6-6

The cascade voltage doubler and the bridge voltage doubler operate on the same principle as the conventional voltage doubler. In the former circuit, C_1 is charged (through D_2) in the negative half-cycle. In the positive half-cycle, C_1 discharges in series with the supply voltage charging C_2. Across the open output terminals a voltage of $2\,V_m$ can be obtained. The capacitor C_1 should be rated at V_m, C_2 at $2\,V_m$, and the rectifiers should have a peak inverse and voltage rating of $2\,V_m$.

In the bridge circuit of Figure 6-6(b), the capacitor C_2 is charged to V_m and current flows through the load, on the negative half-cycle. On the positive half-cycle, the voltage of C_2 and the source will appear at the output. The capacitor and rectifier ratings are the same as those required in normal bridge circuits. The ripple frequency will be two times the frequency of the supply.

The cascade voltage doubler is difficult to regulate accurately, because the charge on C_1 must supply the charge to C_2. This circuit has the advantage of a common connection between the output and the input; consequently, additional sections may be added. The bridge circuit has better regulation than the conventional voltage doubler; however, it requires additional rectifiers.

To compare the particular features of the three voltage doubling circuits, the circuits may be evaluated using similar components. The resulting characteristics are given in Table 6-1.

Table 6-1. Voltage Doubling Circuit Characteristics

Circuit Configuration	V_s Volts	R_s Ohms	R_L Ohms	C μF	V_0 Volts	I_0 mA	γ %
Conventional	117	20	1K	20	205	205	12.0
Cascade	117	20	1K	20	160	160	16.6
Bridge	117	20	1K	20	225	225	12.5

Voltage Tripling Circuits

The full-wave voltage tripler operates as follows: On the negative half-cycle of the supply voltage, C_1 and C_3 (in parallel) charge to V_m. On the positive half-cycle C_1 and C_3 (in series with the supply voltage) charge C_2. A voltage of $3\,V_m$ will appear at the output terminals of the circuit. The voltage rating of C_1 and C_3 must be greater than V_m, and the rating of

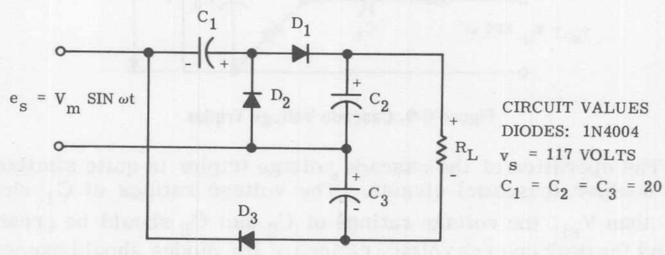


Figure 6-7. Full-Wave Voltage Tripler Circuit

C_2 must be greater than $2\ V_m$. The diodes should be able to withstand twice the maximum value of the supply voltage when blocking. The ripple frequency of the output will be twice that of the input.

The output characteristics for the circuit shown in Figure 6-7, are given in Figure 6-8.

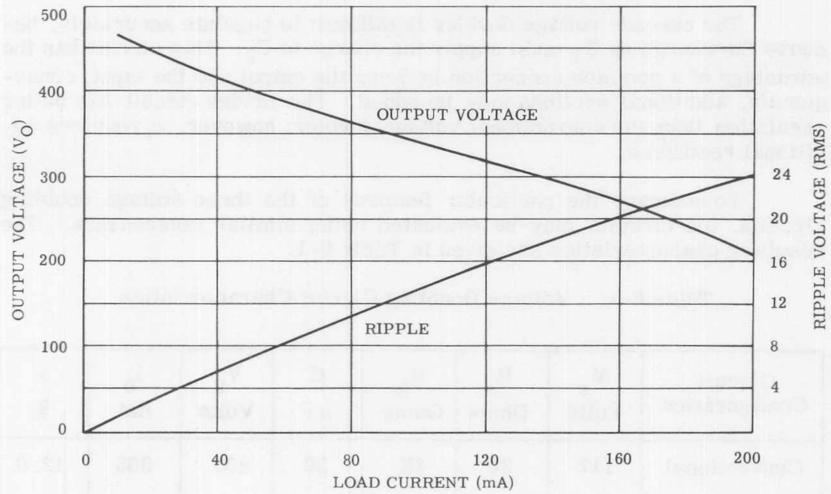


Figure 6-8. Output Characteristics of a Full-Wave Voltage Tripler Circuit

As noted previously, the cascade voltage doubler may be extended to obtain a voltage tripler. This circuit is shown in Figure 6-9.

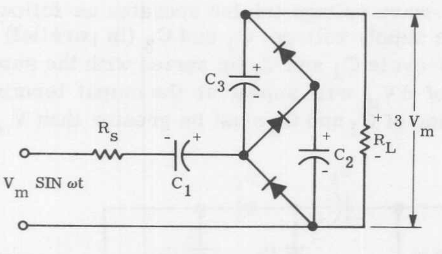


Figure 6-9. Cascade Voltage Tripler

The operation of the cascade voltage tripler is quite similar to the voltage doubler (cascade) circuit. The voltage ratings of C_1 should be greater than V_m, the voltage ratings of C_2 and C_3 should be greater than $2\ V_m$, and the peak inverse voltage ratings of the diodes should exceed $2\ V_m$. The ripple frequency of the output voltage will be the same as the frequency of the applied voltage. This is true of all half-wave circuits.

The regulation of the cascade voltage tripler is inferior to that of the full-wave voltage tripler. For comparison of the two circuits, refer to Table 6-2.

Table 6-2.

Circuit Configuration	R_L Ohms	V_0 Volts	I_0 mA	γ %	R_L Ohms	V_0 Volts	I_0 mA	γ %
Full Wave	5.0K	385	77	2.4	1.5K	255	170	8.0
Half Wave	5.0K	328	66	28.0	1.5K	170	112	37.0

Note that the full-wave voltage tripler has much better regulation than the half-wave voltage tripler.

Voltage Quadrupling Circuit

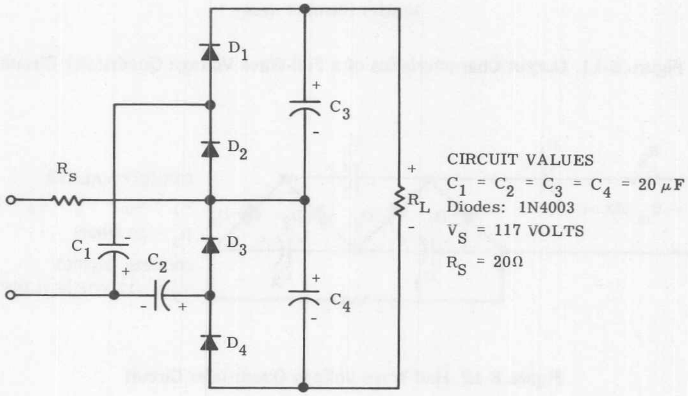


Figure 6-10. Full-Wave Voltage Quadrupler

In the full-wave circuit of Figure 6-10, capacitors C_1 and C_2 charge to V_m on the negative half-cycle of the supply voltage. On the positive half-cycle, these capacitors discharge in series with the supply to charge C_3 and C_4 to $2\,V_m$. Thus, an output voltage approaching $4\,V_m$ can be obtained at the output terminals. The capacitors should be rated at $2\,V_m$, and the peak inverse rating of the diodes should be greater than $2\,V_m$.

The half-wave voltage quadrupling circuit is shown in Figure 6-12. This is a further extension of the cascade network of Figure 6-6(a).

The operation of this circuit is basically the same as the other cascade networks. The capacitor C_1 should be rated at V_m while the remaining capacitors should be rated at $2\,V_m$. The peak inverse voltage rating of

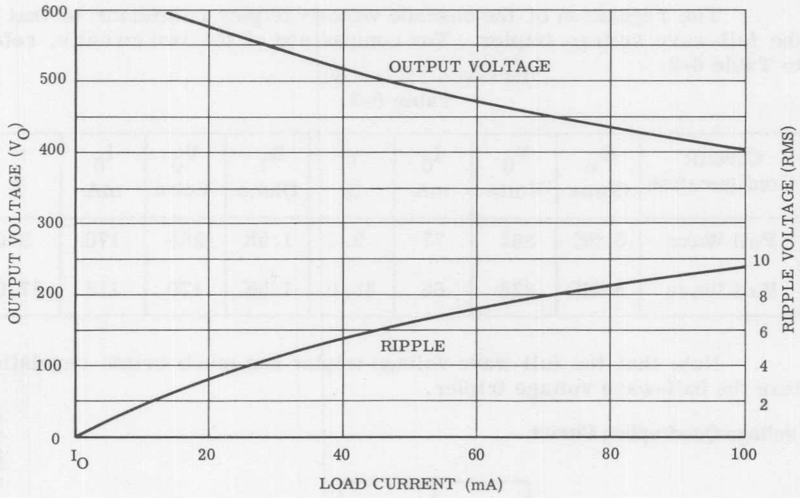


Figure 6-11. Output Characteristics of a Full-Wave Voltage Quadrupler Circuit

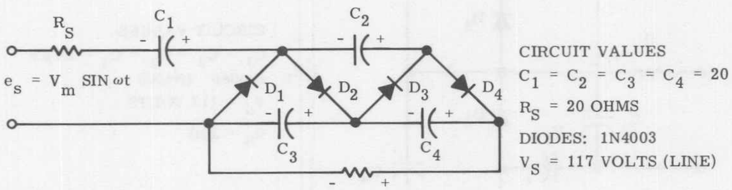


Figure 6-12. Half-Wave Voltage Quadrupler Circuit

the rectifiers must be greater than $2\,V_m$. The ripple frequency of the output will be the same as that of the supply.

The regulation of the half-wave voltage quadrupler is inferior to the other circuits.

To improve regulation, it is often necessary to increase the value of capacitors C_1 and C_2. To illustrate this improvement, the output characteristics of the circuit (Figure 6-12) were obtained (using component values listed in Figure 6-12). The same procedure was then repeated using values of 40 μF for C_1 and C_2. The results are shown in Figure 6-13.

As noted in Figure 6-13, considerable improvement is obtained by increasing the value of the capacitors C_1 and C_2. Even better regulation and lower ripple voltage is attained if all the capacitors are increased in size.

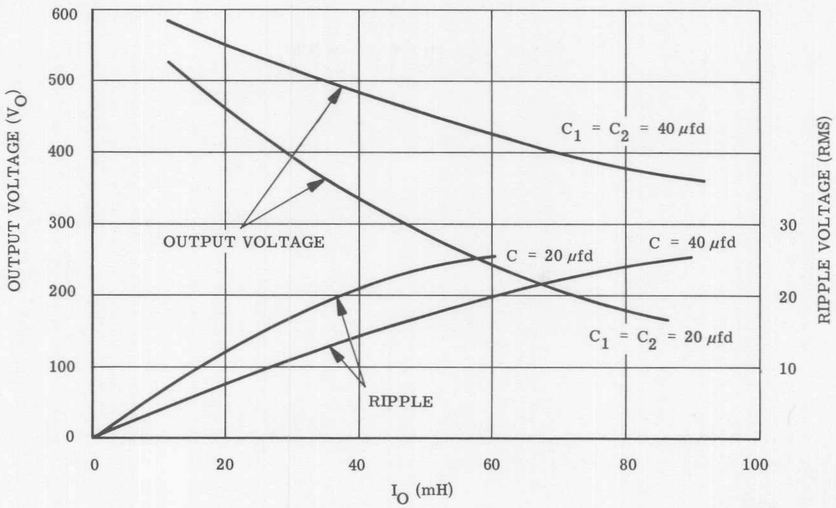


Figure 6-13. Output Characteristics of the Half-Wave Voltage Quadrupler Circuit

HIGH ORDER CASCADE VOLTAGE MULTIPLIERS

In theory, the number of sections which can be added to basic cascade voltage doubler circuits is unlimited. In practice, the number of sections is limited by the peak inverse voltage ratings of the rectifiers, the voltage ratings of the capacitors, and the required output characteristics. The regulation of such circuits becomes progressively more difficult as additional sections are added.

The basic cascade voltage multiplier can be extended to include n-sections as illustrated in Figure 6-14.

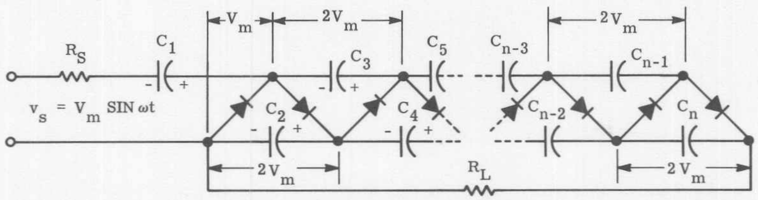


Figure 6-14. n-Section Voltage Multiplier Circuit

It should be noted that both even and odd multiples of V_m can be obtained with the circuit of Figure 6-14. The capacitor connected to the supply charges to V_m. The remaining capacitors on that side of the circuit charge to 2 V_m. Thus, odd multiples of V_m can be obtained from the upper branch and even multiples from the lower branch.

In all the circuits discussed in this chapter, the polarity of the output can be reversed by reversing the polarity of the rectifiers and capacitors.

CHAPTER 7

Miscellaneous Diode Circuits

Introduction

The capabilities of the rectifier have expanded from a low-current, low-power device to a high-power, 1000-ampere, current-handling device. Within the power-current range there are hundreds of applications. This chapter attempts to present only a few of the more interesting ones.

Arc Suppression

The silicon diode can be used quite effectively as an arc suppressor for switches and relays. By suitable methods of arc suppression, switching contacts will have longer mechanical life and require less maintenance.

A simple switching circuit containing a highly inductive load, such as a relay coil, is shown in Figure 7-1. R_L in the circuit represents the coil resistance. When the switch is opened, the magnetic field will collapse, and high voltage will appear across the switch. Arcing across the switch can result in damage to the switch and possible insulation breakdown of the inductor.

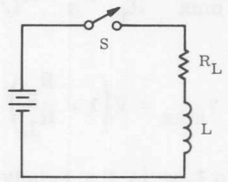


Figure 7-1. Simple Switching Circuit With Highly Inductive Load

Silicon rectifiers can be used to suppress any arcing across the switch (Figure 7-2). These methods are effective in dc circuits.

When the switch is opened, the voltage induced in the inductor will decrease exponentially. The decay time is controlled by the L/R time constant. The controlling equations can be obtained by applying Kirchoff's Law to the above circuit, and solving the resulting differential equation. Using this method, the current flow in the closed loop is given by:

$$i = I e^{-(tR/L)} \qquad (7\text{-}1)$$

where $I = V/R_L$ (the steady-state current)

L = Coil inductance

$R = R_L + R_s + R_d$ (diode resistance).

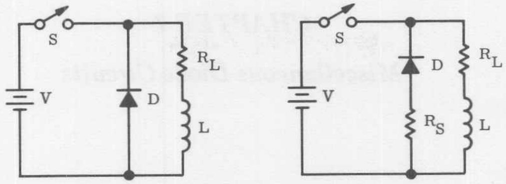


Figure 7-2. Rectifiers Used as Arc Suppressors

The maximum current is clearly the steady-state current, flowing when the switch is opened. The diode resistance R_d is 1 ohm or less. It is usually insignificant when compared to the coil resistance R_L. The induced voltage of the coil is given by

$$v = L\left(\frac{di}{dt}\right) = IR\,e^{-(tR/L)} \qquad (7\text{-}2)$$

$$v = \frac{V}{R_L}(R_s + R_L)\,e^{-(tR/L)} \qquad (7\text{-}3)$$

The maximum value of this voltage, when t = 0, is given by

$$v_{max} = \frac{V}{R_L}(R_s + R_L)$$

$$v_{max} = V\left(1 + \frac{R_s}{R_L}\right) \qquad (7\text{-}4)$$

Applying Kirchoff's Law to the supply circuit, it can be seen that the voltage given by Equation (7-4) will also appear across the switch.

From the above equations, two important effects can be seen: First, the resistance in the arc suppressor increases the maximum induced voltage and, thus, the voltage across the switch; secondly, the added resistance decreases the time constant L/R, and the induced voltage decays faster. These effects are illustrated in Figure 7-3.

For applications where decay time is not important, the value of R_S should be small. If the decay time is critical, the correct value of R_S must be found by a trial and error method applied to the following equation, provided the drop-out voltage is known.

$$V_{(drop\text{-}out)} = IR\,e^{-(tR/L)}$$

The solution to such problems may be aided considerably by the use of Figure 7-4 where the exponential term may be solved graphically for different ratios of L/R and the decay time t.

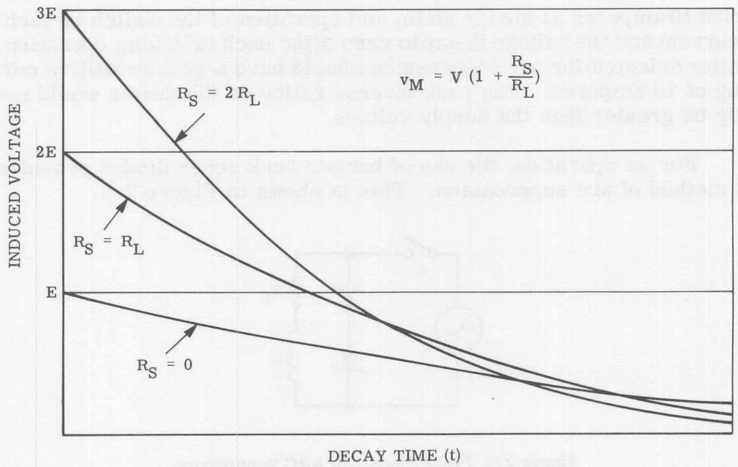


Figure 7-3. Induced Voltage Versus Decay Time

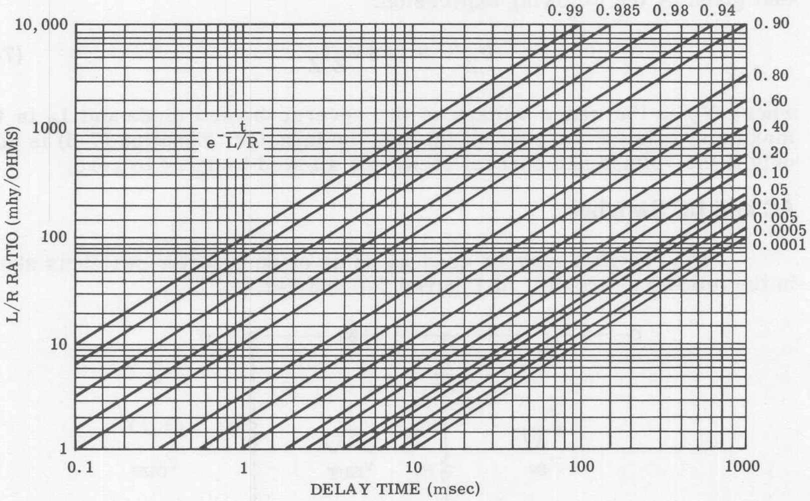


Figure 7-4. L/R Ratio Versus Delay Time

The selection of the rectifier for a given application will depend primarily on the peak value of the current through the device. Since this peak current is equal to the steady-state current through the relay coil, device selection is relatively easy. For example, if the inductive load carries 10 amperes at steady state, and operation of the switch is such that the current and the voltage decay to zero after each switching operation, the rectifier selected for arc suppression should have a peak repetitive current rating of 10 amperes. The peak inverse rating of the device would necessarily be greater than the supply voltage.

For ac operation, the use of back-to-back zener diodes provides the best method of arc suppression. This is shown in Figure 7-5.

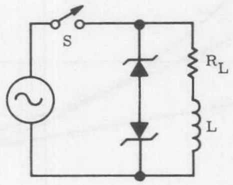


Figure 7-5. Zener Diodes for ARC Suppression

Back-to-back zener diodes may also be used for dc operation to provide a fast decay time. In either case, the minimum voltage of the zeners should be 2 or 3 volts higher than the supply voltage (maximum voltage for ac operation), and the power rating P_Z of the device should not be less than that given by the following expression.

$$P_Z = 0.316\,V_Z I_Z \qquad (7\text{-}6)$$

where V_Z is the zener voltage of the reverse-biased diode and I_Z is the maximum value of the current through the inductor. Equation (7-6) is good only if the voltage and current decay are allowed to decay to zero.

AC and DC Switches

The rectifier may be used as an ac or dc selector switch as shown in the following circuits, of Figures 7-6 and 7-7.

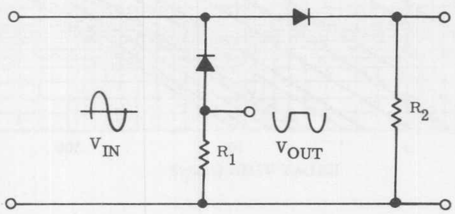


Figure 7-6. Rectifier as an AC or DC Selector Switch

The first circuit would be useful in any application where two loads operate on pulsating direct current, such as two model trains or two light bulbs where separate control is required from a single-source voltage.

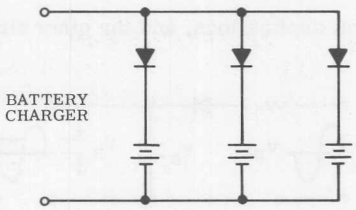


Figure 7-7. Rectifier as an AC or DC Selector Switch

Waveform Selector

Often it is necessary to remove the peak of an input voltage waveform when low-current outputs are required. The circuit illustrated in Figure 7-8 is designed for this function. The diode-cathode is held at positive potential by the battery. As the input voltage increases, the voltage on the rectifier and battery will increase also. The rectifier does not carry current until the anode potential is greater than the cathode potential.

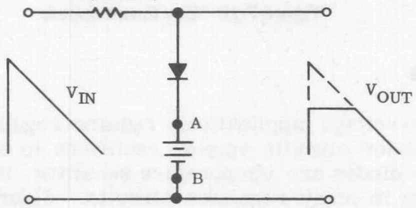


Figure 7-8. Waveform Clipper (Positive Peaks)

Negative peaks may also be clipped by using the circuit shown in Figure 7-9.

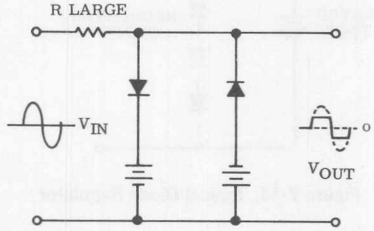
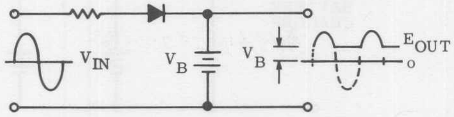
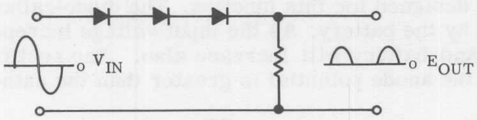


Figure 7-9. Waveform Clipper (Negative Peaks)

It is also possible to clip-off the "bottom" of the waveform rather than its top, as in the preceding circuits. Figure 7-10 provides two circuits designed to perform this function. One circuit, Figure 7-10(a), is designed for low-current applications, and the other circuit, Figure 7-10(b), is for high current.



(a)



(b)

Figure 7-10. Waveform Clippers

Diode Regulators

Many low-voltage applications require regulated outputs. Many inexpensive regulator circuits employ rectifiers to obtain excellent performance. Since diodes are temperature sensitive, this property may be used to advantage in many regulator circuits. Figure 7-11 illustrates a typical diode regulator.

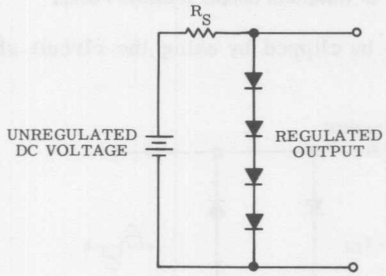


Figure 7-11. Typical Diode Regulator

Rectifiers also provide an excellent means of providing reverse bias on the gate-to-cathode of silicon controlled rectifiers. This not only improves silicon controlled rectifier characteristics, but insures that no greater reverse voltage will be applied gate-to-cathode, than the forward drop of the diode.

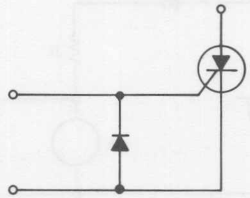


Figure 7-12. Rectifier Provides Reverse Bias for SCR

Diodes as Nonlinear Resistors

Nonlinear resistors can be useful in a number of applications. The resistor offers an ideal device for use as a nonlinear resistor, especially with the addition of a series resistor. One application, for example, would be low-level noise suppression on a telephone receiver.

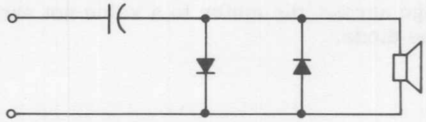


Figure 7-13. Rectifier as a Non-Linear Resistor

Other Diode Circuits

It is often desirable to lower the reverse voltage impressed upon a silicon controlled rectifier. The rectifier circuits shown in Figure 7-14 are designed to accomplish this purpose. The diode in Figure 7-14(a) carries the same amount of current as the silicon controlled rectifier. The circuit of Figure 7-14(b) has approximately the same reverse voltage reduction properties as the circuit of Figure 7-14(a), but the rectifier may have much lower current-handling ratings. This shunt diode should be a high-voltage low-current type. The circuit of Figure 7-14(b) is often used in high-reliability systems.

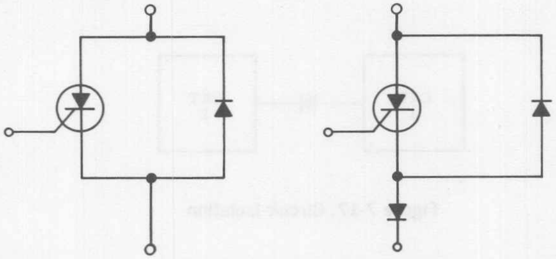


Figure 7-14. Rectifier Used to Lower Impressed Voltage on SCR

Rectifiers find many useful applications in measurement circuits. An example is Figure 7-15, the peak reading voltmeter. This circuit may

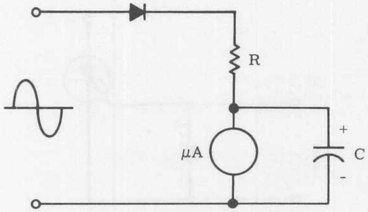


Figure 7-15. Peak-Reading Voltmeter

be used to measure the peak voltage of any waveform (with sufficient frequency to keep the shunt capacitor charged).

Protection circuits are also widely used in measurement applications. Figure 7-16 shows a dc meter protection circuit designed to limit the reverse voltage across the meter to a value not exceeding the forward voltage drop of the diode.

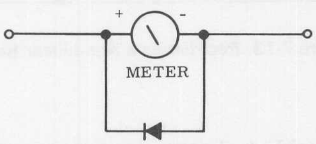


Figure 7-16. DC Meter Protection Circuit

Figure 7-17 presents an interesting example of circuit isolation. Circuit 1 has a low-impedance path to circuit 2, whereas circuit 2 has a high-impedance path to circuit 1. This coupling method is widely used in transistor circuits.

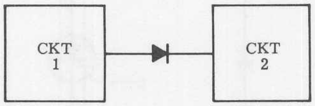


Figure 7-17. Circuit Isolation

The last circuit illustrates a simple, but highly effective means of providing "automatic feedback". The voltage drop across the diodes is such that the collector junction can never become forward-biased. Any excess base current is bypassed by the upper diode, as shown in Figure 7-18.

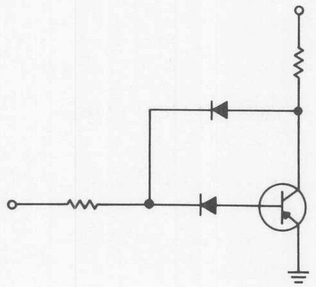


Figure 7-18. "Automatic Feedback" Circuit

CHAPTER 8

Series Connection Silicon Rectifiers

Introduction

In high-voltage rectifier applications where single cell rectifiers cannot meet the necessary reverse voltage required of the circuit, it becomes necessary to "stack", or connect several rectifiers in series. In this manner the total reverse voltage is divided equally among the individual rectifiers in the string.

Series connection of rectifiers requires established design techniques if the circuit is to be used successfully, due to normal variations in rectifier characteristics. A number of devices connected in series will behave as a single circuit element with a higher forward voltage drop and a higher reverse voltage rating than any individual device. In the forward direction, each rectifier passes the forward current of the stack and a stable voltage drop is established across each device. Thus, the forward current rating of each individual device establishes the forward current capability of the stack. In a properly designed stack, if a device fails in the reverse direction, its forward and reverse performance will not be affected provided the rectifier does not create an open circuit.

When a reverse voltage is applied to a rectifier stack, the voltage may not be distributed equally between the individual rectifiers. In such cases, one unit may see a voltage which exceeds its reverse voltage rating while another unit may see only a fraction of its rating. Thus, in applications which require series connecting of rectifiers, the reverse voltage characteristics of the individual rectifiers become the prime considerations.

Equivalent Circuit of Series Diodes

Two rectifiers in series may be characterized by an equivalent circuit (shown in Figure 8-1).

The rectifiers in the equivalent circuit are idealized: That is, a short circuit to forward current flow, and open-circuit to reverse current flow. R_F and R_R are the respective nonlinear forward and reverse resistances offered to the circuit by a real rectifier. C_s is the nonlinear junction capacitance which is associated with and is one of the shunting elements. Four typical C_s curves for a silicon rectifier are shown as a function of reverse voltage in Figure 8-2. Since R_F is small, it can usually be ignored in circuit design work. The reverse resistance (R_R) is large, and varies nonlinearly in magnitude with temperature and voltage. R_R can also vary considerably between different individual rectifiers selected from the same device family. The parameters of the equivalent circuit that affect reverse voltage diversion will be discussed in the following sections. It should be remembered throughout the following discussions that the equivalent circuit parameters are nonlinear. Also, they have different values at various voltages and temperatures.

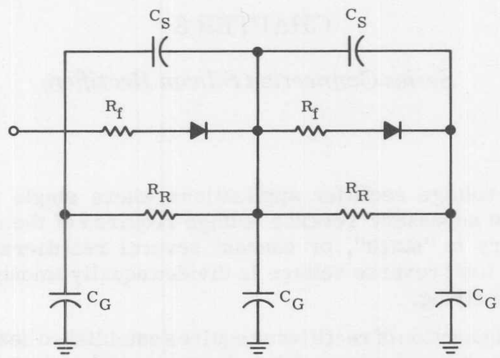


Figure 8-1 Equivalent Circuit for Two Rectifiers in Series

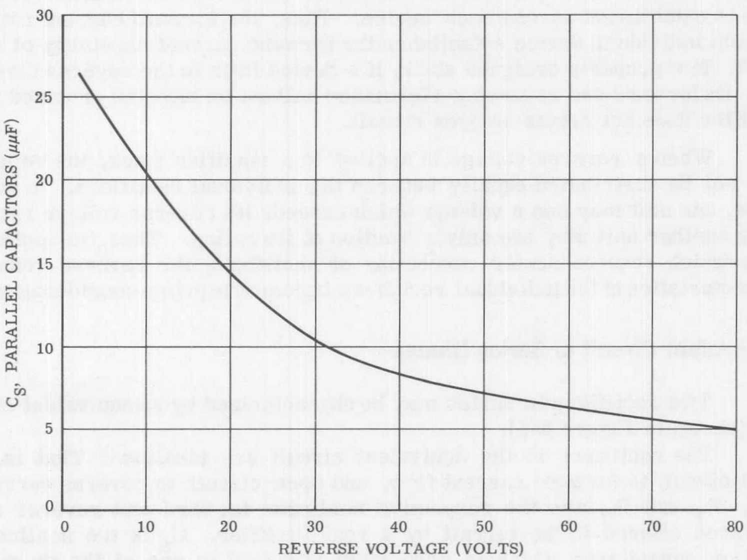


Figure 8-2 Parallel Capacitance (C_S Typical) As a Function of Reverse Voltage

Device Consideration for Series Rectifiers

There are three major effects that contribute to an unequal distribution of voltage between series rectifiers. One effect is due to the finite differences between the reverse resistances associated with all semiconductor rectifiers. Another cause of unequal voltage division is unequal storage times within units. This effect is associated with short rise time voltages on circuit transients. A third cause is variations in the capacitance of each unit to ground.

Figure 8-3 is used to demonstrate an unequal distribution of a steady-state reverse voltage, due to different reverse current characteristics. The curves show different characteristics which are possible within units of the same type and meeting the same specifications.

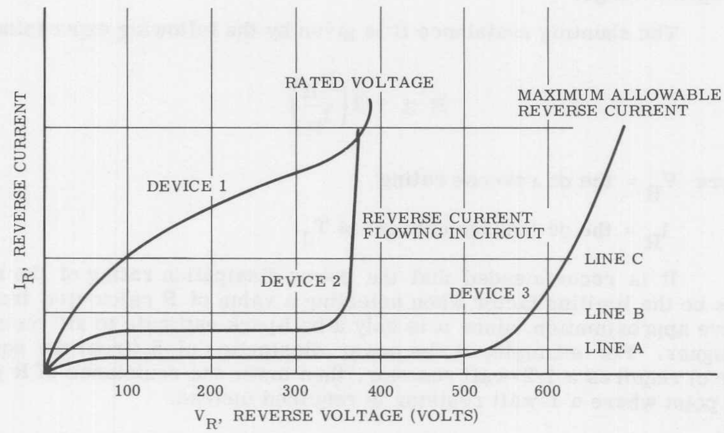


Figure 8-3. Reverse Steady-State Voltage Distribution Across Three Rectifiers In Series

Connecting the three devices in series and applying a reverse bias voltage will yield uneven voltage division between the devices. For example, if 600 volts is applied to the stack and the reverse current which flows corresponds to line A of Figure 8-3, then the voltage that device 3 blocks will be approximately 530 volts, device 2 will block 50 volts and device 1 will block only 20 volts. If the reverse current was such as to correspond to the level indicated by line B, then the voltage division of the rectifiers will be as follows: Device 1 - 35 volts, device 2 - 350 volts and device 3 - 590 volts. This shows the dc static voltage division which may be encountered when rectifiers are randomly selected and stacked. It is interesting to note that the "best" unit, the one which has the larger reverse resistance, receives the greatest blocking voltage and would most likely be the first to fail.

Achieving Equal Voltage Division with Resistors

The most practical solution to the above problem is to shunt each rectifier with a resistance which forces each of the reverse resistances to be nearly equal in value and, therefore, divides the voltages accordingly. The shunting resistances should be as small as possible, yet still afford a high resistance to reverse current. A conservative method of determining the value of the shunting resistance is to use one-half the minimum reverse resistance. The minimum reverse resistance is calculated from the maximum reverse current at maximum dc reverse voltage (at maximum operating temperature). This information is available on rectifier data sheets. As an example, the resistance needed to shunt the Motorola fast recovery diode (1N3883) when used in a series stack is 1/2 (400 V/4 mA) or 50.0 kohms. The additional amount of leakage current is slight when using this method, since the minimum reverse resistance of silicon rectifiers is in the 0.5 to 2 megohm range.

The shunting resistance R is given by the following expression:

$$R \leq 1/2\left(\frac{V_R}{I_R}\right)$$

where V_R = the dc reverse rating

I_R = the dc leakage current at T_J.

It is recommended that the power dissipation rating of the resistors be the limiting factor when selecting a value of R calculated from the above approximation, since it is only a ball-park estimate to aid the circuit designer. For example, if the power dissipation of R (from the equation above) requires a 1/2-watt resistor, then lower the resistance of R just to the point where a 1-watt resistor is required instead.

The power rating of the shunting resistor is given by the blocking voltage of the individual device and the value of the shunting resistor. For single-phase operation, the power dissipation is given by $(V_R)^2/R$ or $(V_{RM})^2/4R$. This is the fundamental V^2/R method of computing power dissipation. If the power losses of the shunting resistors are too great, the value of the shunting resistance may be increased to a value equaling the minimum rectifier resistance. However, the percentage of voltage unbalance would be much greater.

Achieving Equal Voltage Division by Device Matching

Careful matching of reverse rectifier characteristics provides a means of assuring equal voltage division without using shunting resistors.

Matching reverse currents at a fixed voltage will not be satisfactory because operating voltages are not fixed. Transients and line voltage fluctuations can shift operating points considerably. Thus, matching reverse characteristics at one point will not assure equal voltage division for all conditions.

To satisfactorily match reverse characteristics, the devices must have identical current-voltage characteristics throughout the range of operation. For the reason it is desirable to select units with equal characteristics.

Another important characteristic which must be considered when matching reverse-voltage characteristics is the temperature coefficients of the devices. In silicon rectifiers, the reverse saturation current and the voltage avalanche breakdown increase with increasing temperature. For purposes of matching, the current and voltage increase must be the same over the operating temperature range. Other parameters which must also be matched are the reverse capacitance and the reverse recovery time of the junctions. Thus, adequate matching of rectifier characteristics is not often a practical approach to series operation of rectifiers.

The junction capacitance associated with silicon rectifiers is a negative exponential curve as shown in Figure 8-2. This capacitance is voltage dependent, and varies with junction area, as well as with different methods of junction construction. Typical values range from 1 and 2 pF in small-area junction devices to 100 and 200 pF in large-area devices. A complete description of junction capacitance involves many variables and complexities which directly affect the dynamic performance and characteristics of silicon rectifiers. The different junction capacitance of rectifiers in a series string can present problems in achieving voltage balance under dynamic conditions; therefore, a practical solution to this problem lies in providing an external shunting capacitor for voltage balancing under dynamic conditions.

Proper Usage of Shunting Capacitors

A shunting capacitor is usually used to equalize the different values of junction capacitance, and is chosen large enough to swamp out all values encountered over the operating range. When selecting shunting capacitors, the storage and reverse recovery time of the rectifiers dictate the size of the capacitors. The capacitors selected on this basis will also swamp out the effects of junction capacitance.

The reverse recovery time becomes important in stacking rectifiers. This time consists of the storage time and a recovery phase. After a rectifier has been conducting on the forward portion of a cycle, the minority charges injected into the high resistivity region of the rectifier have built up to some constant value, and must be cleared out on the reverse cycle before the blocking characteristic of the device is again achieved. The amount of time required for this clearing out is called the recovery time of the device. The action of this charge storage causes the rectifier to exhibit a small resistance for a finite time (a few microseconds) even though a reverse voltage is applied to the circuit.

This charge storage phenomenon can become a problem when one device in a series string has a shorter storage time than the rest of the units. When a reverse voltage is applied to a string of devices and only one device has recovered, the total applied voltage then appears across the device until the other devices recover. This recovery time is quite small compared with one-half a normal cycle, but it is important since this voltage across one unit could greatly exceed its reverse voltage rating.

Figure 8-4 demonstrates storage time effects. Curves A and B show the voltage wave found across devices 2, 3, and 1, respectively, when they are placed individually in series with a series load R_L. It can be seen that the voltage across each device is essentially zero for a time, even after the square wave has reached a negative value. This is the storage time (time required to remove the minority carriers). It should also be noted that the storage times for devices 2 and 3 are longer than for device 1. In Figure 8-4 the storage times are exaggerated for a normal wave cycle. This is necessary to demonstrate the entire waveform.

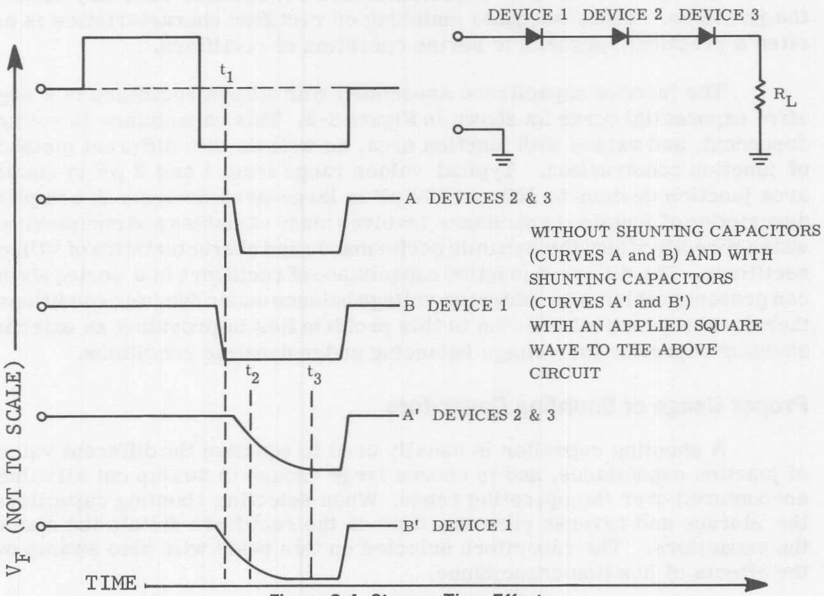


Figure 8-4. Storage Time Effects

When the three devices are placed in series and an input wave is applied, the storage time will remain the same for individual devices. With this part in mind, it can be seen from curves A and B that at a time t_1, the input device will drop the entire magnitude of the negative square wave (which could be any applied short-rise-time waveform including transients) across the junction of device 1. This occurs because at this time devices 2 and 3 are still in their storage time region. This entire voltage across device 1 could result in a unit breakdown. To correct this situation each device is shunted with a capacitor. The curves A' and B' now represent the resulting voltage waveforms across the respective devices. At time t_1, device 1 is seen starting to oppose the reverse voltage although the capacitor is absorbing a protective voltage. During the time interval t_2 to t_3, all devices share the reverse voltage.

It should be remembered, the vertical voltage scales on curves A, A', B, and B' are relative, since each device will not share at time t_3 a voltage equal to the magnitude of the input wave. The curves are primarily to show the waveform of a single device in series with the load R_L.

To determine the capacitance necessary to offset storage time effects, the circuit of Figure 8-5 may be used. The input of the circuit will be a square wave with a peak of V volts and a period of 2t seconds. The parallel R and C networks represent n number of rectifiers in series with a load and source resistance R_L. To simplify the calculations, C_g and the nonlinear C_s are omitted. This is possible since C in Figure 8-5 will be large enough to swamp out C_s. C in the figure is the added external shunting capacity for each device, and R represents the nonlinear reverse and forward rectifier resistance of each device [depending on which cycle (negative or positive] the wave is operating). It is further assumed that the resistance R and the capacitances are equal.

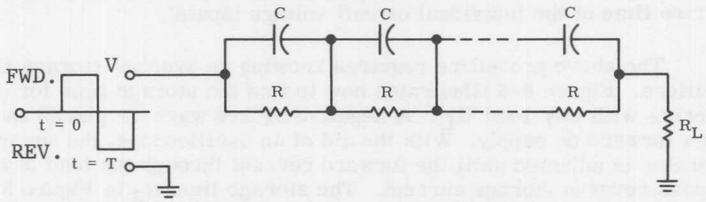


Figure 8-5 Equivalent Circuit for n Rectifiers in Series with Load R_L, Square-Wave Input

It can be shown that the voltage across each rectifier for one cycle is given by:

$$V(t) = \frac{V}{(R_L/R)+n}\left[1 - e^{-(1/RC + n/R_L C)t}\right]_{o}^{t'} + \left\{-\frac{V}{(R_L/R)+n}\left[1 - e^{-(1/RC + n/R_L C)(t-t')}\right]\right\}_{t'}^{2T} \qquad (8\text{-}1)$$

On the forward cycle, R (being the forward resistance) is much smaller than R_L, or in other words, $V/(R_L/R + n)$ is essentially zero. Therefore, the waveform can be represented (approximately) by Equation (8-2).

$$V(t) = -\frac{V}{(R_L/R)+n}\left[1 - e^{-(1/RC + n/R_L C)(t-t')}\right]_{t'}^{2T} \qquad (8\text{-}2)$$

It should be remembered from Figure 8-4 that the voltage of the device is still zero until the storage time has elapsed, even though the input voltage is in the negative cycle. This restricts the terms with $t - t'$ to be nonexistent until $t \geqq t'$, where $t' = T$ + storage time; here T is the time when the input wave goes negative, or the time for one-half cycle.

To summarize, the voltage due to the small forward resistance across each rectifier is essentially zero for the duration of the positive cycle and the storage time. After the storage time has elapsed, R shifts very quickly to high reverse resistance. The corrective fall time (used to equalize the reverse voltage across each unit as pointed out in Figure 8-4) is the predominant fall time constant $R_L C/n$. The fall time constant $R_L C/n$ clearly shows that the added capacitance C depends on the number of series rectifiers as well as the load resistance.

To give ample protection for each device in a series string, the time constant $R_L C/n$ should be equal to five times the longest storage time of any unit used in the string. This requirement gives a design equation for the value of C. That is, R_LC/n equals five times t_s of the slowest unit, where R_L is the source and load resistance, C is the capacitance which will shunt each individual unit, and n is the number of series rectifiers. If, for example, the storage time for one unit of three rectifiers (n = 3) to be placed in series is 5 microseconds, and if the source and load resistances are 700 ohms, C from $R_LC/n = 25 \times 10^{-6}$ can be found to be 0.10 F. The preceding rise time formula is conservative and the value of C may be reduced to optimize a particular circuit (depending on the rise time of the individual circuit voltage inputs).

The above procedure requires knowing an average storage time for rectifiers. Figure 8-6 illustrates how to find the storage time for one unit in series with any load R_L. A negative square wave is placed in series with a forward dc supply. With the aid of an oscilloscope, the square wave generator is adjusted until the forward current through the load is equal to the peak reverse storage current. The storage time (t_s in Figure 8-6) can be read directly at the 90 per cent point. Figure 8-6 shows the resulting current waveform through the rectifier and load with the proper capacitance shunting the unit.

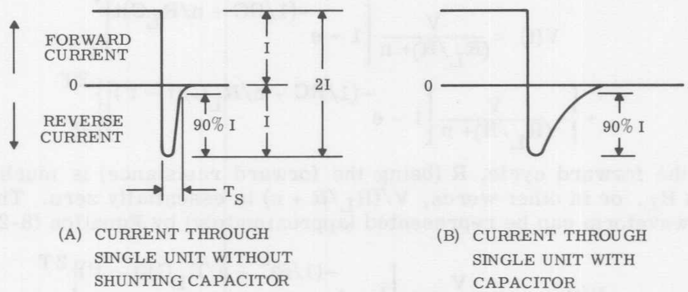


Figure 8-6 Rectifier Current Wave Forms

The value of the shunting capacitor needed is directly proportional to the storage time, which is the total recovery time of the diode. High-voltage, high-capacitance capacitors are expensive and set limitations on the high-voltage stack. To lower the capacitor value needed, a rectifier with faster recovery times is very desirable.

Reverse voltages are also upset due to the capacitance-to-ground C_g associates with each device. This is especially true in a string containing a large number of devices. The voltage across each unit is relatively small compared with voltage that is present across individual units to ground. Displacement currents can upset high-frequency voltage division. Displacement currents-to-ground are proportional to the rate of rise of the voltage-to-ground and the stray capacitance-to-ground. Therefore, in most applications, transients and voltage waves with fast rise fronts are responsible for unequal voltage distribution in the rectifier string. Careful placement of high-voltage stack components will virtually eliminate C_g. The value of the shunting capacitor C is given by the following equation:

$$C = \frac{5t_s n}{R_L}$$

where t_s = storage time

n = number of series devices

R_L = total resistors of R source and R load.

As was the case with the shunting resistor R, this calculation also varies depending on the source information. Other methods use the approximation of three times the junction capacitance at zero bias. The choice and placement of the resistors and capacitors must be such as to keep the inductance to a minimum.

CHAPTER 9

Parallel Operation of Silicon Rectifiers

Introduction

Many power applications require current-carrying capabilities which cannot be achieved with present day single-cell rectifiers. To overcome these current limitations, rectifiers have been designed employing many diodes in parallel. The design and operation of such units require some method of insuring current-carrying balance through the parallel units when the device is conducting in the forward direction.

The primary concern when operating silicon rectifiers is the forward resistance of the individual units. Unequal forward resistance between parallel units will cause one or more rectifiers to pass more than its share of current. This effect may be illustrated by the use of Figure 9-1 which shows the voltage-current characteristics of two unmatched rectifiers operating in parallel.

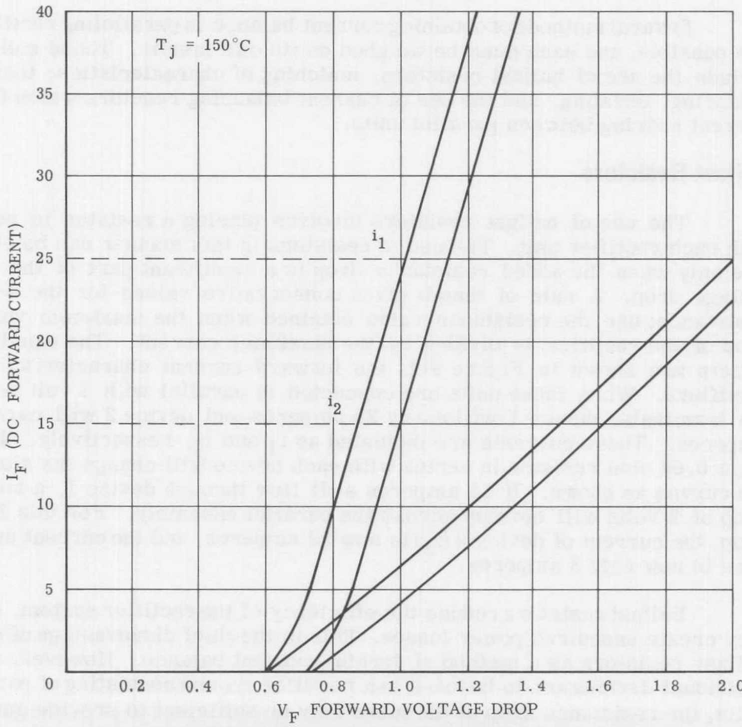


Figure 9-1 Voltage-Current Characteristics of Unmatched Silicon Rectifiers

As with any silicon rectifier, the current increases rapidly with small changes in voltage. Units placed in parallel have the same voltage drop. Because of the steepness of the characteristic curve, a large current unbalance will exist between the two cells.

The condition of unbalanced current in rectifiers is further aggravated by the negative temperature coefficient associated with the forward voltage characteristics of silicon rectifiers. As the rectifier carrying the greatest current heats up, its forward resistance will decrease allowing more current to flow through the device. The rectifier then begins to "hog" the current and an eventual failure may result due to junction heating known as thermal runaway.

When a high-current rectifier consisting of many parallel units is subjected to a reverse bias voltage, each rectifier unit will be required to sustain the reverse voltage. Thus, if breakdown occurs, it will occur in the rectifier unit having the lowest breakdown voltage. The breakdown of such a cell is not influenced by the action of any other cell. Thus, such factors as reverse resistance, junction capacitance, and storage time do not acquire the importance they have when diodes are placed in series.

Several methods of obtaining current balance in paralleling rectifiers are possible, and each must be weighed on its own merits. These methods include the use of ballast resistors, matching of characteristics, thermal balancing, derating, and the use of current balancing reactors which force current sharing between parallel units.

Ballast Resistors

The use of ballast resistors involves placing a resistor in series with each rectifier unit. The use of resistors in this manner can be effective only when the added resistance drop is a significant part of the total voltage drop. A rule of thumb gives conservative values for the series resistance; use the resistance value obtained when the maximum voltage drop of the rectifier is divided by the maximum current. The equalizing effects are shown in Figure 9-1, the forward current characteristics of rectifiers. When these units are connected in parallel with 1 volt across the terminals, device 1 will carry 25 amperes and device 2 will carry 15 amperes. These currents are indicated as i_1 and i_2, respectively. Placing a 0.04 ohm resistor in series with each device will change the slope of the curves as shown. If 25 amperes still flow through device 1, a voltage drop of 2 volts will develop across the parallel assembly. For this 2-volt drop, the current of device 2 (i_2) is now 22 amperes, and the current unbalance is now only 3 amperes.

Ballast resistors reduce the efficiency of the rectifier system, since they create undesired power losses. This is the chief disadvantage of using ballast resistors as a method of forcing current balance. However, when individual devices are to be fused in a rectifier system consisting of parallel units, the resistance drop of the fuses may be sufficient to provide current balance, if the forward resistance mismatch is not too great.

Matching Forward Characteristics

Balanced current sharing may be attained by matching the forward voltage characteristics of the individual devices. This procedure requires accurate measurements, careful coding, and numbering systems. For replacement purposes, rectifiers from the same code group must be used. Due to the nature of matching rectifiers, selection must be made from a large volume, and factory-matched devices add to the cost of the rectifier.

In parallel operation, the forward characteristics of the individual devices are the prime consideration. Current unbalance between rectifiers is due to the difference in effective resistance between individual devices. Therefore, the volt-ampere characteristics must be matched over the complete operating range. The degree to which such devices are matched establishes the amount of unbalance which will exist in the final assembled unit. Characteristics of devices matched at one load may vary at other loads. However, most devices which are matched at high currents will not deviate appreciably at lower currents. Temperature coefficients of different units must also be considered. Variation between cells of the same type from the same production line usually will not vary by more than 10 per cent. The use of a common heat sink is extremely important; this assures that all devices operate at or very close to the same temperature, and that temperature effects will be more nearly uniform in all cells.

Due to the extremely low resistance of the forward conducting rectifier, extreme care must be taken in mounting and connecting rectifiers in parallel. Unequal resistances incurred in mechanically mounting and connecting rectifiers will cause further unbalance in the rectifier assembly.

Motorola high-current rectifiers are constructed using the technique of matching forward current characteristics. These techniques are possible due to Motorola's high rectifier volume and careful production control. The basic cells used in these rectifiers are fabricated from small silicon junctions mounted in a steel can. The fabrication process parallels the same techniques used for other single-cell rectifiers.

The basic cells are matched to within 20 millivolts at 100 amperes. This assures closer matching at 25 amperes. The basic cells are then connected in parallel to form a single device. The paralleling includes mounting the individual cells on a common copper-plated base which couples each cell thermally for optimum heat transfer and uniform heating. A molded, void-free external case completes the assembly, furnishing mechanical strength, electrical isolation, and protection from corrosive elements. These devices are then thoroughly tested to insure good electrical and mechanical characteristics.

Some manufacturers employ derating factors for reducing the percentage of failures caused by overloading cells. The use of derating factors also adds to the cost of paralleling rectifiers, since these factors reduce the rating of each cell, and additional rectifier cells must be added to meet the requirements of specific applications. Derating factors are sometimes applied when paralleling rectifiers which have matched forward characteristics or where ballast resistors are used.

Current Balancing Reactors

Current balancing reactors have been employed for some time in paralleling mercury-arc rectifiers. The operation of such reactors makes them equally applicable to the parallel operation of silicon rectifiers. The use of balancing reactors, when properly designed, will provide equal current sharing in parallel rectifiers, and may be less expensive than using ballast resistors, matching forward characteristics, or derating.

A balancing reactor for paralleling two rectifiers is shown by the simple schematic in Figure 9-2.

The balancing reactor shown in Figure 9-2 forces current sharing between the two rectifiers. When the currents through the two rectifiers are equal, the magnetic flux resulting from each of these currents cancels the other. When the currents are unequal, a magnetizing current (which is the difference in the two currents) will produce a resulting net flux which tends to reduce this current unbalance. Thus, the unbalance between the rectifiers is due to the magnetizing current of the reactor core. Since the currents in the rectifiers tend to be equal, a difference in voltage drops across the rectifiers will be present, and this difference plotted against a time scale will yield an energy difference (measured in volt-seconds). The volt-second difference between the rectifiers must be absorbed by the reactor. This volt-second difference in terms of flux linkages fixes the minimum cross section of the core, and the number of turns of the reactor.

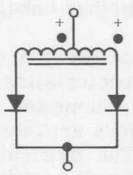


Figure 9-2 Paralleling Operation of Silicon Rectifiers Using Balancing Reactors

The cores for balancing reactors should have a high saturation flux density and a low residual flux density. This will insure a maximum change in total flux. In this category, oriented magnetic-steel cores, rolled or punched, have the smallest magnetizing current, and the highest maximum flux density. However, these cores also have the highest residual flux densities. Cores with small air gaps have residual flux densities. Consequently, these may be used to a limited extent.

The reactor system of Figure 9-2 may be extended to one containing 2^n diodes. This is shown in Figure 9-3.

For an uneven number of diodes, certain variations of this arrangement can be used. The reactors of Figure 9-3 must necessarily be of diferent design. Since each rectifier carries the same current, reactors R_1 and R_2 must be designed to carry twice the current of one diode. Reactor R_3 must be designed for four times this current, and so on for the remaining reactors.

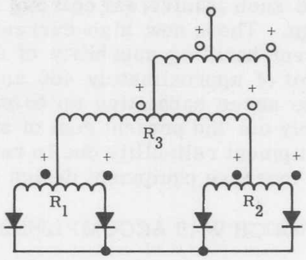


Figure 9-3 Balancing Reactors Used with 2^n Diodes

Figure 9-4 illustrates another method of balancing reactors. This method has the advantage of each winding carrying only the current of one diode. This is commonly called the closed-chain reactor circuit.

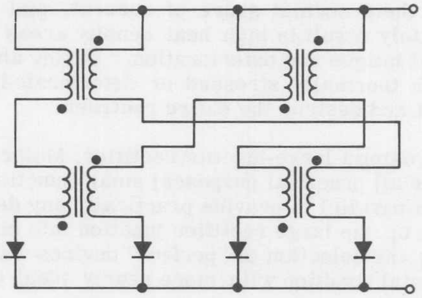


Figure 9-4 Balancing Reactors in a Closed-Chain System

It is evident that any form of balancing other than a highly controlled matching system is expensive.

Very-High-Current-Rectifiers

For years, high-current rectifier manufacturers have been searching for a universal rectifier cell which would be adaptable for use in numerous configurations and capable of filling virtually any rectification application. Motorola has perfected such a universal cell and is using it in a new high-current rectifier design. These new high-current silicon rectifiers will: (1) increase the current-handling capability of a single device from its present maximum limit of approximately 400 amperes to 1,000 or more amperes, and increase surge capacities up to six times that of present devices; (2) appreciably cut the present cost of such devices; (3) provide an extra margin of equipment reliability due to reserve capacity and built-in redundance; and (4) increase equipment design flexibility.

HOW THE BREAKTHROUGH WAS ACCOMPLISHED

There are two basic methods of making high-current rectifiers. One method uses large single-rectifier junctions to carry the required current (as the current requirements are increased, these single junctions must become larger and larger); the second method is to parallel a number of lower current rectifiers.

There are a number of problems associated with large single-junction rectifiers. Large-area rectifier junctions cannot be made without some imperfections, and the larger the area (higher current capability) the greater the number of imperfections.

When current is passed through such a device, the current is not necessarily distributed equally over the entire area. Some areas will assume more than their normal share of current, and these high-current areas may ultimately result in high heat density areas ("hot spots") which can cause thermal fatigue and deterioration. During abnormally high current surges, such thermally stressed or deteriorated areas can assume excessive current and destroy the entire rectifier.

Instead of using a large-junction rectifier, Motorola employs a number of perfect (for all practical purposes) small-junction, medium-current units connected in parallel to provide practically any desired total current rating. Breaking up the large rectifier junction into many small rectifier junctions permits the selection of "perfect" devices which then are paralleled to form a total junction with more nearly ideal characteristics and greater capabilities.

To overcome the basic problem inherent in the use of multiple paralleled rectifier cells (i.e., achieving equal current distribution), Motorola matches and guarantees the forward-voltage characteristics of each cell to within 20 millivolts at 100 amperes. These closely matched rectifier cells are then mounted on a common copper base in a manner which intimately couples each cell thermally. A 50-ampere rectifier uses two cells; a 650-ampere device uses 28 cells. Under normal operating conditions, the thermal difference between cells is so low that any current unbalance is negligible.

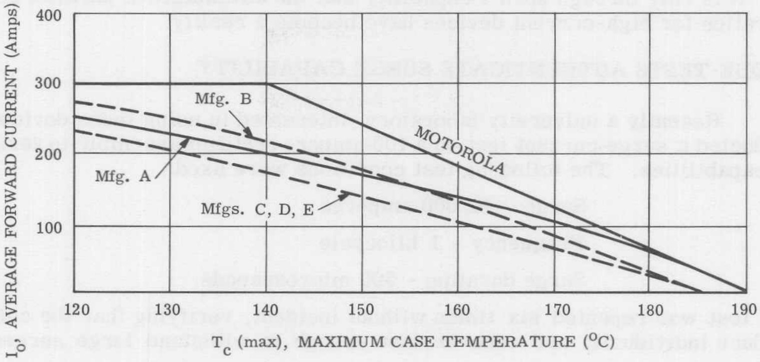


Figure 9-5 Maximum Case Temperature vs. Current Rating Curves for Typical 240-ampere Rectifiers

ADDITIONAL ADVANTAGES

Other advantages of the parallel-cell concept are: (1) the entire rectifier assembly can be factory tested prior to final assembly and any substandard cells can be replaced; (2) a number of reserve cells can be "built in" to provide an extra current margin; (3) current-handling potential is virtually unlimited (a 2,000-ampere unit is now performing satisfactorily in an on-the-job customer test program); and (4) higher current devices mean a sharp reduction in the number of expensive "accessories" (balancing transformers, paralleling reactors, etc.) previously required on many applications.

In addition, because there is no fragile insulator-to-metal hermetic seal between external leads and case (an inherent characteristic of single-junction devices), the user can bolt the unit to bussing without a torque wrench — there is virtually no possibility of damaging the individual cells by overtightening either the stud bolt or the lead connection.

PRACTICE MAKES PERFECT

Implementation of the parallel-cell concept was never before practical because the only economical way of achieving the close tolerances necessary is to start with a manufacturing output so large and so closely controlled that the selection of matched devices becomes almost automatic. Over the past five years, Motorola has developed the required volume and is now manufacturing medium-current rectifiers at a rate of more than 20 million per year. These devices have been so thoroughly engineered that their reliability and uniformity insure an extremely high yield to even the most stringent specifications. And — due to high-volume production — the cost per device is far below the most optimistic predictions of a few years ago. It is only through such a capability that the advantages of parallel-cell operation for high-current devices have become a reality.

UNIQUE TESTS AUTHENTICATE SURGE CAPABILITY

Recently a university laboratory, interested in using these devices, conducted a surge-current test on a 400-ampere rectifier assembly to verify its capabilities. The following test conditions were used:

Surge - 40,000 amperes

Frequency - 1 kilocycle

Surge duration - 500 microseconds

The test was repeated six times without incident, verifying that the cells conduct individually and recover fast enough to withstand large surges.

To determine exactly what happens if one cell fails, a 400-ampere rectifier was surged while operating at 400 amperes, 150°C temperature (V_R applied after surge), with 10 consecutive half-cycles of 8,000 amperes. One cell began to fail after this test was performed 12 times. Within an additional three half-cycles, the internal connecting lead of that cell opened and removed the cell from the circuit. Despite this open cell, the rectifier continued to function normally as a 400-ampere device. These test conditions were many times more severe than the device rating.

These tests supplemented the innumerable tests and experiments which were conducted at Motorola prior to the decision to adopt the new process into production. They provide practical proof that this is a truly revolutionary breakthrough in the high-current rectifier field.

CHAPTER 10

Overcurrent Protection of Silicon Rectifiers

Introduction

The fusing of silicon rectifiers is, perhaps, the area of rectifier fabrication furthest behind in technical advancement. Until the state-of-the-art is such that better fusing techniques are available, manufacturers must rely on design experience. Rectifier circuits must be designed with the provisions for overcurrent protection. The use of silicon diodes has been widely acclaimed in the rectifying industry because of silicon's electrical characteristics. It is, however, very susceptible to overcurrent. In this chapter, the circuit designer's approach to the overcurrent protection of silicon rectifiers will be discussed.

Failure Mechanism in Silicon Diodes

An understanding of the failure mechanism associated with silicon rectifiers will greatly aid the design engineer in providing adequate protection from overcurrent surges. When rated power is dissipated in a silicon rectifier, the average temperature of the p-n junction rises. Within a few cycles of operation the temperature stabilizes in accordance with the thermal time constant of the device. If the device is subjected to current overloads, the junction temperature will rise rapidly to a value destructive to the rectifier. This fact is reflected in the short thermal time constant associated with silicon rectifiers. However, the thermal capacity of the rectifier is sufficient for very short overloads. Consequently, surge ratings for silicon rectifiers are well in excess of continuous ratings.

Cell failures usually occur due to fracture, melting of the junction, or melting of the solders and wires used in fabricating the device. Fracture of the silicon die is due to the mechanical and thermal stresses which result from faulty construction and large temperature excursions. Good fabrication and testing techniques can reduce cell failure by fracture to insignificance. Most rectifier failures result from the melting of the silicon junction, or from the materials used in joining chip to the rectifier case. For high-current surges of less than one millisecond duration, melting of the silicon die is more likely to occur, whereas, for longer current surges, melting of the joining solders and wires may also occur.

When a rectifier cell fails due to excessive junction temperature, the failure results in a shorted device since the rectifier looses its reverse blocking capability. In most power systems, a shorted cell will present a direct short to the supply voltage. If there is no series-limiting impedance or fuse, the magnitude and duration of the surge current becomes great enough to cause vaporization of the joining solders and wires, consequently causing the unit to open. If is important to try to prevent this condition since this type of overcurrent is dangerous to associated components.

Current-Limiting Fuses and Their Application

There are available two basic types of fuses. One is the standard "one-time" fuse or the conventional fuse. The other is the silver sand or fast-acting fuse. Both have uses in silicon diode overcurrent protection. It is imperative to know not only the properties of the diode but also of the fuses.

Fuse manufacturers will give typical ratings which characterize the fuse approximately. But, there are relatively wide tolerances within which a given fuse number will vary, even when the current rating is held constant. One item which design engineers often overlook is that a fuse changes characteristics at elevated temperatures. It is not uncommon for a fuse to carry 75 per cent less current at 125°C ambient than at 50°C ambient. It is also not uncommon to find the arcing time much in excess of the melting time.

A good recommendation for fusing procedures is as follows. Determine first, if there is any current-limiting resistance. This can be accomplished by the use of an oscilloscope and a piece of nichrome wire (which is calibrated for one-tenth of an ohm). Insert 0.1 ohm (nichrome wire) in series with the diode. (Use a large diode for this test.) During the short circuit condition, monitor both the applied peak voltage and peak current. From this, calculate the current-limiting impedance. (In cases of very large systems, it is advisable to insert a high resistance to prevent damage to associated components.) Subtract this value from the total series resistance. If this series resistance is sufficiently large to limit the peak let-through current to a value within the surge current rating of the device, now that the necessary value of the current-limiting series resistance is known, the engineer can see that the appropriate fuse should be the least expensive conventional one-time fuse with this resistance value. This fuse would then have a current rating of something slightly higher than the maximum average current which will flow under the range of operation. The purpose of the fuse, then, is only to prevent large time overloads of about three cycles or greater, because the diode can withstand the single cycle overload without damage.

Assuming that this peak let-through current is greater than the data sheet allows for the originally chosen diode, perhaps the next higher current device will withstand the surge. It behooves the design engineer to weigh the economics of the more expensive diode for reliability against the cheaper fuse.

Perhaps even the next higher diode is not sufficient, it then becomes mandatory to use the fast-acting fuse which clears in a matter of milliseconds.

Figure 10-1 shows the limiting action of a current-limiting fuse. The solid line shows the actual fault current due to the limiting action of the fuse. The dashed line shows the available fault current which would flow with no current-limiting action. As shown, melting of the fuse occurs at point A. The time of this occurrence is called the melting time. Depending on fuse design and the circuit, the current may rise to a peak let-

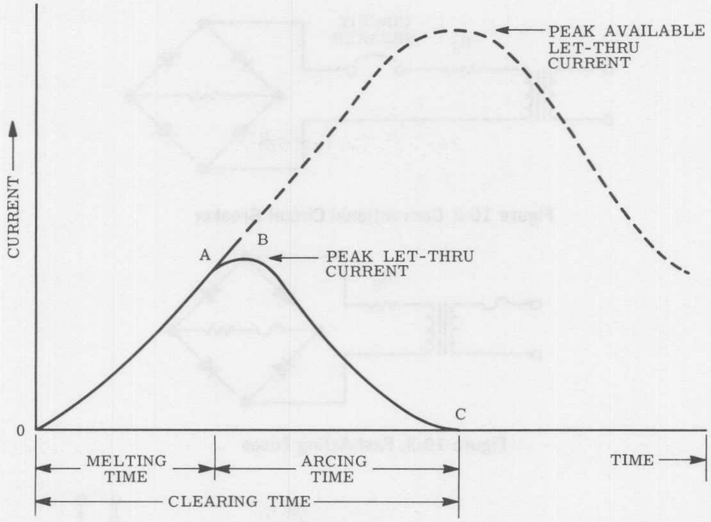


Figure 10-1. Limiting Action of Current Limiting Fuse

through current as shown at point B. Beyond point B, the impedance of the arcing fuse will force the fault current to zero at some point C. The time from point A to point C is the arcing time of the fuse. The melting time and the arcing time together make up the total clearing time of the fuse. A good current-limiting fuse will have an arcing time, approximately equal to the melting time of the cell. In no case should the arcing time exceed twice the melting time.

The first step in the fuse selection procedure is to select a fuse with a current rating higher than the current which the diode will carry at the maximum condition and which also has a lower I^2t rating than the diode. Then, with at least 20 fuses and 10 diodes, under actual operating conditions, create the overload condition. Use an oscilloscope to determine the peak let-through current, melting time, and arcing time. Make sure that peak let-through current is below the maximum peak surge current rating of the device. If this is not the case, then a higher current is necessary. The fuse should always open the circuit before the diode is damaged, under the complete operating range. Note the arcing time and melting time to insure that there is an adequate tolerance within the fuse.

Placement of Fuses

In low-cost circuits, where fusing with current-limiting is too expensive, the diode may be considered expendable and the only fuse used is a standard-line fuse. In most industrial applications, the use of current-limiting fuses, standard fuses, and circuit breakers is commonly associated with diode protection. The placement of fuses will depend upon the type of circuit, the wiring, the location for good transient reduction, and ambient temperature. The following schematics are useful for overcurrent protection.

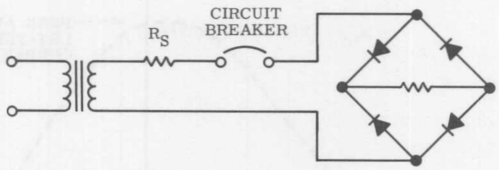


Figure 10-2 Conventional Circuit Breaker

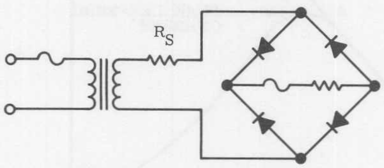


Figure 10-3. Fast-Acting Fuses

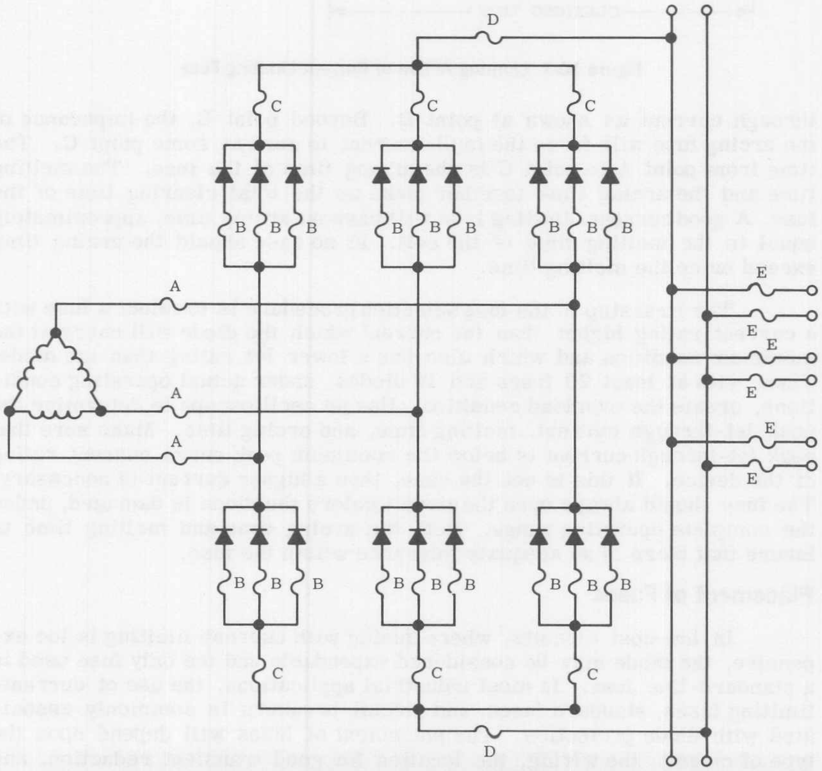


Figure 10-4. Various Fuse Placements

Figure 10-2 illustrates the use of a conventional circuit breaker, useful when there is a current-limiting resistor and the peak let-through current is below the rating of the diodes. The breaker could be replaced with a standard fuse.

Figure 10-3 shows the placement of either standard or fast-acting fuses in the input and output of the assembly.

Figure 10-4 illustrates various fuse placements. The A set of fuses provides protection for the individual input lines. The B set of fuses is not only for protection of a diode but to keep the system operating even though a diode could have failed. The fuses of set C are diode protectors and are only used when B is not used for economy purposes. D and E fuses are output protection fuses. E separates various loads from the single-source dc potential.

Figure 10-5 illustrates an example of auxiliary circuits which could be used for long-term overcurrents where the diodes in the bridge circuit could support the load for about three or four cycles.

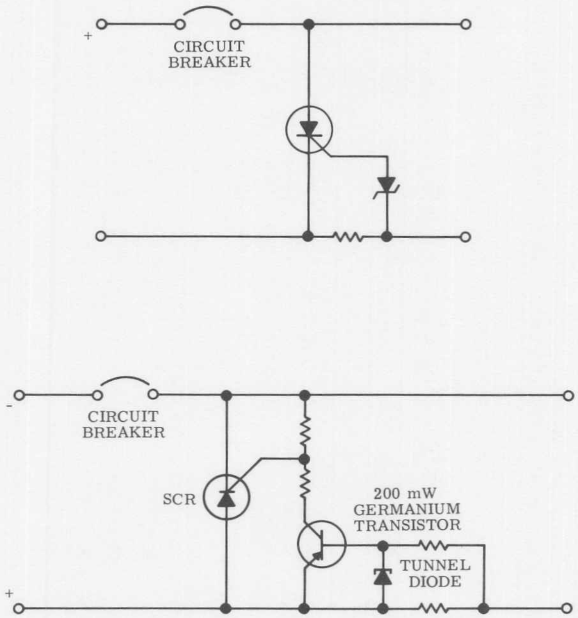


Figure 10-5. Auxiliary Circuit for Long-Term Overcurrent Protection

CHAPTER 11

Protection of Silicon Rectifiers Against Voltage Transients

Introduction

High peak inverse voltage transients in rectifier circuits are the major cause of diode failures. Silicon rectifiers, as with any semiconductor device, are quite sensitive to excess reverse voltages. In the early history of silicon diodes, the reverse voltage ratings were primarily dependent on surface breakdown since surface preparation technology was in its infancy. Now, however, surface preparation has improved and the reverse characteristics are based on bulk breakdown. This technology has brought the device to the state of art whereby the reverse power rating is as significant a rating as the forward power rating. This excessive power causes hot spot conditions which actually melt the silicon material, thereby destroying the p-n junction.

The transient voltage must therefore be prevented from destroying the diode by means of external circuitry. Only rarely will the transient be a calculated item since many transient conditions (regardless of the basic circuit) are highly dependent on the wiring layout. Often a breadboard layout is relatively free from transients because wiring is usually spread out and the design engineer falls into transient laxity only to be awakened when the final wired assembly starts destroying diodes. For this very reason, the following chapter is devoted to transient causes, detection, and protection.

Causes of Voltage Transients

Transient voltages are generated in circuits when a rapid change of current exists with an inductance. It is extremely difficult to have any circuit which is free of wiring inductance and, even if this is possible, the supply voltage remains a primary source of transients.

One major transient problem occurs when the diodes are located on the secondary side of the transformer and the switching is accomplished in the primary. The type of switch used will have an effect on the amplitude and pulse width of the transient generated during its opening and closing. Due to the leakage reactance and wiring capacitance of the transformer, an oscillation with long-time transients may result. Transients are relatively easy to handle provided their on-time is short, consequently transformers should be designed with low-leakage reactance and low capacitance.

Another source of transients is the diodes themselves. For this very reason transient voltages can be detected in diode circuitry even when both the input and output are transient-protected. This, however, is a minor source of transients.

Detection of Transients

The only acceptable means of learning the nature of the voltage transients is by the use of a very high-frequency oscilloscope and an attached camera. (The oscilloscope should be capable of 15 megacycles or greater.) Commercial transient indicators are excellent for troubleshooting in the field.

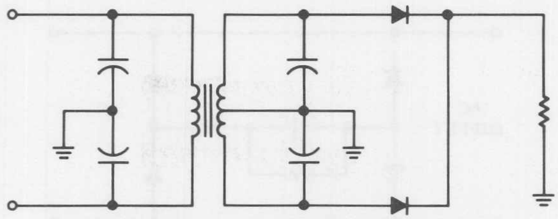
Assuming that an oscilloscope is used for detection, the first step is to apply maximum voltage to the input. Then with the oscilloscope placed directly across the diode (as short a lead as possible and all scope leads kept away from the circuit wiring), proceed with the normal cycle of operation for the equipment. During this process, note the point of operation which generates the greatest observable transient. Be sure that all the transient voltage is on the scope viewing area. Record this transient on a picture. Then, turn the brightness intensity on the scope up to a point where this dot has a ring around it and then proceed with the above procedure. This guarantees that the smallest transient has been seen. This procedure should be repeated at different times of the day for a period of about 15 minutes each. Then, repeat the above procedure with the line voltage at the lowest required of the circuit. Sometimes the greatest transient generation is with low line voltage. While this procedure is conducted, note the highest transient and its pulse width and also the widest transient including oscillation and its total on-time. Then place suppression circuits required to reduce the transients to an acceptable level. Another important procedure is to move the wiring of the final assembly to various places during the transient detection stage.

Suppression of Voltage Transients

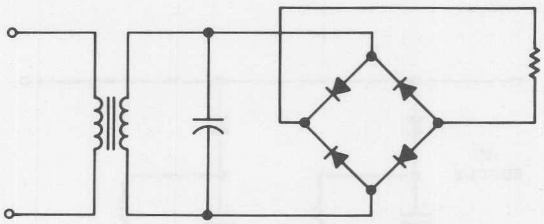
Suppression of voltage transients has many aspects; first, always use diodes in the prototype circuit which have a very high voltage capability. While the procedure for detection of transients is being conducted, always deal with the circuit components themselves before the addition of suppression circuits. Dealing with the circuit components means the placement of wiring and the changing or rearranging of switching and static elements such as transformers. Note also that transients are conducted not only by wiring capacitance but also through the air. After all means of suppression with the circuit components themselves has been exhausted, proceed with an examination of additional suppression circuits. Always note the before and after conditions of the transient voltage. All capacitors used for suppression circuits should have a good high-frequency response.

The first set of schematics deals with transient suppression on the ac input to a diode circuit using various components. Figures 11-1, 11-2, 11-3, and 11-4 are for transient or short-term excessive voltages. Figure 11-5 is for a long-term overvoltage where the silicon controlled rectifier is turned on by virtue of the zener current, subsequently opening the circuit breaker. Figure 11-6 is a method for three-phase supplies.

The second set of schematics deals with transient suppression circuits applied directly across components such as diodes, switches, etc. Primarily the diode protection suppression circuits are to remove the transients before they change the device, while the switch or contacts are to remove the transient which they have generated before they reach other circuit components.



(a) Full-Wave Center Tapped Rectifier Circuit



(b) Full-Wave Bridge Circuit

Figure 11-1 Transient Suppression with Non-Polarizing Capacitors

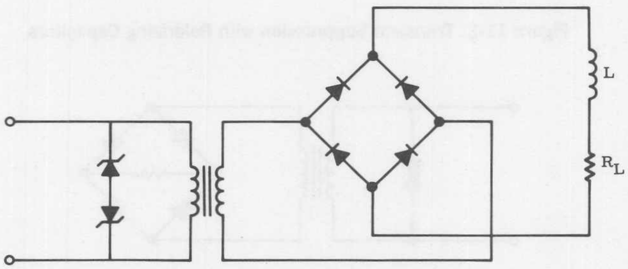
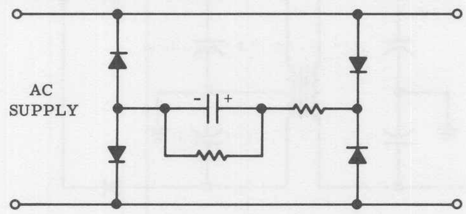


Figure 11-2. Transient Suppression with Zener Diodes

The third set of schematics deals with the transient voltage suppression on the output from the diode assembly. Oftentimes it becomes necessary to remove transients which are generated from the load itself or from external conditions near the load.

Quite often it becomes necessary to use one or more of these systems to adequately protect silicon diodes. The voltage and current capability of each protective device should be determined for each case by



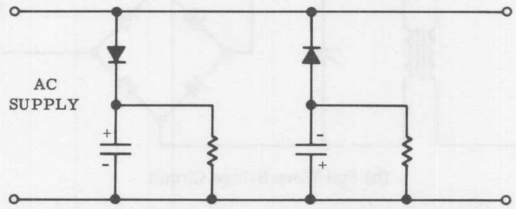


Figure 11-3. Transient Suppression with Polarizing Capacitors

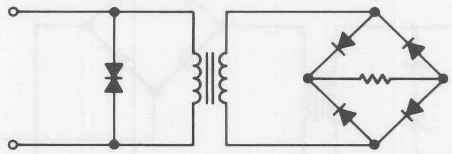


Figure 11-4. Transient Suppression with Selenium Non-Polarizing Diodes

laboratory tests, since mathematical calculations are sometimes over-swamped by unpredictable circumstances.

In cases where series RC circuits are used, the typical values for R are 11 to 47 ohms, and for C are over 0.01 to 0.5 μF. R should be a carbon-deposit type and C a high-frequency capacitor.

In cases where the capacitor is used as a dc capacitor, values up to 5 μF are possible. The high-frequency type capacitor is often expensive when high capacitance is required. There are cases when disc capacitors are used in parallel with the larger capacitors for good high-frequency short pulse-width capability.

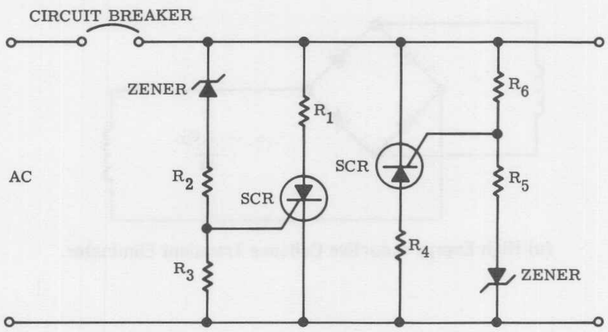


Figure 11-5. SCR Crowbar Over-Voltage Protection Circuit for AC Circuit Operation

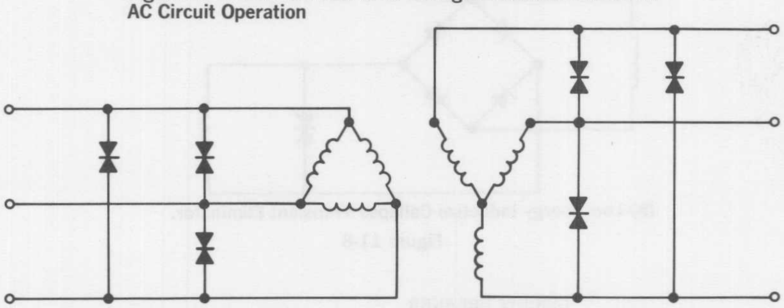
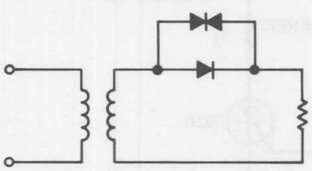
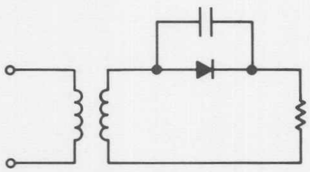


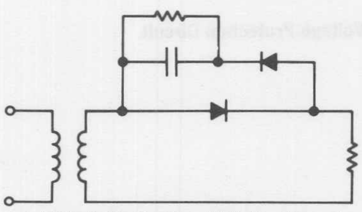
Figure 11-6. Transient Suppression on Three-Phase Circuit with Selenium



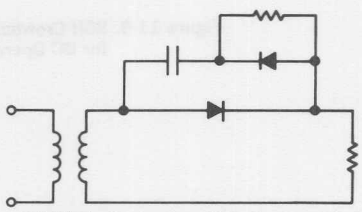
(a) Diode Protection With the Use of Selenium Diodes.



(b) Diode Protection With the Use of Capacitors.

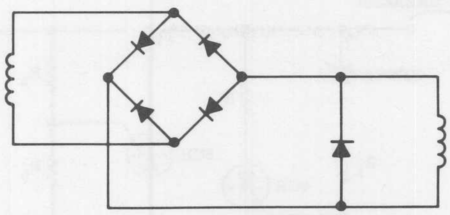


(c) Diode Protection With the Use of Capacitors & Diodes.

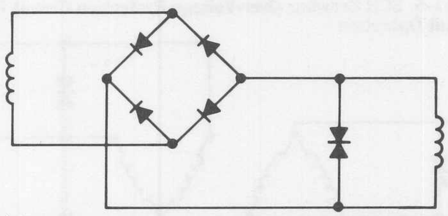


(d) Diode Protection With the Use of Capacitors & Diodes.

Figure 11-7



(a) High Energy Inductive Collapse Transient Eliminator.



(b) Low Energy Inductive Collapse Transient Eliminator.

Figure 11-8

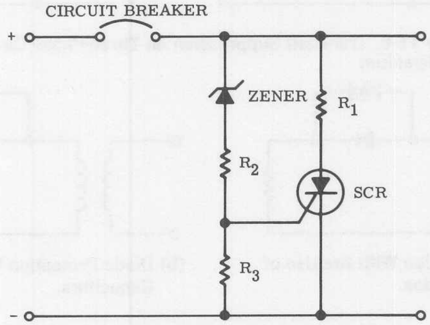


Figure 11-9. SCR Crowbar Over-Voltage Protection Circuit for DC Operation.

CHAPTER 12

Thermal Design for Silicon Rectifiers

Introduction

One of the least discussed, but most important subjects concerned with the application of silicon rectifiers is effective cooling techniques. Since most rectifier device failures are ultimately temperature failures, it is imperative that good cooling techniques be employed. Any semiconductor will operate more reliably at 25°C below its maximum rated operating temperature. In most applications where natural convection cooling is employed, a rectifier cannot carry its rated current.

Mounting and Cooling of Silicon Rectifiers

Since junction heating is the limiting factor in the rating of rectifiers, particular attention must be paid to the controlling equations.

$$T_J = P_D \theta_{JA} + T_A \qquad (12\text{-}1)$$

where T_J = junction temperature

T_A = ambient temperature

P_D = total power dissipated in the device

θ_{JA} = thermal resistance junction-to-ambient.

The thermal resistance θ_{JA} consists of several series resistances and may be written as

$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA} \qquad (12\text{-}2)$$

where θ_{JC} = thermal resistance junction-to-case

θ_{CS} = thermal resistance case-to-sink

θ_{SA} = thermal resistance sink-to-ambient.

Thus, Equation (12-1) may be rewritten as

$$T_J = P_D(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A \qquad (12\text{-}3)$$

Equation (12-3) may be used to calculate all thermal designs referring to the junction temperature. For all calculations involving junction temperature, the term θ_{JC} should include transient thermal conditions. Since many data sheets do not include this transient thermal data, as a general rule, it is easier to work with case temperature. All data sheets give a case temperature versus current derating curve. This curve always incorporates the transient thermal characteristics of the device.

Due to the very long time constant of the heat sink, the "dc" Equations (12-1), (12-2), and (12-3) may be used with high accuracy. A heat sink of 5" × 5" × 0.125" will take about fifteen minutes or more to reach its final stabilization temperature. Useful design equations incorporating the case temperature are

$$T_C = P_D \theta_{CS} + P_D \theta_{SA} + T_A \tag{12-4}$$

$$T_A = -P_D(\theta_{CS} + \theta_{SA}) + T_C \tag{12-5}$$

$$\theta_{SA} = \frac{T_C - T_A - P_D \theta_{CS}}{P_D} \tag{12-6}$$

Note that for Motorola's large multicell devices the θ_{CS} is approximately zero for nearly all applications in which the device is bolted to a heat sink and lubricated. Consequently, Equations (12-4), (12-5), and (12-6) are simplified somewhat for high-current Motorola devices.

$$T_C = P_D \theta_{SA} + T_A \tag{12-7}$$

$$T_A = T_C - P_D \theta_{SA} \tag{12-8}$$

$$\theta_{SA} = \frac{T_C - T_A}{P_D} \tag{12-9}$$

Lead Mounted Rectifiers

Lead mounted silicon rectifiers, designed for low-current applications, require relatively small heat dissipating area. Heat developed in these devices is transmitted to the contact area. For applications using lead mounted rectifiers, some practical considerations will aid in keeping the junction within its limit of operating temperature range. The first rule of mounting is to keep the lead lengths as small as possible. Figure 12-1 shows the effect of increasing the lead length versus the θ_{JA}. Clearly, the longer the lead length the greater the θ_{JA}. Figure 12-2 shows the effect of different mountings on θ_{JA} when the lead length is held constant. Figure 12-2(a) shows the effect of ambient air temperature. The diodes should be mounted above the board to permit ambient air convection. Figure 12-2(b) proves out Figure 12-2(a) since the thermal impedance went up as convection effects were cut down. Figure 12-2(c) shows the effect of larger area clips. These θ_{JA} values as shown are obtainable in practice. These are actual measured θ_{JA} values for the MR1036A diodes.

Other considerations are shielding from high temperature generating by components such as resistors, tubes, transformers, etc. These components will increase the T_A and reduce the radiating capability of the diode.

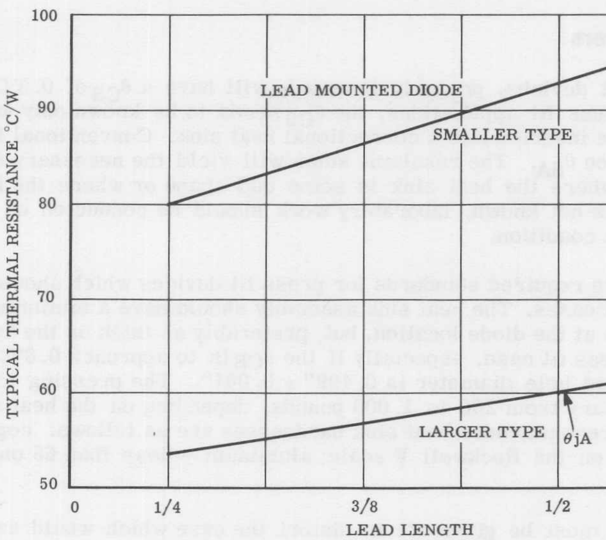


Figure 12-1. Lead Length Versus θ_{JA}

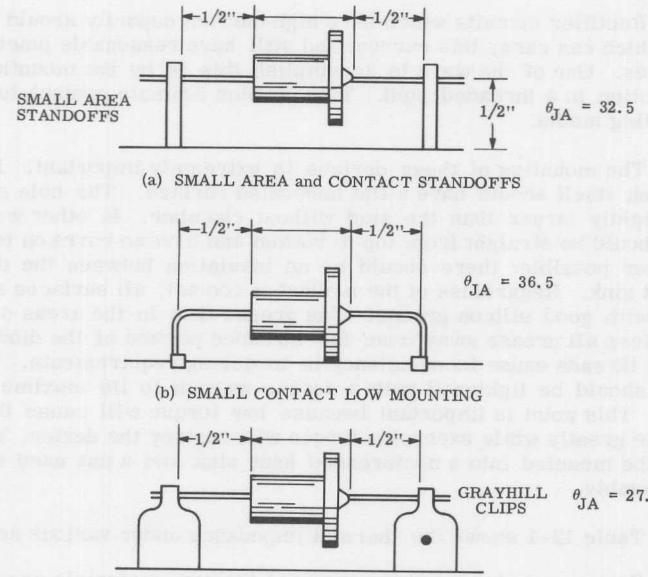


Figure 12-2. Clip Area Versus θ_{JA}

Press Fit Rectifiers

Press fit devices, properly inserted, will have a θ_{CS} of 0.8°C/W to 1°C/W. In press fit applications, the θ_{CS} needs to be known only when the diode is to be inserted into a correctional heat sink. Conventional heat sinks have data on θ_{SA}. The resultant sums will yield the necessary θ_{CA}. In applications where the heat sink is some odd shape or where the heat sink capability is not known, laboratory work should be conducted on the case-to-ambient condition.

There are required standards for press fit devices which should be adhered to in all cases. The heat sink assembly should have a minimum of 0.125" thickness at the diode location, but, preferably as thick as the knurl length of the press fit case, especially if the θ_{CS} is to approach 0.8°C/W. The recommended hole diameter is 0.499" ± 0.001". The pressing force necessary will vary from 250 to 1,000 pounds, depending on the heat sink material. The recommended heat sink hardnesses are as follows: copper — less than 50 on the Rockwell F scale; aluminum — less than 65 on the Brinell scale.

All care must be given not to distort the case which would cause thermal problems or cracking of the silicon die.

Stud Mounted Rectifiers

Rectifier circuits which have high-current capacity should have devices which can carry this current and still have reasonable junction temperatures. One of the ways to accomplish this is by the mounting of the p-n junction to a threaded stud. This enables intimate contact to the heat dissipating media.

The mounting of these devices is extremely important. First the heat sink itself should have a flat noncoated surface. The hole should be only slightly larger than the stud without chamber. In other words, the sides should be straight from top to bottom and have no burrs on the edges. Wherever possible, there should be no insulation between the diode and the heat sink. Regardless of the method of contact, all surfaces should be coated with good silicon grease. The grease fills in the areas of no contact. Keep all grease away from the threaded portion of the diode. Lubricated threads cause inconsistency in torqueing requirements. Then the device should be tightened with a torque wrench to its maximum torque rating. This point is important because low torque will cause the θ_{CS} to increase greatly while excessive torque will destroy the device. The diode should be mounted into a nonthreaded heat sink and a nut used to tighten the assembly.

Table 12-1 shows the thermal impedance under various conditions.

Copper and aluminum are the most common materials used for heat sinks. Copper heat sinks have the higher thermal conductivity, but are more expensive. Aluminum has a lower conductivity, is less expensive and weighs considerably less. Where cost is a critical factor, steel may be used. The use of aluminum heat sinks adds an additional problem: Galvanic

Table 12-1

Stud Size	Hex Size across flats	Torque (lb)	Thermal Resistance (case-to-sink)			
			Metal-to-Metal		Mica Insulation	
			Dry	Lubrication	Dry	Lubrication
10-32	7/16	15	0.41	0.22	1.24	1.06
1/4-28	11/16	25	0.38	0.20	0.89	0.70

action may occur between rectifier and sink, if the assembly is placed in a corrosive atmosphere. To counteract this undesired action, Motorola rectifiers are normally nickel plated. Consequently, precautions must be taken not to mar this nickel-plated finish on the rectifiers.

Heat sinks for rectifiers are often rectangular sheets of aluminum or copper. Such heat sinks are quite effective and afford ease in mounting and isolation. The relationship between heat sink area and thermal resistance can be obtained and plotted as shown in Figure 12-3.

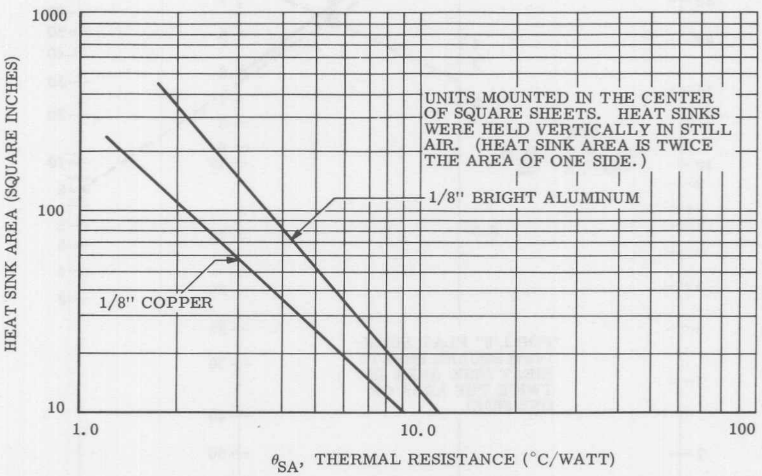


Figure 12-3 Heat Sink Area versus Thermal Resistance

A nomograph which relates allowable power dissipation, temperature, and required heat sink area is given in Figure 12-4 for square plates of aluminum 1/8" thick.

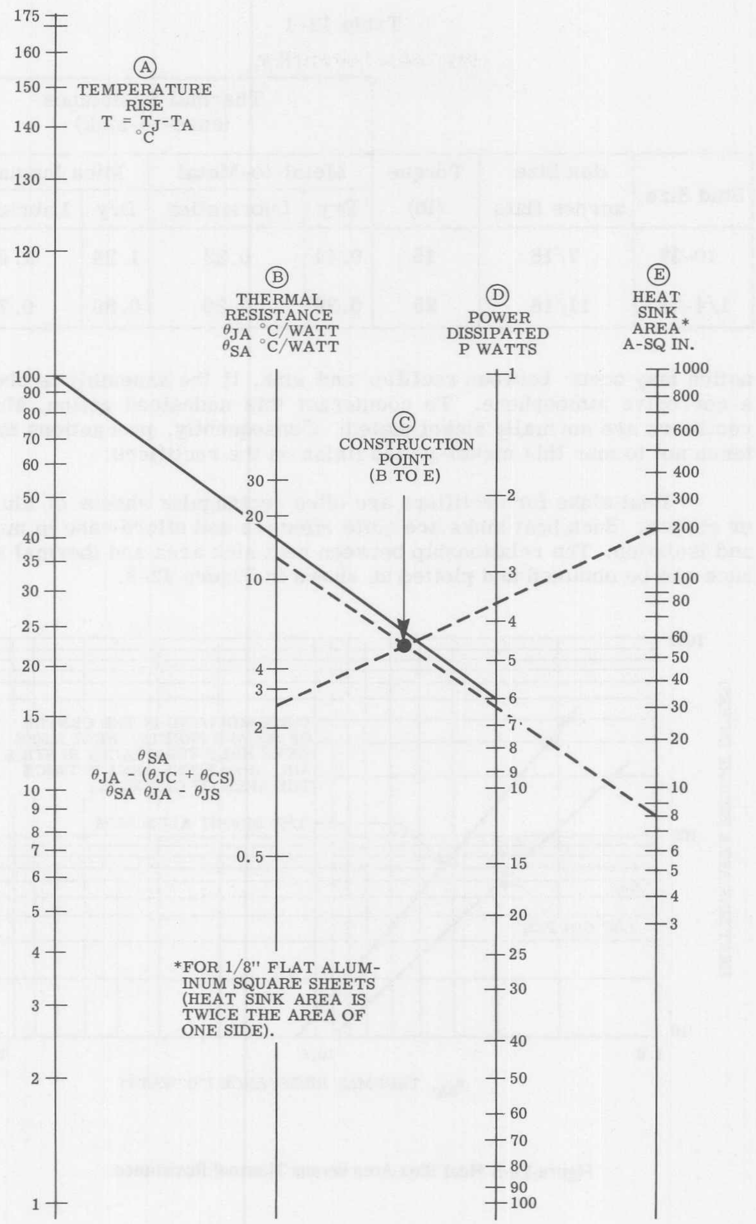


Figure 12-4 General Heat Sink Nomograph

An example of the general nomograph is as follows:

$$T_{J(max)} = 175°C$$

$$T_A = 75°C$$

$$P_{av} = 6 \text{ watts}$$

$$\theta_{JC} = 2.4°C/W$$

$$\theta_{CS} = 0.4°C/W$$

Solution: (refer to Figure 12-4)

(1) $\theta_{JS} = \theta_{JC} + \theta_{CS} = 2.8°C/W$

(2) $T_J - T_A = 100°C$; enter scale A at 100°C

(3) Enter scale D at 6 watts

(4) Join 100°C and 6 watts with a straight line intersecting line B

(5) Obtain θ_{JA} from nomograph line B = 15°C/W

(6) Obtain θ_{SA} (heat sink thermal resistance) mathematically;

$$\theta_{SA} = \theta_{JA} - \theta_{JS} = 15 - 2.8 = 12.2°C/W$$

(7) Enter line B at 12.2°C/W, and construct a line from this point through the construction point C extending to E

(8) Read 8 sq. in. This would be 4 sq. in. per side or a flat square sheet 1/8" × 2" × 2".

Nomographs could be constructed for sheets of copper in the same manner as for aluminum sheets. However, copper plates are more expensive and less likely to be used where aluminum sheets are sufficient. The relative advantages of copper over aluminum sheets can be seen from Figure 12-3.

Commercial Heat Sinks

A wide variety of commercial heat sinks is available for rectifier applications. These range from small-area devices which clamp onto the rectifier case (axial leaded or single ended diodes) to large heat sinks which employ forced air cooling. When selecting commercial heat sinks, such factors as power dissipation, shape, weight, material, finish, and volume, as well as sink-to-ambient thermal resistance should be considered.

Commercial heat sinks are of two general classifications, natural convection coolers and forced air coolers. In natural convection systems, air is moved past the metal surfaces by the local heating of the air next to the plate. Forced air coolers use fans to increase the air flow over the heat sink.

Natural Convection Heat Sinks

The natural convection heat sinks are rated according to the temperature rise (of the sink) above the ambient temperature. Thus, natural convection coolers require a curve of temperature rise versus applied power. Figures 12-5 through 12-8 show four typical medium-power natural convection heat sinks.

A short example of the calculations required for a typical heat sinking application will illustrate the use of the design equations.

$$P_D = 30 \text{ watts}$$

$$T_J = 175°C$$

$$T_A = 50°C$$

$$\theta_{JC} = 2.4°C/W$$

$$\theta_{CS} = 0.4°C/W$$

$$\theta_{JS} = \theta_{JC} + \theta_{CS} = 2.8°C/W$$

$$\theta_{SA} = \frac{T_J - T_A - P_D(\theta_{CS} + \theta_{JC})}{P_D}$$

$$= \frac{175 - 50 - 30(0.4 + 2.4)}{30}$$

$$= \frac{41}{30} = 1.37°C/W$$

$$P_D = 30 \text{ watts}$$

$$T_C = 103°C$$

$$T_A = 50°C$$

$$\theta_{CS} = 0.4°C/W$$

$$\theta_{SA} = \frac{T_C - T_A - P_D\theta_{CS}}{P_D}$$

$$= \frac{103 - 50 - 30(0.4)}{30}$$

$$= \frac{41}{30} = 1.37°C/W$$

This example (which uses the junction temperature) is correct only if the value of θ_{JC} is known for the appropriate current waveform (which includes the transient thermal impedance). The example referencing the temperature-to-case does not include transient thermal impedance.

Forced Air Cooling

At one time engineers preferred not to use forced air cooling, and justifiably so. The available forced air fans were not reliable for continuous duty for long periods of time. This is no longer true. There are simple thermal contact switches available from such firms as Therm-O-Disc, which are mounted on heat sinks for thermal interlocks as an additional safety feature. Forced air correction enables the design to utilize the diode at its maximum current rating. It also enables the heat sink assembly to be manufactured cheaper. The forced air, after it leaves the diodes, can also be used as a cooling medium for other circuit components.

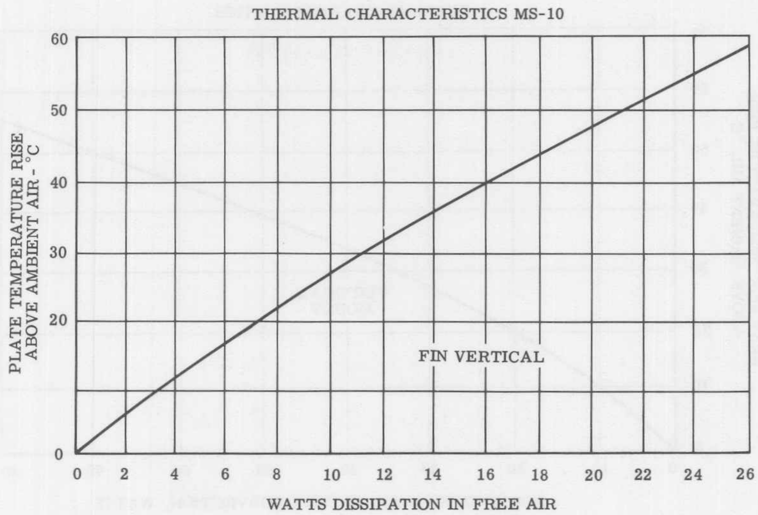


Figure 12-5. Motorola MS-10 Heat Sink Thermal Characteristics

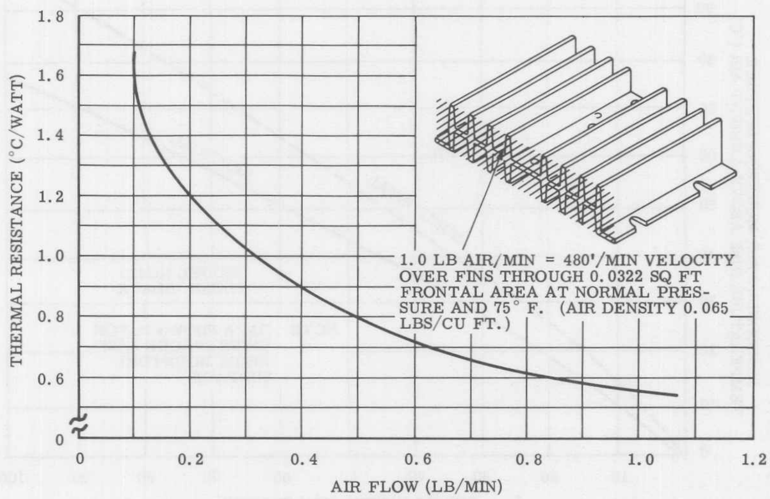


Figure 12-6. Performance Under Forced Air Flow of Motorola MS-10 Natural Convection Transistor Heat Sink.

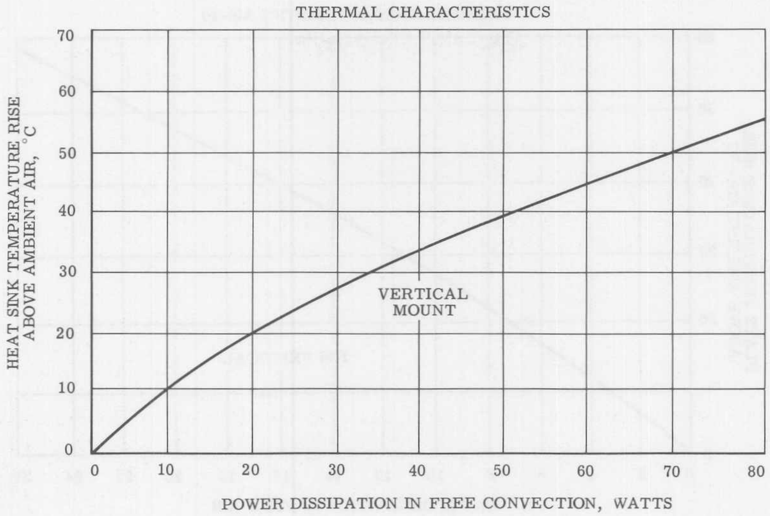


Figure 12-7. Astro Dynamics Model 2507 Thermal Characteristics

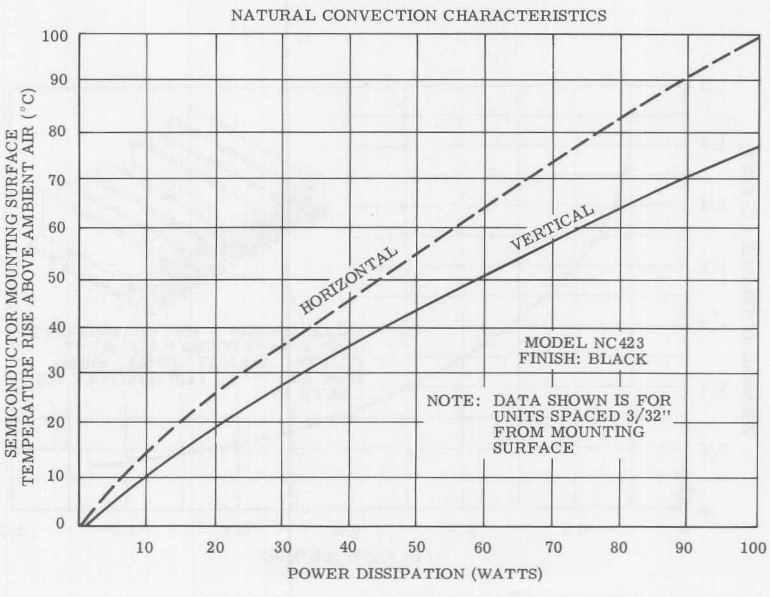


Figure 12-8. Wakefield Engineering — Delta T Model 423 Thermal Characteristics.

Heat Sink Emperical Verification

After the mathematical calculations have dictated the choice of the heat sink, and the assembly is inserted in its actual operating condition, it is desirable to conduct a series of thermal tests. These tests insure the satisfactory operation of the diodes. It is often not possible to know the ambient air temperature during the initial calculations. For example, all natural heat sink curves as shown by the manufacturer are for a vertical unobstructed air flow rating. If the heat sink is tested in an enclosed chamber, the heat sink will have an increase in θ_{SA}. Therefore, the placement of the heat sink will have a bearing on the end result.

Tests on about six diodes will give an excellent relative confidence level. The test should follow the procedure as outlined. Attach a thermocouple to the case by means of direct metal contact. If an inexpensive temperature indicator is to be used, the Simpson portable indicator is excellent. Never use a thermometer. Mount the diode in the heat sink in final assembly position. With the equipment operating under the worst-case condition, measure the case temperature. Allow at least one hour operating time before recording the case temperature. After the case temperature is measured and the average current through the diode is known, refer to the appropriate diode data sheet. The empirical point must fall below the maximum operating point on the T_C versus I_{av} derating curve. For reliable operation, it is good to have this point about 25°C below the published curves. Where possible, cycle the equipment through all operating conditions, and record the temperatures for future reference which may be needed in cases of troubleshooting.

Heat Sink Empirical Verification

After the mathematical calculations have checked the choice of the heat sink, and the assembly is inserted in its actual operating condition, it is desirable to conduct a series of thermal tests. These tests insure the satisfactory operation of the diodes. It is often not possible to know the ambient air temperature during the initial calculations. For example, all natural heat sink curves as shown by the manufacturer are for a vertical unobstructed air flow setting. If the heatsink is tested in an enclosed chamber, the heat sink will have an increase in T_A. Therefore, the placement of the heat sink will have a bearing on the end result.

Tests on stud mount diodes will give an excellent relative confidence level. The test should follow the procedure as outlined. Attach a thermocouple to the case by means of epoxy metal cement. If an inexpensive temperature indicator is to be used, the Simpson thermometer indicator is excellent. Never use a thermometer. Mount the diode in the heat sink in final assembly position. With the equipment operating under the worst case condition, measure the case temperature. Allow at least one hour operating time before recording the case temperature. After the case temperature is measured and the average current through the diode is known, enter in the appropriate diode data sheet. The empirical point must fall below the maximum operating point on the T_C versus I_{av} derating curve. For reliable operation, it is good to have this point about 25°C below the published curves. Where possible, cycle the equipment through all operating conditions, and record the temperatures for future reference which may be needed in cases of troubleshooting.

CHAPTER 13

Rectifier Test Circuits

Introduction

The following test circuits are presented to aid the users of rectifier components in testing, comparing, and troubleshooting rectifier circuits.

The test circuits used by Motorola to establish rectifier ratings and characteristics conform to NEMA-EIA standards. Although automated equipment is used at Motorola, the same basic techniques may be applied without this equipment.

When testing rectifiers against specifications, it is essential that the meaning of ratings and characteristics is well understood. "Characteristics" are rectifier parameters which are measured under specified conditions. Characteristics are given as typical data or as maximum or minimum limits. Ratings give absolute maximum conditions not to be exceeded if long life and high reliability are expected. Ratings are not measured directly, but are established by the judgment of the manufacturer. Such ratings are usually quite conservative.

Basic Test Circuits

DC FORWARD VOLTAGE DROP

The dc forward voltage drop of a rectifier may be measured with the circuit shown in Figure 13-1.

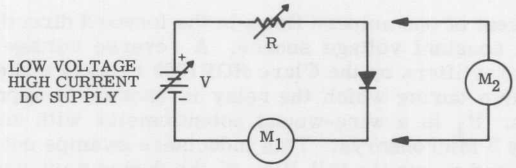


Figure 13-1. DC Forward Voltage Drop Test Circuit

The test procedure is as follows: V and R are adjusted such that the specified test current (as measured by M_1) flows through the diode in the forward direction. The forward voltage is read on the voltmeter M_2, which can be almost any accurate multimeter since the forward diode impedance is very low.

Example: Test Motorola MR1032

(1) The steady-state current is set to 3 amperes (on M_1).

(2) V_F is read (on M_2). (V_F will be less than 0.9 volt.)

Note: Ambient temperature is 25°C.

DC REVERSE CURRENT

The dc static reverse current can be obtained using the circuit of Figure 13-2.

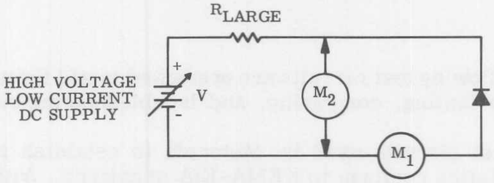


Figure 13-2. DC Reverse Current Test Circuit

The test procedure is as follows: V is adjusted until the reverse voltage of the diode (as read on M_2) is at its rated value. The dc reverse current is read on M_1. The meter M_1 must have sufficient sensitivity to read the reverse leakage current.

Example: Test Motorola MR1032

(1) V is set to 200 volts (on M_2).

(2) I_R is recorded (on M_1). (I_R will be less than 0.5 mA.)

Note: Ambient temperature is 25°C.

Recovery Time Test Circuit

The recovery time of a diode can be measured using the test circuit shown in Figure 13-3.

A current of one ampere flows in the forward direction through the diode from a constant voltage source. A reverse voltage of 30 volts is applied to the rectifiers by the Clare HGP1002 relay (a make-before-break type). The time during which the relay is shorted is approximately 200 microseconds. R_1 is a wire-wound potentiometer with an inductance of approximately 3 microhenrys. This inductance swamps out the inductance of the circuit and shows the fall time of the device so it can be observed. The primary function of R_1 is to limit the overshoot current of the rectifier when the voltage goes negative. R_2 is a sensing resistor which provides voltage deflection for the oscilloscope.

The test procedure is as follows: The constant voltage supply is adjusted until one ampere of ac current flows through the rectifier. The switching relay is energized and the overshoot current is adjusted to some predetermined level. The recovery time (the time required for the current to pass through zero) is read, and the time the rectifier requires to recover to 90 per cent of its rated reverse leakage current is also read.

Example: Test Motorola 1N3879

(1) The forward dc current is set to one ampere.

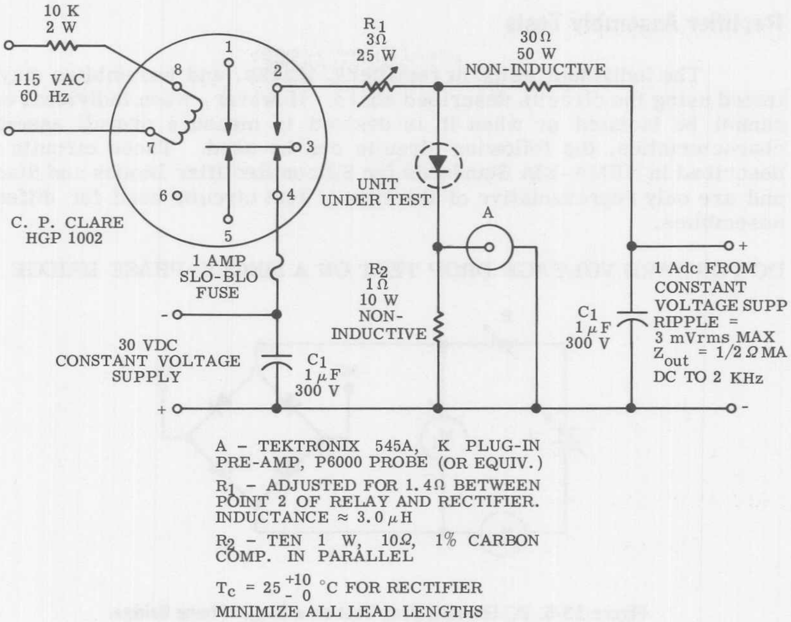


Figure 13-3. Reverse Recovery Time Test Circuit

(2) The relay and resistor R_1 are set so that the overshoot current is limited to two amperes.

(3) The reverse recovery time on the oscilloscope is read as illustrated in Figure 13-4.

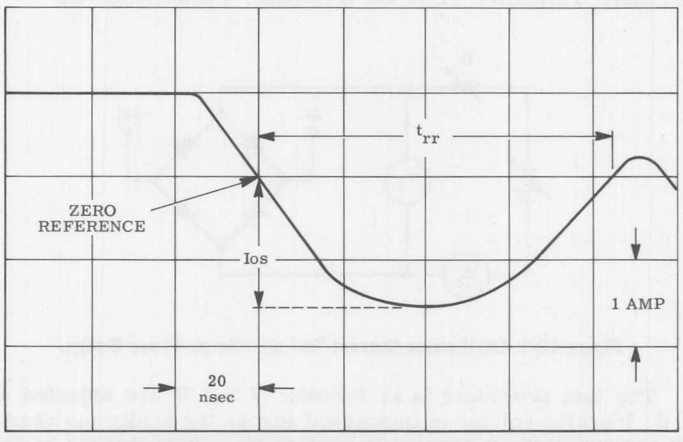


Figure 13-4. Typical Reverse Recovery Pattern

Rectifier Assembly Tests

The individual cells in rectifiers, stacks, and assemblies may be tested using the circuits described above. However, when individual units cannot be isolated or when it is desired to measure overall assembly characteristics, the following circuits can be used. These circuits are described in NEMA-EIA Standards for Silicon Rectifier Diodes and Stacks, and are only representative of the type of test circuits used for different assemblies.

DC FORWARD VOLTAGE DROP TEST ON A SINGLE-PHASE BRIDGE

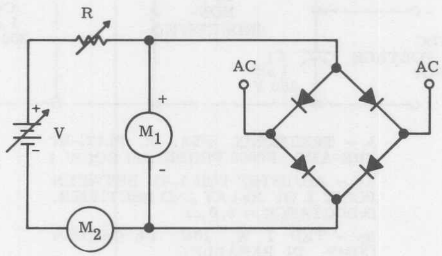


Figure 13-5. DC Forward Drop Test on a Single-Phase Bridge.

The test procedure is as follows: V and R are adjusted until the rated average current through the bridge can be read on meter M_2. The forward voltage drop is recorded from M_1. Note that the ac terminals of the bridge are open and the power supply is connected to terminals of opposite polarity on the rectifier bridge.

DC REVERSE CURRENT TEST ON A SINGLE-PHASE BRIDGE

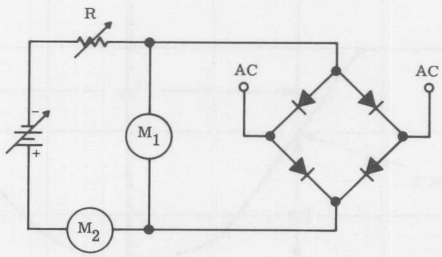


Figure 13-6. DC Reverse Current Test on a Single-Phase Bridge.

The test procedure is as follows: V and R are adjusted until the rated dc blocking voltage is impressed across the bridge (as read on M_1). The dc reverse leakage current is read on M_2. Note that the ac terminals of the bridge are open.

Bridge Output Voltage

Figure 13-7 shows a test schematic useful in checking the operating condition of diodes in a bridge circuit.

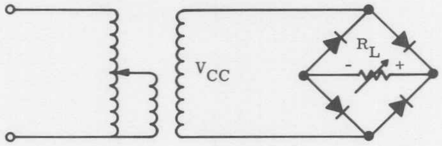


Figure 13-7. Bridge Assembly Test Circuit

The test procedure is as follows: The input voltage is set at the rated bridge-operating voltage (R_L is large). An oscilloscope is used to insure that full-wave rectification is taking place.

Bridge Output Voltage

Figure 13-7 shows a test circuit which is useful in checking the operating conditions of diodes in a bridge circuit.

Figure 13-7. Bridge Assembly Test Circuit

This test procedure is as follows: The input voltage is set at the rated bridge operating voltage (V_s) in degrees. An oscilloscope is used to insure that units are performing as to existing specs.

CHAPTER 14

Reliability Of Motorola Multicell Power Rectifiers

Life Tests

As part of an in-plant testing and evaluation program, operating and storage life tests have been performed on the basic rectifier cells used in all Motorola medium and high-current power rectifiers.

Storage life tests were performed at a minimum of 175°C ambient temperature for 1,000 hours with initial parameter specifications used for test end points. Steady-state operating life tests have also been performed at a minimum case temperature of 150°C with maximum rated current of 20 amperes average per cell; 600 volts applied for 1,000 hours. Initial specifications were also used as test end points. Results of the operational life tests have demonstrated a device failure rate at a 90 per cent confidence level of less than 1.4 per cent per 1,000 hours under these maximum rated conditions. At a 60 per cent confidence level this provides a 0.75 per cent per 1,000 hour value. These results are consistent with the requirements of general Military specifications. In over 270,000 device-hours of testing at maximum stress, only one failure (noncatastrophic) has been recorded. In addition, reliability studies have shown that when silicon devices of this type are operated at lower, more typical temperatures and under less stress, substantially lower failure rates result. Present data shows that the basic cells, when operated at normal case temperatures in the 100°C range and under normal current and voltage requirements, will easily achieve low failure rates of less than 0.01 per cent per 1,000 hours of operation. This inherent reliability that is designed into every Motorola basic rectifier cell is, in turn, reflected in every multicell power rectifier through built-in redundancy and conservative design and device rating. These facts have been verified through operational life testing of multicell rectifiers at maximum ratings for over 14,000 hours continuously in which a failure rate of less than 0.5 per cent per 1,000 hours was achieved. This testing represented over 1,400,000 device-hours of basic cell operation and indicates a maximum expected failure rate as low as 0.005 per cent per 1,000 hours for the total multicell device under normal derated conditions.

In addition, Motorola power rectifiers have been subjected to and passed such stringent Military environmental tests in accordance with MIL-STD-750 requirements as:

Temperature cycling	Vibration (variable frequency)
Thermal shock	Constant acceleration
Moisture resistance	Salt spray
Mechanical shock	Barometric pressure (reduced)
Vibration fatigue	Hermetic seal

Equipment Usage Life Tests

In another test program, 80-ampere and 240-ampere multicell rectifiers were tested in an actual equipment application under normal industrial service requirements. Forty of these rectifiers have provided over 12,000 hours of continuous service without a single failure or any equipment down-time. This test amounted to over 450,000 device-hours of reliable operation in a typical industrial electro-chemical plating application. In one customer evaluation program, sixty 240-ampere multicell rectifiers have provided over 16,000 hours of trouble-free service from 15 welding machines under maximum field conditions. This outstanding record of over one million device-hours of reliable operation had never been achieved in this equipment by any other rectifier manufacturer until Motorola. These results have prompted this customer to consider using only multicell rectifiers in his equipment.

In an industrial fork-lift truck application, 240, 400, and 650-ampere multicell rectifiers are required to sustain the full armature current of large dc motors and also to withstand extremely high surge currents under a stalled motor condition. In these equipments where no other rectifier had ever been completely successful, Motorola has supplied over 4,000 devices which have operated many thousands of hours without a single rejection or electrical failure recorded.

In another industrial power supply application, 60 Motorola 400-ampere rectifiers are required to deliver 15,000 amperes continuous output from a polyphase rectifier circuit for chemical processing. This number of multicell power rectifiers represents over 1,000 basic cells operating in the same circuit. In over one year of continuous service, no failures or equipment down-time have been experienced. This record amounts to over 480,000 device-hours of reliable service from these 60 power rectifiers and over 8,500,000 device-hours when considering the number of basic rectifier cells being used.

Conclusion

These have been just a few brief examples of the testing and field experience of Motorola multicell power rectifiers. These devices have achieved an excellent record in the past few years since their development, and are successfully serving in a wide variety of equipment applications such as:

Industrial power supplies	Steel mill power supplies
Mining equipment	Electronic computer power supplies
Automotive alternators	Telephone equipment
Battery chargers	Magnetic testing equipment
Plating equipment	Military defense equipment
Welders	Traction equipment

CHAPTER 15

Rectifier and Assembly Specifications

SILICON RECTIFIERS

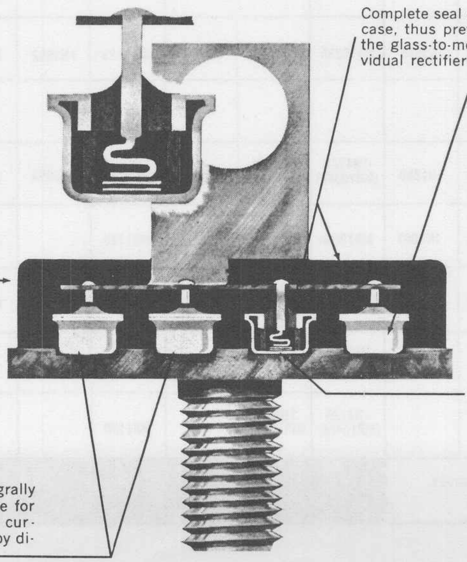
The trend in rectifiers, today, is toward silicon. Technically, there are many reasons why this is so. In comparison with thermionic tubes, silicon rectifiers offer a new era of reliability and performance, and no other solid-state rectifier has the inherant advantages of silicon. Silicon shrugs at operating temperatures that would quickly wilt other solid-state devices. The high forward conductance and low-reverse-leakage current of silicon outclasses selenium, and no other type of rectifier packs as much current-carrying capacity into as small a package. Moreover, these advantages of silicon rectifiers are now available at costs that are more than competitive with other types.

Motorola manufactures a complete line of silicon rectifiers for current requirements ranging from milliamperes to kiloamperes. These are housed in a variety of package types, making them suitable for every electrical and electronic application.

In addition, rectifier assemblies for higher voltage and current devices and for applications such as bridges and other circuit configurations are available as standard devices and can easily be made to order for custom applications.

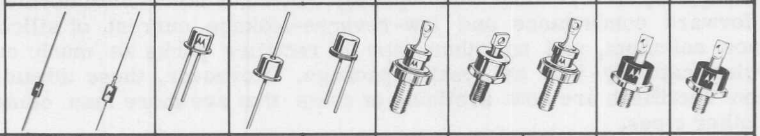
MULTI-CELL RECTIFIERS

For high-current rectifiers, Motorola employs the multi-cell concept. This approach not only permits the fabrication of higher-current rectifiers, but also eliminates many of the problems associated with large single-junction devices. The construction of a typical multi-cell rectifier is shown below.



MOTOROLA PREFERRED SILICON RECTIFIER SELECTION GUIDE

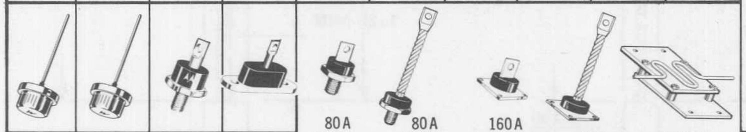
...a digest of the broadest line of quality rectifiers available



	1 A		1.5 A	3 A		6 A	12 A		15 A	20 A
V_{RM} (REP)	Surmetic‡ CASE A	FAST RECOVERY CASE B	CASE C	CASE D	CASE E	FAST RECOVERY CASE F	CASE G	FAST RECOVERY CASE F	CASE H	CASE H
50 V	1N4001	MR1337-1		1N4719 (MR1030A)	1N4997 (MR1030B)	1N3879	MR1120	1N3889	1N3208	1N248B
100 V	1N4002	MR1337-2	1N1563	1N4720 (MR1031A)	1N4998 (MR1031B)	1N3880	MR1121	1N3890	1N3209	1N249B
150 V										1N1193
200 V	1N4003 *1N3611	MR1337-3	1N1564	1N4721 (MR1032A)	1N4999 (MR1032B)	1N3881	MR1122	1N3891	1N3210	1N250B
250 V										
300 V		MR1337-4	1N1565	MR1033A	MR1033B	1N3882	MR1123	1N3892	1N3211	1N1195
350 V										
400 V	1N4004 *1N3612	MR1337-5	1N1566	1N4722 (MR1034A)	1N5000 (MR1034B)	1N3883	MR1124	1N3893	1N3212	1N1196
500 V		MR1337-6	1N1567	MR1035A	MR1035B		MR1125		1N3213	1N1197
600 V	1N4005 *1N3613	MR1337-7	1N1568	1N4723 (MR1036A)	1N5001 (MR1036B)		MR1126		1N3214	1N1198
800 V	1N4006			1N4724 (MR1038A)	1N5002 (MR1038B)		MR1128			
1000 V	1N4007			1N4725 (MR1040A)	1N5003 (MR1040B)		MR1130			

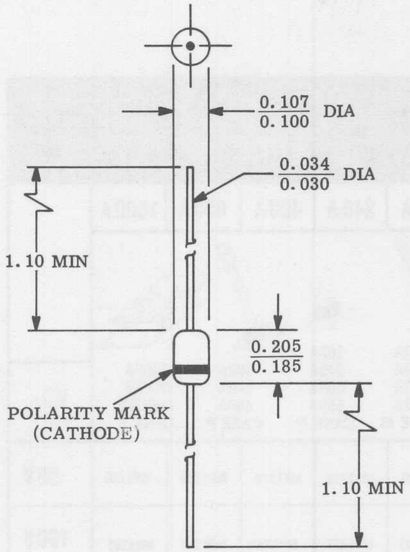
*Available to USN Spec MIL-S-19500/228
‡Trademark Motorola Inc.

†This list covers only the most popular Motorola rectifiers and by no means represents all the devices available from stock or currently under development. The user is urged to contact the nearest Motorola regional office for information on current and voltage ratings not shown or for any special electrical and/or mechanical requirements as well as complete specifications for all devices listed.

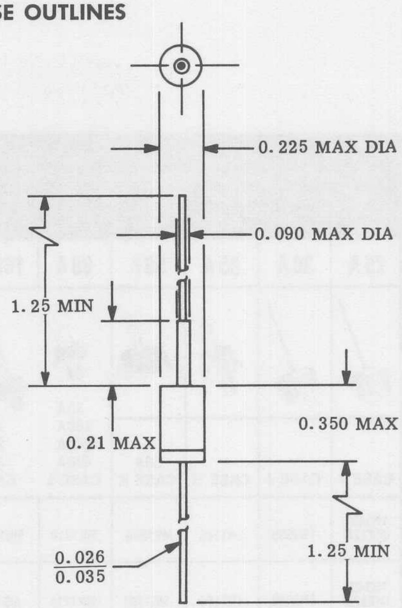
25 A	30 A	35 A	50 A	80 A	160 A	240 A	400 A	650 A	1000 A	
										
CASE J	CASE J	CASE H	50 A CASE K	80 A 160 A 240 A 400 A CASE L	80 A 160 A 240 A 400 A CASE M	160 A 240 A 400 A 650 A CASE N		160 A 240 A 400 A CASE P	1000 A (WATER COOLED) CASE R	V_{RM} (REP)
1N3491 (MR322)	1N3659	1N1183	MR1200	MR1210	MR1220	MR1230	MR1240	MR1260	MR1290	50 V
1N3492 (MR323)	1N3660	1N1184	MR1201	MR1211	MR1221	MR1231	MR1241	MR1261	MR1291	100 V
		1N1185	MR1202	MR1212	MR1222	MR1232	MR1242	MR1262	MR1292	150 V
1N3493 (MR324)	1N3661	1N1186	MR1203	MR1213	MR1223	MR1233	MR1243	MR1263	MR1293	200 V
			MR1204	MR1214	MR1224	MR1234	MR1244	MR1264	MR1294	250 V
1N3494 (MR325)	1N3662	1N1187	MR1205	MR1215	MR1225	MR1235	MR1245	MR1265	MR1295	300 V
			MR1206	MR1216	MR1226	MR1236	MR1246	MR1266	MR1296	350 V
1N3495 (MR326)	1N3663	1N1188	MR1207	MR1217	MR1227	MR1237	MR1247	MR1267	MR1297	400 V
MR327		1N1189								500 V
MR328		1N1190								600 V
MR330										800 V
MR331										1000 V

REVERSE POLARITIES AVAILABLE IN ALL 3A TO 1000A TYPES

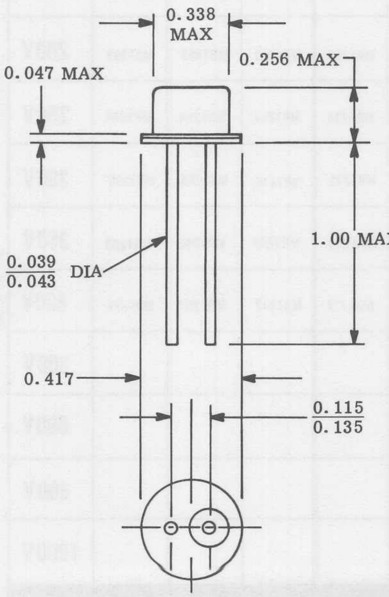
RECTIFIER CASE OUTLINES



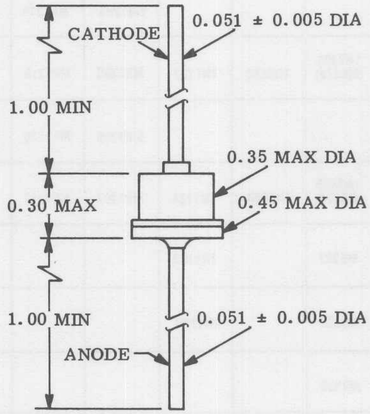
CASE A



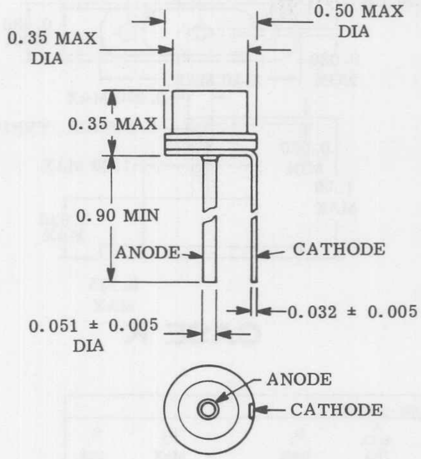
CASE B



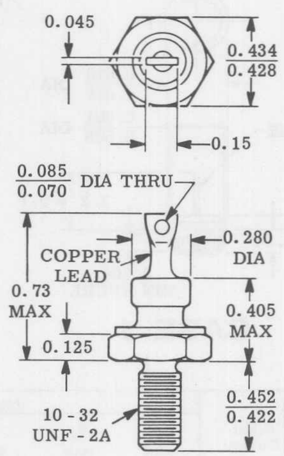
CASE C



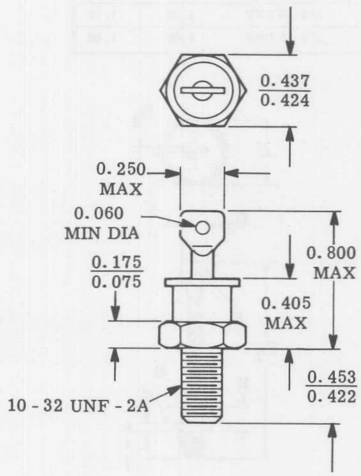
CASE D



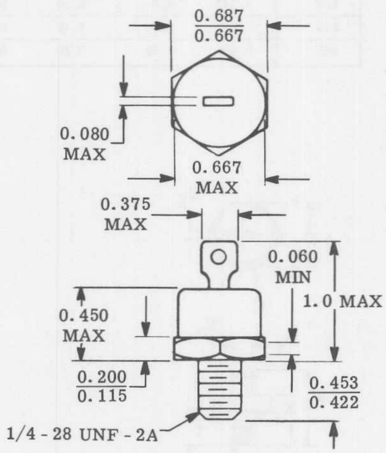
CASE E



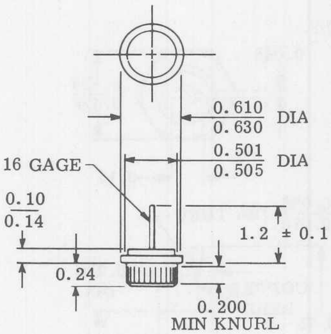
CASE F



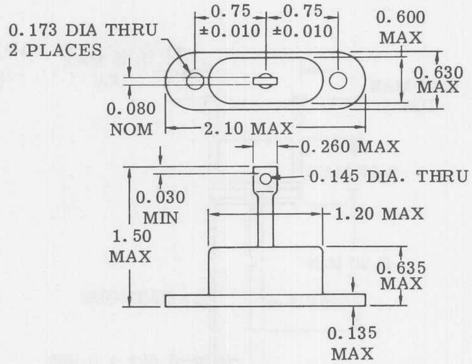
CASE G



CASE H

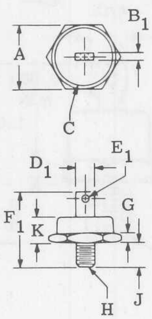


CASE J

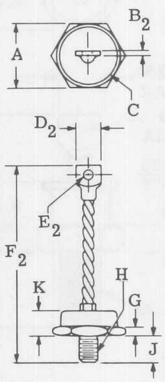


CASE K

I_o Output Current	A HEX	B_1 MAX	B_2 MAX	C MAX DIA	D_1 MAX	D_2 MAX	E_1 DIA
	DIMENSIONS—INCHES						
80	1.250	0.135	0.113	1.20	0.525	0.590	0.250
160	1.75	0.260	0.155	1.72	0.760	0.64	0.375
240	2.00	0.260	0.200	1.94	1.10	1.00	0.562
400	2.250	0.320	0.260	2.20	1.10	1.155	0.562
	E_2 DIA	F_1 MAX	F_2 MAX	G	H THREAD	J MAX	K MAX
80	0.281	2.25	6.25	0.125	10-32	0.500	0.570
160	0.343	3.0	8.10	0.375	3/4-16 UNF	1.00	1.10
240	0.531	3.50	8.10	0.375	3/4-16 UNF	1.00	1,10
400	0.562	3.72	8.10	0.375	3/4-16 UNF	1.00	1.10

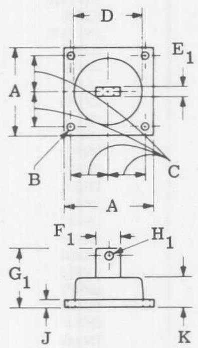


CASE L

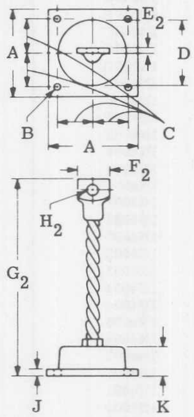


CASE M

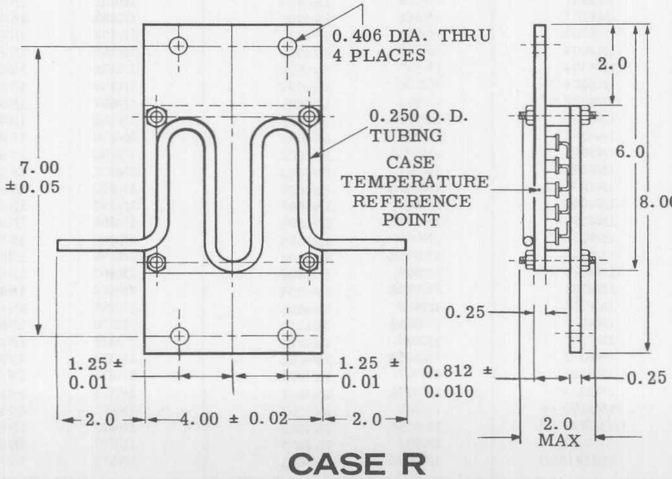
I_o Output Current	DIMENSIONS–INCHES A	B DIA	C MAX	D MAX DIA	E_1 MAX	E_2 MAX	F_1 MAX
160	2.25	0.203	0.880	1.720	0.260	0.155	0.760
240	3.00	0.281	1.255	2.100	0.260	0.200	1.100
400	3.00	0.281	1.255	2.200	0.320	0.260	1.100
650	3.25	0.281	1.380	2.885	0.500	—	1.30
	F_2 MAX	G_1 MAX	G_2 MAX	H_1 DIA	H_2 DIA	J MAX	K MAX
160	0.64	1.9	7.10	0.375	0.343	0.260	1.00
240	1.00	2.50	6.90	0.562	0.531	2.260	1.00
400	1.155	2.70	6.90	0.562	0.562	0.260	1.00
650	—	2.50	—	0.562	—	0.260	1.00



CASE N



CASE P



CASE R

MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE

In most cases, the performance ratings of Motorola types will exceed those of the competitive devices they replace, consequently, they may be considered electrically superior. It should not be inferred, however, that the Motorola devices are physically identical to the devices they replace; detailed specifications should be consulted for any minor differences that might exist.

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
1N248	1N248A	1N412B	MR1211SB	1N610	1N4003
1N248A	1N248B	1N413B	MR1213SB	1N610A	1N4003
1N248B	1N248B	1N440	1N4002	1N611	1N4004
1N248C	1N248C	1N440B	1N4002	1N611A	1N4004
1N249	1N249A	1N441	1N4003	1N612	1N4004
1N249A	1N249B	1N441B	1N4003	1N612A	1N4004
1N249B	1N249B	1N442	1N4004	1N613	1N4005
1N249C	1N249C	1N442B	1N4004	1N613A	1N4005
1N250	1N250A	1N443	1N4004	1N614	1N4005
1N250A	1N250B	1N443B	1N4004	1N614A	1N4005
1N250B	1N250B	1N444	1N4005	1N645	1N4004
1N250C	1N250C	1N444B	1N4005	1N645A	1N4004
1N253	1N4002	1N445	1N4005	1N646	1N4004
1N254	1N4003	1N445B	1N4005	1N647	1N4004
1N255	1N4004	1N530	1N4002	1N648	1N4005
1N256	1N4005	1N531	1N4003	1N649	1N4005
1N316	1N4001	1N532	1N4004	1N676	1N4002
1N316A	1N4001	1N533	1N4004	1N677	1N4002
1N317	1N4002	1N534	1N4005	1N678	1N4003
1N317A	1N4002	1N535	1N4005	1N679	1N4003
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1N318A	1N4003	1N537	1N4002	1N682	1N4004
1N319	1N4004	1N538	1N4003	1N683	1N4004
1N319A	1N4004	1N539	1N4004	1N684	1N4004
1N320	1N4005	1N540	1N4004	1N685	1N4005
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1N322A	1N4007	1N551	1N4003	1N689	1N4005
1N323A	1N4001	1N552	1N4004	1N846	1N4001
1N324A	1N4002	1N553	1N4004	1N847	1N4002
1N325A	1N4003	1N554	1N4005	1N848	1N4003
1N326A	1N4004	1N555	1N4005	1N849	1N4004
1N327A	1N4005	1N560	1N4006	1N850	1N4004
1N328A	1N4007	1N561	1N4007	1N851	1N4005
1N329A	1N4007	1N562	1N4006	1N852	1N4005
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1N333	1N4004	1N596	1N4005	1N854	1N4006
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1N335	1N4004	1N598	1N4007	1N856	1N4007
1N336	1N4003	1N599	1N4001	1N857	1N4001
1N337	1N4003	1N599A	1N4001	1N858	1N4002
1N338	1N4002	1N600	1N4002	1N859	1N4003
1N339	1N4002	1N600A	1N4002	1N860	1N4004
1N340	1N4002	1N601	1N4003	1N861	1N4004
1N341	1N4004	1N601A	1N4003	1N862	1N4005
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1N360A	1N4002	1N606A	1N4005	1N872	1N4004
1N361A	1N4003	1N607	1N4001	1N873	1N4005
1N362A	1N4004	1N607A	1N4001	1N874	1N4005
1N363A	1N4005	1N608	1N4002	1N875	1N4006
1N364A	1N4007	1N608A	1N4002	1N876	1N4006
1N365A	1N4007	1N609	1N4003	1N877	1N4007
1N411B	MR1210SB	1N609A	1N4003	1N878	1N4007

MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE (continued)

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
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1N882	1N4004	1N1193	1N1193	1N1341A	MR1120
1N883	1N4004	1N1193R	1N1193R	1N1342	MR1121
1N884	1N4005	1N1194	1N1194	1N1342A	MR1121
1N885	1N4005	1N1194R	1N1194R	1N1343	MR1122
1N886	1N4006	1N1195	1N1195	1N1343A	MR1122
1N887	1N4006	1N1195A	1N1195A	1N1344	MR1122
1N888	1N4007	1N1195R	1N1195R	1N1344A	MR1122
1N889	1N4007	1N1195AR	1N1195AR	1N1345	MR1123
1N1081	1N4002	1N1196	1N1196	1N1345A	MR1123
1N1082	1N4003	1N1196A	1N1196A	1N1346	MR1124
1N1083	1N4004	1N1196R	1N1196R	1N1346A	MR1124
1N1084	1N4004	1N1196AR	1N1196AR	1N1347	MR1125
1N1095	1N4005	1N1197	1N1197	1N1347A	MR1125
1N1096	1N4005	1N1197A	1N1197A	1N1348	MR1126
1N1100	1N4002	1N1197R	1N1197R	1N1348A	MR1126
1N1101	1N4003	1N1197AR	1N1197AR	1N1396	MR1210SB
1N1102	1N4004	1N1198	1N1198	1N1397	MR1211SB
1N1103	1N4004	1N1198A	1N1198A	1N1398	MR1212SB
1N1104	1N4005	1N1198R	1N1198R	1N1399	MR1213SB
1N1105	1N4005	1N1198AR	1N1198AR	1N1400	MR1215SB
1N1115	1N4720	1N1199	MR1120	1N1401	MR1217SB
1N1116	1N4721	1N1199A	MR1120	1N1443	1N4007
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1N1118	1N4722	1N1200A	MR1121	1N1466	MR1221FB
1N1119	MR1035A	1N1201	MR1122	1N1467	MR1223FB
1N1120	1N4723	1N1201A	MR1122	1N1468	MR1225FB
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1N1124	1N4721	1N1202A	MR1122	1N1478	MR1241SB
1N1124A	1N4721	1N1203	MR1123	1N1479	MR1243SB
1N1125	MR1033A	1N1203A	MR1123	1N1480	MR1245SB
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1N1183A	MR1200FL	1N1219	1N4003	1N1540	1N4003
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1N1185A	MR1202FL	1N1224	1N4005	1N1584	MR1123
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1N1186RA	MR1203FLR	1N1226A	1N4006	1N1613	MR1121
1N1187	1N1187	1N1227	1N4719	1N1614	MR1122
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1N1187A	MR1205FL	1N1229	1N4721	1N1616	MR1126
1N1187RA	MR1205FLR	1N1230	1N4721	1N1617	1N4002
1N1188	1N1188	1N1231	MR1033A	1N1618	1N4003
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1N1188A	MR1207FL	1N1233	MR1035A	1N1620	1N4004
1N1188RA	MR1207FLR	1N1234	1N4723	1N1660	MR1210SB
1N1189	1N1189	1N1235	1N4724	1N1661	MR1211SB
1N1189R	1N1189R	1N1236	1N4724	1N1662	MR1212SB
1N1190	1N1190	1N1251	1N4002	1N1663	MR1213SB
1N1190R	1N1190R	1N1252	1N4002	1N1664	MR1215SB
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MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE (continued)

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
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1N1694	1N4004	1N2135	MR1207FL	1N2884	MR991
1N1695	1N4004	1N2135A	MR1207FL	1N2885	MR991
1N1696	1N4005	1N2154	1N1183	1N2886	MR991
1N1697	1N4005	1N2155	1N1184	1N2887	MR991
1N1701	1N4001	1N2156	1N1186	1N2889	MR992
1N1702	1N4002	1N2157	1N1187	1N2890	MR992
1N1703	1N4003	1N2158	1N1188	1N2891	MR992
1N1704	1N4004	1N2159	1N1189	1N2892	MR993
1N1705	1N4004	1N2160	1N1190	1N2893	MR993
1N1706	1N4005	1N2373	1N4005	1N2894	MR994
1N1707	1N4001	1N2374	1N4007	1N2895	MR994
1N1708	1N4002	1N2375	MR991	1N2896	MR994
1N1709	1N4003	1N2376	MR992	1N2897	MR994
1N1710	1N4004	1N2377	MR993	1N2898	MR995
1N1711	1N4004	1N2378	MR994	1N2899	MR995
1N1712	1N4005	1N2379	1N2382	1N2900	MR995
1N1730	1N4007	1N2380	1N2383	1N2901	MR995
1N1763	1N4004	1N2381	1N2385	1N3085	MR1221SB
1N1764	1N4005	1N2426	MR1210SB	1N3086	MR1223SB
1N1907	1N4001	1N2427	MR1211SB	1N3087	MR1225SB
1N1908	1N4002	1N2428	MR1212SB	1N3088	MR1227SB
1N1909	1N4003	1N2429	MR1213SB	1N3111	MR1220SB
1N1911	1N4004	1N2430	MR1214SB	1N3161	MR1230SB
1N1912	1N4005	1N2431	MR1215SB	1N3161R	MR1230SBR
1N1913	1N4005	1N2432	MR1216SB	1N3162	MR1231SB
1N1914	1N4006	1N2433	MR1217SB	1N3162R	MR1231SBR
1N1915	1N4006	1N2482	1N4003	1N3163	MR1232SB
1N1916	1N4007	1N2483	1N4004	1N3163R	MR1232SBR
1N2054	MR1230SB	1N2484	1N4005	1N3164	MR1233SB
1N2055	MR1231SB	1N2485	1N4003	1N3164R	MR1233SBR
1N2056	MR1232SB	1N2486	1N4004	1N3165	MR1234SB
1N2057	MR1233SB	1N2487	1N4004	1N3165R	MR1234SBR
1N2058	MR1234SB	1N2488	1N4005	1N3166	MR1235SB
1N2059	MR1235SB	1N2489	1N4005	1N3166R	MR1235SBR
1N2060	MR1236SB	1N2609	1N4001	1N3167	MR1236SB
1N2061	MR1237SB	1N2610	1N4002	1N3167R	MR1236SBR
1N2069	1N4003	1N2611	1N4003	1N3168	MR1237SB
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1N2071A	1N4005	1N2616	1N4006	1N3193	1N4003
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1N2073	1N4002	1N2725	1N4720	1N3195	1N4005
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1N2075	1N4003	1N2731	MR1033A	1N3208	1N3208
1N2076	1N4004	1N2734	1N4722	1N3208R	1N3208R
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1N2104	1N4002	1N2795	1N1185	1N3211	1N3211
1N2105	1N4003	1N2796	1N1186	1N3211R	1N3211R
1N2106	1N4004	1N2797	1N1187	1N3212	1N3212
1N2107	1N4004	1N2798	1N1187	1N3212R	1N3212R
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1N2129	MR1201FL	1N2859	1N4002	1N3254	1N4004
1N2129A	MR1201FL	1N2860	1N4003	1N3255	1N4005
1N2130	MR1202FL	1N2861	1N4004	1N3256	1N4006
1N2130A	MR1202FL	1N2862	1N4004	1N3260	MR1220SB
1N2131	MR1203FL	1N2863	1N4005	1N3260R	MR1220SBR
1N2131A	MR1203FL	1N2864	1N4005	1N3261	MR1221SB
1N2132	MR1204FL	1N2878	1N4006	1N3261R	MR1221SBR
1N2132A	MR1204FL	1N2879	1N4006	1N3262	MR1222SB
1N2133	MR1205FL	1N2880	1N4007	1N3262R	MR1222SBR
1N2133A	MR1205FL	1N2881	1N4007	1N3263	MR1223SB

MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE (continued)

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
1N3263R	MR1223SBR	1N3881	1N3881	5A6	1N4005
1N3264	MR1224SB	1N3882	1N3882	5A8	1N4006
1N3264R	MR1224SBR	1N3883	1N3883	5A10	1N4007
1N3265	MR1225SB	1N3889	1N3889	5E4	1N4004
1N3265R	MR1225SBR	1N3890	1N3890	5E5	1N4005
1N3266	MR1226SB	1N3891	1N3891	5E6	1N4006
1N3266R	MR1226SBR	1N3892	1N3892	5MA2	1N4003
1N3267	MR1227SB	1N3893	1N3893	5MA4	1N4004
1N3267R	MR1227SBR	1N3988	MR1128	5MA5	1N4005
1N3288	MR1211SB	1N3989	MR1130	5MA6	1N4005
1N3288R	MR1211SBR	1N3990	MR1130	5MA8	1N4006
1N3289	MR1213SB	1N4044	MR1230SB	5MA10	1N4007
1N3289R	MR1213SBR	1N4044R	MR1230SBR	5MS5	1N4001
1N3290	MR1215SB	1N4045	MR1231SB	5MS10	1N4002
1N3290R	MR1215SBR	1N4045R	MR1231SBR	5MS20	1N4003
1N3291	MR1217SB	1N4046	MR1232SB	5MS30	1N4004
1N3291R	MR1217SBR	1N4046R	MR1232SBR	5MS40	1N4004
1N3544	1N4002	1N4047	MR1233SB	5MS50	1N4005
1N3545	1N4003	1N4047R	MR1233SBR	6F80A	MR1128
1N3546	1N4004	1N4048	MR1234SB	6F100A	MR1130
1N3547	1N4004	1N4048R	MR1234SBR	10B1	1N4002
1N3548	1N4005	1N4049	MR1235SB	10B2	1N4003
1N3549	1N4005	1N4049R	MR1235SBR	10B3	1N4004
1N3569	1N4720	1N4050	MR1237SB	10B4	1N4004
1N3570	1N4721	1N4050R	MR1237SBR	10B5	1N4005
1N3571	MR1033A	1N4136	MR1213SL	10B6	1N4005
1N3572	1N4722	1N4137	MR1217SL	10B8	1N4006
1N3573	MR1035A	1N4138	MR1219SL	10B10	1N4007
1N3574	1N4723	1N4139	1N4719	10D2	1N4003
1N3585	MR1240SB	1N4140	1N4720	10D3	1N4004
1N3586	MR1241SB	1N4141	1N4721	10D4	1N4004
1N3587	MR1243SB	1N4142	1N4722	10D5	1N4005
1N3588	MR1245SB	1N4143	1N4723	10D6	1N4005
1N3589	MR1247SB	1N4144	1N4724	10D7	1N4006
1N3611	1N4003	1N4145	1N4725	10D8	1N4006
1N3612	1N4004	1N4245	1N4003	10D10	1N4007
1N3613	1N4005	1N4246	1N4004	12F80A	MR1128
1N3614	1N4006	1N4247	1N4005	12F100A	MR1130
1N3615	MR1120	1N4248	1N4006	16F5	MR1120
1N3616	MR1121	1N4249	1N4007	16F10	MR1121
1N3617	MR1122	1N4250	1N4006	16F15	MR1122
1N3618	MR1122	1N4251	1N4007	16F20	MR1122
1N3619	MR1123	1N4361	1N4007	16F30	MR1123
1N3620	MR1124	1N4364	1N4002	16F40	MR1124
1N3621	MR1125	1N4365	1N4003	16F50	MR1125
1N3622	MR1126	1N4366	1N4004	16F60	MR1126
1N3623	MR1128	1N4367	1N4004	16F80	MR1128
1N3624	MR1130	1N4368	1N4005	16F100	MR1130
1N3639	1N4003	1N4369	1N4005	20C1	1N4720
1N3640	1N4004	1N4383	1N4003	20C2	1N4721
1N3641	1N4005	1N4384	1N4004	20C3	MR1033A
1N3642	1N4006	1N4385	1N4005	20C4	1N4722
1N3649	MR1128	2E4	1N4004	20C5	MR1035A
1N3650	MR1130	3F10	1N4720	20C6	1N4723
1N3670	MR1128	3F20	1N4721	20C8	1N4724
1N3670A	MR1128	3F30	MR1033A	20C10	1N4725
1N3671	MR1128	3F40	1N4722	25H5	MR1200FL
1N3671A	MR1128	3F50	MR1035A	25H10	MR1201FL
1N3672	MR1130	3F60	1N4723	25H15	MR1202FL
1N3672A	MR1130	3F80	1N4724	25H20	MR1203FL
1N3673	MR1130	3F100	1N4725	25H25	MR1204FL
1N3673A	MR1130	3MS5	1N4001	25H30	MR1205FL
1N3736	MR1233SB	3MS10	1N4002	25H35	MR1206FL
1N3736R	MR1233SBR	3MS20	1N4003	25H40	MR1207FL
1N3737	MR1235SB	3MS30	1N4004	25HB5	MR1200FL
1N3737R	MR1235SBR	3MS40	1N4004	25HB10	MR1201FL
1N3738	MR1237SB	3MS50	1N4005	25HB15	MR1202FL
1N3738R	MR1237SBR	5A2	1N4003	25HB20	MR1203FL
1N3879	1N3879	5A4	1N4004	25HB25	MR1204FL
1N3880	1N3880	5A5	1N4005	25HB30	MR1205FL

MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE (continued)

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
25HB35	MR1206FL	305S	1N4724	366C	MR1122
25HB40	MR1207FL	305Z	1N4725	366D	MR1122
45L5	MR1220SB	320A	1N4001	366F	MR1123
45L10	MR1221SB	320B	1N4002	366H	MR1124
45L15	MR1222SB	320C	1N4003	366K	MR1125
45L20	MR1223SB	320D	1N4003	366M	MR1126
45L25	MR1224SB	320F	1N4004	367A	MR1120
45L30	MR1225SB	320H	1N4004	367B	MR1121
45L35	MR1226SB	320M	1N4005	367C	MR1122
45L40	MR1227SB	320K	1N4005	367D	MR1122
45M5	MR1220SB	320P	1N4006	367F	MR1123
45M10	MR1221SB	320S	1N4006	367H	MR1124
45M15	MR1222SB	320Z	1N4007	367K	MR1125
45M20	MR1223SB	335A	1N1183R	367M	MR1126
45M25	MR1224SB	335B	1N1184R	368A	MR1120
45M30	MR1225SB	335C	1N1185R	368B	MR1121
45M35	MR1226SB	335D	1N1186R	368C	MR1122
45M40	MR1227SB	335F	1N1187R	368D	MR1122
70U5	MR1230SB	335G	1N1188R	368F	MR1123
70U10	MR1231SB	335H	1N1188R	368H	MR1124
70U15	MR1232SB	335K	1N1189R	368K	MR1125
70U20	MR1233SB	335M	1N1190R	368M	MR1126
70U25	MR1234SB	336A	1N1191R	371A	1N1183
70U30	MR1235SB	336B	1N1192R	371B	1N1184
70U35	MR1236SB	336C	1N1193R	371C	1N1185
70U40	MR1237SB	336D	1N1194R	371D	1N1186
300A	MR1210SB	336F	1N1195R	371F	1N1187
300B	MR1211SB	336G	1N1196R	371H	1N1188
300C	MR1212SB	336H	1N1196R	371K	1N1189
300D	MR1213SB	336K	1N1197R	371M	1N1190
300E	MR1214SB	336M	1N1198R	374A	MR1210SL
300F	MR1215SB	337A	MR1120R	374B	MR1211SL
300G	MR1216SB	337B	MR1121R	374C	MR1212SL
300H	MR1217SB	337C	MR1122R	374D	MR1213SL
302A	1N1183	337D	MR1122R	374F	MR1215SL
302B	1N1184	337F	MR1123R	374H	MR1217SL
302C	1N1185	337H	MR1124R	376A	MR1220SL
302D	1N1186	337K	MR1125R	376B	MR1221SL
302F	1N1187	337M	MR1126R	376C	MR1222SL
302G	1N1188	341A	MR1120	376D	MR1223SL
302H	1N1188	341B	MR1121	376F	MR1225SL
302K	1N1189	341C	MR1122	376H	MR1227SL
302M	1N1190	341D	MR1122	377A	MR1230SL
303A	1N1191	341F	MR1123	377B	MR1231SL
303B	1N1192	341H	MR1124	377C	MR1232SL
303C	1N1193	341K	MR1125	377D	MR1233SL
303D	1N1194	341M	MR1126	377F	MR1235SL
303F	1N1195	341P	MR1128	377H	MR1237SL
303H	1N1196	341S	MR1128	400A	MR1210SB
303K	1N1197	346A	MR1120R	400B	MR1211SB
303M	1N1198	346B	MR1121R	400C	MR1212SB
304A	MR1120	346C	MR1122R	400D	MR1213SB
304B	MR1121	346D	MR1122R	400F	MR1215SB
304C	MR1122	346F	MR1123R	400H	MR1217SB
304D	MR1122	346H	MR1124R	400VB5	MR1240SB
304F	MR1123	346K	MR1125R	400VB10	MR1241SB
304H	MR1124	346M	MR1126R	400VB15	MR1242SB
304K	MR1125	346P	MR1128R	400VB20	MR1243SB
304M	MR1126	346S	MR1128R	400VB25	MR1244SB
304P	MR1128	359B	1N4002	400VB30	MR1245SB
304S	MR1128	359D	1N4003	400VB40	MR1247SB
305A	1N4719	359F	1N4004	400VBR5	MR1240SBR
305B	1N4720	359H	1N4004	400VBR10	MR1241SBR
305C	1N4721	359K	1N4005	400VBR15	MR1242SBR
305D	1N4721	359M	1N4005	400VBR20	MR1243SBR
305F	MR1033A	359P	1N4006	400VBR25	MR1244SBR
305H	1N4722	359S	1N4006	400VBR30	MR1245SBR
305K	MR1035A	359Z	1N4007	400VBR40	MR1247SBR
305M	1N4723	366A	MR1120	401A	MR1210SBR
305P	1N4724	366B	MR1121	401B	MR1211SBR

MOTOROLA RECTIFIER REPLACEMENT AND INTERCHANGEABILITY GUIDE (continued)

TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.	TYPE NO. TO BE REPLACED	REPLACE WITH MOTOROLA TYPE NO.
401C	MR1212SBR	446B	MR1121R	A90C	MR1235SB
401D	MR1213SBR	446C	MR1122R	A90D	MR1237SB
401F	MR1215SBR	446D	MR1122R	A91B	MR1233SBR
401H	MR1217SBR	446F	MR1123R	A91C	MR1235SBR
404A	MR1120	446H	MR1124R	A91D	MR1237SBR
404B	MR1121	446K	MR1125R	A295PB	MR1243SBR
404C	MR1122	446M	MR1126R	A295PC	MR1245SBR
404D	MR1122	446P	MR1128R	A295PD	MR1247SBR
404F	MR1123	446S	MR1128R	AH805	1N4006
404H	MR1124	446V	MR1130R	AH810	1N4006
404K	MR1126	446Z	MR1130R	AH815	1N4006
404P	MR1128	478C	1N3881	AH1005	1N4007
404S	MR1128	478E	1N3882	AH1010	1N4007
404V	MR1128	479C	1N3891	AH1015	1N4007
404Z	MR1130	479E	1N3892	AM3	1N4001
405A	1N3208	703A	1N3491	AM13	1N4002
405B	1N3209	703RA	1N3492R	AM23	1N4003
405C	1N3210	703B	1N3492	AM33	1N4004
405D	1N3210	703RB	1N3492R	AM43	1N4004
405E	1N3211	703C	1N3493	AM53	1N4005
405F	1N3211	703RC	1N3493R	AM63	1N4005
405H	1N3212	703D	1N3493	G100K	1N4006
405AR	1N3208R	703RD	1N3493R	G100M	1N4007
405BR	1N3209R	703F	1N3494	PA3	1N4004
405CR	1N3210R	703RF	1N3494R	PA069	1N4003
405DR	1N3210R	703H	1N3495	PA070	1N4004
405ER	1N3211R	703RH	1N3495R	PA071	1N4005
405FR	1N3211R	A10A	1N4002	PA305	1N4001
405HR	1N3212R	A10B	1N4003	PA310	1N4002
429A	MR1220SB	A10C	1N4004	PA315	1N4003
429B	MR1221SB	A10D	1N4004	PA320	1N4003
429C	MR1222SB	A10E	1N4005	PA325	1N4004
429D	MR1223SB	A10M	1N4005	PA330	1N4004
429E	MR1224SB	A10N	1N4006	PA340	1N4004
429F	MR1225SB	A10P	1N4007	PA350	1N4005
429G	MR1226SB	A13A2	1N4002	PA360	1N4005
429H	MR1227SB	A13B2	1N4003	PA380	1N4006
437A	MR1120R	A13C2	1N4004	PT3	1N4004
437B	MR1121R	A13D2	1N4004	PT5	1N4004
437C	MR1122R	A13E2	1N4005	PT5B	1N4005
437D	MR1122R	A13F2	1N4001	PT505	1N4001
437F	MR1123R	A13M2	1N4005	PT510	1N4002
437H	MR1124R	A40A	1N1192	PT515	1N4003
437K	MR1125R	A40B	1N1194	PT520	1N4003
437M	MR1126R	A40C	1N1195	PT525	1N4004
437P	MR1128R	A40D	1N1196	PT530	1N4004
437S	MR1128R	A40E	1N1197	PT540	1N4004
437V	MR1128R	A40F	1N1191	PT550	1N4005
437Z	MR1130R	A40M	1N1198	PT560	1N4005
439A	MR1230SB	A41A	1N1192R	S91	1N4002
439B	MR1231SB	A41B	1N1194R	S91H	1N4002
439C	MR1232SB	A41C	1N1195R	S92	1N4003
439D	MR1233SB	A41D	1N1196R	S92H	1N4003
439E	MR1234SB	A41E	1N1197R	S93	1N4004
439F	MR1235SB	A41F	1N1191R	S93H	1N4004
439G	MR1236SB	A41M	1N1197R	S94	1N4004
439H	MR1237SB	A45A	1N3492R		
441A	MR1120	A45B	1N3493R		
441B	MR1121	A45C	1N3494R		
441C	MR1122	A45D	1N3495R		
441D	MR1122	A45E	MR327R		
441F	MR1123	A45F	1N3491R		
441H	MR1124	A45M	MR328R		
441K	MR1125	A70B	MR1213SB		
441M	MR1126	A70C	MR1215SB		
441P	MR1128	A70D	MR1217SB		
441S	MR1128	A71B	MR1213SBR		
441V	MR1130	A71C	MR1215SBR		
441Z	MR1130	A71D	MR1217SBR		
446A	MR1120R	A90B	MR1233SB		

RECTIFIER SELECTION DATA

1N248B,C thru 1N250B,C

1N1191 thru 1N1198
1N1195A thru 1N1198A
1N3213 thru 1N3214

MAXIMUM RATINGS (See Thermal Derating Graph 1)

Characteristics	Symbol	Rating	Unit
Peak Repetitive Reverse Voltage and DC Blocking Voltage	V_{RM} (rep) V_R		Volts
1N248B, 1N1191		50	
1N248C		55	
1N249B, 1N1192		100	
1N249C		110	
1N1193		150	
1N250B, 1N1194		200	
1N250C		220	
1N1195, 1N1195A		300	
1N1196, 1N1196A		400	
1N1197, 1N1197A, 1N3213		500	
1N1198, 1N1198A, 1N3214		600	
RMS Reverse Voltage	V_r		Volts
1N248B, 1N1191		35	
1N248C		38.5	
1N249B, 1N1192		70	
1N249C		77	
1N1193		105	
1N250B, 1N1194		140	
1N250C		154	
1N1195, 1N1195A		210	
1N1196, 1N1196A		280	
1N1197, 1N1197A, 1N3213		350	
1N1198, 1N1198A, 1N3214		420	
Average 1/2-Wave Rectified Forward Current (Resistive Load, 60 cps, $T_C = 150^oC$)	I_O	20	Amps
Peak Repetitive Forward Current ($T_C = 150^oC$)	I_{FM} (rep)	90	Amps
Peak Surge Current ($T_C = 150^oC$, superimposed on Rated Current at Rated Voltage, 1/2-Cycle, 1/120 sec)	I_{FM} (surge)	350	Amps

ELECTRICAL CHARACTERISTICS

Characteristics	Symbol	Max	Unit
Full Cycle Average Forward Voltage Drop ($I_{O\ (max)}$, rated V_r, 60 cps, $T_C = 150^oC$)	$V_{F(AV)}$	0.6	Volts
Instantaneous Forward Voltage Drop (i_F = 100 Amps, $T_J = 25^oC$)	V_F	1.5	Volts

1N248B,C thru 1N250B,C (continued)

ELECTRICAL CHARACTERISTICS (continued)

Characteristics	Symbol	Max	Unit
Full Cycle Average Reverse Current ($I_{O\,(max)}$, rated V_r, 60 cps, T_C = 150°C)	$I_{R(AV)}$		mA
1N248B thru 1N250B, 1N1191 thru 1N1198		5.0	
1N248C		3.8	
1N249C		3.6	
1N250C		3.4	
1N1195A		3.2	
1N1196A		2.5	
1N1197A		2.2	
1N1198A		1.5	
1N3213 and 1N3214		10.0	
DC Reverse Current (Rated V_R, T_C = 25°C)	I_R	1.0	mA

1N1124, A thru 1N1128, A

Obsolete, discontinued types, replace with devices from the MR1030 series.

1N1183 thru 1N1190

MAXIMUM RATINGS (See Thermal Derating Graph 2)

Characteristic	Symbol	Rating	Unit
Peak Repetitive Reverse Voltage and DC Blocking Voltage	$V_{RM\,(rep)}$ V_R		Volts
1N1183		50	
1N1184		100	
1N1185		150	
1N1186		200	
1N1187		300	
1N1188		400	
1N1189		500	
1N1190		600	
RMS Reverse Voltage	V_r		Volts
1N1183		35	
1N1184		70	
1N1185		105	
1N1186		140	
1N1187		210	
1N1188		280	
1N1189		350	
1N1190		420	
Average 1/2-Wave Rectified Forward Current (Resistive Load, 60 cps, T_C = 140°C)	I_O	35	Amperes
Peak Repetitive Forward Current (T_C = 140°C)	$I_{FM\,(rep)}$	150	Amperes

1N1183 thru 1N1190 (continued)

MAXIMUM RATINGS (continued)

Characteristic	Symbol	Rating	Unit
Peak Surge Current (T_C = 140°C, superimposed on Rated Current at Rated Voltage)	$I_{FM\ (surge)}$	400	Amperes
Operating and Storage Temperature	T_J, T_{stg}	-65 to +190	°C
Thermal Impedance	θ_{JC}	1.0	°C/W, DC steady state

ELECTRICAL CHARACTERISTICS

Characteristics	Symbol	Rating	Unit
Max. Full Cycle Average Forward Voltage Drop ($I_{O\ (max)}$, rated V_r, 60 cps, T_C = 140°C)	$V_{F(AV)}$	0.6	Volts
Max Instantaneous Forward Voltage Drop (i_F = 100 Amps, T_J = 25°C)	V_F	1.3	Volts
Max Full Cycle Average Reverse Current ($I_{O\ (max)}$, rated V_r, 60 cps, T_C = 140°C)	$I_{R(AV)}$	10.0	mA
Max DC Reverse Current (Rated V_R, T_C = 25°)	I_R	1.0	mA

1N1191 thru 1N1198

For Specifications, See IN248B Data Sheet

1N1563, A thru 1N1568, A

MAXIMUM RATINGS (See Thermal Derating Graph 3)

Rating	Symbol	1N1563A 1N1563	1N1564A 1N1564	1N1565A 1N1565	1N1566A 1N1566	1N1567A 1N1567	1N1568A 1N1568	Unit
Peak Repetitive Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ V_R	100	200	300	400	500	600	Volts
RMS Reverse Voltage	V_r	70	140	210	280	350	420	Volts
Average Half-Wave Rectified Forward Current (55°C Ambient) (150°C Ambient)	I_O	1500 300	1500 300	1500 300	1500 300	1500 300	1500 300	mA mA
Peak Surge Current (1/2 Cycle Surge, 60 cps)	$I_{FM(surge)}$	70	70	70	70	70	70	Amps
Peak Repetitive Forward Current	$I_{FM(rep)}$	10	10	10	10	10	10	Amps
Operating and Storage Temperature Range	$T_J + T_{stg}$	-65 to +175						°C

1N1563,A thru 1N1568,A (continued)

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	1N1563A 1N1568A Rating	1N1563 1N1568 Rating	Unit
Maximum Forward Voltage Drop @ 500 mA, Continuous DC (25°C) (150°C)	V_F	1.2 0.9	1.2 1.0	Volts
Maximum Reverse Current @ Rated DC Voltage (25°C)	I_R	1.5		μA
Maximum Full-Cycle Average Reverse Current @ Max Rated PIV and Current (as Half-Wave Rectifier, Resistive Load (25°C) (150°C)	$I_{R(AV)}$	3.0 150	5.0 500	μA

1N2609 thru 1N2617

Obsolete, discontinued types, replace with devices from the 1N4001 series.

1N3189 thru 1N3191

Obsolete, discontinued types, replace with devices from the 1N4001 series.

1N3208 thru 1N3212

MAXIMUM RATINGS (See Thermal Derating Graph 4)

Rating	Symbol	1N3208 1N3208R	1N3209 1N3209R	1N3210 1N3210R	1N3211 1N3211R	1N3212 1N3212R	Unit
D-C Blocking Voltage	V_R	50	100	200	300	400	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	Volts
Average Half-Wave Rectified Forward Current With Resistive Load	I_O*	15	15	15	15	15	Amps
Peak One Cycle Surge Current (60 cps & 25°C Case Temp)	$I_{FM(surge)}$	250	250	250	250	250	Amps
Operating Junction Temperature	T_J	-65 to + 175					°C
Storage Temperature	T_{stg}	-65 to + 175					°C

*T_C = 150°C

ELECTRICAL CHARACTERISTICS (All Types) at 25°C Case Temp.

Characteristic	Symbol		
Maximum Forward Voltage at 40 Amp D-C Forward Current	V_F	1.5	Volts
Maximum Reverse Current at Rated D-C Reverse Voltage	I_R	1.0	mAdc
Typical Thermal Resistance, Junction To Case	θ_{JC}	1.7	C/W

1N3213, 1N3214

For Specifications, See IN248B Data Sheet

1N3282 thru 1N3286

MAXIMUM RATINGS (See Thermal Derating Graph 5)

Rating	Symbol	1N3282	1N3283	1N3284	1N3285	1N3286	Unit
Peak Repetitive Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ V_R	1000	1500	2000	2500	3000	Volts
RMS Reverse Voltage	V_r	700	1050	1400	1750	2100	Volts
Average Half-Wave Rectified Forward Current (25°C Ambient) (100°C Ambient)	I_O	100 50	100 50	100 50	100 50	100 50	mA mA
Peak Surge Current (1/2-cycle, 60 cps)	$I_{FM(surge)}$	2.5	2.5	2.5	2.5	2.5	Amps
Peak Repetitive Forward Current	$I_{FM(rep)}$	0.50	0.50	0.50	0.50	0.50	Amps
Operating and Storage Temperature Range	T_j, T_{stg}	-65 to + 150					°C

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Rating	Unit
Maximum Forward Voltage Drop @ 100 mA, Continuous DC (25°C)	V_F	2.5	Volts
Maximum Full-Cycle Average Forward Voltage Drop @ Rated Current (100°C)	$V_{F(AV)}$	1.2	Volts
Maximum Reverse Current @ Rated DC Voltage (25°C) (100°C)	I_R	1.0 10.0	μA
Maximum Full-Cycle Average Reverse Current @ Max Rated PIV and Current (as Half-Wave Rectifier, Resistive Load, 100°C)	$I_{R(AV)}$	10.0	μA
Typical Thermal Resistance, Junction to Air Ambient	θ_{JA}	400°	C/W

1N3491 thru 1N3495

FORMERLY

MR 322 thru MR 326

MAXIMUM RATINGS (See Thermal Derating Graph 6)

Rating	Symbol	1N3491 MR322	1N3492 MR323	1N3493 MR324	1N3494 MR325	1N3495 MR326	Unit
Peak Repetitive Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ V_R	50	100	200	300	400	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	Volts

1N3491 thru 1N3495 (continued)

MAXIMUM RATINGS (continued)

Rating	Symbol	1N3491 MR322	1N3492 MR323	1N3493 MR324	1N3494 MR325	1N3495 MR326	Unit
Average Half-Wave Rectified Forward Current With Resistive Load 100°C / 150°C	I_O*	25 / 18	25 / 18	25 / 18	25 / 18	25 / 18	Amps
Peak Repetitive Forward Current (60 cps & 25°C Case Temp.)	$I_{FM(rep)}$	75	75	75	75	75	Amps
Peak One Cycle Surge Current (60 cps & 25°C Case Temp.)	$I_{FM(surge)}$	300	300	300	300	300	Amps
Operating Junction Temperature	T_J	-65 to +175					°C
Storage Temperature	T_{stg}	-65 to +175					°C

ELECTRICAL CHARACTERISTICS (At 25°C case temperature unless otherwise specified)

Characteristic	Symbol	1N3491 MR322	1N3492 MR323	1N3493 MR324	1N3494 MR325	1N3495 MR326	Unit
Maximum Forward Voltage at 100 Amp DC Forward	V_F	1.5	1.5	1.5	1.5	1.5	Volts
Maximum Full-Cycle Average Forward Voltage Drop @ Rated Current and Voltage	$V_{F(AV)}$	0.7	0.7	0.7	0.7	0.7	Volts
Maximum Reverse Current at Rated DC Reverse Voltage	I_R	1.0	1.0	1.0	1.0	1.0	mAdc
Maximum Full-Cycle Average Reverse Current at Rated Current and Voltage (as Half-Wave Rectifier, Resistive Load, 150°C Case)	$I_{R(AV)}$	10	10	8	6	4	mAdc
Thermal Resistance	θ_{JC}	1					°C/W

USN1N3611 thru USN1N3613

MAXIMUM RATINGS

CHARACTERISTIC	SYMBOL	USN1N3611	USN1N3612	USN1N3613	UNITS
Working Peak Reverse Voltage / DC Blocking Voltage	$V_{RM(wkg)}$ / V_R	200	400	600	Volts
Peak Repetitive Reverse Voltage	$V_{RM(rep)}$	240	480	720	Volts
Average Rectified Forward Current $T_A = 100^oC$ / $T_A = 150^oC$	I_O	← 1.0 → / 0.3			Adc
Non-Repetitive Peak Surge Current (1/2 cycle, 60 cps)	$I_{FM(surge)}$	← 10 →			Amps
Operating and Storage Temperature Range	T_A, T_{stg}	-65 to +175			^oC

USN1N3611 thru USN1N3613 (continued)

ELECTRICAL CHARACTERISTICS

Characteristics and Conditions	Symbol	Minimum	Maximum	Unit
Forward Voltage (I_F = 1.0 Adc, T_A = 100°C)	V_F	0.6	1.2	Vdc
Reverse Current (V_R = 200 Vdc) USN 1N3611 (V_R = 400 Vdc) USN 1N3612 (V_R = 600 Vdc) USN 1N3613	I_R	— — —	5 5 5	μAdc
Reverse Current at Rated $V_{RM(rep)}$ ($V_{RM(rep)}$ = 240 Vdc) USN 1N3611 ($V_{RM(rep)}$ = 480 Vdc) USN 1N3612 ($V_{RM(rep)}$ = 720 Vdc) USN 1N3613	I_R	— — —	100 100 100	μAdc
High Temperature Operation: Reverse Current @ T_A = 150°C (V_R = 200 Vdc) USN 1N3611 (V_R = 400 Vdc) USN 1N3612 (V_R = 600 Vdc) USN 1N3613	I_R	— — —	300 300 300	μAdc

1N3649 thru 1N3650

Obsolete, discontinued types, replace with devices from the MR1030 series.

1N3659 thru 1N3663

MAXIMUM RATINGS (See Thermal Derating Graph 7)

Rating	Symbol	1N3659 1N3659R	1N3660 1N3660R	1N3661 1N3661R	1N3662 1N3662R	1N3663 1N3663R	Units
Peak Repetitive Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ V_R	50	100	200	300	400	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	Volts
Average Half-Wave Rectified Forward Current with Resistive Load @ 100°C case @ 150°C case	I_O	30 25	30 25	30 25	30 25	30 25	Amps Amps
Peak One Cycle Surge Current (150°C case temp, 60 cps)	$I_{FM(surge)}$	400	400	400	400	400	Amps
Operating Junction Temperature	T_J	−65 to +175					°C
Storage Temperature	T_{stg}	−65 to +200					°C

1N3659 thru 1N3663 (continued)

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	1N3659 1N3659R	1N3660 1N3660R	1N3661 1N3661R	1N3662 1N3662R	1N3663 1N3663R	Unit
Maximum Forward Voltage at 25 Amp DC Forward Current	V_F	1.2	1.2	1.2	1.2	1.2	Volts
Maximum Full Cycle Average Forward Voltage Drop @ Rated PIV and Current	$V_{F(AV)}$	0.7	0.7	0.7	0.7	0.7	Volts
Maximum Full Cycle Average Reverse Current @ Rated PIV and Current (as half-wave rectifier, resistive load, 150°C)	$I_{R(AV)}$	5.0	4.5	4.0	3.5	3.0	mA
Thermal Resistance	θ_{JC}			1			°C/W

1N3879 thru 1N3883
6 AMPERES
1N3889 thru 1N3893
12 AMPERES

MAXIMUM RATINGS (See Thermal Derating Graph 8)

Rating	Symbol	1N3879 1N3889	1N3880 1N3890	1N3881 1N3891	1N3882 1N3892	1N3883 1N3893	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	200	300	400	Volts
Non-Repetitive Peak Reverse Voltage (half-wave, single phase, 60 cycle peak)	$V_{RM(non\text{-}rep)}$	100	200	300	400	500	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	Volts

Rating	Symbol	1N3879 thru 1N3883	1N3889 thru 1N3893	Unit
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 100°C)	I_O	6	12	Amperes
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_C = 100°C)	$I_{FM(surge)}$	75	150	Amperes
I^2t Rating (non-repetitive, for t greater than 1 msec and less than 8.3 msec)	I^2t	15	50	$A_{(rms)}^2$sec

1N3879 thru 1N3883 (continued)

ELECTRICAL CHARACTERISTICS

1N3879 thru 1N3883

Characteristic	Symbol	Max Limit	Unit
DC Forward Voltage Drop (I_F = 6.0 Adc, T_C = 25°C)	V_F	1.4	Vdc
Full Cycle Average Reverse Current (I_O = 6.0 Amps and Rated V_r, 60 cps T_C = 100°C, single phase)	$I_{R(AV)}$	3.0	mA
DC Reverse Current (Rated V_R, T_C = 100°C)	I_R	1.0	mA

1N3889 thru 1N3893

Characteristic	Symbol	Max Limit	Unit
DC Forward Voltage Drop (I_F = 12.0 Adc, T_C = 25°C)	V_F	1.4	Vdc
Full Cycle Average Reverse Current (I_O = 12.0 Amps and Rated V_r, 60 cps T_C = 100°C, single phase)	$I_{R(AV)}$	5.0	mA
DC Reverse Current (Rated V_R, T_C = 100°C)	I_R	3.0	mA

1N4001 thru 1N4007

MAXIMUM RATINGS (See Thermal Derating Graph 9)

Rating	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
Peak Repetitive Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ V_R	50	100	200	400	600	800	1000	Volts
RMS Reverse Voltage	V_r	35	70	140	280	420	560	700	Volts
Average Half-Wave Rectified Forward Current (75°C Ambient) (100°C Ambient)	I_O	1000 750	1000 750	1000 750	1000 750	1000 750	1000 750	1000 750	mA mA
Peak Surge Current @ 25°C (1/2 Cycle Surge, 60 cps)	$I_{FM(surge)}$	30	30	30	30	30	30	30	Amps
Peak Repetitive Forward Current	$I_{FM(rep)}$	10	10	10	10	10	10	10	Amps
Operating and Storage Temperature Range	T_J, T_{stg}	← −65 to +175 →							°C

1N4001 thru 1N4007 (continued)

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Rating	Unit
Maximum Forward Voltage Drop (1 Amp Continuous DC, 25°C)	V_F	1.1	Volts
Maximum Full-Cycle Average Forward Voltage Drop (Rated Current @ 25°C)	$V_{F(AV)}$	0.8	Volts
Maximum Reverse Current @ Rated DC Voltage (25°C) (100°C)	I_R	0.01 0.05	mA
Maximum Full-Cycle Average Reverse Current (Max Rated PIV and Current, as Half-Wave Rectifier, Resistive Load, 100°C)	$I_{R(AV)}$	0.03	mA

1N4719 thru 1N4725
MR1030 thru MR1036, MR1038, MR1040

MAXIMUM RATINGS (See Thermal Derating Graph 10)

Rating	Symbol	1N 4719 MR 1030	1N 4720 MR 1031	1N 4721 MR 1032	MR 1033	1N 4722 MR 1034	MR 1035	1N 4723 MR 1036	1N 4724 MR 1038	1N 4725 MR 1040	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	200	300	400	500	600	800	1000	Volts
Non-Repetitive Peak Reverse Voltage (one half-wave, single phase, 60 cycle peak)	V_{RM} (non-rep)	100	200	300	400	500	600	720	1000	1200	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	350	420	560	700	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_A = 75°C) see figure 4	I_O	3.0									Amps
Peak Repetitive Forward Current (T_A = 75°C)	$I_{FM(rep)}$	25									Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_A = 75°C) see figure 1	$I_{FM(surge)}$	300 (for 1/2 cycle)									Amps
I^2t Rating (non-repetitive, 1 msec<t<8.3 msec)	I^2t	185									$A(rms)^2sec$
Operating and Case Temperature	T_J, T_{stg}	-65 + 175									°C
Thermal Resistance	θ_{JA}	30									°C/Watt

1N4719 thru 1N4725 (Continued)

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Max Limit	Unit
Full Cycle Average Forward Voltage Drop (I_O = 3.0 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier)	$V_{F(AV)}$	0.45	Volts
DC Forward Voltage Drop (I_F = 3.0 Adc, T_A = 25°C)	V_F	0.9	Volts
Full Cycle Average Reverse Current (I_O = 3.0 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier)	$I_{R(AV)}$	1.5	mA
DC Reverse Current (Rated V_R, T_A = 25°C)	I_R	0.5	mA

MR322 thru MR326

For Specifications, See IN3491 Data Sheet

MR990 thru MR994

MAXIMUM RATINGS (See Thermal Derating Graph 11)

Rating	Symbol	MR990	MR991	MR992	MR993	MR994	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	1000	1500	2000	2500	3000	Volts
RMS Reverse Voltage	V_r	700	1050	1400	1750	2100	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_A = 75°C)	I_O	← 250 →					mA
Peak Repetitive Forward Current (T_A = 75°C)	$I_{FM(rep)}$	← 2.0 →					Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_A = 75°C)	$I_{FM(surge)}$	← 15 (for 1/2 cycle) →					Amps
Junction Operating and Storage Temperature Range	T_J, T_{stg}	← -65 to +150 →					°C

MR990 thru MR994 (continued)

ELECTRICAL CHARACTERISTICS (At 60 cps Sinusoidal, Resistive or Inductive)

Characteristics	Symbol	Max	Unit
Full Cycle Average Forward Voltage Drop (I_O = 0.25 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier)	$V_{F(AV)}$	1.7	Volts
DC Forward Voltage Drop (I_F = 0.25 Adc, T_A = 25°C)	V_F	3.5	Volts
Full Cycle Average Reverse Current (I_O = 0.25 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier)	$I_{R(AV)}$	100	μA
DC Reverse Current (Rated V_R, T_A = 25°C)	I_R	10	μA

MR1030 thru MR1036
MR1038, MR1040

For Specifications, See 1N4719 Data Sheet.

MR1120 thru MR1126
MR1128
MR1130

MAXIMUM RATINGS (See Thermal Derating Graph 12)

Rating	Symbol	MR 1120	MR 1121	MR 1122	MR 1123	MR 1124	MR 1125	MR 1126	MR 1128	MR 1130	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RM} (rep) V_{RM} (wkg) V_R	50	100	200	300	400	500	600	800	1000	Volts
Non-Repetitive Peak Reverse Voltage (one half-wave, single phase, 60 cycle peak)	V_{RM} (non-rep)	100	200	300	400	500	600	720	1000	1200	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	350	420	560	700	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 150°C) see figure 4	I_O	← 12.0 →									Amps
Peak Repetitive Forward Current (T_C = 150°C)	$I_{FM(rep)}$	← 75 →									Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_C = 150°C) see figure 3.	$I_{FM(surge)}$	← 300 (for 1/2 cycle) →									Amps
I^2t Rating (non-repetitive, 1 msec < t < 8.3 msec)	I^2t	← 375 →									$A(rms)^2sec$
Maximum Junction Operating and Storage Temperature Range	T_J, T_{stg}	← -65 to +190 →									°C

MR1120 thru MR1126, MR1128, MR1130 (continued)

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Max Limit	Unit
Full Cycle Average Forward Voltage Drop (I_O = 12.0 Amps and Rated V_r, T_C = 150°C, Half Wave Rectifier)	$V_{F(AV)}$	0.55	Volts
DC Forward Voltage Drop (I_F = 12.0 Adc, T_C = 25°C)	V_F	1.0	Volts
Full Cycle Average Reverse Current (I_O = 12.0 Amps and Rated V_r, T_C = 150°C, Half Wave Rectifier)	$I_{R(AV)}$	1.5	mA
DC Reverse Current (Rated V_R, T_C = 25°C)	I_R	0.5	mA

MR1200 thru MR1207

MAXIMUM RATINGS (See Thermal Derating Graph 13)

Rating	Symbol	MR 1200	MR 1201	MR 1202	MR 1203	MR 1204	MR 1205	MR 1206	MR 1207	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one half-wave, single phase, 60 cycle peak)	$V_{RM\,(non\text{-}rep)}$	100	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, see Figure 3) T_C = 150°C	I_O	← 50 →								Amperes
Non-Repetitive Peak Surge Current (surge applied at rated load conditions, see Figure 5) T_C = 150°C	$I_{FM\,(surge)}$	← 800 (for 1/2 cycle) → ← 500 (for six consecutive cycles) →								Amperes
I^2t Rating (non-repetitive, for t greater than 1 ms and less than 8.3 ms)	I^2t	← 1,300 →								$A_{(rms)}{}^2sec$
Operating and Storage Junction Temperature Range (see Figure 4 for other conditions)	T_J, T_{stg}	← -65 to +190 →								°C

MR1200 thru MR1207 (continued)

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Max	Units
Full Cycle Average Forward Voltage Drop (rated I_O and V_r, single phase, 60 cps, T_C = 150°C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_O and V_r, single phase, 60 cps, T_C = 150°C)	$I_{R(AV)}$	10	mA

MR1210 thru MR1217

MAXIMUM RATINGS (See Thermal Derating Graph 14)

Rating	Symbol	MR 1210	MR 1211	MR 1212	MR 1213	MR 1214	MR 1215	MR 1216	MR 1217	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one halfwave, single phase, 60 cycle peak)	$V_{RM(non-rep)}$	100	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, see Figure 3) T_C = 135°C T_C = 150°C	I_O	← 100 → ← 80 →								Amperes
Non-Repetitive Peak Surge Currents (surge applied at rated load conditions, see Figure 5) T_C = 150°C	$I_{FM(surge)}$	← 2,000 (for 1/2 cycle) → ← 1,200 (for six consecutive cycles) →								Amperes
I^2t Rating (non-repetitive, for t greater than 1 ms and less than 8.3 ms)	I^2t	← 8,300 →								$A_{(rms)}{}^2sec$
Operating and Storage Junction Temperature Range (see Figure 4 for other conditions)	T_J, T_{stg}	← -65 to +190 →								°C

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Max	Units
Full Cycle Average Forward Voltage Drop (rated I_O and V_r, single phase, 60 cps, T_C = 150°C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_O and V_r, single phase, 60 cps, T_C = 150°C)	$I_{R(AV)}$	15	mA

MR1220 thru MR1227

MAXIMUM RATINGS (See Thermal Derating Graph 15)

Rating	Symbol	MR 1220	MR 1221	MR 1222	MR 1223	MR 1224	MR 1225	MR 1226	MR 1227	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one halfwave, single phase, 60 cycle peak)	$V_{RM(non\text{-}rep)}$	100	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, see Figure 3) $T_C = 135°C$ $T_C = 150°C$	I_O	← 200 → ← 160 →								Amperes
Non-Repetitive Peak Surge Currents (surge applied at rated load conditions, see Figure 5) $T_C = 150°C$	$I_{FM(surge)}$	← 3,600 (for 1/2 cycle) → ← 2,000 (for six consecutive cycles) →								Amperes
I^2t Rating (non-repetitive, for t greater than 1 ms and less than 8.3 ms)	I^2t	← 27,000 →								$A_{(rms)}^2sec$
Operating and Storage Junction Temperature Range (see Figure 4 for other conditions)	T_J, T_{stg}	← -65 to +190 →								°C

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Max	Units
Full Cycle Average Forward Voltage Drop (rated I_O and V_r, single phase, 60 cps, $T_C = 150°C$)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_O and V_r, single phase, 60 cps, $T_C = 150°C$)	$I_{R(AV)}$	20	mA

MR1230 thru MR1237

MAXIMUM RATINGS (See Thermal Derating Graph 16)

Rating	Symbol	MR 1230	MR 1231	MR 1232	MR 1233	MR 1234	MR 1235	MR 1236	MR 1237	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one halfwave, single phase, 60 cycle peak)	$V_{RM(non\text{-}rep)}$	100	200	250	300	350	400	450	500	Volts

MR1230 thru MR1237 (continued)

MAXIMUM RATINGS (continued)

Rating	Symbol	MR 1230	MR 1231	MR 1232	MR 1233	MR 1234	MR 1235	MR 1236	MR 1237	Units
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 150°C) see figure 3	I_o	← 240 →								Amperes
Non-Repetitive Peak Surge Currents (superimposed on rated current at rated voltage, T_C = 150°C) see figure 5	$I_{FM(surge)}$	← 5,000 (for 1/2 cycle) → ← 3,000 (for six consecutive 1/2 cycles) →								Amperes
I^2t Rating (non-repetitive, for t greater than 1 msec and less than 8.3 msec)	I^2t	← 52,000 →								$A^2_{(rms)}$sec

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Maximum Limit	Units
Full Cycle Average Forward Voltage Drop (rated I_o and V_r, single phase, 60 cps, T_C = 150° C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_o and V_r, single phase, 60 cps, T_C = 150° C)	$I_{R(AV)}$	35	mA

MR1240 thru MR1247

MAXIMUM RATINGS (See Thermal Derating Graph 17)

Rating	Symbol	MR 1240	MR 1241	MR 1242	MR 1243	MR 1244	MR 1245	MR 1246	MR 1247	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one halfwave, single phase, 60 cycle peak)	$V_{RM(non\text{-}rep)}$	150	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 150°C) see figure 3	I_o	← 400 →								Amperes
Non-Repetitive Peak Surge Currents (superimposed on rated current at rated voltage, T_C = 150°C) see figure 5	$I_{FM(surge)}$	← 8,000 (for 1/2 cycle) → ← 4,500 (for six consecutive 1/2 cycles) →								Amperes

MR1240 thru MR1247 (continued)

MAXIMUM RATINGS (continued)

Rating	Symbol	MR 1240	MR 1241	MR 1242	MR 1243	MR 1244	MR 1245	MR 1246	MR 1247	Units
I^2t Rating (non-repetitive, for t greater than 1 msec and less than 8.3 msec)	I^2t	← 133,000 →								$A_{(rms)}{}^2$sec
Thermal Resistance	θ_{J-C}	← 0.075 →								°C/Watt
Operating and Storage Temperature	T_J, T_{stg}	← -65 to +190 →								°C

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Maximum Limit	Units
Full Cycle Average Forward Voltage Drop (rated I_o and V_r, single phase, 60 cps, T_C= 150° C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_o and V_r, single phase, 60 cps, T_C = 150° C)	$I_{R(AV)}$	50	mA

MR1260 thru MR1267

MAXIMUM RATINGS (See Thermal Derating Graph 18)

Rating	Symbol	MR 1260	MR 1261	MR 1262	MR 1263	MR 1264	MR 1265	MR 1266	MR 1267	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one half-wave, single phase, 60 cycle peak)	$V_{RM\,(non\text{-}rep)}$	150	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 150°C) see figure 3	I_o	← 650 →								Amperes
Non-Repetitive Peak Surge Currents (superimposed on rated current at rated voltage, T_C = 150°C) see figure 5	$I_{FM\,(surge)}$	← 12,000 (for 1/2 cycle) → ← 8,000 (for six consecutive 1/2 cycles) →								Amperes
I^2t Rating (non-repetitive, for t greater than 1 msec and less than 8.3 msec)	I^2t	← 300,000 →								$A_{(rms)}{}^2$sec
Thermal Resistance	θ_{J-C}	← 0.045 →								°C/Watt
Operating and Storage Temperature	T_J, T_{stg}	← -65 to +190 →								°C

MR1260 thru MR1267 (continued)

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Maximum Limit	Units
Full Cycle Average Forward Voltage Drop (rated I_o and V_r, single phase, 60 cps, T_C=150°C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_o and V_r, single phase, 60 cps, T_C=150°C)	$I_{R(AV)}$	100	mA

MR1290 thru MR1297

MAXIMUM RATINGS (See Thermal Derating Graph 19)

Rating	Symbol	MR 1290	MR 1291	MR 1292	MR 1293	MR 1294	MR 1295	MR 1296	MR 1297	Units
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	150	200	250	300	350	400	Volts
Non-Repetitive Peak Reverse Voltage (one half-wave, single phase, 60 cycle peak)	$V_{RM(non-rep)}$	100	200	250	300	350	400	450	500	Volts
RMS Reverse Voltage	V_r	35	70	105	140	175	210	245	280	Volts
Continuous Average Rectified Forward Current (single phase, resistive load, 60 cps, T_C = 150°C) see figure 5	I_o	← 1000 →								Amps
Non-Repetitive Peak Surge Currents (suiperimposed on rated current at rated voltage, T_C = 150°C) see figure 7	$I_{FM(surge)}$	← 18,000 (for 1/2 cycle) → ← 13,500 (for six consecutive 1/2 cycles) →								Amps
Thermal Resistance DC 1 and 3 phase 6 phase	θ_{JC}	0.035 0.045 0.060								°C/Watt
Operating and Storage Temperature	T_J, T_{stg}	← -65 to +190 →								°C

ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Maximum Limit	Units
Full Cycle Average Forward Voltage Drop (rated I_o and V_r, single phase, 60 cps, T_C = 150°C)	$V_{F(AV)}$	0.4	Volts
Full Cycle Average Reverse Current (rated I_o and V_r, single phase, 60 cps, T_C = 150°C)	$I_{R(AV)}$	0.2	Amps

MR1337-1 thru MR1337-5

MAXIMUM RATINGS (See Thermal Derating Graph 20)

Rating	Symbol	MR 1337-1	MR 1337-2	MR 1337-3	MR 1337-4	MR 1337-5	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	50	100	200	300	400	Volts
Non-Repetitive Peak Reverse Voltage (half-wave, single phase, 60 cycle peak)	$V_{RM(non\text{-}rep)}$	100	200	300	400	500	Volts
RMS Reverse Voltage	V_r	35	70	140	210	280	Volts
		All Types					
Average Rectified Forward Current (single-phase resistive load) $T_A=25°C$ Figure 2 $T_A=75°C$	I_O	1.0 0.75					Amperes
Non-Repetitive Peak Surge Current Figure 3 (superimposed on rated current at rated voltage, $T_A = 75\ °C$)	$I_{FM(surge)}$	30					Amperes
Peak Repetitive Forward Current ($T_A = 75°C$)	$I_{FM(rep)}$	4.0					Amperes
I^2t Rating (non-repetitive, for t greater than 1 msec and less than 8.3 msec)	I^2t	3.75					$A_{(rms)}{}^2sec$
Maximum Junction Operating Temperature Range Maximum Case Storage Temperature Range	T_J T_{stg}	-65 to +150 -65 to +175					°C
Maximum Steady State DC Thermal Resistance	θ_{JA}	100					°C/Watt

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Max Limit	Unit
DC Forward Voltage Drop ($I_F = 1.0$ Adc, $T_A = 25°C$)	V_F	1.1	Vdc
Full Cycle Average Forward Voltage Drop ($I_O = 0.75$ Amps and Rated V_r, $T_A = 75°C$, Half Wave Rectifier)	$V_{F(AV)}$	0.55	Volts
Full Cycle Average Reverse Current ($I_O = 0.75$ Amp and Rated V_r, $T_A = 75°C$, single phase)	$I_{R(AV)}$	0.75	mA
DC Reverse Current (Rated V_R, $T_A = 25°C$)	I_R	0.25	mA
Maximum Reverse Recovery Time ($I_F = 1$ Amp min)	t_{rr}	200	nsec
Maximum Overshoot Current	I_{os}	2.0	Amps

MR2261 thru MR2265

MAXIMUM RATINGS (See Thermal Derating Graph 21)

Rating	Symbol	MR 2261	MR 2262	MR 2263	MR 2264	MR 2265	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	10	20	30	40	50	Volts
RMS Reverse Voltage	V_r	7	14	21	28	35	Volts
Average Rectified Forward Current (single phase, resistive load, 60 cps, $T_C = 100°C$)	I_O	← 25 →					Amps
Peak Repetitive Forward Current ($T_A = 75°C$)	$I_{FM(rep)}$	← 100 →					Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, $T_C = 100°C$)	$I_{FM(surge)}$	← 300 (for 1/2 cycle) →					Amps
Operating and Storage Temperature Range	T_J, T_{stg}	← -65 to +175 →					°C

ELECTRICAL CHARACTERISTICS all types ($T_A = 25°C$ unless otherwise noted)

Characteristics	Symbol	Max Limit	Unit
Full Cycle Average Forward Voltage Drop (I_O = 25 Amps and Rated V_r, $T_C = 100°C$, Half Wave Rectifier)	$V_{F(AV)}$	0.70	Volts
DC Forward Voltage Drop (I_F = 25 Adc, $T_A = 25°C$)	V_F	1.5	Volts
Full Cycle Average Reverse Current (I_O = 25 Amps and Rated V_r, $T_C = 100°C$, Half Wave Rectifier)	$I_{R(AV)}$	10.0	mA
DC Reverse Current (Rated V_R, $T_A = 25°C$)	I_R	1.0	mA

MR2266
MR2273

MAXIMUM RATINGS

Rating	Symbol	MR2273	MR2266	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	200	800	Volts
RMS Reverse Voltage (Sine wave operation)	V_r	140	560	Volts
Average Rectified Forward Current (single-phase, resistive load, 60 cps) (75°C Ambient) (100°C Ambient)	I_O	1.0 0.75	1.0 0.75	Amps

MR2266, MR2273 (continued)

MAXIMUM RATINGS (continued)

Rating	Symbol	MR2273	MR2266	Unit
Peak Repetitive Forward Current (T_A = 25°C)	$I_{FM(rep)}$	10		Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_A = 25°C)	$I_{FM(surge)}$	30 (for 1/2 cycle)		Amps
Operating and Storage Temperature Range	T_J, T_{stg}	-65 to +175		°C

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristics		Symbol	Value	Unit
Full-Cycle Average Forward Voltage Drop (Rated Current @ 25°C, sine wave operation)		$V_{F(AV)}$	0.8	Volts
DC Forward Voltage Drop (1 Amp Continuous DC, 25°C)		V_F	1.1	Volts
DC Reverse Current @ Rated V_r	(25°C) (100°C)	I_R	0.01 0.05	mA
Typical Forward Peak Voltage Overshoot (Figure 1, Figure 2)	MR2266, I_F = 2 A	V_{fp}	10	Volts
	MR2273, I_F = 5 A	V_{fp}	28	Volts

MR2271

MAXIMUM RATINGS (See Thermal Derating Graph 22)

Rating	Symbol	Rating	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	300	Volts
Non-Repetitive Peak Reverse Voltage (half-wave, single phase, 60 cycle peak)	$V_{RM(non-rep)}$	400	Volts
RMS Reverse Voltage (Sine wave operation)	V_r	210	Volts
Average Rectified Forward Current (Sine wave operation) (single-phase resistive load) T_A = 25°C T_A = 75°C	I_O	1.0 0.75	Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_A = 75°C)	$I_{FM(surge)}$	30 (for 1/2 cycle) @ 60 cps	Amps
Peak Repetitive Forward Current (T_A = 75°C)	$I_{FM(rep)}$	4.0	Amps
Junction Operating and Storage Temperature Range	T_J, T_{stg}	-65 to +150	°C

MR2271 (continued)

ELECTRICAL CHARACTERISTICS

Characteristics	Symbol	Value	Unit
Maximum DC Forward Voltage Drop (I_F = 1.0 Adc, T_A = 25°C)	V_F	1.1	Vdc
Maximum Full Cycle Average Forward Voltage Drop (I_O = 0.75 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier, 60 cps)	$V_{F(AV)}$	0.55	Volts
Maximum Full Cycle Average Reverse Current (I_O = 0.75 Amp and Rated V_r, T_A = 75°C, single phase, 60 cps)	$I_{R(AV)}$	0.75	mA
Maximum DC Reverse Current (Rated V_R, T_A = 25°C)	I_R	0.25	mA
Maximum Reverse Recovery Time (I_{RR} = 50 mA) Test Circuit Figure 3 - Typical Waveform Figure 5	t_{rr}	200	nsec
Rectification Efficiency (Typical) Test Circuit Figure 6 - Typical Waveform Figure 4	RE	90	%

MR2272

MAXIMUM RATINGS (See Thermal Derating Graph 23)

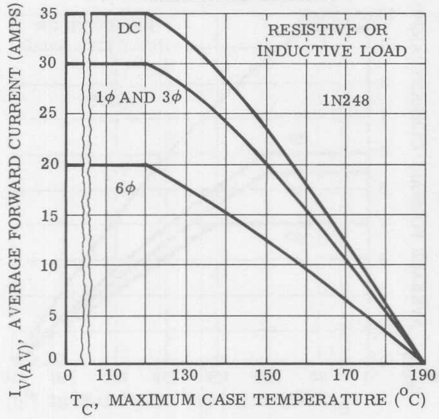
Rating	Symbol	Rating	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	$V_{RM(rep)}$ $V_{RM(wkg)}$ V_R	400	Volts
RMS Reverse Voltage (Sine wave operation)	V_r	280	Volts
Average Rectified Forward Current (Sine wave operation) (75°C Ambient) (100°C Ambient)	I_O	 1.0 0.75	Amps
Peak Repetitive Forward Current (T_A = 75°C)	$I_{FM(rep)}$	10	Amps
Non-Repetitive Peak Surge Current (superimposed on rated current at rated voltage, T_A = 75°C)	$I_{FM(surge)}$	30 (for 1 2 cycle) @ 60 cps	Amps
Juction Operating and Storage Temperature Range	T_J, T_{stg}	-65 to +175	C

MR2272 (continued)

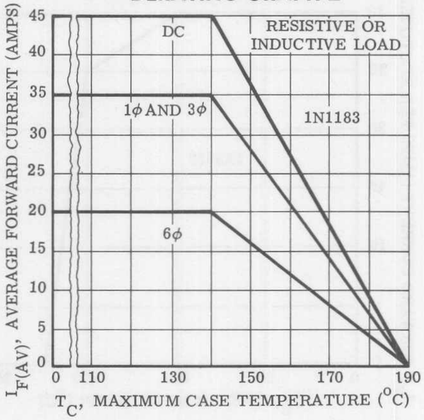
ELECTRICAL CHARACTERISTICS

Characteristics	Symbol	Value	Unit
Maximum Forward Voltage Drop (1 Amp Continuous DC, 25°C)	V_F	1.1	Volts
Maximum Full Cycle Average Forward Voltage Drop (I_O = 0.75 Amps and Rated V_r, T_A = 75°C, Half Wave Rectifier, 60 cps)	$V_{F(AV)}$	0.5	Volts
Maximum Reverse Current @ Rated DC Voltage (25°C)	I_R	0.01	mA
Maximum Reverse Recovery Time (I_{RR} = 0.5 Amp) Test Circuit Figure 4 - Typical Waveform Figure 6	t_{rr}	1.5	μsec
Rectification Efficiency (Typical) Test Circuit Figure 7 - Typical Waveform Figure 5	RE	55	%

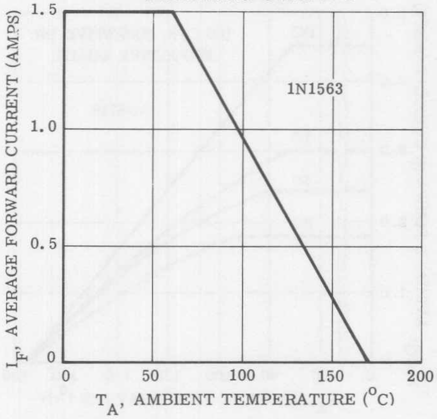
DERATING GRAPH 1



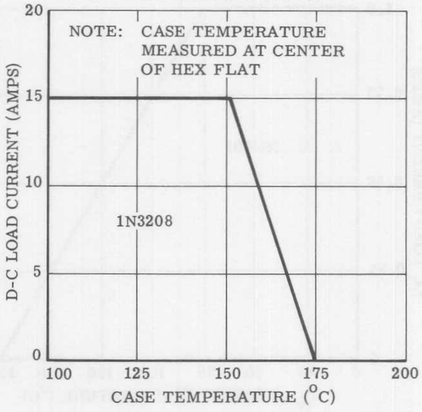
DERATING GRAPH 2



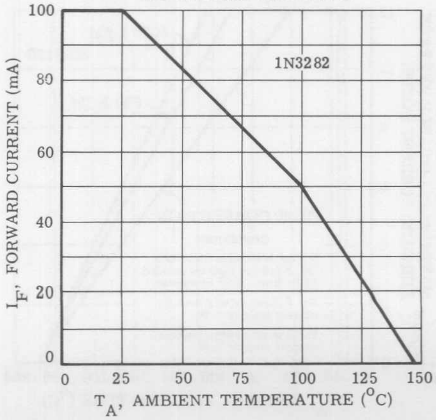
DERATING GRAPH 3



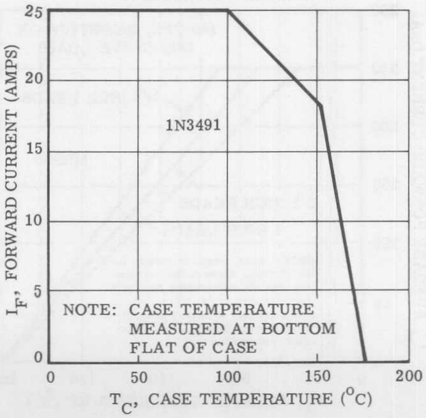
DERATING GRAPH 4



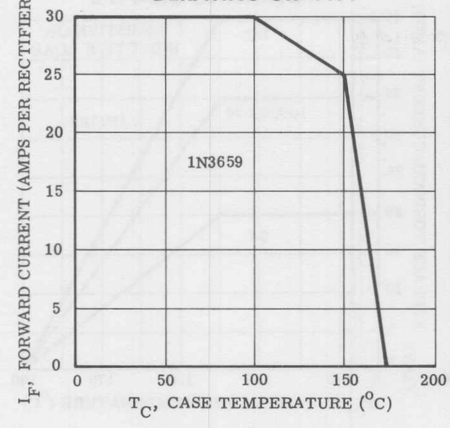
DERATING GRAPH 5



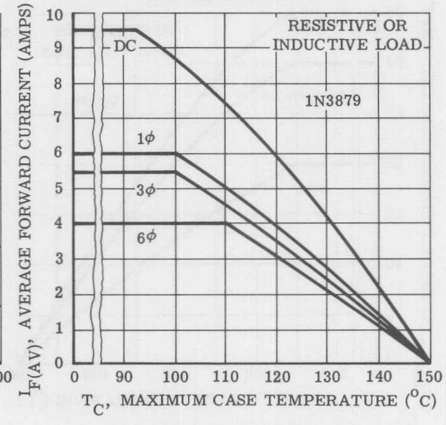
DERATING GRAPH 6



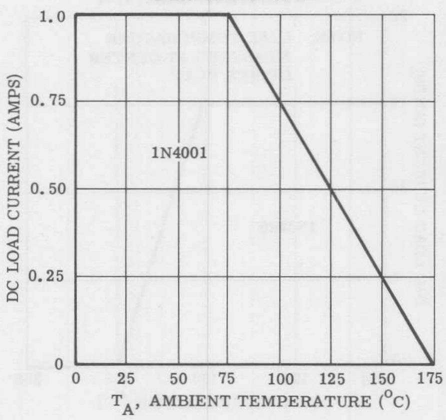
DERATING GRAPH 7



DERATING GRAPH 8



DERATING GRAPH 9



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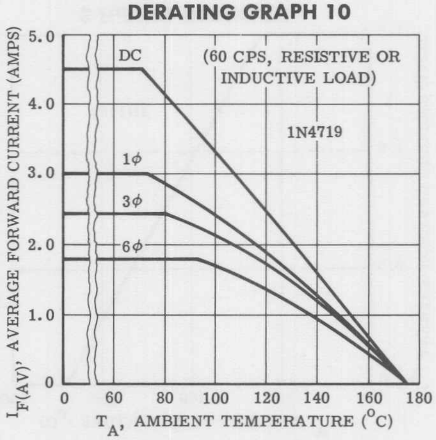

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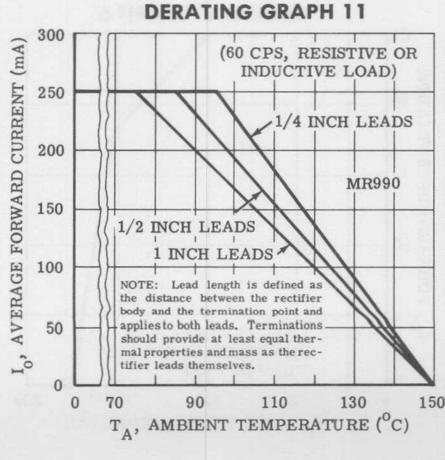

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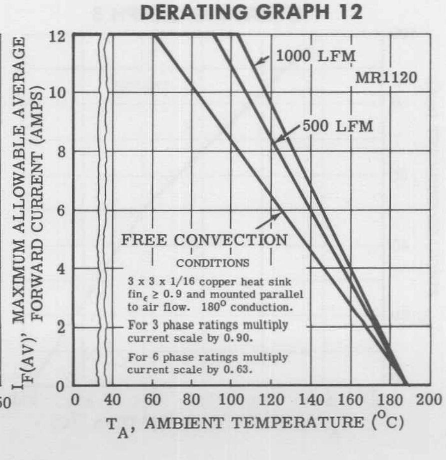

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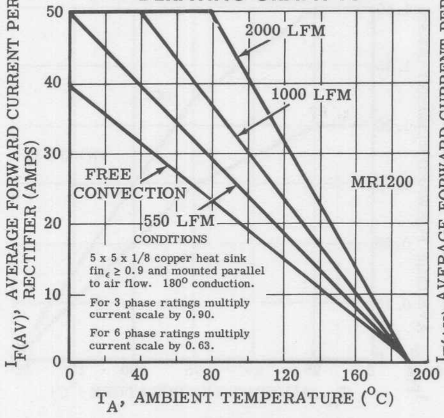

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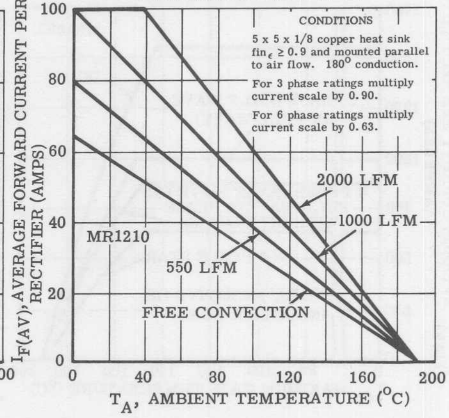
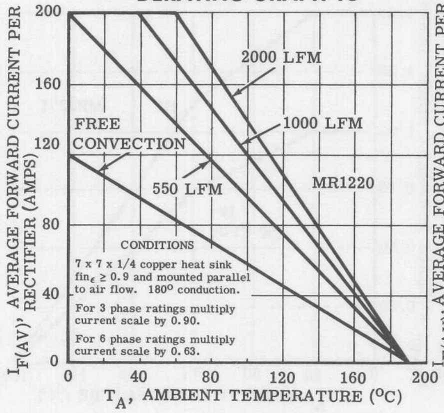
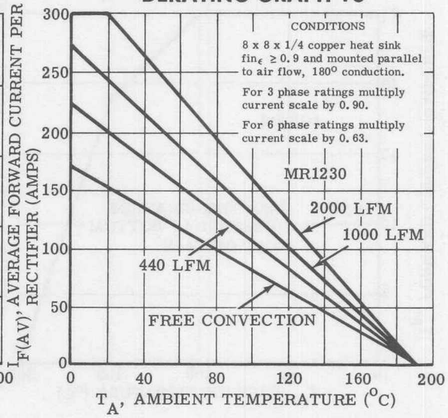


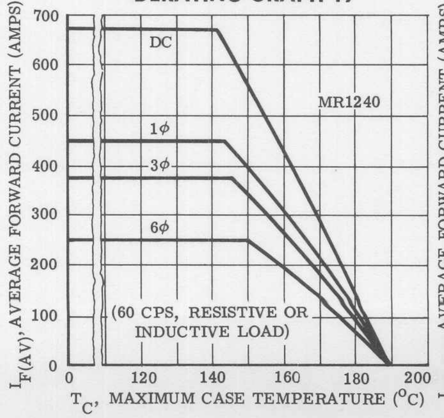
DERATING GRAPH 15



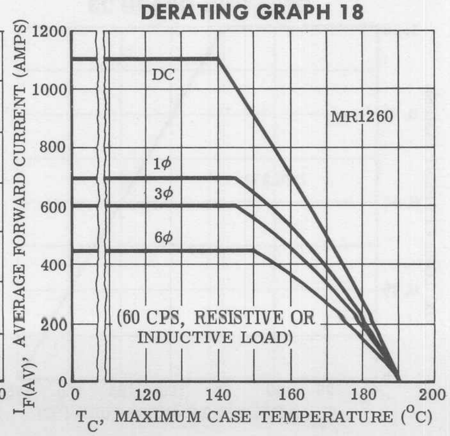
DERATING GRAPH 16



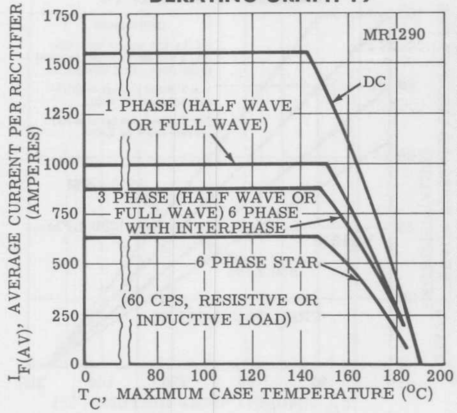
DERATING GRAPH 17



DERATING GRAPH 18



DERATING GRAPH 19



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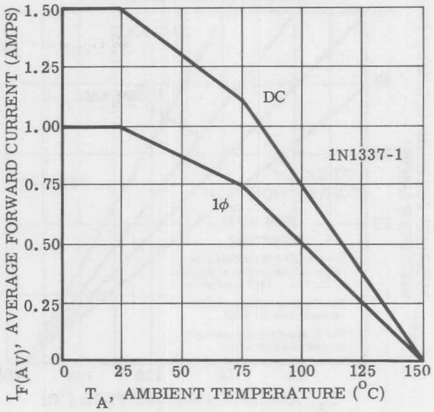
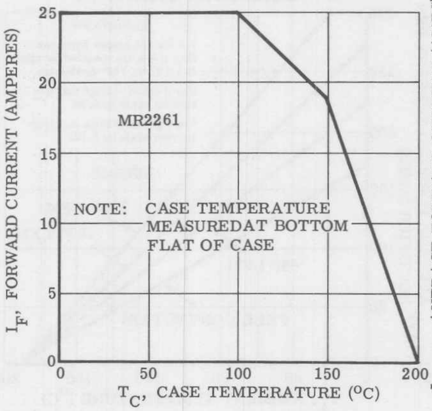
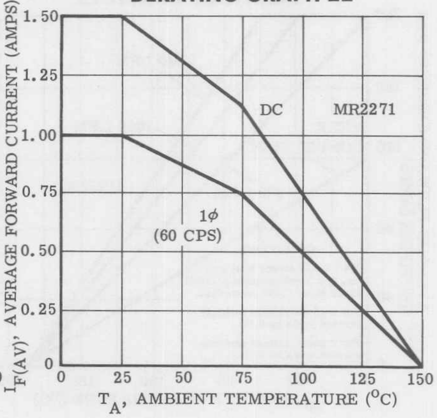


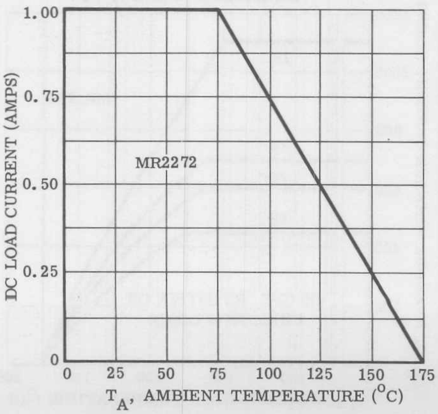
DERATING GRAPH 21



DERATING GRAPH 22



DERATING GRAPH 23

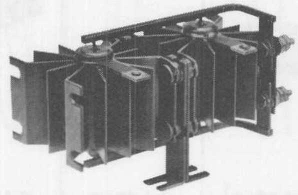


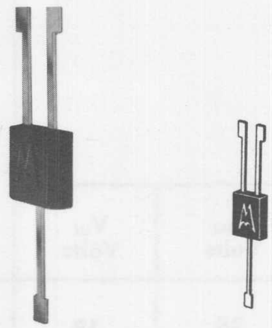
SILICON RECTIFIER ASSEMBLIES

Silicon rectifiers are available as individual cells with a wide variety of current and voltage ratings, as described in the rectifier section of this manual. In addition, these devices are available in standard and custom assemblies, which greatly increase the range of applications that can be satisfied with single-unit preassembled devices.

Included in these standard assemblies are:

High and low current rectifier circuit configurations

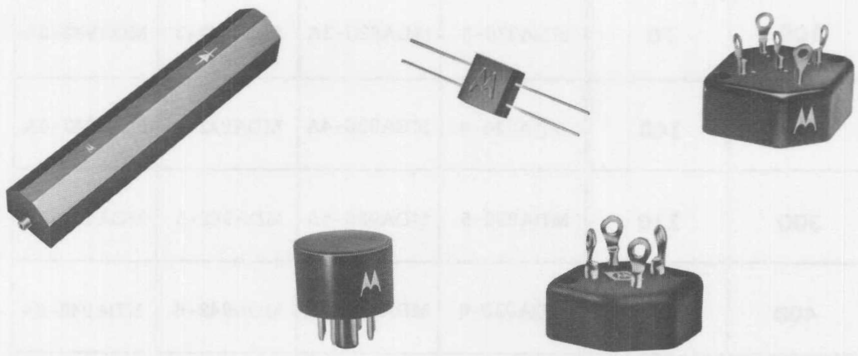




Actual Size

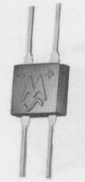
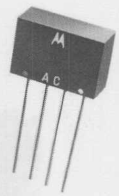
and

Series-connected high-voltage rectifier assemblies.



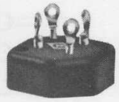
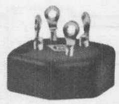
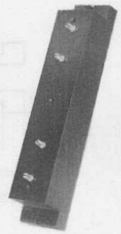
Custom assemblies, including both zener diode and rectifier assemblies, can be obtained inexpensively in quantity by specifying the type of devices needed (from a large selection of individual diodes and rectifiers) and the desired circuit configuration.

MOTOROLA ASSEMBLY

I_{out} Amps		1 Amp		1.5 Amps	
I_{FM}(Surge) Amps		32 Amps		25 Amps	
		Single Phase Full Wave Bridges			
					
V_{RM} Volts	V_{IN} Volts	CASE A†	CASE B†	CASE C	CASE D
25	18	MDA920-1	MDA920-1A	MDA942-1	MDA942-1A
50	35	MDA920-2	MDA920-2A	MDA942-2	MDA942-2A
100	70	MDA920-3	MDA920-3A	MDA942-3	MDA942-3A
200	140	MDA920-4	MDA920-4A	MDA942-4	MDA942-4A
300	210	MDA920-5	MDA920-5A	MDA942-5	MDA942-5A
400	280	MDA920-6	MDA920-6A	MDA942-6	MDA942-6A
600	420	MDA920-7	MDA920-7A	MDA942-7	MDA942-7A

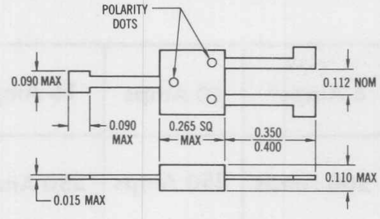
†Also available as voltage doublers, and center taps in all voltage listed.

SELECTION GUIDE

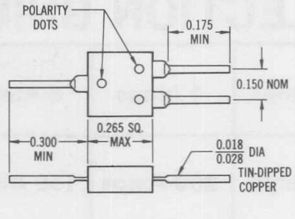
1.5 Amps	4 Amps	6 Amps	8 Amps*	10 Amps	16 Amps
25 Amps	200 Amps	150 Amps	200 Amps	250 Amps	250 Amps
Single Phase Full Wave Bridges					
 CASE E	 CASE E	 CASE F	 CASE G	 CASE H	 CASE J
MDA1491-1	MDA1591-1	MDA952-1	MDA1505-1	MDA962-1	MDA972-1
MDA1491-2	MDA1591-2	MDA952-2	MDA1505-2	MDA962-2	MDA972-2
MDA1491-3	MDA1591-3	MDA952-3	MDA1505-3	MDA962-3	MDA972-3
MDA1491-4	MDA1591-4	MDA952-4	MDA1505-4	MDA962-4	MDA972-4
MDA1491-5	MDA1591-5	MDA952-5	MDA1505-5	MDA962-5	MDA972-5
MDA1491-6	MDA1591-6	MDA952-6	MDA1505-6	MDA962-6	MDA972-6

*Three Phase, Full-wave Bridge

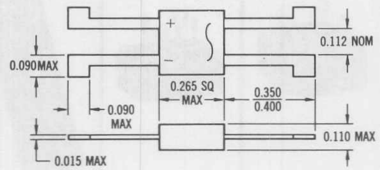
ASSEMBLY CASE OUTLINES



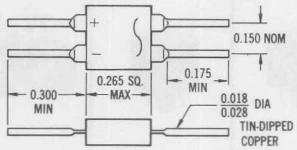
CASE A



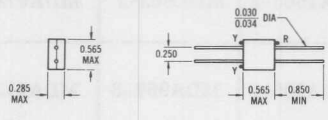
CASE B



CASE C

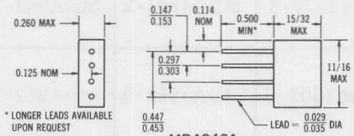


CASE D



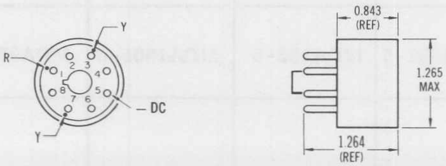
MDA942

CASE E



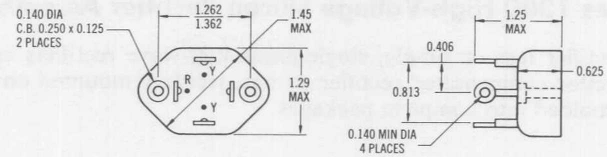
MDA942A

CASE F

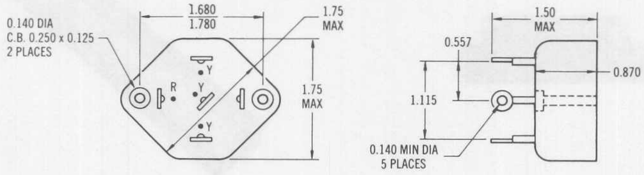


CASE G

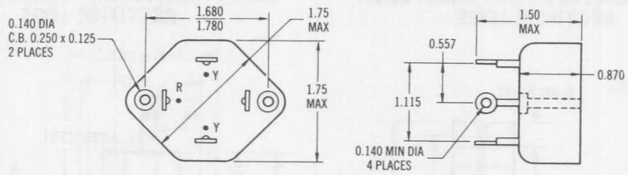
ASSEMBLY CASE OUTLINES



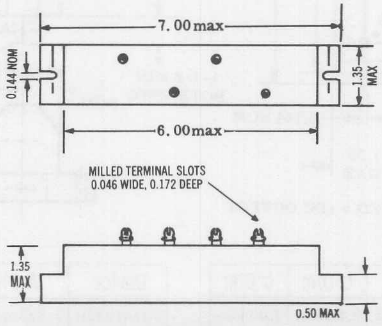
CASE H



CASE I



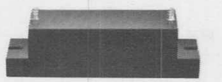
CASE J

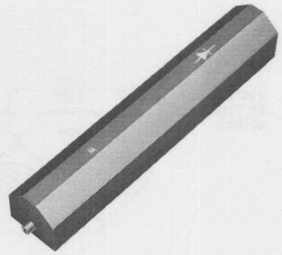


CASE K

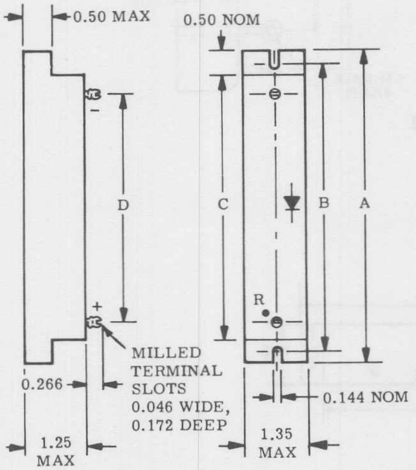
Series 1300 High-Voltage Silicon Rectifier Assemblies

. . . basic rectifier legs or simple, single-phase half-wave rectifiers consisting of resistor-capacitor compensated rectifier strings, securely mounted on component boards and molded into complete packages.

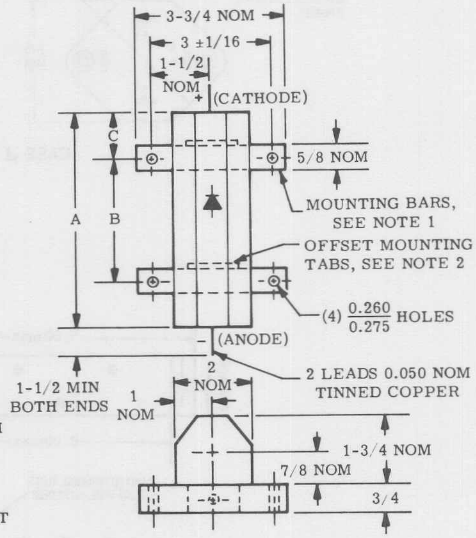




BASIC MDA1330H and MDA1331H RECTIFIER LEGS



BASIC MDA1332H and MDA1333H RECTIFIER LEGS



Device	A Dim	B Dim	C Dim	D Dim
MDA1330H	4.25max	3.70±0.05	3.25max	3.00nom
MDA1331H	7.00max	6.39±0.05	6.00max	5.25nom

Device	A Dim	B Dim	C Dim
MDA1332H	5-5/8 nom	3-5/16±1/16	1-1/8 nom
MDA1333H	11-1/4 nom	6-5/8±1/16	2-3/8 nom

ABSOLUTE MAXIMUM RATINGS

Rating	Symbol	MDA1330H	MDA1331H	MDA1332H	MDA1333H	Units
Peak Repetitive Reverse Voltage ① (Rated Current, Over Operating Temperature Range)	$V_{RM(rep)}$	5,000	10,000	5,000	10,000	Volts
RMS Reverse Voltage ② (Rated Current Over the Complete Operating Temperature Range)	V_r	3,500	7,000	3,500	7,000	Volts
DC Blocking Voltage (Over Operating Temperature Range)	V_R	3,000	6,000	3,000	6,000	Volts
Average Half Wave Rectified Forward Current (Resistive Load, 180° Conduction Angle, 60 cps, Free Convection Cooling) $T_A = 40°C$ / $T_A = 100°C$	I_O	1.0 0.3	1.0 0.3	2.5 0.5	2.5 0.5	Amps
Peak 1 Cycle Surge Current ($T_A = 40°C$, Superimposed on Rated Current at Rated Voltage)	$I_{FM(surge)}$	25	25	250	250	Amps
Operating Frequency Range	←		DC to 400		→	cps
Operating and Storage Temperature Range	←		−55 to +100		→	°C

①Motorola "Series 1300" Stacks have $V_{RM(rep)}$ ratings of 5,000 or 10,000 volts peak which are both the maximum repetitive and non-repetitive ratings. The Design Voltage to Rated Voltage safety factor to be used is left at the discretion of the designer. Where voltage transient suppresion is employed, these assemblies can be reliably operated at the maximum ratings.

②The DC Blocking Voltage rating (V_R), is established by the continuous power dissipation ratings of the shunting resistors and is not a function of the series rectifiers.

ELECTRICAL CHARACTERISTICS

Rating	Symbol	MDA1330H	MDA1331H	MDA1332H	MDA1333H	Units
Maximum Full-Cycle Average Forward Voltage Drop (Half-Wave, Resistive Load, Rated Current and Voltage, $T_A = 40°C$)	$V_{F(AV)}$	5.0	10.0	5.0	10.0	Volts
Maximum Full-Cycle Average Reverse Current (Half-Wave, Resistive Load, Rated Current and Voltage, $T_A = 40°C$)	$I_{R(AV)}$	0.2	0.2	3.0	3.0	mA

NOTE: Ambient temperatures are measured at the cold air source point i.e. immediately below the rectifier legs under convection cooling and on the cool air side with forced air cooling.

Series 300 Silicon Rectifier Stacks

Motorola rectifier stacks offer a new concept in compact, thermal-efficient circuit packages. Stacks utilize medium current rectifier cells interconnected in any of six common rectifier circuits and securely mounted in extruded-fin aluminum coolers to provide optimum heat sink surface contact.

Motorola Silicon Rectifier

3 — **STACK SERIES NUMBER**

3 — Series 300

H — **COOLER ORIENTATION**

V — Vertical, primarily designed for free convection cooling

H — Horizontal, primarily designed for forced air cooling

2 — **COOLER AXIAL LENGTH**

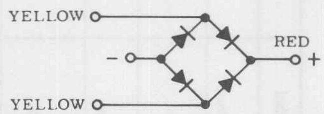
1 — ¾ inch

2 — 1½ inch

3 — 3 inches

B — **RECTIFIER CIRCUITS**

B — Single Phase Bridge
C — Single Phase, Center Tap, common Cathode
U — Single Phase, Center Tap, common Anode
D — Single Phase Doubler
F — Three Phase, Full Wave Bridge
H — Single Phase Half-Wave
Y — Three Phase Half-Wave, common cathode
W — Three Phase Half-Wave, common anode



B — SINGLE PHASE FULL WAVE BRIDGE

MAX. DC OUTPUT	VERTICAL — Free Convection Cooling									
Current +55°C	12.0A		16.0A		22.0A		32.0A		48.0A	
+100°C	5.0A		7.0A		10.0A		14.0A		19.0A	
$V_{RM(rep)}$ (DIODE)		Outline No.		Outline No.		Outline No.		Outline No.		Outline No.
50	3V1B1A1A2	2	3V2B1A1A2	6	3V3B1A1A2	6	3V2B1A1A4	8	3V3B1A1A4	8
100	B	2	B	6	B	6	B	8	B	8
200	C	2	C	6	C	6	D	8	C	8
300	D	2	D	6	D	6	C	8	D	8
400	E	2	E	6	E	6	E	8	E	8
300	D2A4	4	D2A4	8	D2A4	8				
400	E	4	E	8	E	8				
	HORIZONTAL — Forced Air Cooling (1000 LFM)									
Current +55°C	37.0A		44.0A		59.0A		68.0A		70.0A	
+100°C	15.0A		19.0A		26.0A		34.0A		39.0A	
$V_{RM(rep)}$ (DIODE)		Outline No.		Outline No.		Outline No.		Outline No.		Outline No.
50	3H1B1A1A2	9	3H2B1A1A2	10	3H3B1A1A2	11	3H2B1A1A4	12	3H3B1A1A4	12
100	B	9	B	10	B	11	B	12	B	12
200	C	9	C	10	C	11	C	12	C	12
300	D	9	D	10	D	11	D	12	D	12
400	E	9	E	10	E	11	E	12	E	12
300			D2A4	12	D2A4	12				
400			E	12	E	12				

General Specifications

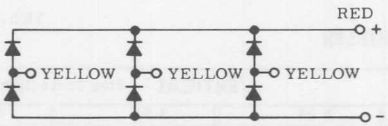
Rectifier Stacks
- Storage and Operating Temperature Range — −65 to +125°C

Individual Rectifier Cells (at 25°C)
- DC Forward Voltage Drop at 100 Adc — $V_F = 1.5$ Vdc max
- Reverse Current at rated DC Reverse Voltage — $I_R = 1.0$ mAdc max
- Peak Recurrent Forward Current at 60 cps — $I_F = 115$ A max

Stack Coding System

1	A	1	A	2
RECTIFIER CELL PACKAGE	INDIVIDUAL RECTIFIER CELL PIV	NUMBER OF RECTIFIER CELLS IN SERIES IN EACH CIRCUIT LEG*	NUMBER OF RECTIFIER CELLS IN PARALLEL IN EACH CIRCUIT LEG*	NUMBER OF COOLERS IN COMPLETE STACK
1 — Press-fit rectifiers	A — 50 Volts	1 thru 8	A — one	1 thru 4
	B — 100 Volts		B — two	
	C — 200 Volts		C — three	
	D — 300 Volts		D — four	
	E — 400 Volts		E — five	

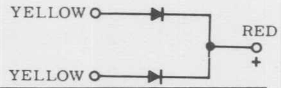
*All series or parallel connected rectifiers are matched units.



F — THREE PHASE FULL WAVE BRIDGE

MAX. DC OUTPUT	**VERTICAL** — Free Convection Cooling					
Current +55°C	18.0A		24.0A		33.0A	
+100°C	7.5A		10.5A		15.0A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.	
50	3V1F1A1A3	3	3V2F1A1A3	7	3V3F1A1A3	7
100	B	3	B	7	B	7
200	C	3	C	7	C	7
300	D	3	D	7	D	7
400	E	3	E	7	E	7
	HORIZONTAL — Forced Air Cooling (1000 LFM)					
Current +55°C	55.0A		66.0A		88.5A	
+100°C	22.5A		28.5A		39.0A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.	
50	3H1F1A1A3	9	3H2F1A1A3	10	3H3F1A1A3	11
100	B	9	B	10	B	11
200	C	9	C	10	C	11
300	D	9	D	10	D	11
400	E	9	E	10	E	11

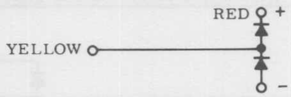
C — SINGLE PHASE CENTER TAP, COMMON CATHODE
V — SINGLE PHASE CENTER TAP, COMMON ANODE



MAX. DC OUTPUT	VERTICAL — Free Convection Cooling									
Current +55°C	12.0A		16.0A		22.0A		32.0A		48.0A	
+100°C	5.0A		7.0A		10.0A		14.0A		19.0A	
$V_{RM(rep)}$ (DIODE)	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓
50	3V1C1A1A1	1	3V2C1A1A1	5	3V3C1A1A1	5	3V2C1A1A2	6	3V3C1A1A2	6
100	B	1	B	5	B	5	B	6	B	6
200	C	1	C	5	C	5	C	6	C	6
300	D	1	D	5	D	5	D	6	D	6
400	E	1	E	5	E	5	E	6	E	6
300	D2A2	2	D2A2	6	D2A2	6	D2A4	8	D2A4	8
400	E	2	E	6	E	6	E	8	E	8
300	D4A4	4	D4A4	8	D4A4	8				
400	E	4	E	8	E	8				

	HORIZONTAL — Forced Air Cooling (1000 LFM)									
Current +55°C	37.0A		44.0A		59.0A		68.0A		70.0A	
+100°C	15.0A		19.0A		26.0A		34.0A		39.0A	
$V_{RM(rep)}$ (DIODE)	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓
50	3H1C1A1A1	9	3H2C1A1A1	10	3H3C1A1A1	11	3H2C1A1A2	10	3H3C1A1A2	11
100	B	9	B	10	B	11	B	10	B	11
200	C	9	C	10	C	11	C	10	C	11
300	D	9	D	10	D	11	D	10	D	11
400	E	9	E	10	E	11	E	10	E	11
300	D2A2	9	D2A2	10	D2A2	11	D2A4	12	D2A4	12
400	E	9	E	10	E	11	E	12	E	12
300			D4A4	12	D4A4	12				
400			E	12	E	12				

D — SINGLE PHASE DOUBLER



MAX. DC OUTPUT	VERTICAL — Free Convection Cooling									
Current +55°C	4.5A		6.0A		8.0A		12.0A		18.0A	
+100°C	1.8A		2.6A		3.7A		5.0A		7.0A	
$V_{RM(rep)}$ (DIODE)	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓
50	3V1D1A1A1	1	3V2D1A1A1	5	3V3D1A1A1	5	3V2D1A1A2	6	3V3D1A1A2	6
100	B	1	B	5	B	5	B	6	B	6
200	C	1	C	5	C	5	C	6	C	6
300	D	1	D	5	D	5	D	6	D	6
400	E	1	E	5	E	5	E	6	E	6
300	D2A2	2	D2A2	6	D2A2	6	D2A4	8	D2A4	8
400	E	2	E	6	E	6	E	8	E	8
300	D4A4	4	D4A4	8	D4A4	8				
400	E	4	E	8	E	8				

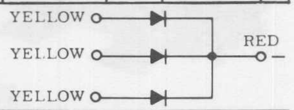
	HORIZONTAL — Forced Air Cooling (1000 LFM)									
Current +55°C	13.8A		16.5A		22.0A		25.5A		26.5A	
+100°C	5.5A		7.0A		9.5A		12.5A		14.5A	
$V_{RM(rep)}$ (DIODE)	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓	Outline No.	↓
50	3H1D1A1A1	9	3H2D1A1A1	10	3H3D1A1A1	11	3H2D1A1A2	10	3H3D1A1A2	10
100	B	9	B	10	B	11	B	10	B	10
200	C	9	C	10	C	11	C	10	C	10
300	D	9	D	10	D	11	D	10	D	10
400	E	9	E	10	E	11	E	10	E	10
300	D2A2	9	D2A2	10	D2A2	11	D2A4	12	D2A4	12
400	E	9	E	10	E	11	E	12	E	12
300			D4A4	12	D4A4	12				
400			E	12	E	12				

H — SINGLE PHASE HALF-WAVE RECTIFIER

MAX. DC OUTPUT	VERTICAL — Free Convection Cooling									
Current +55°C	6.0A		8.0A		11.0A		16.0A		24.0A	
+100°C	2.5A		3.5A		5.0A		7.0A		9.5A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.		Outline No.		Outline No.	
50					3V1H1A1A1	1	3V2H1A1A1	5	3V3H1A1A1	5
100					B	1	B	5	B	5
200					C	1	C	5	C	5
300					D	1	D	5	D	5
300					E	1	E	5	E	5
300	3V1H1D2A1	1	3V2H1D2A1	5	3V3H1D2A1	5	D3A3	7	D3A3	7
400	E	1	E	5	E	5				
400	D4A2	2	D4A2	6	D4A2	6				
400	E	2	E	6	E	6	E3A3	7	E3A3	7
400	E6A3	3	E6A3	7	E6A3	7	E4A4	8	E4A4	8
400	E8A4	3	E8A4	8	E8A4	8				

HORIZONTAL — Forced Air Cooling (1000 LFM)										
Current +55°C	18.5A		22.0A		29.5A		34.0A		35.0A	
+100°C	7.5A		9.5A		13.0A		17.0A		19.5A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.		Outline No.		Outline No.	
50					3H1H1A1A1	9	3H2H1A1A1	10	3H3H1A1A1	11
100					B	9	B	10	B	11
200					C	9	C	10	C	11
300					D	9	D	10	D	11
400					E	9	E	10	E	11
300	3H1H1D2A1	9	3H2H1D2A1	10	3H3H1D2A1	11	D3A3	10	D3A3	11
400	E	9	E	10	E	11				
300	D4A2	9	D4A2	10	D4A2	11				
400	E	9	E	10	E	11	E3A3	10	E3A3	11
400	E6A3	9	E6A3	10	E6A3	11	E4A4	12	E4A4	12
400			E8A4	12	E8A4	12				

Y — THREE PHASE HALF-WAVE, COMMON CATHODE
W — THREE PHASE HALF-WAVE, COMMON ANODE



MAX. DC OUTPUT	VERTICAL — Free Convection Cooling									
Current +55°C	18.0A		24.0A		33.0A		48.0A		72.0A	
+100°C	7.5A		10.5A		15.0A		21.0A		28.5A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.		Outline No.		Outline No.	
50					3V1Y1A1A3	3	3V2Y1A1A3	7	3V3Y1A1A3	7
100					B	3	B	7	B	7
200					C	3	C	7	C	7
300					D	3	D	7	D	7
400					E	3	E	7	E	7
300	3V1Y1D2A3	3	3V2Y1D2A3	7	3V3Y1D2A3	7				
400	E	3	E	7	E	7				

HORIZONTAL — Forced Air Cooling (1000 LFM)										
Current +55°C	55.5A		66.0A		88.5A		102.0A		105.0A	
+100°C	22.5A		28.5A		39.0A		51.0A		58.5A	
$V_{RM(rep)}$ (DIODE)	Outline No.		Outline No.		Outline No.		Outline No.		Outline No.	
50					3H1Y1A1A3	9	3H2Y1A1A3	10	3H3Y1A1A3	11
100					B	9	B	10	B	11
200					C	9	C	10	C	11
300					D	9	D	10	D	11
400					E	9	E	10	E	11
300	3H1Y1D2A3	9	3H2Y1D2A3	10	3H3Y1D2A3	11				
400	E	9	E	10	E	11				

Installation Dimensions

All dimensions are in inches

ALL TYPES
Dim. A (mounting terminals) 6-32 thread
Dim. B (hole diameter) 0.156 ± .010
(For example see figure 1)

The dimensions given on the photograph are the maximums required to mount any similar unit regardless of circuit configuration, busbar and terminal locations.

FIG. 1

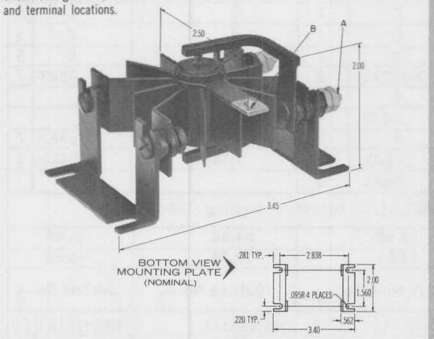


FIG. 2

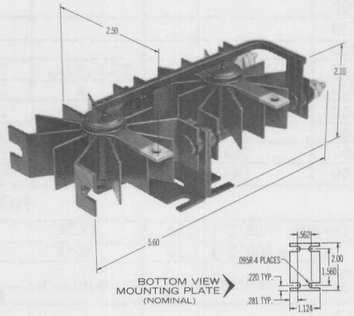


FIG. 3

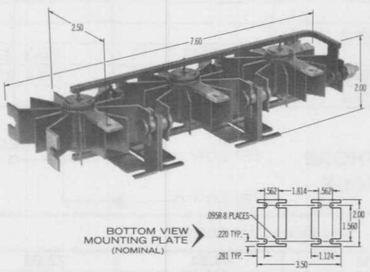


FIG. 4

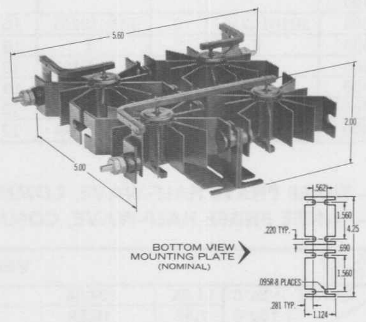


FIG. 5

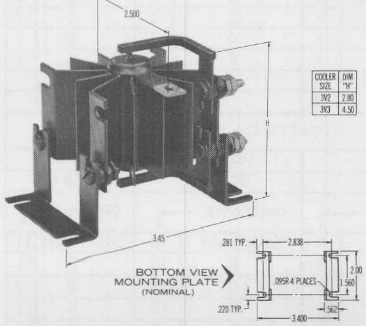
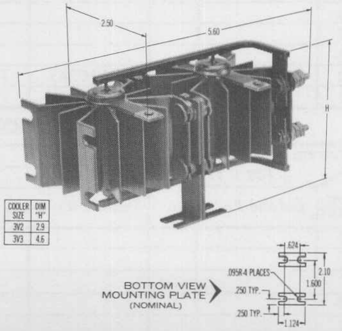


FIG. 6



Installation Dimensions

All dimensions are in inches

FIG. 7

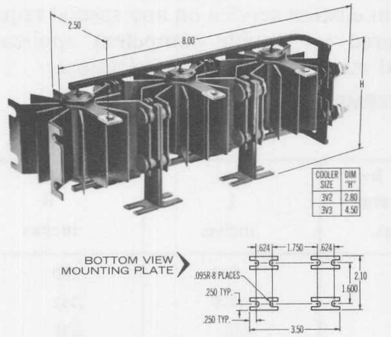


FIG. 8

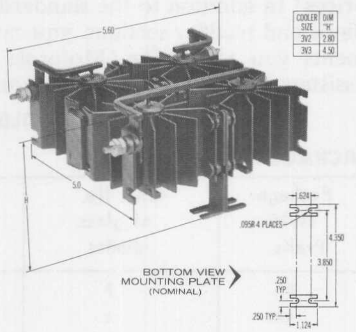


FIG. 9

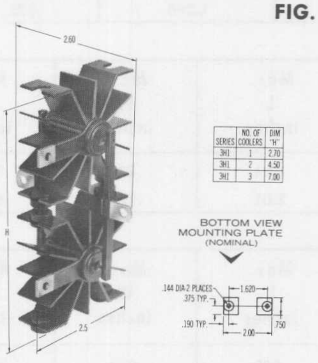


FIG. 10

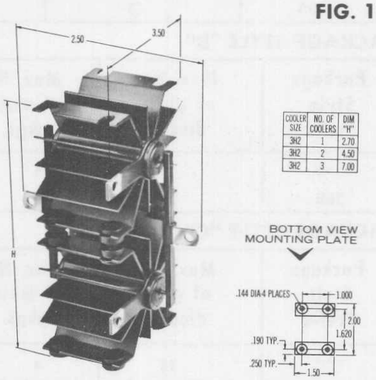


FIG. 11

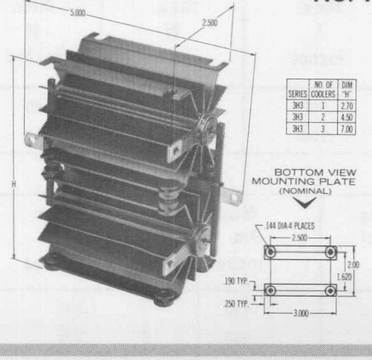
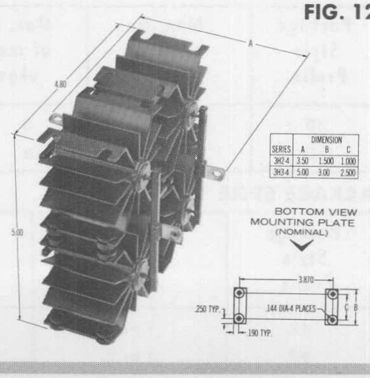


FIG. 12



Custom Assemblies

As part of its program of total service to the semiconductor user, Motorola has established a complete in-house facility capable of handling high volume orders for virtually any semiconductor assembly requirement — and at economy prices! In addition to the standard units on the following pages and in the zener diode and rectifier sections, you can obtain custom service on any special requirements you may have. Motorola is geared to provide competent application assistance as well as prompt, economical custom-assembly fabrication.

TYPICAL MOLDED ASSEMBLY PACKAGES

PACKAGE STYLE "A"

Package Style Prefix	Max. No. of glass diodes	Max. No. of metal pkgs.	Max. L inches	Max. D inches
2A	2	-	.900	.150
4A	4	-	.500	.313
10A	10	2	1.00	.313
18A	18	4	.625	.625
36A	36	8	1.200	.625

PACKAGE STYLE "B"

Package Style Prefix	Max. No. of glass diodes	Max. No. of metal pkgs.	Max. L inches	Max. W inches	Max. H inches
19B	19	4	1.01	.300	.610
38B	38	8	2.01	.300	.610

PACKAGE STYLE "C"

Package Style Prefix	Max. No. of glass diodes	Max. No. of metal pkgs.	Max. L inches	Max. W inches	Max. H inches
16C	16	4	.600	.600	.625

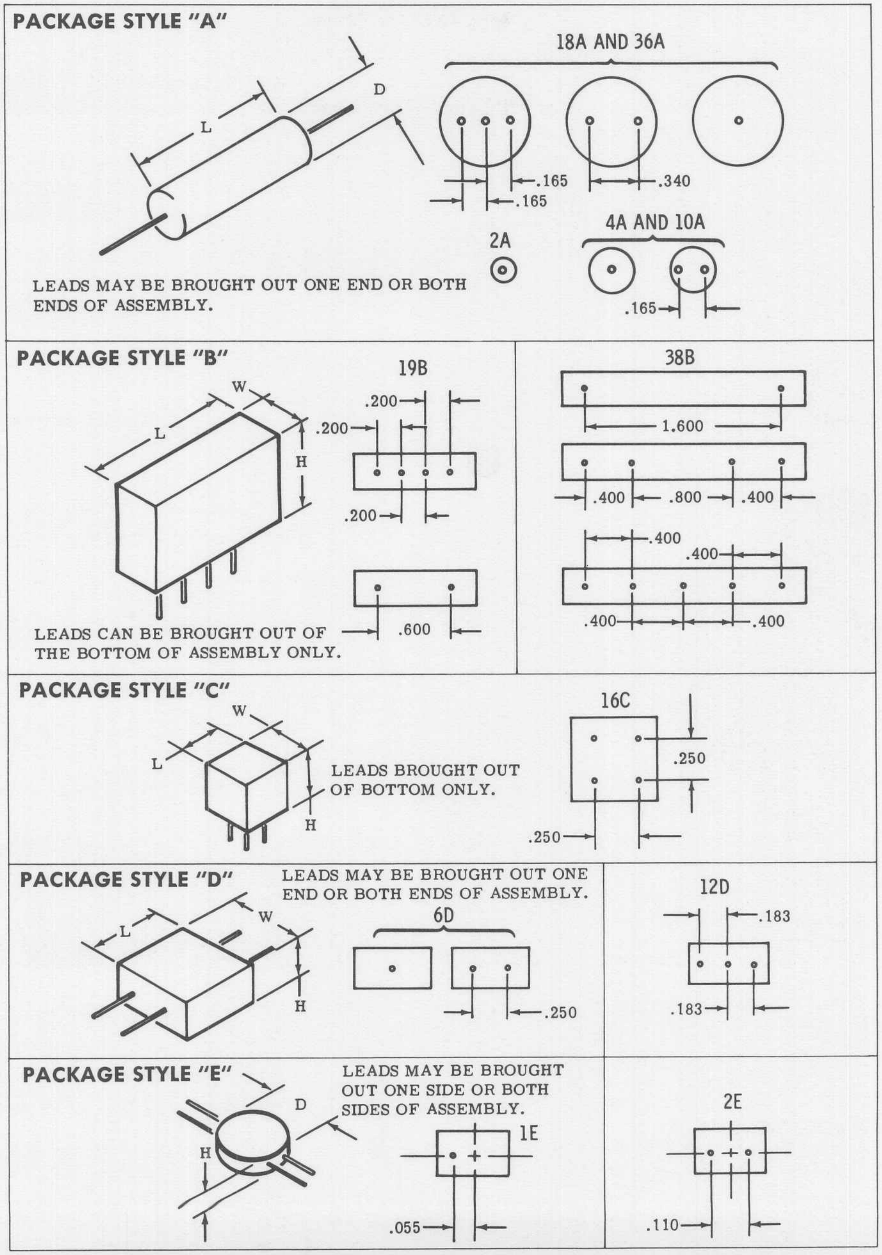
PACKAGE STYLE "D"

Package Style Prefix	Max. No. of glass diodes	Max. No. of metal pkgs.	Max. L inches	Max. W inches	Max. H inches
6D	6	0	.565	.565	.285
12D	12	2	.750	.565	.285

PACKAGE STYLE "E"

Package Style Prefix	Max. No. of glass diodes	Max. No. of metal pkgs.	Max. Dia. D inches	Max. H inches
1E	1 or 2	-	.400	.200
2E	1 or 2	-	.400	.200

LEAD* LOCATIONS AVAILABLE



* LEAD DIAMETERS .030 ± .005 INCHES.
LEAD TOLERANCE BETWEEN CENTERS ± .005".
LEAD LENGTH 1.125" MIN.

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RECTIFIER CIRCUIT VOLTAGE CHARACTERISTICS

(PARAMETER$_1$) = (PARAMETER$_2$) X (CIRCUIT VALUES)				CIRCUIT NUMBERS							
				1	2	3	4	5	6	7	LOAD
AVERAGE DC OUTPUT VOLTAGE	=	SECONDARY R. M. S. VOLTS PER LEG	X	0.450	C.T. 0.900	0.900	N 1.170	N 2.34	N 1.350	1.170	RL
				1.414	1.414	1.414	1.414	2.70	1.414	1.414	C
R. M. S. DC OUTPUT VOLTAGE	=	SECONDARY R. M. S. VOLTS PER LEG	X	0.707	1.00	1.00	1.191	2.34	1.350	1.170	RL
R. M. S. DC OUTPUT VOLTAGE	=	AVERAGE DC OUTPUT VOLTAGE	X	1.57	1.11	1.11	1.02	1.00	1.00	1.00	RL
PEAK DC OUTPUT VOLTAGE	=	AVERAGE DC OUTPUT VOLTAGE	X	3.14	1.57	1.57	1.21	1.05	1.05	1.05	RL
R. M. S. SECONDARY VOLTS PER LEG	=	AVERAGE DC OUTPUT VOLTAGE	X	2.22	C.T. 1.11	1.11	N 0.855	N 0.428	N 0.741	0.855	RL
				0.707	0.707	0.707	0.408	0.707	0.707	0.707	C
R. M. S. SECONDARY VOLTS LINE TO LINE	=	AVERAGE DC OUTPUT VOLTAGE	X	2.22	2.22	1.11	1.48	0.740	1.48	1.71	RL
PEAK REVERSE VOLTS PER RECTIFIER	=	AVERAGE DC OUTPUT VOLTAGE	X	3.14	C.T. 3.14	1.57	N 2.09	N 1.05	N 2.09	2.09	RL
				2.00	2.00	1.00	2.00	1.00	2.00	2.00	C
PEAK REVERSE VOLTS PER RECTIFIER	=	R. M. S. SECONDARY VOLTS PER LEG	X	1.41	2.828	1.414	2.45	2.45	2.828	2.45	RL
PEAK REVERSE VOLTS PER RECTIFIER	=	R. M. S. SECONDARY VOLTS LINE TO LINE	X	1.414	1.414	1.414	1.414	1.414	1.414	1.414	RL
INTERPHASE TRANSFORMERS VOLTAGE LINE-NEUTRAL	=	AVERAGE DC OUTPUT VOLTAGE	X							0.252	
3 $V_{LINE-NEUTRAL}$	=	$V_{LINE-LINE}$									

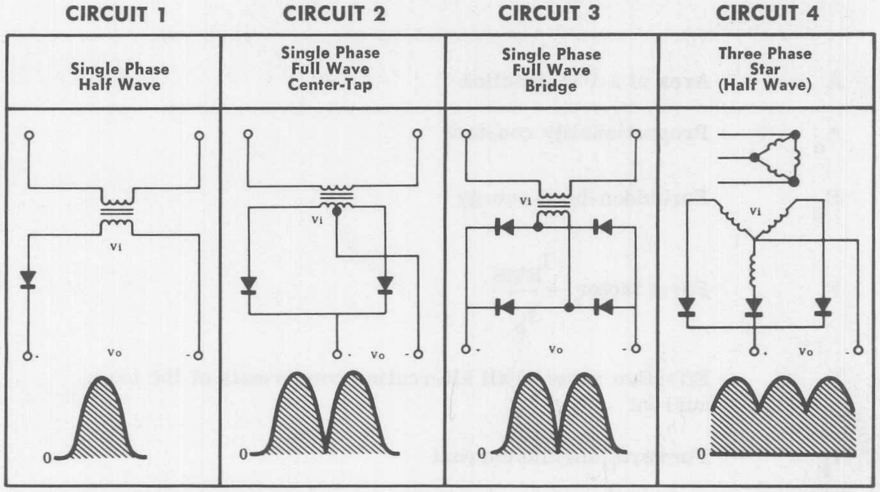
RECTIFIER CIRCUIT CURRENT CHARACTERISTICS

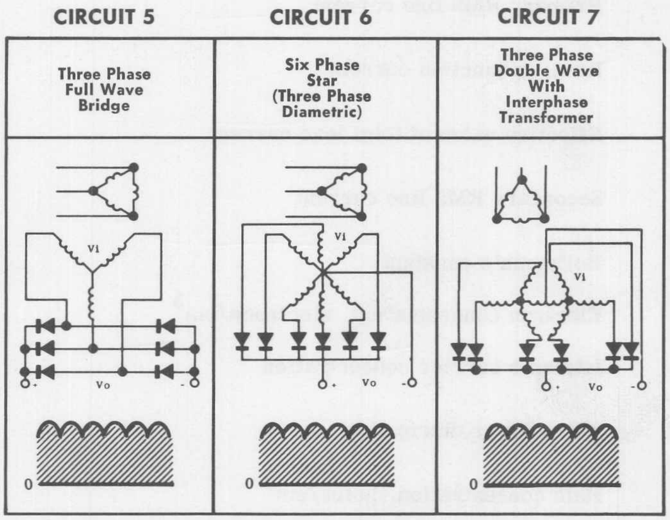
$(PARAMETER_1)$ = $(PARAMETER_2)$ X (CIRCUIT VALUES)				CIRCUIT NUMBERS							
				1	2	3	4	5	6	7	LOAD
AVERAGE DC OUTPUT CURRENT PER RECTIFIER LEG	=	AVERAGE DC OUTPUT CURRENT	X	1.00	0.50	0.50	0.333	0.333	0.167	0.167	RLC
PEAK CURRENT THROUGH RECTIFIER	=	AVERAGE DC OUTPUT CURRENT	X	3.14	1.57	1.57	1.21	1.05	1.05	0.525	R
					1.00	1.00	1.00	1.00	1.00	0.500	L
R.M.S. LINE CURRENT TO EACH RECTIFIER (SECONDARY)	=	AVERAGE DC OUTPUT CURRENT	X	R 1.57	0.707	1.00	0.578	0.816	0.408	0.289	L
R.M.S. CURRENT PER RECTIFIER ELEMENT	=	AVERAGE DC OUTPUT CURRENT	X	1.57	0.785	0.785	0.587	0.579	0.409	0.293	R
					0.707	0.707	0.578	0.578	0.408	0.289	L
PRIMARY R.M.S. LINE CURRENT	=	ARRAY LOAD CURRENT X PER LEG VOLTAGE PRIMARY LINE VOLTAGE	X	R 1.57	1.00	1.00	0.817	1.41	0.817	0.707	L

RECTIFIER CIRCUIT MISCELLANEOUS CHARACTERISTICS

$(PARAMETER_1)$ = $(PARAMETER_2)$ X (CIRCUIT VALUES)				CIRCUIT NUMBERS							
				1	2	3	4	5	6	7	LOAD
TRANSFORMER TOTAL SECONDARY VA	=	AVERAGE DC WATTS OUTPUT	X	3.49	1.75	1.23	1.50	1.05	1.81	1.49	R
				3.14	1.57	1.11	1.48	1.05	1.81	1.48	L
TRANSFORMER TOTAL PRICING VA	=	AVERAGE DC WATTS OUTPUT	X	3.49	1.23	1.23	1.23	1.05	1.28	1.06	R
				3.14	1.11	1.11	1.21	1.05	1.28	1.05	L
		CORROSION EFFICIENCY		40.6	81.2	81.2	97	99.5	99.5	99.5	
		% RIPPLE		121	47	47	17	4	4	4	R
		LINE POWER FACTOR			0.90	0.90	0.826	0.955	0.955	0.955	

RECTIFIER CIRCUIT CHARACTERISTICS





Abbreviations

A	Area of a P-N junction
A_o	Proportionality constant
E_g	Forbidden-band energy
F	Form factor $\frac{I_{RMS}}{I_o}$
I_{ac}	Effective value of all alternating components of the load current
I_F	Forward junction current
I_m	Peak current through a rectifier
I_0	Average value of the load current
I_p	Primary RMS line current
I_R	Reverse junction current
I_{RMS}	Effective value of total load current
I_s	Secondary RMS line current
k	Boltsman's constant
n	Electron concentration, electrons/cm^3
n_i	Intrinsic carrier concentration
P_D	Total power dissipation
p	Hole concentration, holes/cm^3
PIV	Peak inverse voltage of a rectifier
P_0	Average power

q	Electron charge
R_L	Load resistance
R_S	Total equivalent series resistance
T	Temperature, ^oK
t_s	Storage time
T_J	Junction temperature ^oC
T_A	Ambient temperature ^oC
UF	Utility factor
V_o	DC output voltage
V_m	Peak rectifier voltage
V_s	Secondary line voltage
V_P	Primary RMS line voltage
W_D	Width of the depletion region

GREEK SYMBOLS

γ	dynamic resistance of a diode
γ_n	ripple factor due to nth harmonic
ϵ	dielectric constant of material ripple factor
η_R	rectification efficiency
θ_{CS}	thermal resistance case-to-sink
θ_{JA}	thermal resistance junction-to-ambient
θ_{JC}	thermal resistance junction-to-case
θ_{SA}	thermal resistance sink-to-ambient
τ_p	mean lifetime of holes
ω	$2\pi_f$ where f is the line-supply frequency

Index