Characteristics and Applications of Selenium-Rectifier Cells

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Synopsis: The rectification properties of selenium cells were first discovered in the year 1883. C. T. Fritts described them in the *American Journal of Science.*[11,12] However, they were never used to any extent, except possibly as photocells.

After the introduction of the copper-oxide rectifier, research activities were stimulated, and selenium cells were again rediscovered. The first commercial cells were made in Germany in the early '30's, and, as the technique of manufacture improved, better cells were made with better life expectancy.

The General Electric Company, after a period of developmental activity, started to make cells in 1938, first in its research laboratories, and subsequently a manufacturing plant was set up which permits producing cells in large quantities within relatively close electrical tolerances.

This paper contains data pertaining to these cells particularly, and the information may not apply in detail to cells manufactured by other methods without some correction factors.

CONSTRUCTION

THE selenium rectifier cell consists essentially of a carrier plate made of either aluminum or iron, supporting on one side a very thin film of specially treated selenium. The adhesion is quite intimate to prevent contact losses. This selenium film is given a series of controlled heat treatments to obtain a suitable crystalline structure.

Finally, a low melting point alloy is metal-sprayed onto the selenium surface. This layer is known as the "counterelectrode."

By means of subsequent electrochemical processes a film or blocking layer is formed between the counterelectrode and the selenium surface. Current flows freely between the selenium and the counterelectrode and is practically blocked in the other direction. Figure 1 shows a typical cross section of a cell.

THEORY

Several theories have been suggested to explain the action of rectifiers of the type under discussion. The physicists do not all agree, and, therefore, no attempt will be made to discuss all these theories in detail.

One of the theories that appears the most logical to understand and that applies to all types of metal rectifiers is the following:

Metal rectifiers consist essentially of a semiconductor and a good conductor separated by a barrier or blocking layer which is, in itself, an insulator but through which electrons can pass in either direction. In the selenium rectifier the selenium layer is the semiconductor and the sprayed-metal counterelectrode the good conductor, the barrier or blocking layer being formed between these two substances. The sprayed-metal layer has an abundance of free electrons, while in the selenium layer, which is a relatively poor conductor, the free electrons are quite small.

When the two electrodes are connected to a source of supply, the opposite polarities set up an electric field across the barrier or blocking layer. Since this layer is very thin, a comparatively small electromotive force will produce a steep potential gradient. If the sprayed metal

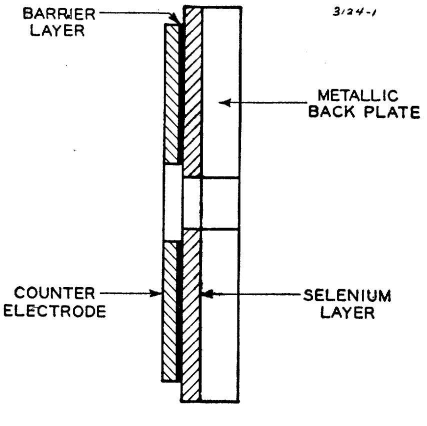

Figure 1. Cross section of a selenium cell

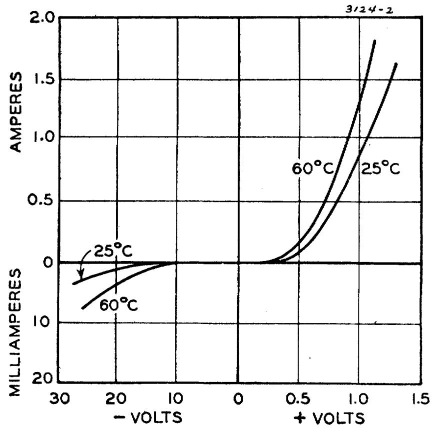

Figure 2. D-c characteristics

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Appendix IV. Nomenclature

A—Area of the stator bore in square inches.
g—Single air gap in inches.
g'—Single air gap with he rotor displaced $(g-\Delta)$ in inches.
Δ—Amount the rotor is displaced from the center of the stator in inches.
K_c—Carter's coefficient for an air gap g.
K_c'—Carter's coefficient for an air gap g'.
B_g—Air-gap flux density at normal voltage in kilolines per square inch.
B—Air-gap flux density at any voltage.
b—Rise in the gap flux density.
e—Voltage in per unit corresponding to air-gap flux.
E—Per unit voltage at which maximum pull occurs.
I_g—Magnetizing current for the air gap at normal voltage.
I_s—Magnetizing current for saturation at normal voltage.
i_m—Magnetizing current at any voltage.
X_1—Stator leakage reactance in per unit.
X_m—Magnetizing reactance in per unit.
C_1—Form factor of the no-load field form of a synchronous motor.
m—Saturation curve exponent defined by $i_s=e^mI_s$.
K_S—Factor allowing for the effect of saturation on density rise.
K_R—Factor allowing for the effect of saturation and primary reactance on density rise.
a—Factor depending on the number of parallels.

References

1. MAGNETIC PULL IN ELECTRIC MACHINES, E. Rosenberg. AIEE TRANSACTIONS, volume 37, 1918, pages 1425–69.

2. CRITICAL REVIEW OF THE BIBLIOGRAPHY ON UNBALANCED MAGNETIC PULL IN DYNAMO-ELECTRIC MACHINES, Alexander Gray, J. G. Pertsch, Jr. AIEE TRANSACTIONS, volume 37, 1918, pages 1417–24.

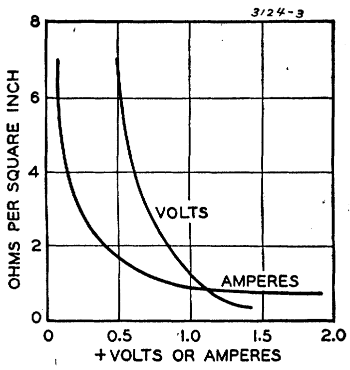


Figure 3. Resistance change with voltage or current

is connected to the negative pole of the source, the free negative electrons are accelerated to a sufficient velocity to enable them to pass through the barrier layer and the intercrystalline spaces of the selenium and reach the metal supporting disk, with the result that a flow of electrons is established which constitutes a current of electricity in the forward direction. When the polarity is reversed, the same action takes place in the opposite direction, but, since the number of free electrons in the semiconducting selenium is less than in the metal disk, the resulting current is much smaller. Because of this asymmetrical property, it is possible to rectify alternating current.

Electrical Characteristics of the Elements

Because it is almost impossible to make all cells exactly alike as to characteristics, even though materials and manufacturing methods are held within very close limits, the data that follow and also all published curves should be considered as representing average conditions. A slight deviation should be expected between individual cells.

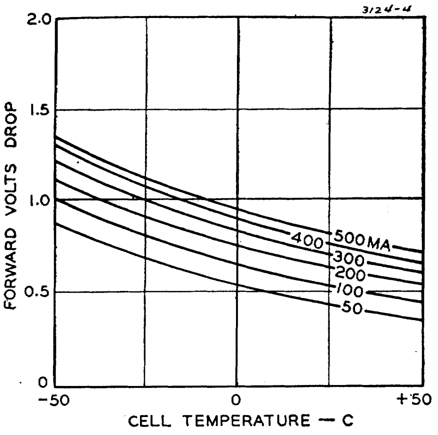


Figure 4. Temperature–forward voltage characteristics

One square inch area

D-C Characteristics

If a d-c voltage of varying potential is impressed first in the blocking direction and then in the flow direction and readings taken of the current that flows, a curve as shown in Figure 2 is obtained. This curve is based on selenium cells having one square inch of effective rectifying area.

In a similar way Figure 3 shows resistance versus voltage and resistance versus current. It should be noted and remembered that these curves are nonlinear and that they do not obey Ohm's law.

Effect of Temperature

The selenium rectifier cells have negative temperature coefficient which results in current increasing for a given voltage as the temperature goes up and decreasing as the temperature goes down.

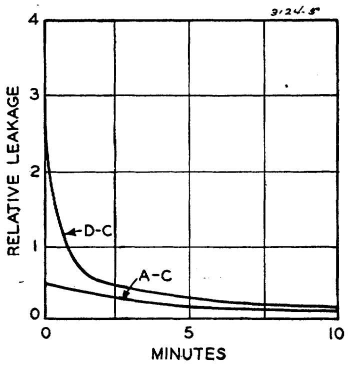


Figure 5. Leakage–time characteristics

Figure 4 shows this relation.

It should be noted that temperature also affects the leakage current in the blocking direction as shown on Figure 2.

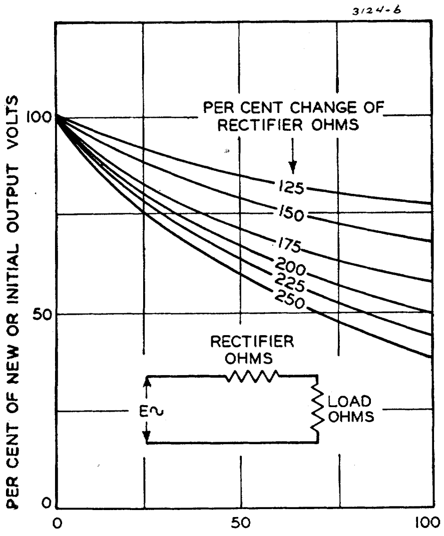


Figure 6. Effect of changing rectifier resistance on output

Because of this characteristic, ratings should be such that the losses caused by heating should be kept under control; otherwise they may keep on adding, resulting in overheating and the eventual destruction of the rectifying film. In general, it may be stated that the rectifier will operate satisfactorily in a range of ambient temperature from −50 to +50 degrees centigrade.

Forward Characteristics and Stability

The forward characteristic is very stable when a-c or d-c voltage is applied in this direction. However, as the cell heats up, changes occur. Over a period of time, the resistance of the cell appears to change and take a set. The rate of change increases with cell temperature, and at 100 degrees centigrade the cell is damaged.

An increase in forward resistance with time means that the difference between the input voltage and the output voltage will become greater. Therefore, to maintain a given output voltage constant, it is necessary to increase the input voltage. Great care must be taken to rate correctly these rectifier cells when new to prevent overloading in voltage after aging takes place.

Reverse Characteristics and Stability

The reverse or leakage characteristic on alternating current is quite good; it is, in general, higher initially but creeps to a minimum value in about two to three minutes. However, when a selenium rectifier cell is subjected to a d-c voltage in the inverse direction, the leakage current is very high initially. A polarizing action similar to that observed with electrolytic capacitors takes place, resulting in a steady decrease in current with time. Typical leakage voltage–time character-

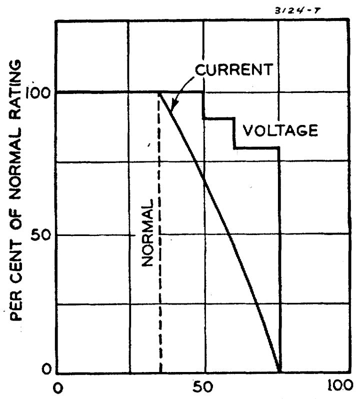


Figure 7. Rating of cells at high ambients

istics are shown on Figure 5. When the cells are continuously de-energized over a period of time, the reverse leakage resistance tends to decrease but will rapidly increase after the cells are again energized. It should again be noted that this same type of characteristic is also present in electrolytic capacitors. This characteristic should be borne in mind when applying these cells in blocking circuits, especially if instantaneous operation is required such as in certain types of high-speed relaying circuits.

CAPACITANCE

A certain capacitance exists because of the presence of the barrier or blocking layer between the two electrodes of the rectifier cell. Measurements indicate this to be of the order of 0.02 microfarad per square centimeter. This may vary somewhat, depending on the past history of the cell.

In high-frequency applications, the capacitance acts like a shunt acrosss each cell, resulting in lowering the leakage resistance and changing the ratio of the forward to the reverse resistance. At normal a-c frequencies up to 2,000 cycles, the capacity effect usually can be disregarded.

Rectifier Circuits

Selenium rectifier cells are readily combined into series and parallel groups, depending on the voltage and current output required. These are used in rectifier circuits to change alternating currents to direct currents. The choice of the particular rectifier circuit rests with the designer. In view of the fact that rectifiers are used by many engineers who are not familiar with these circuits, a tabulation of the more popular circuits is included with this paper. (See Figure 19.)

It should be noted that these data apply to perfect sine waves, perfect rectifiers having no internal resistance and also no leakage whatsoever in the blocking direction. The load is based on a noninductive resistance.

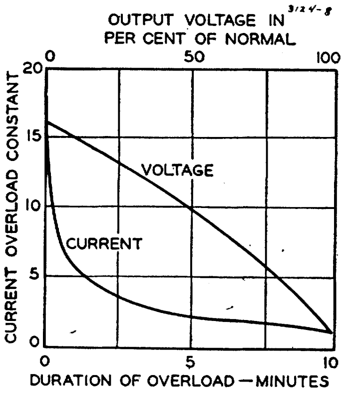


Figure 8. Overload rating of selenium cells

Calculations made with the aforementioned data are only of theoretical use and cannot be applied to actual design work without using correction factors.

Selenium rectifier cells have a fundamental resistance characteristic; this resistance is not constant and varies with current, temperature, and also time. Therefore, computations arrived at from formulas are not absolute, unless all these variables are considered. Design work should be based on empirical data based on years of experience to avoid trouble. Any correction factors must also have their own correction factors, since these will vary with time, temperature, and current.

In designing a practical selenium rectifier circuit, it is evidently very essential to pay particular attention to the fact that the rectifier resistance is not constant and changes with time, current, and temperature.

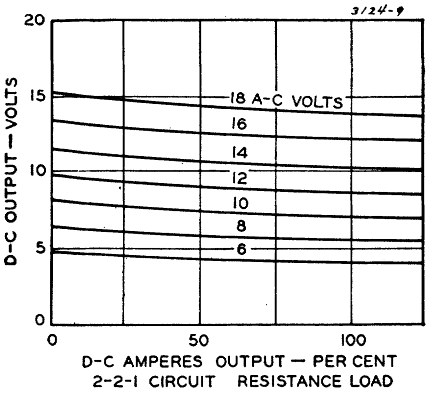


Figure 9. A-c to d-c characteristics of single-phase unit bridge rectifier with resistance load

One square inch area, 25 degrees centigrade

To minimize its effect on the rectifier circuit, it is quite essential to make the rectifier resistance small as compared to the total circuit resistance.[4] This is shown graphically in Figure 6.

The recommended ratings have been so chosen as to make the rectifier resistance about 10 to 15 per cent of the circuit resistance.

By referring to Figure 6, it can be noted that even though the rectifier resistance may double, the effect on the circuit is small.

However, when rectifiers are overloaded, the rectifier resistance in effect becomes a larger percentage of the circuit resistance, and, therefore, more changes should be expected in the output as readily shown in Figure 6.

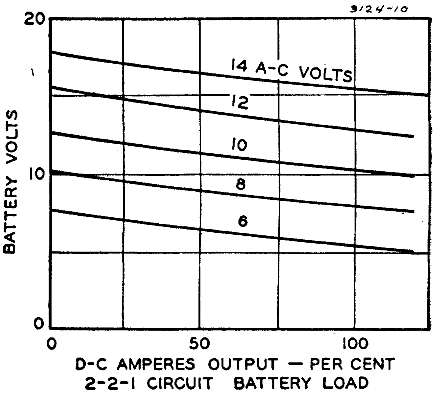


Figure 10. A-c to d-c characteristics of single-phase unit bridge rectifier with battery load

One square inch area, 25 degrees centigrade

MAXIMUM RATINGS

Table I and II show the voltage and current ratings for the various size cells which are available at the present time.

The circuit names as used by the metallic rectifier industry have been retained in Tables I and II.

The circuit symbolic notation is an attempt to overcome the objections raised to the circuit names by replacing them by a symbolic equation 3.

The first digit is the reciprocal of the fraction of time a cell carries current during the cycle. The second digit shows the cells in series and the third digit the cells in multiple carrying current instantaneously. This notation applies to unit rectifiers.

These ratings are based on the usual limiting factors of temperature rise, aging, and voltage breakdown. The in-

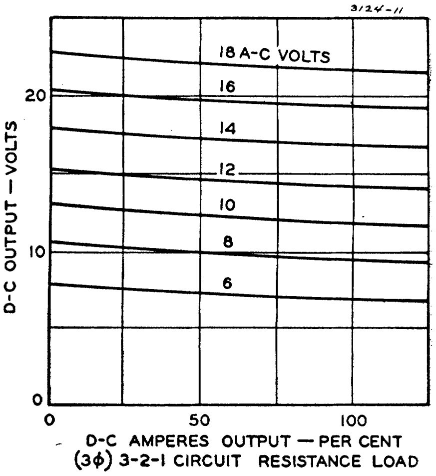


Figure 11. A-c to d-c characteristics of three-phase rectifier, bridge type, with resistance load

One square inch area, 25 degrees centigrade

Table I. Rating as Valves at 35 Degrees Centigrade

Code letter	*F*	*A*	*C*	*H*
Diameter of cells	1 Inch	$1^1/_2$	$2^3/_{16}$	$4^3/_8$
Inverse rms volts	18	18	18	18
Blocking volts d-c	15	15	15	15

ternal losses heat the rectifier cell, and the final permissible total temperature limits the output rating. It should be borne in mind that aging increases the heating, and, therefore, it is very important to run the rectifier cells somewhat cooler when new. This factor has been taken into consideration in the published ratings. The relation of cell spacing to cell diameter in a rectifier-stack assembly has been chosen for optimum cooling.

PERMISSIBLE TEMPERATURE RISE

Although selenium rectifier cells may be operated up to a total temperature of 75 degrees centigrade, the ratings given in the previous paragraph are based on an ambient temperature of 35 degrees centigrade allowing a maximum temperature rise of 40 degrees centigrade. However, if the normal temperature is liable to be exceeded, the full-load ratings must be changed and reduced to prevent the total temperature from exceeding 75 degrees centigrade.

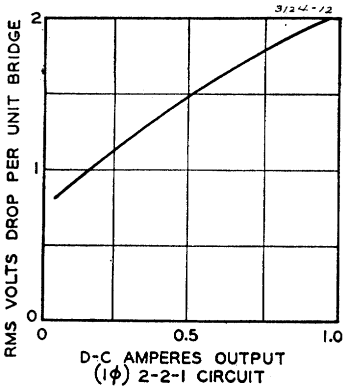


Figure 12. Rms volts drop in a unit bridge single-phase rectifier at different values of current

One square inch area, 25 degrees centigrade

Figure 7 shows the recommended practice.

OVERLOAD AND INTERMITTENT RATING

Selenium rectifier cells will withstand short-time current overloads beyond the normal current, provided the cell is not heated above 75 degrees centigrade. If the cell is allowed to cool back to normal between loading periods, higher current overloads can be applied than in the case of insufficient cooling periods.

Figure 8 shows permissible current overload data and also how the voltage drops as the current increases.

Voltage overloads are not permissible, even for short periods, because of the danger of breaking down the blocking layer.

If the breakdown current is limited, the punctured cells sometimes self-heal. However, every healed spot robs the rectifying surface of some cross section, resulting in increasing effective resistance of the cell.

UNIT RECTIFIER

For convenience in designing rectifiers, data have been prepared on a unit rectifier. This can be defined as any rectifier circuit having one cell in each arm. By reducing all measurements to a unit rectifier, it is possible to obtain general data that will apply to any rectifier, providing the number of cells in series in each arm is known. These same data can also be applied where two or more unit rectifiers are operated in multiple.

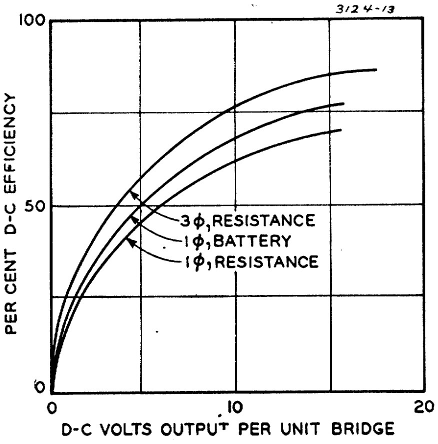


Figure 13. Efficiency of selenium cells at full-load current

Full-load amperes, 25 degrees centigrade

A-C–D-C CHARACTERISTICS OF A SINGLE-PHASE FULL-WAVE UNIT BRIDGE RECTIFIER WITH A RESISTANCE LOAD

By impressing various voltages across a unit bridge rectifier, a group of curves may be obtained as in Figure 9, showing d-c voltages plotted against d-c amperes output for various impressed a-c voltages.

A-C–D-C CHARACTERISTICS OF A SINGLE-PHASE FULL-WAVE UNIT BRIDGE RECTIFIER AS A BATTERY CHARGER

If the resistance load is replaced by a battery load, and data as shown previously are again repeated, a family of curves as shown in Figure 10 is obtained.

A-C–D-C CHARACTERISTICS OF A THREE-PHASE FULL-WAVE UNIT BRIDGE RECTIFIER

If a three-phase rectifier is operated at different a-c voltages and different loads, a family of curves as shown in Figure 11 is obtained.

A-C VOLTS DROP WITHIN A UNIT BRIDGE RECTIFIER

If a d-c ammeter is used as a load across a unit bridge rectifier and the a-c input is varied, a curve as shown in Figure 12 is obtained. This permits calculating the a-c input voltage provided correction factors are used, depending on the circuit and its form factor.

EFFICIENCY

Because of the presence of an a-c component in the d-c output of all rectifiers, it is quite essential to use the correct type

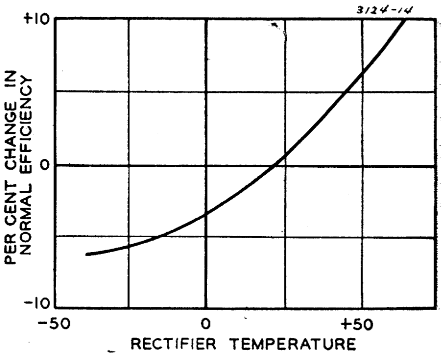


Figure 14. Correction curve to obtain efficiency at different temperatures

Table II. Current Ratings at 35 Degrees Centigrade for Resistance and Inductance Loads

Circuit	1 Inch	$1^1/_2$ Inches	$2^3/_{16}$ Inches	$4^3/_8$ Inches	D-C Volts	Circuit Symbolic Notation
One-phase half-wave	0.075	0.2	0.500	2.15	6	1-1-1
One-phase bridge	0.150	0.4	1.00	4.3	12	2-2-1
One-phase center tap	0.150	0.4	1.00	4.3	6	2-1-1
Three-phase half-wave	0.200	0.5	1.25	5.3	8	3-1-1
Three-phase bridge	0.220	0.600	1.4	6.5	16	3-2-1
Three-phase center tap with no interphase coil	0.270	0.7	1.8	8.0	8	6-1-1
Three-phase center tap and interphase coil	0.400	1.0	2.5	11.0	8	3-1-2
D-c valves	0.120	0.320	0.80	3.0	15	1-1-1

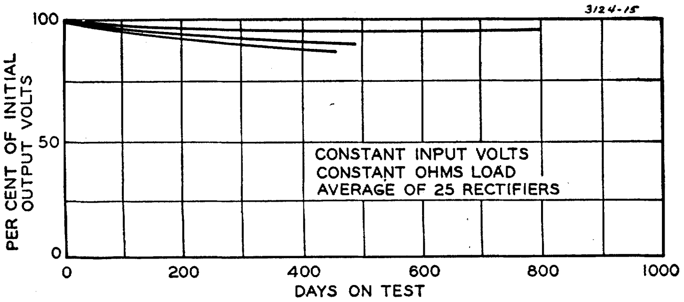


Figure 15. Aging of selenium rectifiers

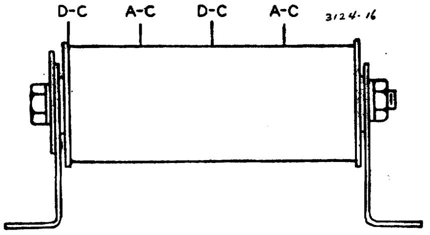


Figure 16 (right). Full-wave single-phase rectifier-stack assembly

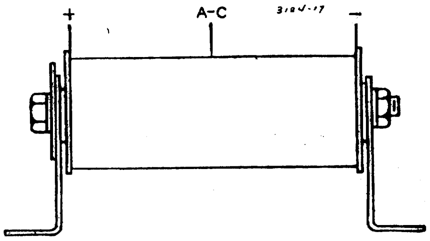


Figure 17 (right). Half-wave three-terminal-type rectifier-stack assembly

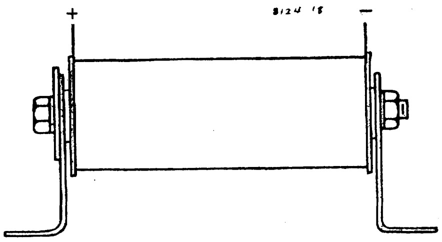


Figure 18 (right). Half-wave two-terminal-type rectifier-stack assembly

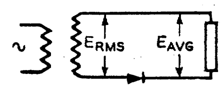
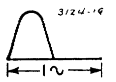
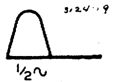
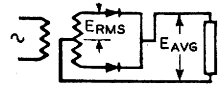
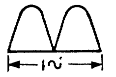
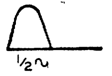
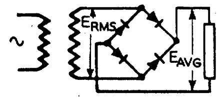
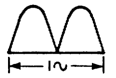
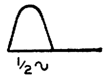
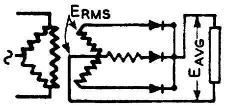
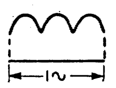
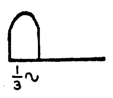
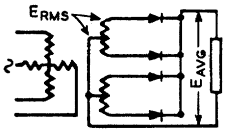
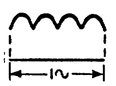
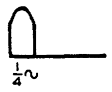
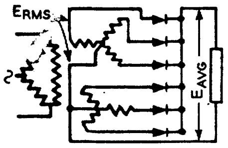
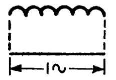
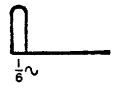
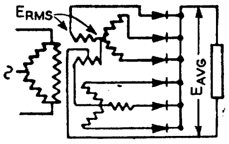
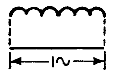
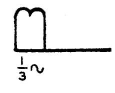
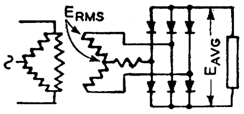
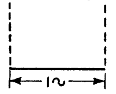
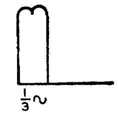
of instruments to measure the power output.

The input is always measured with an a-c wattmeter and reads all of the power delivered to the rectifier.

If the nature of the load is such that both the a-c and d-c components of the rectifier output produce useful work, then an a-c wattmeter in the output measures the correct output. Examples of this type of load are resistances, lamps, radio-tube filaments, electromagnets, series motors, and so forth.

However, if the a-c component is not utilized, then the output should be measured with a d-c voltmeter and d-c ammeter of the D'Arsonval type. For example, battery charging, plating work,

Figure 19 (below). Fundamental rectifier circuits

		Output Wave Values				D-C Ripple	Rectifier Cell-Wave Values					Trans. Capacity	
Symbolic Notation	Circuit	Wave Form	E_{avg}	E_{eff}	Form Fact.	%	Wave Form	I_{avg}	I_{eff}	Form Fact.	E Inverse	Pri.	Sec.
1-1-1			0.45 E_{rms}	0.707 E_{rms}	1.57	121		1.00 I_{dc}	1.57 I_{dc}	1.57	1.414 E_{rms}	3.49 EI_{dc}	3.49 EI_{dc}
2-1-1			0.900 E_{rms}	1.0 E_{rms}	1.11	48		0.500 I_{dc}	0.786 I_{dc}	1.57	2.828 E_{rms}	1.235 EI_{dc}	1.75 EI_{dc}
2-2-1			0.900 E_{rms}	1.0 E_{rms}	1.11	48		0.500 I_{dc}	0.786 I_{dc}	1.57	1.414 E_{rms}	1.235 EI_{dc}	1.235 EI_{dc}
3-1-1			1.17 E_{rms}	1.19 E_{rms}	1.02	21		0.333 I_{dc}	0.587 I_{dc}	1.76	2.45 E_{rms}	1.508 EI_{dc}	1.508 EI_{dc}
4-1-1			1.27 E_{rms}	1.28 E_{rms}	1.005	11		0.250 I_{dc}	0.502 I_{dc}	2.01	2.828 E_{rms}	1.116 EI_{dc}	1.58 EI_{dc}
6-1-1			1.350 E_{rms}	1.351 E_{rms}	1.001	4		0.167 I_{dc}	0.408 I_{dc}	2.45	2.828 E_{rms}	1.28 EI_{dc}	1.81 EI_{dc}
3-1-2			1.170 E_{rms}	1.170 E_{rms}	1.001	4		0.167 I_{dc}	0.293 I_{dc}	1.76	2.45 E_{rms}	1.068 EI_{dc}	1.51 EI_{dc}
3-2-1			2.340 E_{rms}	2.341 E_{rms}	1.001	4		0.333 I_{dc}	0.579 I_{dc}	1.74	2.45 E_{rms}	1.047 EI_{dc}	1.047 EI_{dc}

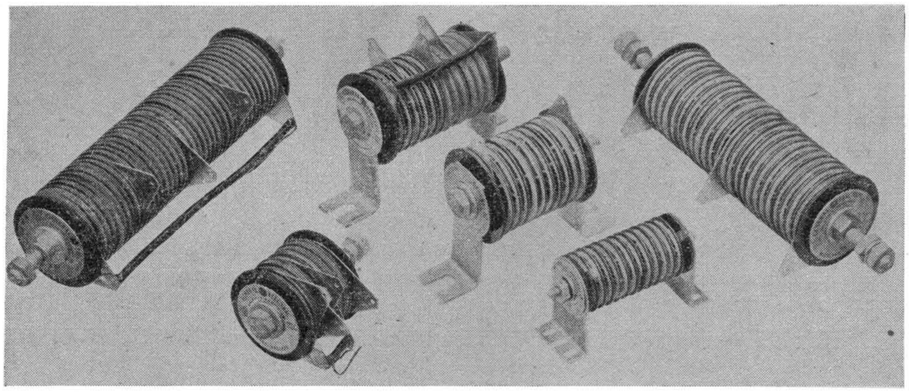


Figure 20. Typical selenium rectifiers for industrial applications

chemical work, electrolysis, shunt motors, and so forth. Therefore, the efficiency can be expressed as either

$$\text{RMS efficiency } \% = \frac{\text{a-c watts output}}{\text{a-c watts input}} \times 100$$

or

$$\text{D-c or average efficiency } \% = \frac{\text{d-c volts} \times \text{d-c amperes}}{\text{a-c watts input}} \times 100$$

In polyphase work, the rms efficiency approximately equals the average efficiency.

However, in single-phase work, there is a difference of approximately 15 points in efficiency between the average and rms values, the latter being the highest.

Typical efficiency curves are shown in Figure 13 at different voltages and at full-load current densities. Figure 14 shows correction factors at different temperatures.

LIFE TESTS

General Electric selenium rectifiers have undergone extensive tests and show promise of better aging characteristics than some of the European elements previously tested.[4] Typical life tests are shown in Figure 15. It should be noted that these tests represent aging as seen from the user's viewpoint.

Practical Rectifier Design

It is believed that a worked-out example will show how to use the data contained in this paper.

For example, assume that we want a 30-volt rectifier at one ampere working on a resistance load from a single-phase circuit. By reference to the tabulation on ratings, we find that the most voltage we can obtain from a unit bridge rectifier at full current density for each type cell is 12 volts. Dividing $30/12 = 2.5$, therefore, three is the minimum number of series cells to be selected.

The voltage to be supplied by each unit bridge rectifier will be $30/3 = 10$. By reference to Figure 9, we find that, at full-load current and ten volts, we need 13.2 volts alternating current per bridge, or $3 \times 13.2 = 39.6$ for the rectifier under discussion.

The size of the cell can be determined by reference to the tabulation on ratings. To carry one ampere a type *C* cell having $2^{3}/_{16}$-inch diameter is required. If the current rating required does not match that of the four available sizes, then it will be necessary either to operate at slightly less than full rating or to use several smaller cells in multiple.

From the aforementioned calculations, to obtain 30 d-c volts at 1.0 ampere direct current, a bridge rectifier using three cells in series would be required. The a-c input is 39.6 volts, and the transformer should have sufficient taps to take care of line voltage variations. To take care of aging, it is advisable to tap the transformer up to 3×18 rms volts or 54 volts. The approximate efficiency is 63 per cent at 25 degrees centigrade as seen from Figure 13 and will be higher at the operating temperature as shown on Figure 14.

Construction of Selenium-Rectifier Stacks

Selenium rectifier cells are assembled into either full-wave or half-wave stacks, depending on their voltage and current rating. Low-voltage stack can generally be assembled into single stack, using a construction as shown in Figure 16.

For higher voltages, two stacks are sometimes used, embodying a construction as shown in Figure 17.

For still higher voltages four units are used as shown in Figure 18.

The cells are spaced to permit free ventilation on both sides, light spring washers being used to collect current.

The stacks are clamped under light pressure and come either with or without mounting brackets as shown in Figure 20.

INSTALLATION OF RECTIFIER STACKS

Selenium rectifier stacks should be installed in well ventilated cabinets to permit free circulation of air.

They should be located preferably at the bottom of cabinets so that any heat from other heat dissipating apparatus does not have a cumulative effect.

If installed in closed cabinets, a certain amount of derating should be made to take care of the higher internal ambient temperatures as previously explained.

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