DESIGN CRITERIA: TRANSMITTER HIGH VOLTAGE SOLID STATE RECTIFIERS

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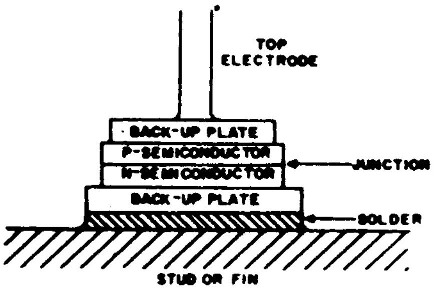
It is the purpose of this paper to set forth the problems encountered when one sets out to design a high voltage power supply using semiconductor rectifiers. Also, to indicate possible solutions to these problems.

The nature of the semiconductor itself must be understood before it can be properly applied. Despite their high efficiency, the small internal losses of the rectifiers are the prime criteria for their application. Unlike many other electrical devices such as transformers, motors and even vacuum tubes, semiconductor rectifiers have a very low thermal capacity. The P-N junction is the heart of the semiconductor rectifier and it is the temperature rise of this junction that governs the successful application of the rectifier cell. Long life and high reliability will be experienced if the junction temperature is limited to a safe value under continuous duty conditions. In addition, a satisfactory margin of safety must be maintained to enable the rectifier cell to withstand voltage and current transients that may occur during operation of the equipment.

Figure 1 shows the cross section of a typical silicon rectifier. The main elements of the device are the P and N type silicon which forms the active junction at their interface, suitable backup plates for matching the coefficient of expansion of the silicon, and the top and bottom electrodes that act both as electrical connections and a path for removing heat from the junction.



RECTIFIER CROSS SECTION

FIG I

Heat is generated in the junction during operation of the cell due to two major losses:

1. The voltage drop across the cell due to the forward current flowing through it, and
2. the reverse current through the cell during the time it is not conducting and is subjected to its inverse voltage. I^2R losses of other portions of the cell do not become significant except under extreme overload conditions, when the cell may be conducting high foward currents.

It can now readily be seen that the major cause for cell failure is overheating of the junction. When this occurs the semiconductor material loses its rectifying properties and becomes a short circuit. It is indeed fortunate that the cell fails in this manner as it improves the reliability of series connected rectifiers because the failure of an individual cell will not result in an interruption of operation.

When one sets out to design a high voltage power supply, using semiconductor rectifiers, the prime objective is to select the proper rectifier that will result in an efficient, reliable and economical equipment. However, before an intelligent selection can be made the operational characteristics demanded of the power supply must be known and carefully analyzed.

1. What will be the maximum load voltage and current?
2. What rectifier configuration is desired?
3. Will the unit be subjected to continuous or intermittent service?
4. Will the rectifier load be steady, as in the CW transmitter or will it vary as in the case of an amplitude modulated transmitter?
5. What magnitude of voltage and current transients can be tolerated during operation?

6. What is the maximum short circuit current the supply transformer can deliver?

7. What environmental conditions will be encountered?

8. What will be the operating ambient temperature?

9. What method of cooling will be employed?

All of these questions must be answered before the proper rectifier cell can be selected.

The first step in selecting a rectifier for a high voltage power supply is to determine the forward current that will flow through the cell during normal operation. This is easily calculated from the full load current demanded of the supply and the desired rectifier configuration. From this information it can be determined whether a low, medium, or high current cell is required. However, the final cell type can not be selected until the method of cooling and its effects on the cells current handling ability have been determined. Obviously, a much huskier cell will be required if it is to be cooled by free convection rather than by forced air cooling in conjunction with a large fin. The current handling ability of the rectifier cell is easily obtained from the cooling data curves published by the rectifier manufacturer.

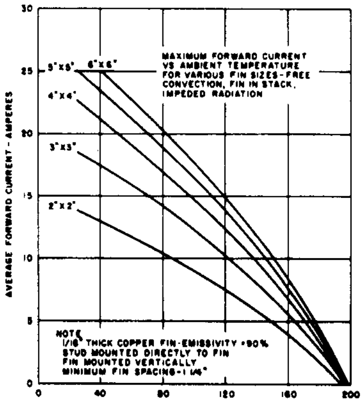
Figure 2 is an example of cooling data curves for a typical silicon rectifier and relates fin size and ambient temperature to the maximum allowable average forward current in amperes. This set of curves is plotted for the single phase rectifier configuration. When the rectifier configuration is other than this the following multiplying factors must be applied to the average forward current: DC, 0.80; three phase, 1.15; and six phase, 1.4. The curves are used in the following manner:

1. Enter the graph at the horizontal axis at the expected ambient temperature.

2. Intercept the desired fin curve.

3. Read on the vertical axis the maximum allowable average forward current. Apply proper multiplying factor.

All manufacturers publish similar curves for their rectifiers. Unfortunately, however, an exact set of standards has not been established and when considering the rectifiers of several manufacturers for a particular job it is important to compare the data very carefully. Make particular note of the ambient and junction temperature at which the data curves have been prepared. It is a good idea to plot some curves of your own, comparing the parameters of interest on one graph.



REQUIRED FIN SIZE—
FREE CONVECTION, IMPEDED RADIATION

FIG 2

In some instances, such as extremely high voltage applications, it may be desirable to employ liquid cooling of the rectifiers. This could take the form of immersing the entire rectifier assembly in a tank of oil, either by itself or in conjunction with the supply transformer. It is felt that this application will become prevalent in the future. If this method of cooling is selected the rectifier manufacturer must be consulted for his recommendation and current rating under these conditions.

When selecting a cell on the basis of its current handling abilities its surge current rating should be carefully analyzed. This parameter is one of the most important parameters of the cell that must be considered. This will be discussed in more cell detail when considering overcurrent protection requirements.

Once the current rating of the cell has been established, it remains to select the proper inverse voltage rating. It is of course assumed that the output voltage of the power supply is such that it will require connecting a number of cells in series to obtain the desired inverse voltage capability. The operating inverse voltage occurring across one rectifier leg is calculated for the no load condition taking into account the power supply regulation, commutation drop and peaking factor of the transformer. Through the use of thyrites and resistors, transient voltages occurring in the circuit can be limited to less than 150% of the D.C. voltage.

Thus, the calculated no load peak inverse voltage should be increased by a factor of 1.5 to determine the inverse voltage that each rectifier will have to withstand during operation. The use of this voltage to determine the number of rectifier cells results in the minimum safety factor. The exact safety factor chosen should be between 1.5 to 2 and will balance the rate of occurrence and magnitude of the transient voltages against the economics of initial cost.

The number of cells required per rectifier leg is now determined by dividing the total PIV (steady state plus transient safety margin) by the PIV rating of the cell selected. If, as in the case of General Electric rectifiers, a transient PIV rating is given, this value may be used to determine the number of cells required. However, if a transient rating is not given do not make allowances for one.

It is in the selection of the proper voltage rating for the cell that economics must be carefully considered. In many cases it is more economical to use a smaller number of high PIV cells rather than a large number of lower PIV cells. This comes about because the rectifier manufacturers are continually improving their manufacturing techniques resulting in much higher yields of high PIV cells. As a direct result, the cost of a rectifier using high PIV cells is lower than that of one using lower PIV cells.

After a rectifier cell has been selected and the PIV rating is known the problem remains to determine that the inverse voltage will be distributed across the cells in such a way that each cell will carry its share of the total PIV. The conditions of PIV sharing can be broken down into two cases: (1) normal PIV due to the rectifier configuration, and, (2) transient voltage conditions.

Rectifiers can be classified into two groups according to their reverse voltage characteristics. These are the sharp breakdown types and the soft breakdown types. Low and some medium current silicon rectifiers fall into the sharp breakdown group, while germanium and large area silicon rectifiers generally exhibit soft breakdown characteristics.

Figure 3 shows the reverse voltage-current characteristics of two sharp breakdown rectifiers. It should be noted that at a voltage greater than the rated PIV, the reverse current increases very rapidly for a slight increase in inverse voltage. If the reverse current in the breakdown region is not limited, intensive local heating will destroy the cell.

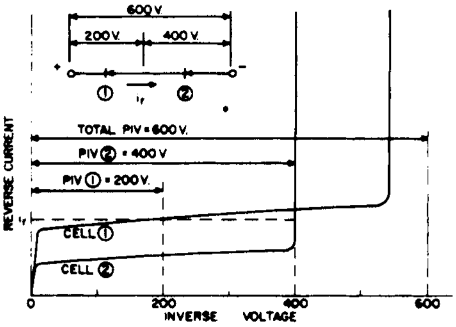


Fig. 3 Voltage sharing between series cells with sharp breakdown. (Small area silicon).

On the other hand if the reverse current in the breakdown is limited by other series cells the cell can carry its full share of the inverse voltage indefinitely with no bad effects, even though the cell is operated at greater than rated PIV. As long as the total reverse voltage across all the series cells does not exceed the sum of their respective breakdown voltages, reliable operation can result even though the reverse characteristics are completely mismatched. For this reason, series matching is usually not required for rectifiers with "sharp breakdown" characteristics.

Figure 4 shows the reverse characteristics of two unmatched cells with soft breakdown characteristics. The reverse current must be the same through both cells if no alternative parallel paths exist. Therefore, it will stabilize at a value, such that the sum of the voltage indicated by the intersection of i_r with the characteristics curves is the total impressed on the circuit. For example,

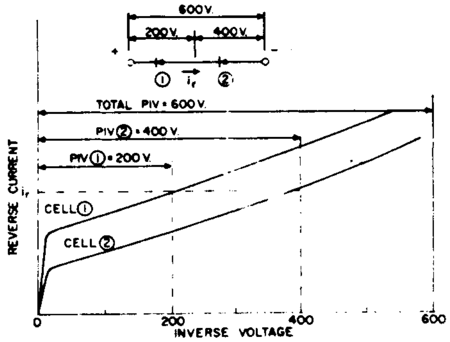


Fig. 4 Voltage sharing between unmatched series cells. (Germanium or large area silicon).

i_r intersects with the characteristic of cell 1 at 200 volts and of cell 2 at 400 volts for a total of 600. This shows the significant difference in reverse voltage sharing for series calls with dissimilar reverse characteristics.

This difference is further aggravated by the exponential increase of the reverse current characteristic with increasing junction temperature. A difference in junction temperature of only a few degrees causes a grossly unequal distribution of voltage between cells though the characteristics are identical at the same temperatures. Differences in junction temperature of several degrees must be expected in practical operation due to variations in forward voltage drop, internal thermal impedance, reverse heating and external heat dissipation.

If, for some reason, the reverse blocking characteristic of cell 2 should start to deteriorate, the characteristics of cell 2 would gradually shift upward with a simultaneous increase in slope. As the characteristics of cell 2 rises, i_r increases slightly, redistributing the voltage carried by each cell, so that cell 2 develops less voltage than initially and cell 1 develops more. Together the cells continue to share the entire 600 V supply.

Thus, a self-correcting action takes place. The cells with the lowest reverse current and the most stable reverse characteristics tend to assume a proportionally larger share of the reverse voltage than the less stable cells with the higher reverse current, imposed by the stable cells. Thus, thermal runaway and failure cannot occur unless all the cells in series in one string run away together. The chances are reduced drastically as the number of series cells increased. Overall circuit reliability is greatly improved by using cells in series.

It can be seen that it is not necessary to force each cell to take an equal share of the inverse voltage. But, rather it is better to let the cells divide up the voltage between themselves according to their abilities. The exception to this is in the case where a very small number of cells, especially of the soft breakdown type, are connected in series. Here it may be advantageous to use resistors to force the division of the inverse voltage. Also, in this case it may be necessary to match the inverse characteristics of the individual cells.

Figure 5 shows a very simple circuit that may be used to observe the reverse characteristic of a semiconductor rectifier on an oscilloscope. The voltage appearing across R_1 is applied to the horizontal deflection plates and the voltage across R_2 is applied to the vertical deflection plates. This will yield a plot of the reverse characteristics with the vertical axis proportional to the reverse current and the horizontal axis proportional to the inverse voltage. The high vacuum diode, V_1, should be a low leakage type for best results.

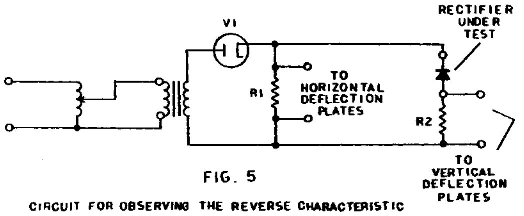


FIG. 5

CIRCUIT FOR OBSERVING THE REVERSE CHARACTERISTIC OF A SEMI-CONDUCTOR RECTIFIER

A more serious problem that must be overcome in the design of a high voltage power supply is the distribution of transient inverse voltages across individual series cells. When a steep voltage wavefront is impressed across a long string of series connected rectifiers the voltage is distributed unequally across the cells, even if they are perfectly matched according to their inverse characteristics. The distribution of the inverse voltage is determined by the stray capacitance of the cells in much the same manner as the voltage distribution occurs across a string of insulators in high voltage AC power lines. That is, the cell farthest from ground will have the highest voltage across it. The solution to the problem is the same in both cases, that is, the stray capacitance is swamped out by the addition of shunt capacity many times larger than the stray capacitance.

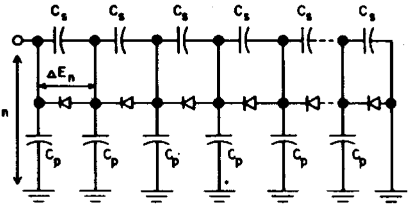
The extent of the inequality of division of the inverse voltage will depend on the number of series cells and the relative magnitude of the cell capacitance and the capacitance from cell to ground as shown in Figure 6. Assuming the rectifier cells have a very high back resistance, and the capacitance of the individual cells and capacitance between cells and ground are uniform throughout the string. Dr. R. DeBuda of Canadian General Electric, has shown that the peak voltage across the cell nearest the line, E_n, can be expressed by the equation in Figure 6 where:

E_n is the peak voltage across the entire rectifier leg.

N is the number of rectifiers in series per leg.

C_p is the capcitance between single cells and ground.

C_s is the series capacitance of a single rectifier.



$$\Delta E_n = E_n \sqrt{\frac{C_p}{C_s}} \quad \mathrm{Coth}\ N\sqrt{\frac{C_p}{C_s}}$$

STEP FUNCTION INPUT VOLTAGE
N = NUMBER OF RECTIFIERS

FIGURE 6

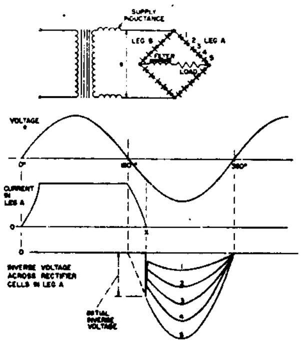
As an example, if C_s is approximately 15 uuf and C_p is in the order of 1 uuf, then if a 50,000 volt transient is impressed across 300 cells in series, the solution of the equation indicates that 12,900 volts will appear across the rectifier cell farthest from ground. This means that 25 per cent of the transient voltage appears across the first cell. Semiconductor cells available today would be destroyed by voltages of this magnitude. Proper solution of the equation will yield a value of capacitance that can be paralleled with C_s which will force the inverse voltage across the individual cells to be within their rating.

The well known causes of the transient voltages in rectifier circuits are switching the primary circuit of the supply transformer, d-c switching of the load and the operation of overcurrent protective devices. Under adverse conditions these transients can be as large as 8-10 times normal voltage. Although most rectifiers can withstand some overvoltage for a short time, they cannot withstand transient voltages of such magnitude. Under these conditions the cell will fail because of internal arcing or dielectric breakdown of the junction material. In most cases it is more economical to include circuit elements that will reduce these transients rather than increasing the rectifier PIV capability.

The maximum transient voltage occurring in the circuit can be reduced to 150 per cent of normal or less by shunting filter reactors with a resistor or thyrite resistor, using the filter capacitor to filter high frequency transients and by connecting thyrite resistors across the transformer secondary windings for the d-c bus.

The rectifier itself is also the source of a voltage transient. This transient can take on serious proportions when it occurs in a rectifier circuit employing long series strings of semiconductor rectifiers. The cause of this transient is the phenomenon called "hole storage" or "cell recovery." After a semiconductor cell conducts forward current, a brief interval (microseconds) is needed to sweep out current carriers from the base region of the semiconductor before the cell can block reverse voltage. Until the cell recovers, it behaves like a short circuit in the reverse direction. Rectifiers of given design vary somewhat in the length of time needed for recovery.

Referring to the simple bridge of Figure 7, assume cell 1 in leg A has a fast recovery and cells 2, 3 and 4 and 5 have slow, but identical recovery time. The flat top of the forward current waveshapes is due to the filter-inductance in the load. The load current flows in leg A beyond the point of supply voltage reversal due to inductance in the AC source.



DISTRIBUTION OF INITIAL INVERSE VOLTAGE ACROSS SERIES CONNECTED RECTIFIERS
FIG 7

At a rate determined by the source inductance, the load current commutates to leg B until, at some point X, the current through leg A reaches zero.

At this instant, the supply voltage has reached a large inverse value. The cell with the fastest recovery time (cell 1) absorbs this entire voltage until the other cells in turn have recovered. This may require only a few microseconds. After all cells recover, the cells in the string share the inverse voltage.

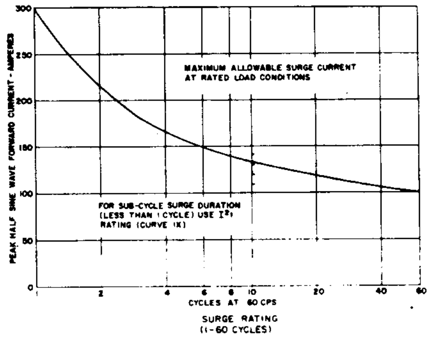
While the angle of overlap is usually quite small, when many rectifiers are in series the initial inverse voltage across a fast recovery cell can be many times the voltage across that cell at the peak of the supply voltage. This voltage spike should be kept within the continuous PIV rating of the cell.

Where the initial inverse voltage exceeds the PIV rating of a single cell, capacitors across individual cells will eliminate the voltage spike. The capacitor size depends on the difference in recovery time between cells. In any event, it need not exceed $C = 10\ I_f/E$ where C is the capacitance to distribute the recovery transient within cell PIV rating (ufd), I_f is the current in amperes flowing immediately preceeding commutation, and E the maximum continuous PIV rating of the cell.

Practice has shown that in most cases on 0.01 ufd capacitor connected across each cell will effectively divide transient inverse voltages and suppress the "cell recovery" transient. It is also possible to use a smaller value of capacity connected across a small number of cells. However, in all cases the voltage rating of the capacitor must be greater than the expected transient voltage that may appear across it.

Unequal distribution of the inverse voltage can also occur because of unequal inverse currents due to corona effects. Corona can be a serious problem when rectifiers are mounted in air, even at voltages on the order of 10 to 20 KV. Where corona appears, the air is electrically broken down and ionized so that it becomes a conductor of current. Corona forms at points of high voltage gradient, such as sharp corners, screw heads, and edges of rectifier fins.. Thus all available means of counteracting the effects of corona must be taken.

Last but not least, the rectifiers must be provided overcurrent protection. As stated previously, the surge current rating of a rectifier is perhaps its most important parameter. Figure 8 indicates the surge current that a typical silicon rectifier can pass without damage. It will be noted that the current is plotted as a function of time using 60 cycles per second as units. As more cycles of current are allowed to flow through the cell, the maximum value of current must be reduced. Obviously then, in order to prevent the rectifiers from being destroyed due to current transients, the protection devices must be coordinated so that at no time does the peak current through the rectifier exceed that shown by Figure 8.



SURGE CURRENT RATING OF A TYPICAL MEDIUM CURRENT SILICON RECTIFIER

FIG 8

For surge currents of less than 1 cycle duration the rectifier is given an I^2 t rating. If surge currents are present during this interval that will exceed I^2 t rating the rectifier will be destroyed due to heating effects. The I^2 t rating is specified by the rectifier manufacturer. This rating is a function of the cell design, initial junction temperature and whether or not inverse voltage is impressed on the cell following the current surge. If the I^2 t rating is not given it can be approximated by converting the one cycle (actually one-half cycle) surge current to RMS amperes and multiplying by the time of one-half cycle (0.0083 second).

In the event that initial cost is no object, the obvious solution is to select the cell so that it has a surge current characteristic such that it will not be exceeded by the maximum surge current that can be developed in the circuit. In the majority of cases this solution is not economically feasible.

Conventional protective devices like fuses, circuit breakers and overload relays are adequate for protection beyond a few cycles, provided they are coordinated with the surge current curve and the continuous rating of the cell.

However, the worst case occurs when a low resistance short circuit fault exists in the equipment. Under such conditions the fault current will undoubtedly exceed the surge current rating of the rectifier during the few cycles required for the conventional protective devices to operate. Current limiting fuses that will interrupt the fault current before it reaches its first peak can be used under these circumstances. The current limiting fuses available (General Electric CLF or Chase-Shawmut Amp-Trap) are usually relatively low voltage types.

This mandates fusing in the primary circuit providing the transformer inrush current is not of sufficient magnitude to flow the fuse when the supply is first energized.

A more practical approach to the problem is to introduce current limiting impedances into the rectifier circuit. These can take the form of increased transformer leakage reactance, resistors or current limiting reactors. The use of such elements must be closely coordinated with the surge current rating of the rectifiers and the regulation requirements of the power supply.

Fast acting fault protection systems have been developed using vacuum switches in both the primary and the secondary of the power supply transformer. There are also available fast acting circuit breakers such as the General Electric AK series. These devices are tripped by sensitive relays and can interrupt faults within 1/2 to two cycles. However, their application will also entail the use of one or more of the current limiting methods described above.

When a prototype power supply is first tested, it is a good idea to start at approximately 25% normal voltage. This will help eliminate any catastrophic failure from unexpected transients. High speed oscilloscopes, peak reading voltmeters, and calibrated spark gaps are excellent devices for detecting and measuring transients. Metering of the inverse current flowing in each rectifier leg is a good means of monitoring the operating condition of the supply. Tests have shown that as the operating temperature of the rectifier increases, the inverse current will increase. Also, a drastic increase of current will indicate deterioration of a number of cells in the rectifier leg. Figure 9 shows a circuit that may be used to continuously monitor the inverse current during operation of the rectifier. When the rectifier leg is not conducting in the forward direction CR2 will offer a low impedance circuit to the stack inverse current and it will flow through the milliameter M-1.

The task of designing a semiconductor rectifier power supply is not difficult, but it must not be passed over lightly. Each application must be carefully considered by itself. When this is done, the result will be a power supply that will be efficient, reliable and economical to operate.

References:

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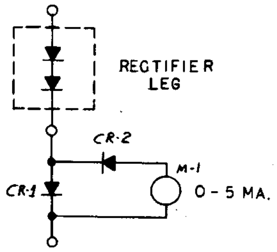

FIG. 9

CIRCUIT FOR MEASURING THE INVERSE CURRENT OF A RECTIFIER STACK