SELENIUM RECTIFIER FOR POWER SERVICE

By

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I INTRODUCTION

In Japan, until several years ago, the selenium rectifier was used to a limited extent only as d-c supply source for various small electrical equipment, battery charging or electric plating of small capacity. The reason it failed in its application on large capacity service was due to its poor efficiency, short life, lack of uniformity and low degree of reliablity.

In Germany, especially the Siemens Co., through research of its own, successfully developed methods for producing the selenium rectifier which is highly efficient, durable and uniform. Thus, expanded use of the selenium rectifier was resulted and its application was made possible as a d-c supply source for electrolysis on such high current as some 10,000 amperes, for service which requires small current but high voltage of some 10,000 volts and various other electrical apparatus of importance. With the objective to supply such selenium rectifiers for power service in Japan, our company, some years ago, introduced the Siemens' technique into our production and initiated manufacture of the selenium rectifiers. As a result, within a few years, Fuji Denki has become capable of supplying the selenium rectifiers for power service as d-c sources for electrolysis which requires currents as high as several 10,000 amperes, electric dust precipitators which operate at voltages as high as some 10,000 volts, factory d-c motors or electric railways.

The selenium rectifiers are also expanding their application field not only as large-capacity power sources but also as weak-current sources for communication apparatus or various electrical equipment for which the selemium rectifier has been used to some extent. Also radios and televisions, which have recently gained popularity, extensively use the selenium rectifiers replacing the former type vacuum tubes. In this paper, however, it will be only described, the basic qualities of our products selenium rectifier, such as high degree of reliability, long life, high efficiency etc., that have led it to a recent expansion in the field of application for power service. The author's opinion based on actual examples will be also expressed on the question of adaptability of selenium rectifier for each service field as well as on such matters that demand special attention.

II CONSTRUCTION, MANUFACTURING METHODS, VOLTAGE AND CURRENT CAPACITY

Fig. 1 shows the cross section of a selenium rectifier of our make. A base plate, usually made of nickel-plated steel sheet, serves no part in rectification but constitutes a mechanical supporter of the selenium layer. Atop this layer is sprayed another layer of cathode alloy, which, is in the case of our products, made of tin and cadmium. Rectification takes place between the layers of selenium and cathode alloy. The thinner and more uniform in thickness of the selenium layer, the better is the result. To achieve this, selenium is vaporized in vacuum and brought to adhere to the base plate—the process, so called deposition in vacua method. The base plate then is heattreated; crystallization follows in the selenium layers. When voltage is applied, rectification takes place, as mentioned above, between the layer of crystalized selenium and tin-cadmium alloy. Current generated flows in the direction of steel → selenium → alloy layer. The crystalized selenium layer cathode alloy layer offer resistance of different values depending on the direction of the voltage applied.

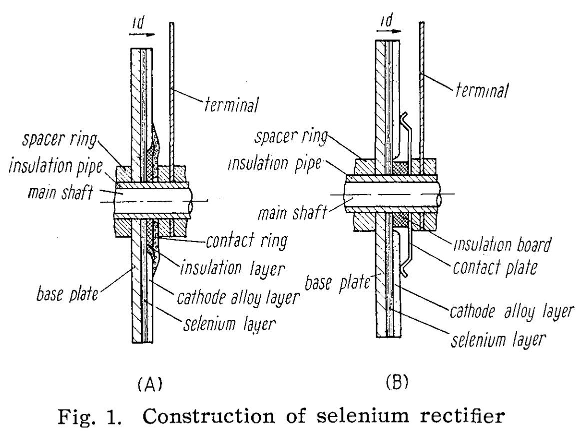


Fig. 1. Construction of selenium rectifier
(A) Ring contact system
(B) Spring contact system

Fig. 2 shows resistance variations based on the direction voltage is applied. The characteristic curve thus formed is not a straight line but reflects the strong influence of the voltage applied. In the case of our products, directional resistance ratio, under a reverse voltage of 20 V, is somewhere 8,000 to 1.

Fig. 3 shows the typical current-voltage characteristics of the selenium rectifier of our make. From this will be observed one of the specific features of our products that the forward resistance is markedly small compared with that of other firms' make. All this is attributable to the adoption of the deposition in vacua method, heat-treatment applied before and after, and special technique employed in composing the selenium and cathode alloy layers.

The voltage and current capacity of the selenium rectifier proper can be determined chiefly by the permissible value of temperature rise. In dealing with this subject, two aspects are presented; the relationship between the permissible temperature and life; and that between the permissible temperature and current-voltage capacity. Leaving the first in a later chapter, the question of voltage-current durability will be taken up first.

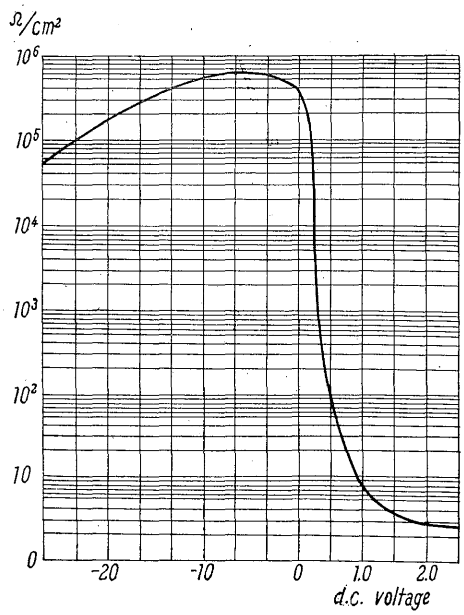
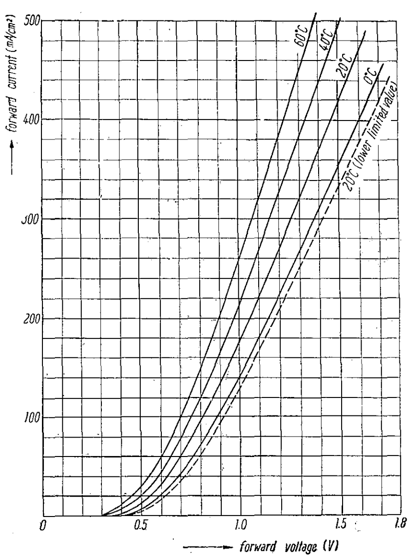
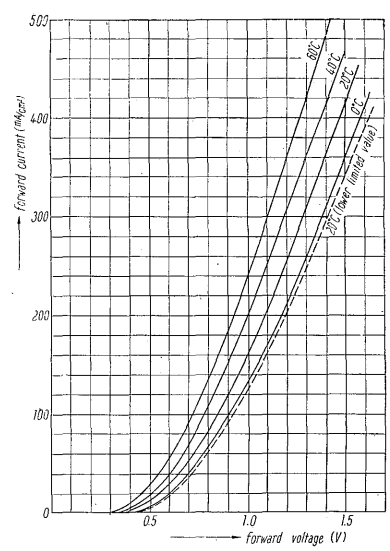


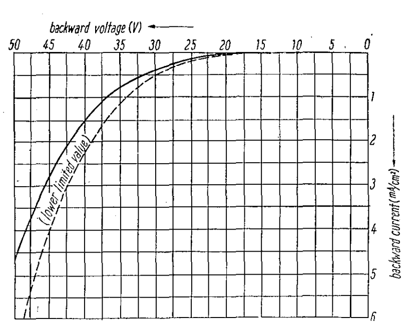
Fig. 2. Resistance curve of selenium rectifier



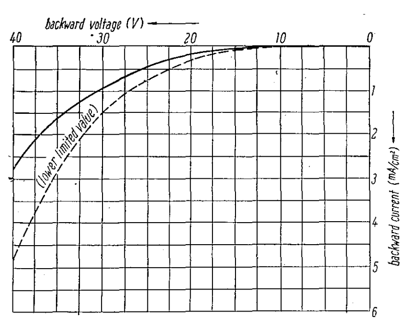
(A) 25 V plate, positive direction characteristics



(B) 30 V plate, positive direction characteristics



(C) 25 V plate, negative direction characteristics



(D) 30 V plate, negative direction characteristics

Fig. 3. Current voltage characteristics of selenium rectifier

1) Voltage Endurance

Use voltage per one selenium plate is 20 to 25 volts high voltage class by a-c input voltage, i.e. effective value of inverse endurance voltage. This figure represents the approximate value of a-c input voltage required when the rated load is applied on a rectifier plate and includes 10%~15% voltage loss of the rectifier body itself and voltage fluctuation ±5% of the line. Should the input a-c voltage exceed the allowable value to the extent of 170% of the rated voltage, the temperature rises very rapidly due to the reverse direction current generated and comes to exceed its allowable limit. Not the limit in temperature itself but that in voltage itself is a matter of great importance because at that limit point, which is about 80 Volts, the rectifier layers commence partial breakage. However, even if its breakage is started, the characteristic of the selenium layer is such that no short-circuit condition is produced. It is believed that minute voids produced in the layer by breakage form insulation walls around their circumference.

Therefore, it is generally admitted that the selenium rectifier can withstand the abnormal voltage rise like impulse voltages.

2) Current Endurance

To meet various current requirements and in economical consideration as to the number of pieces available from a large-size base plate, our products selenium rectifers for power service are made available in standard sizes of 6, 11, 16, 33, 50, 100, 200, 300 and 400 cm^2. Current density, which varies depending on the type of cooling method, is about 0.11 A/cm^2 for self-cooling (d-c out-put current) —0.4 A/cm^2 as a maximum for the forced-cooling method—in each case, representing the values obtained from three-phase, bridge connection but in case of a single phase, the current density becomes less in inverse proportion to the time the current flows. These density values, an apparently large figures if compared with those of the rectifiers previously manufactured in Japan, and have been made possible by an appearance of such rectifiers, in which, the forward current loss is extremely small as shown in Fig. 3. In other words, this infers the selenium rectifier of our make is physically small in size and volume.

These current values mentioned above are for the continuous ratings. The short-time over-load capacity is extremely high. With the selenium plate itself, it is hardly conceivable that there exists a limit in current density ; rather, if it is intermittently loaded, the selenium plate can be safely subjected to the large instantaneous current by allowing the rise in temperature to its permissible limit. In this case, there is one thing to be considered other than this selenium plate itself. It is the current collecting part from the cathode alloy layer, illustrated in Fig. 1. This part has long been considered as one of the weakest points of the selenium rectifier and various contrivances were made for its improvement. Fuji Denki,—highly confident of the superiority of the selenium rectifier particulary in current density as stated above, and deeply impressed with the prospect of the future expansion in the field of application of the selenium rectifier for power service, associated with a demand for rectifiers having short-time, possibly of several cycles, large overcurrent capacity—has made special effort for the elimination of the deficiencies which virtually checked the over-current capacity of the selenium rectifier, and succeeded in it by the adoption of two construction systems—the ring contact system for rectifiers of over 100 cm^2 rectifying area, shown in Fig. 1 (A)—and spring contact system for those of under 50 cm^2, shown in Fig. 1 (B).

The spring contact system, although made in most common form based on spring action, effects the increase in current capacity, due to the selected material and peculiar shape of the contact plate. In the ring contact system, a contact ring is interposed between the cathode alloy and spacer ring, and solidly jointed to the cathode alloy at the relatively large area. By adopting this system contact resistance becomes extremely small, and perfect protection is made possible against moisture as well as the influence of any external conditions. Thus when the rectifier is to be operated under the unusual condition, i.e., by raising the current density by means of forced cooling or at short-time overload current.—this ring contact system enables the most stable, reliable operation of the rectifier. Thus, under the intermittent over-loading with the temperature rise controlled to that of the continuous rating, the result as shown in Fig. 4 will be obtained. This is the case of 10 minutes periodically repeated operation and on the abscissa is

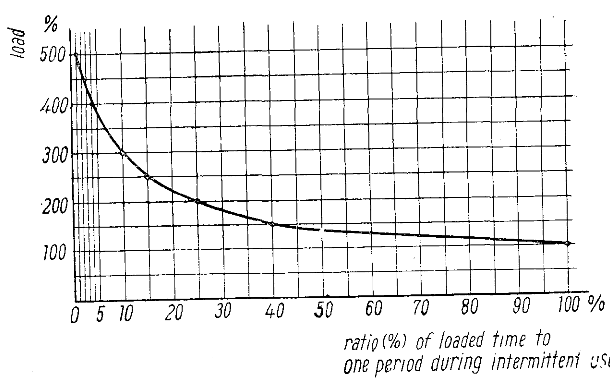


Fig. 4. Intermittent over-load durability of selenium rectifier

duration of flow of load in one periodic cycle represented by per cent.

3) Uniformity of products

As already stated, since the working voltage is approximately 20~25 V per each selenium plate; the working current, in case of three-phase connection and self-cooling, is 41 A, d-c for 400 cm^2 plate; this current value, under forced-cooling, will become three times as large as that under self-cooling—therefore, if greater capacity is demanded, the rectifiers must be connected in series and parallel. In this way, flexibility in the connection of the rectifiers according to the demands in an obvious advantage of the selenium rectifier to the other types of larger capacity rectifiers. This evaluation, however, comes true only when each element of the rectifier is made of uniform quality. The reason that the domestic rectifiers failed in their application on power service in the past is chiefly the lack of uniformity in the elements that caused

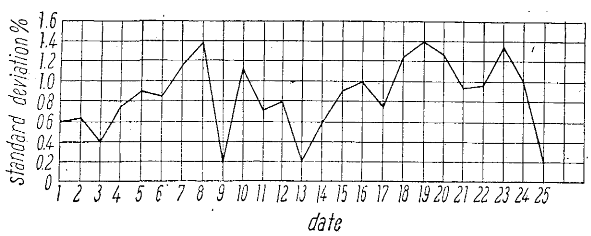


Fig. 5. Management curve of selenium plate

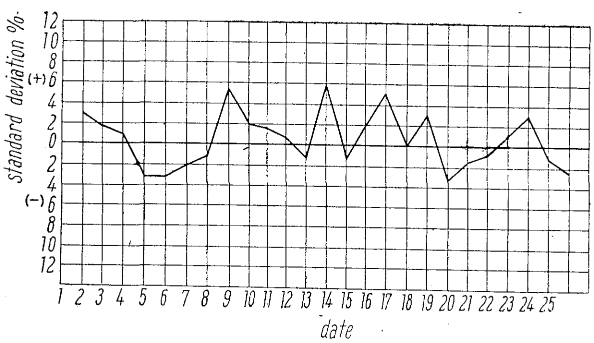


Fig. 6. Management curve of selenium plate

when the rectifiers are connected in number, an unbalanced loading to each selenium plate, resulting in various troubles. With our products, uniformity is fairly well established as the result of the mass production of the higher order based on the adhesion by vacuum-vaparization method as mentioned before and quality control conducted throughout the manufacturing process from the material to the finished products. In our inspection system conducted in our factories, every one of the selenium plates manufactured is placed under test for the positive and negative directions and in Figs. 5 and 6 are illustrated some results of the tests made on one month production.—Fig. 5 showing the calculated standard deviation value in % of one day's production lots with respect to the test standard value and Fig. 6, the difference in % between the average deviation value of each day's lots, and the standard value based on the latter. From these curves, it can be seen that the selenium rectifier is so highly recommendable for power service.

III PERMISSIBLE TEMPERATURE LIMIT AND LIFE

They say, the permissible temperature limit of the former domestic rectifier was about 55°C. In fact, with those rectifiers a temperature rise over this limit often caused rapid deterioration. Our products, permit a temperature rise up to 70°C and a maximum of 75°C locally. On this respect, there is no equal to our products. Furthermore, the permissible temperature limit of the selenium rectifier is correlative to the deterioration of the selenium layers, hence to the life itself. This means, a slight amount of a particular substance, added in formation of the selenium layer to reduce its forward resistance is diminished or lost in use over years, resulting in a gradual increase in the forward resistance. If the temperature limit is exceeded, the consumption of the added substance is accelerated and the life of the selenium rectifier is shortened. The kind of the material added, and its mixing process undoubtedly make great influences to this temperature limit. The achievement reached through the research over many years of us is one of the features unrivaled.

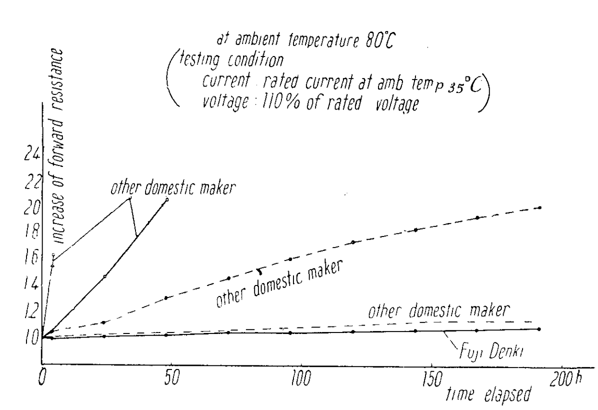


Fig. 7. Example of life test of selenium rectifier (surrounding temperature, 80°C)

In the selenium rectifier, life is defined as the interval of time during which the intenal voltage drop of the rectifier becomes twice as much as that of when it was put in use. With our products, if used within its temperature limit, service life is approximately 200,000 hours (roughly twenty years). Of course, careful life test has been made in our factory over many years at the room temperature of 40°C

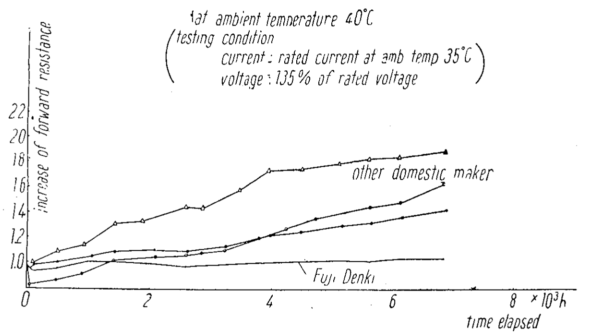


Fig. 8. Example of life test of selenium rectifier (surrounding temperature, 40°C)

which is the normal condition for use and also accelerated life tests under the surrounding temperature 80°C to establish the basis for determining service life of the rectifier. Fig. 7 and 8 show the test results at the room temperatures of 80°C and 40°C respectively in comparison with other firms' products.

In spite of the definition of service life as such, expiration of the anticipated life length does not necessarily signify the unfitness for use. They can be used as usual if an increase in voltage drop, i.e., its resultant decrease in efficiency is admitted or if its electrical rating is lowered. On the contrary from the consideration of low efficiency, it is often profitable to replace them before their effective life expiers. Also in the special case in which life length is not of primary importance as in case of radio and television, the rectifier is used at the elevated temperature, further particulars, however, being omited herein.

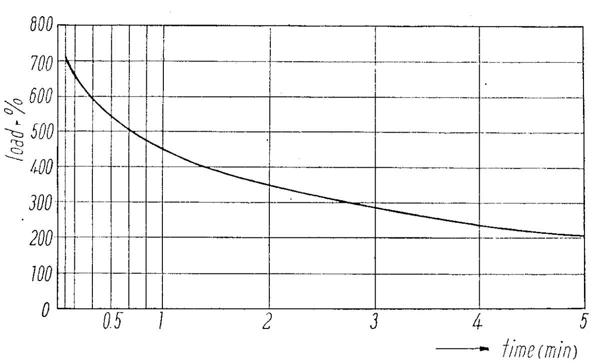


Fig. 9. Short time over-load durability of selenium rectifier

There is also a temperature limit over which rupture of the selenium layer is caused. With our products, it is about 170°C. If this limit is exceeded, rectifying ability can not be recovered even by repeated cooling operation. Accordingly, providing for accidental over-loading or short-cicuiting, design principle of us has been established so as to maintain the internal temperature of the selenium plate not to exceed 130°C. This feature is graphically illustrated in Fig. 9. It is very likely that short-circuit current flow of two～three seconds will not cause rupture, and if protective device functions properly, usefulness of the rectifying body will be least interrupted by short-circuiting.

IV EFFICIENCY AND VOLTAGE REGULATION

The rectifier loss, as referred to in connection with the current-voltage characteristics shown in Fig. 3, is considered as consisting of three losses: the inverse direction loss which has no bearing on current: the definite positive direction voltage drop, i.e., so-called threshold voltage, which exists regardless of current: The resistance loss that increases with an increase in current.

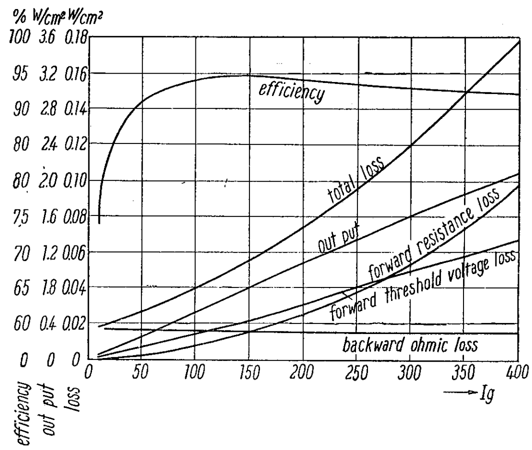


Fig. 10. Loss and efficiency of selenium rectifier (rectifier proper)

The total loss of a rectifier, therefore, is an aggregate of three losses and efficiency determination is made on it. Fig. 10 shows these losses and efficiency of a selenium rectifiers of our make for three-phase bridge connection on the current density basis. From this, it will be observed that the efficiency of our products is about 94% at current density of 0.11A/cm² (in case of self-cooling), 93～92% at current density of 0.35～0.4 A/cm² (in case of forced-cooling). This is a fairly good showing compared with that of other firms' products. This also reflects of the superior qualities of the selenium rectifier, which the special production method adopted by our company has created, and which has led to the wide-scale application of the same for power service. For comparison, some of the current-voltage characteristics of other firms' products are illustrated below in Fig. 11.

Fig. 12 shows the efficiency of the selenium rectifier in comparison with that of the mercury-rectifier (on assumed arc-voltage of 23 volts approx.). The tooth-shaped curve of the selenium rectifier is caused by the fact that the selenium plates of

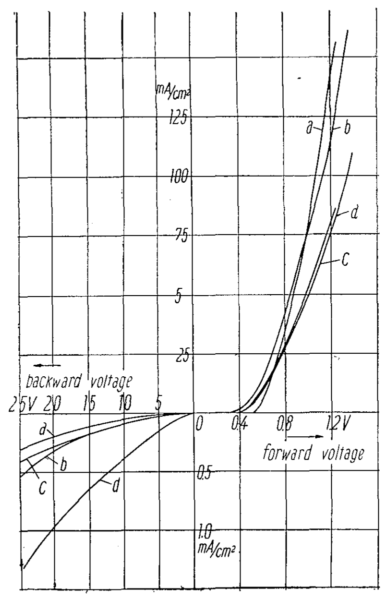


Fig. 11. Current-voltage characteristics of selenium rectifier made in other manufacturers

capacity of 24 volts per piece on series-connected in number, depending on voltage requirements. The higher the voltage boosted, the less the effect of this connection becomes at higher voltages due to an increased number of the selenium plates used. The maximum efficiency is available when the voltage generated by each selenium plate is utilized to its fullest extent and will be represented by a straight line, parallel to the base.

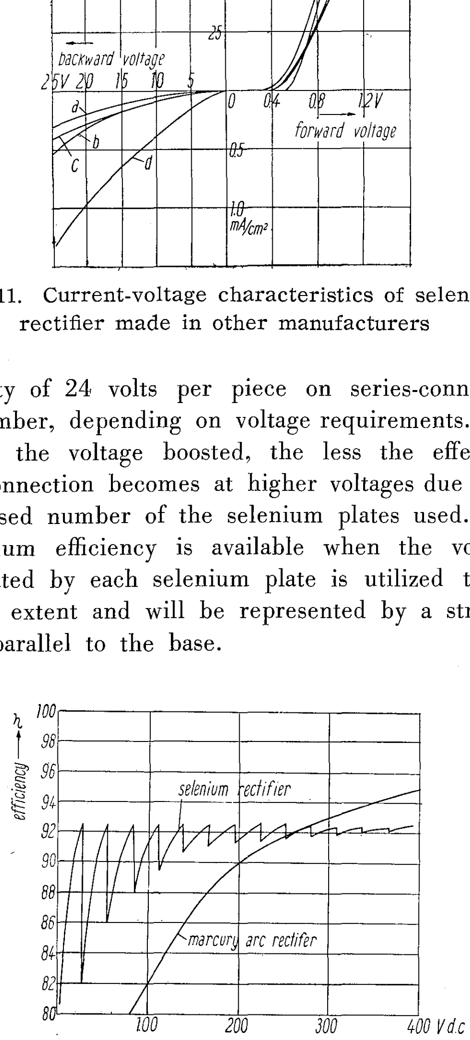


Fig. 12. Comparison of efficiency of rectifiers on d-c voltage
(not contain auxiliary equipment losses)

In this figure, the two characteristic curves intersect at 250 volts approx. When the aggregate efficiency of a rectifier equipment as a unit is considered, the losses of rectifier transformers and various other auxiliary equipment must be taken into account.

If the rectifier is not operated at full-load in its normal operation, the question of efficiency at partial loading comes up. In this case also satisfactory result will be obtained with the selenium rectifier as graphically illustrated in Fig. 13. Again

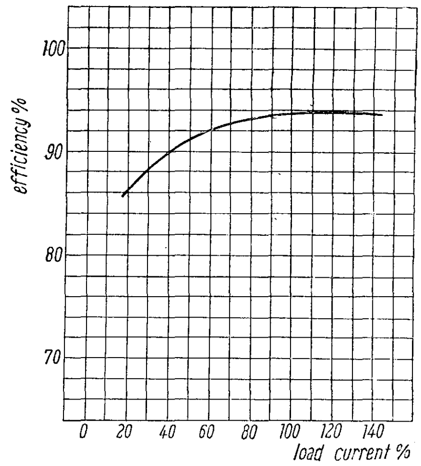


Fig. 13. Efficiency curve of selenium rectifier on load current (self cooling system)

in comparison with the mercury rectifier, the latter produces an approximately uniform voltage loss, irrespective of current, whereas, in the case of the selenium rectifier, the voltage loss varies with current. Inference is, therefore, possible that the selenium rectifier, in general, is much superior to the mercury rectifier in characteristics. If compared with the motor-generator, superiority of the selenium rectifier will still be conspicuous, because, with the latter, efficiency rapidly drops at under-load due to its core loss. Fig. 14 shows the aggregate efficiency of a 100 V, 1000 A seleninm rectifier of forced-cooling type used for factory power service in comparison with that of a motor-generator of the same out-put. Similarly, Fig. 15 shows that of an oil-circulating, water-cooling type selenium rectifier of 90 V, 2,000 A rating, used for electrolysis. These figures, Figs. 14 and 15, show in each case that with the greater current density effected by forced-cooling, efficiency is higher at partial loading than at full loading.

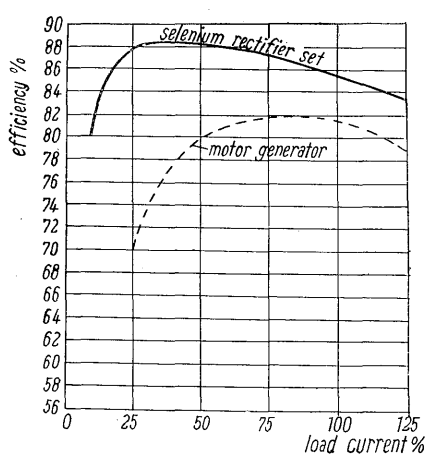


Fig. 14. Total efficiency of 100 V 100 kW rectifier (comparison with MG)

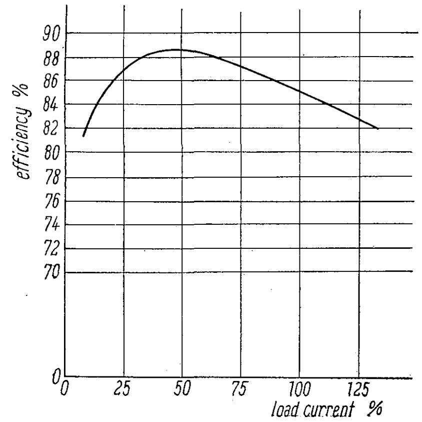


Fig. 15. Total efficiency of 90 V 2,000 A rectifier

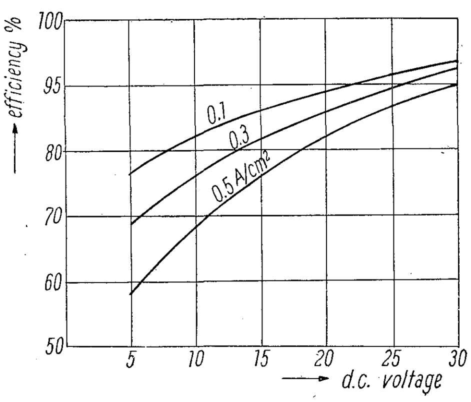


Fig. 16. Efficiency of 3ϕ bridge connection in case under 24 V d-c

As pointed out in Fig. 12, efficiency is considerably low at voltage under 24 volts. This fact is illustrated, in more detail, by taking the current density as a parameter. In such a care as this, the three-phase, bridge connection is not advantageous, since two selenium plates connected in series produces no effect as desired. Instead, if three-phase, star connected, or three-phase, double-star connected, better efficiency will be obtained.

In speaking of the voltage regulator, reference is made to Fig. 17 in which is shown the combined voltage regulation of a selenium rectifier unit com-

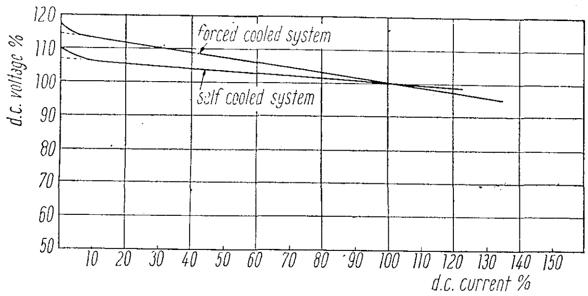


Fig. 17. Voltage regulation curve of selenium rectifier

prising a transformer. It is about 10% by self-cooling, 15% by forced-cooling. In the case of the mercury rectifier, voltage regulation is determined only by the transformer and is usually 5%, whereas, in the case of the selenium rectifier, the latter also acts like a resistance as shown in Fig. 3 (A and B).

V CONSTRUCTION AND COOLING SYSTEM

Old selenium rectifiers, comparatively speaking, were somewhat sensitive to moisture. Therefore if used where humidity is high, deterioration was likely to occur, or arcing and eventual shut-off resulted when brought into operation in haste after a certain period of stand-still. Because of the moisture proof treatment effected in the course of production, our product is well-nigh-perfect in this respect.

For use in chemical factories operated under the risk of harmful gases such as chlorine and sulphurous acid, the rectifier must be of oil-immersed type. This is also true in the case when the voltage in use is order of several 10,000 V or more, because the question of conductor insulation and corona formation is involved. For a large capacity service in which water-cooling system can be employed to an advantage, the oil-immersed type, oil-circulating, and water-cooling system is adopted, the detail of which will be described later.

The self-cooling system is commonly in use for a small capacity service and the rectifier is usually contained in a cubicle with the transformer and other accessories. Frontispiece-2 shows one sample of the most commonly used 35 V, 1 A rectifiers and Frontispiece-1, a 90 V, 200A selenium rectifier of short-time rating used as d-c operation power source for a power substation O.C.B.

The greater the capacity is increased, the greater is the advantage of the forced-air-cooling system over the self-cooling in price and size. In Fig. 18 is shown the theoretical construction of a forced-cooled type selenium rectifier provided with a rationally designed air passage. The selenium rectifier

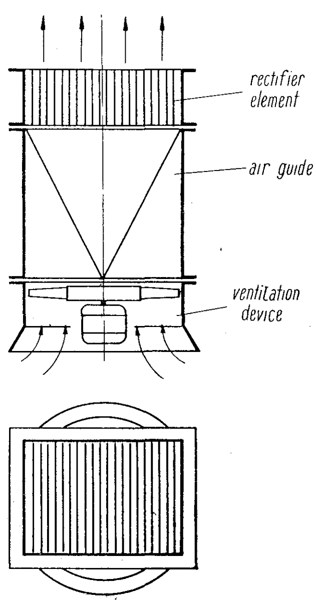


Fig. 18. Principle construction of air-cooled selenium rectifier

which is an assembled body of selenium plates on the same shaft is inherently of a construction most suitable for cooling, by means of the space between each layer suitably designed. Located between the cylindrical body of the cooling fan and rectifier body of rectangular shape is a wind tunnel so designed that uniform air flow into the selenium plates is made feasible. Frontispiece–3 show a 48 V, 400 A, fan-cooled selenium rectifier used in a rayon factory for potmoter braking and Frontispiece–5, a 6 V, 2000 A, fan-cooled selenium rectifier used

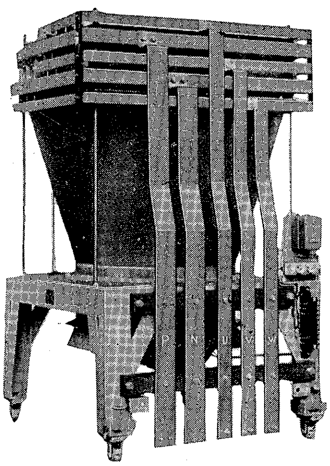


Fig. 19. 100 V 1,000 A air cooled selenium rectifier

for electrolysis. With a large capacity rectifier, it is very convenient to have the selenium rectifier body mounted with its fan on a wheeled stand as shown in Fig. 19 and encased in a cubicle as shown in Frontispiece–8. This is an example of its application that one of the cement factories employed in using it as a source for motor driving. Fig. 20 show the construction of the rectifier elements and a wind pressure relay installed for the purpose of the protection against any possible accident in the cooling system. Connections of the fan-cooled rectifier of this kind is shown in Fig. 22. Frontispiece–4 shows an oil-immersed, water-cooled, 8 V, 2500 A selenium rectifier used in one of the steel works under the severe condition of dust and water sprays. The water cooling pipe outlet and inlet are installed literally on the back of the photograph.

In the oil-immersed type rectifiers, if capacity is increased, the temperature difference between the selenium plates and oil is gradually augmented and it is necessary, for economical reason to bring down this difference to a minimum. To serve this purpose, on the top of the oil tank and over the selenium rectifier body, is installed a small oil-circulation pump immersed in the oil with its driving motor. Fig. 22 shows the construction of a large capacity, water-cooled type rectifier equipped with a pump. This construction, if adopted to the rectifiers for use on electrolysis which requires several

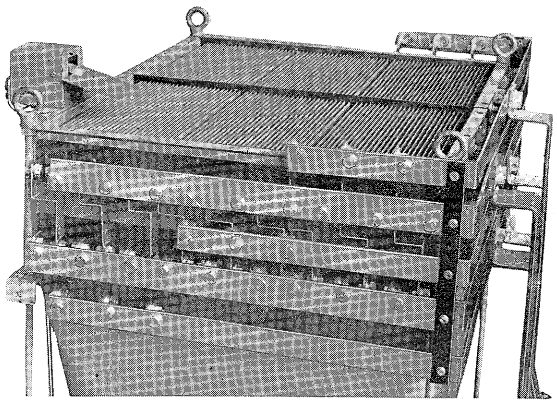


Fig. 20. Construction of air-cooled selenium rectifier and its wind pressure relay

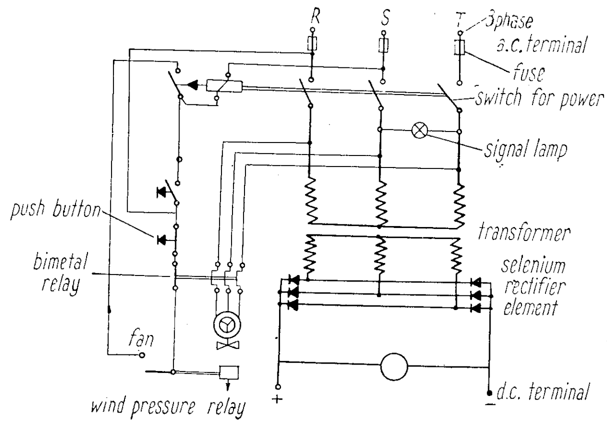


Fig. 21. Connection diagram of air-cooled selenium rectifier

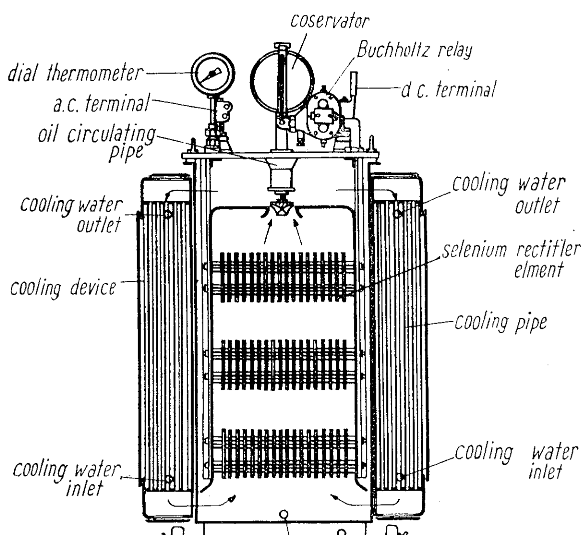


Fig. 22. Construction of oil-circulating water-cooled selenium rectifier

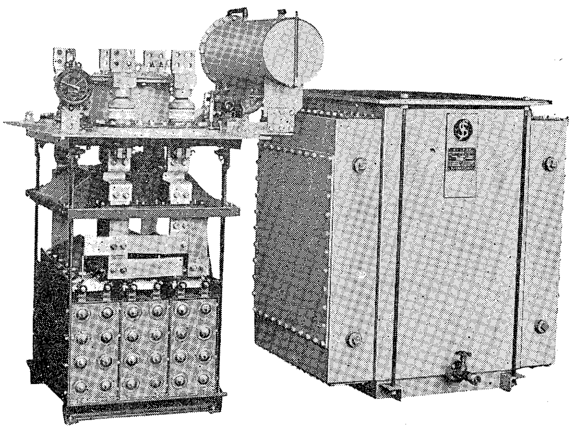


Fig. 23. Inner view of oil circulating water cooled selenium rectifier

10,000 amperes, will give the most economical results. Frontispiece–6 and Fig. 23 show respectively the external view of a relatively small capacity selenium rectifier of this type, rated 90 V, 2000 A and in use for water electrolysis and also its interior view.

For information purpose, economical comparison of various cooling systems is shown in Fig. 24. The self-cooling system is generally most economical up to 5 kW. In the case of the oil immersed or forced-cooling system, the bearing that the total cost of the oil tank, cooling fan and accessories has on that of the whole equipment is minimized in inverse proportion to the increase in output, and the greater is the output, the less is the cost per kW. But in the case of the forced-air-cooling system, if requirement is for more than 250 kW to 300 kW, two sets of fans and accessories are needed. This fact ultimately means the necessity of two sets of 250 kW~300 kW units connected in parallel. Over this, cost per kW remains constant. This limitation in capacity, it is believed, will be further extended with the oil-

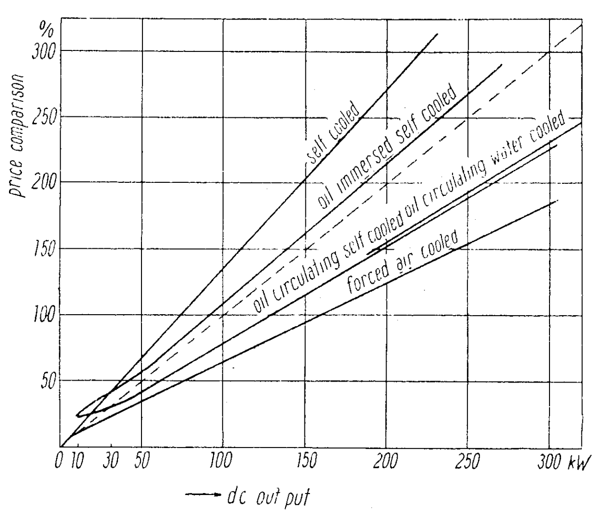


Fig. 24. Economical comparison of various cooling system

circulation, water-cooled system.

Of the oil-immersed type rectifiers, a small capacity one with its transformer also immersed in the same oil tank is sometime found economical. Working temperature limit of the selenium rectifier proper is approximately 70°C, whereas, that of the transformer winding is 95°C. This difference in temperature limits will constitute a waste in a strict economical sense and this ecomical situation will be more aggravated with a large capacity installation. Therefore, in the case of a relatively small capacity unit, it is economically advantageous to have the transformer immersed in a common tank instead of in a separate tank and, if necessary, even at the expense of increasing the radiation area of the oil tank to some extent. This is particulary true in the case of high voltage service when saving of six

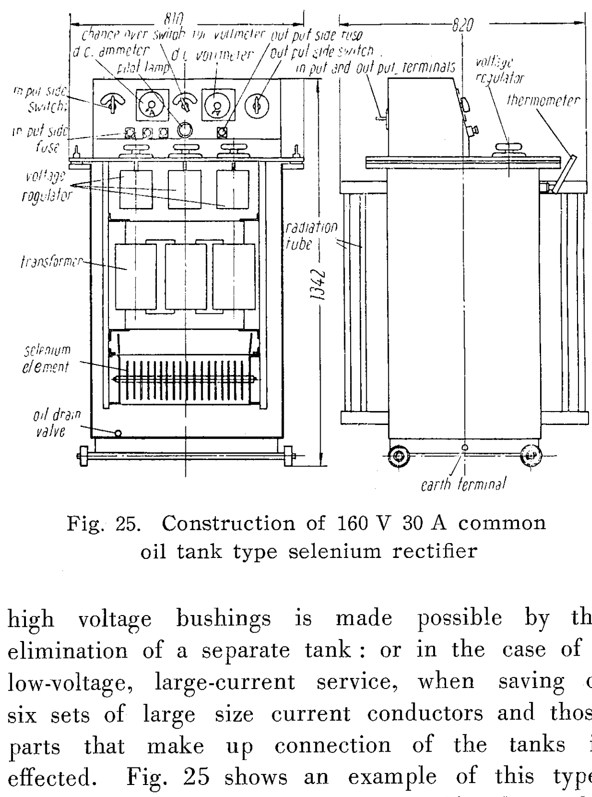


Fig. 25. Construction of 160 V 30 A common oil tank type selenium rectifier

high voltage bushings is made possible by the elimination of a separate tank : or in the case of a low-voltage, large-current service, when saving of six sets of large size current conductors and those parts that make up connection of the tanks is effected. Fig. 25 shows an example of this type, rated 160 V, 30 A, oil-immersed self-cooling, the one used in one of the chemical plants. A design plan was once made for a 8V, 2,500 A, 20 kW, oil-immersed, water-cooled rectifier with a common oil tank from an economical standpoint. Fig. 26 similarly shows an example of a plan of 6 V, 30,000 A for electrolysis. With such an enormous current as 30,000 A, the cost involved in the connecting conductors, and construction of the joint parts on the oil tank, where these conductors go through, is not only exorbitantly great but it also provides technical problems. The common oil-tank method will give it a solution. In this case, the tank is partitioned into the transformer and selenium

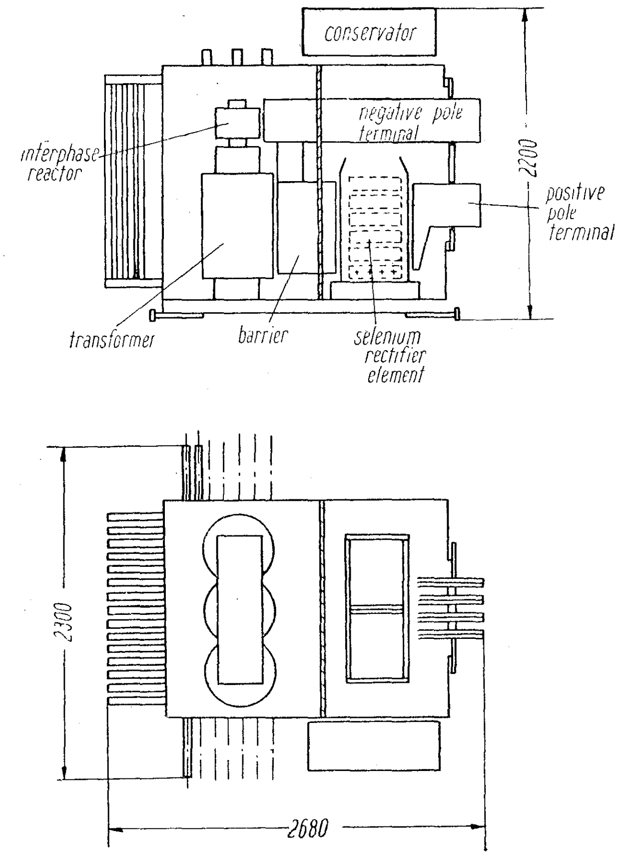


Fig. 26. Construction of 6 V 30,000 A selenium rectifier

compartments with insulation—each with its own cooling system, the former with the oil-immersed, self-cooling and the latter with the oil-circulating, water-cooled system.

VI VOLTAGE ADJUSTING

Voltage adjusting is made by varying the input a-c voltage in selenium rectifier systems. For this,

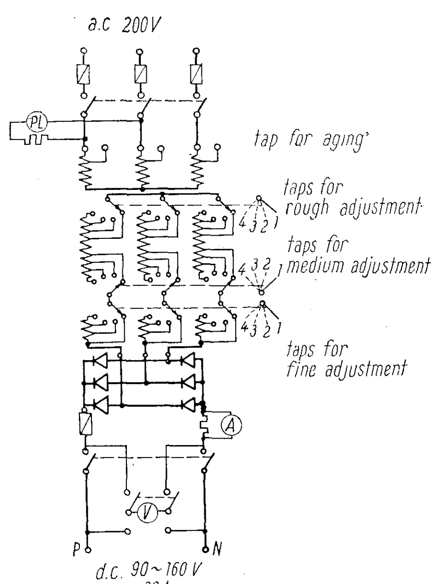


Fig. 27. Regulation of voltage by transformer tap

all the methods that are previously known can be applied. For instance, use of a tap transformer, sliding transformer, induction voltage regulator or d-c saturable reactor. Figs. 27, 28 and 29 show

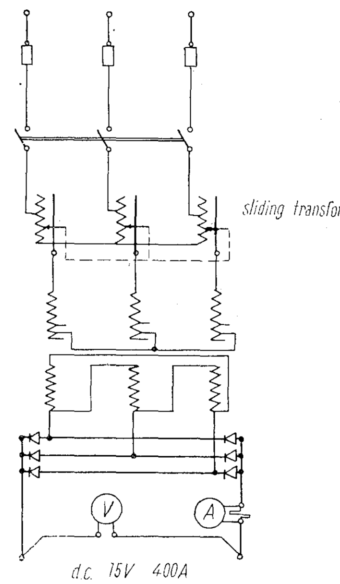


Fig. 28. Regulation of voltage by sliding transformer

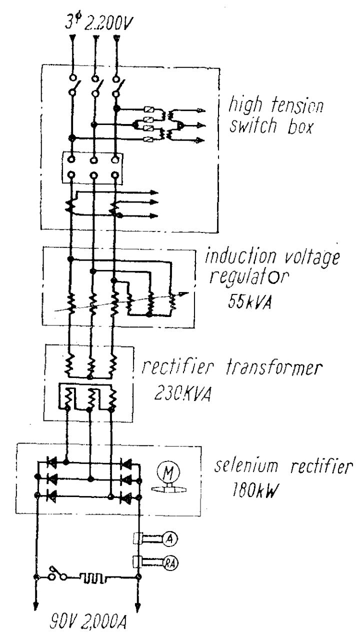


Fig. 29. Regulation of voltage by induction voltage regulator

connections for voltage adjustment by a tap transformer, sliding transformer and induction voltage regulator respectively. Fig. 30 also shows a 6 V, 100 A set, using a sliding transformer. In each case, although different in kinds according to the system employed, accessory equipment is necessary for voltage control of the selenium rectifier.

In Fig. 31 is shown the quick-response voltage regulating system by saturable reactor. By using this system, and if the time constant is properly designed for the signal circuit, quick-response voltage control is feasible within a period of 3~4 c/s.

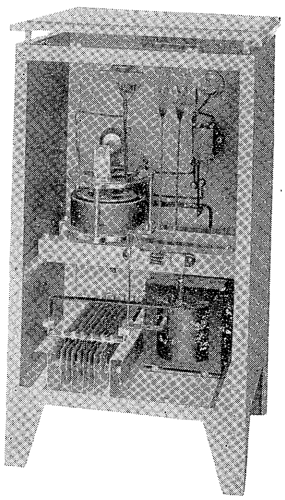


Fig. 30.
6 V 100 A set
(using sliding transformer)

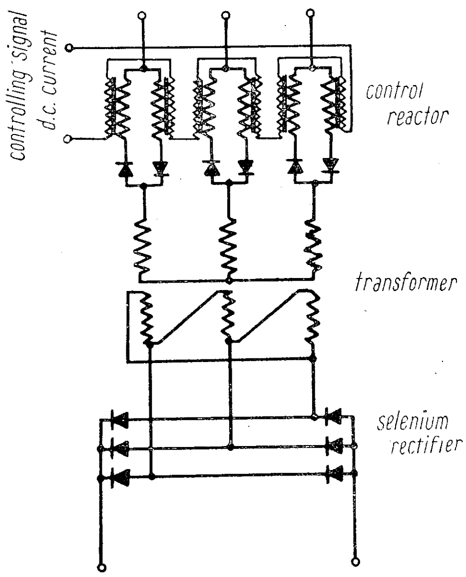


Fig. 31. Quick-response voltage regulating system by saturable reactor

VII ADVANTAGES AND DISADVANTAGES OF SELENIUM RECTIFIER AND ITS APPLICATION FIELD

What hitherto have been used as rectifying equipment for power service are motor-generators, rotary converters, glass and steel-tank mercury-rectifiers and mechanical converters. Motor-generators have commonly been used for relatively low voltage, small capacity service and this field provides the selenium rectifier with the most favorable filed for application. As already pointed out in Fig. 14, the selenium rectifier excels the motor-generators in efficiency, production cost, maintenance and various respects. In view of this, it can be said, that the selenium rectifier, will eventually take over the position held by the motor-generators. The Vertoro (commutator type mechanical rectificr) will likewise meet the same fate. Also it is already an old story that the rotary converter has conceded to the mercury rectifiers. It will not be necessary, therefore, to enter into any comparative study of the two.

The contact converter, which has an aggregate efficiency of 97%, is most superior as a rectifying equipment of constant voltage, large capacity rating for service requiring voltages under 400~600 V. In spite of this, for reason of the contact mechanisms and accessory equipment which brings up production cost high, there is, from the economical point of view, some room is left open to the selenium rectifier for competition in the field of service requiring currents under 4,000~5,000 A and voltages under 200 V. In particular, under 100~150 V, the economic value of the rectifier is evident. Again, the mercury rectifier is highly efficient at voltages over 600 V, quickly responsive in voltage controlling and has gained popularity. The mercury rectifier, greatly reinforced by the recent development of a new construction, which contains no vacuum-pump, has made the most conspicuous expansion in the field of application as a d-c power source for factory, and as a unit for speed control of motors. In comparison, the selenium rectifier is superior in efficiency as shown in Fig. 12 at voltages under 250~200 V. As to the price, a simple conclusive answer is not justifiable, because the capacity of the standard type mucury rectifier is graded by steps. As an example, hower, the case of a 1000 A continuous

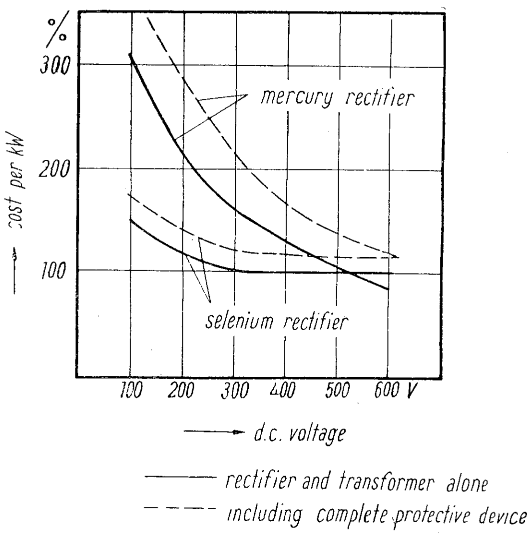


Fig. 32. Relation between d-c voltage and manufacturing cost
(approximate price per 1 kW, at 1,000 A set)

output is taken up and a production cost comparison made on the basis of d-c voltage as shown in Fig. 32. For current capacity of order of 1,000 A and if the total cost of the rectifier body and its transformer is taken into account, the mercury rectifier is cheaper at 600 V. If various protective devices, (including high speed circuit-breaker on the d-c side) which have been customarily considered as essential for the satisfactory operation of the mercury rectifier, are taken into account, the selenium rectifier becomes cheaper. At voltages under 400 V, the economical superiority of the selenium rectifier is decisive. Even in the case of small-current capacity ratings, the selenium rectifier is apparently economical. According to Fig. 32, the mercury rectifier costs more per kW at low voltages. This is to mean that the mercury rectifier of normal construction can stand voltages of about 600 V and has no room for applying the cheaper construction for low voltage service. Also, cost per kW of the selenium rectifier for output under 300 kW gradually decreases and finally comes to a point where it remains practically constant. The reason is, as already explained in chapter V and Fig. 24, that the selenium rectifier unit is best serviceable at 250 kW to 300 kW.

The glass-tube mercury rectifier, which is cheaper in price than the metal-chamber mercury rectifier, is sometime used as a d-c source of voltages up to 600 V. But, because of defects, much as short life, poor overload capacity, sensbility to temperature and etc., its application field has been comparatively confined. In Europe, at advent of the metal-chamber, pump-less rectifier, the glass-tube rectifier has gradually disappeared. It is very likely that, by reason of advantages in cost, life, over-load capacity and sound simplicity in maintenance, the selenium rectifier will gradually overtake the place held by the glass-tube rectifier.

In summarizing, the specific features of the selenium rectifier will be enumerated as follows.

1. At low voltage, the aggregate efficiency of 85%–90% is available.
2. Partial-load efficiency is high.
3. No step-grading of manufacturing capacity exists as in case of mercury rectifiers and mechanical converters.
4. Division-manufacturing is possible, either for parallel or series connections.
5. Ability to withstand fluctuating loads is great and over-load capacity is large.
6. Service life is long.
7. Price is moderate.
8. Construction is simple and mechanically sturdy.
9. Operation is simple.
10. No wear.
11. No maintenance is required.
12. Low temperature is not cared for.
13. No special foundation works are required.

Extending all over the field of applications in which rectifiers are used as a d-c source, opportunity is already at hand when the selenium rectifier completely overtakes the position held by the glass-tube rectifier and motor-generator in the field of battery charging and electric plating—the field where the selenium rectifier has long participated. The selenium

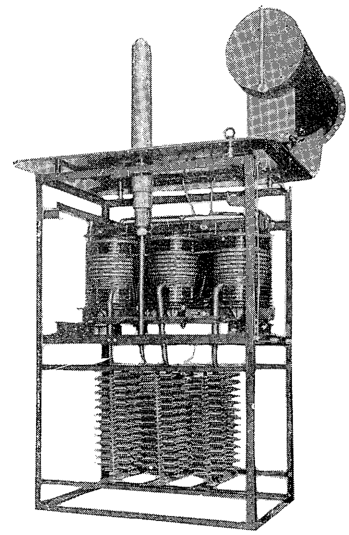


Fig. 33. Inner view of selenium rectifier for Cottrell precipitator

rectifier will also find the favorable place of application as a d-c source : for electrolysis which requires low-voltage, high current : in steel mills and cement factories : in ships : in mines to drive pit-railways which require 250 V power supply : in factories to operate tracks. When a rectifiers is employed for controlling d-c motor speed, and a large capacity required as is the case with the Leonard system, the mercury rectifier is used. But in the case of low voltage, small capacity, it is believed, the selenium rectifier will replace the motor-generators. In this case, if quick-response, accurate controlling is necessary, a d-c saturable reactor can be employed to advantage as illustrated in Fig. 31. For electric railway service, if it is in the class of 1,500 V, advantage will be to the mercury rectifier. Coming to order of 600 V, however, the selenium rectifier has better chance for expansion. In this connection, a full disclosure will be made in another article

Again, the selenium retifier has developed a new field of applications of its own in the use of high-voltage, small-current and is now in a wide-scale use as a d-c source of several 10,000 V for the Cottrell precipitator which was, compelled to depend on an incovenient and inefficient mechanical rectifier for a long time. Frontispiece–7 and Fig. 33 show an example of the rectifier. For specific use for the

Cottrell rectifier, the selenium rectifiers are available, standardized as listed in Table 1. Selenium rectifiers of special design are also under preparation to be used for static painting; as a source for X-ray: as various d-c high-voltage testing apparatus. The field found for the Kenotron will be a next target and it will not be too long before the selenium rectifier find its way in this new field in place of the Kenotron.

Table 1. Standard table of selenium rectifier for Cottrell precipitator

	Transformer		D.C. Voltage		D.C. Current	Dimensions			Type
	Capacity	High tension side voltage	Max. (1)	by resistance loading (2)		Width	Depth	Height	
	kVA	V	V	V	mA				
Single phase	10	65,000	90,000	47,000	130	1,100	1,400	2,250	Separate tanks
						1,400	1,260	2,852	Common tank
	15	65,000	90,000	47,000	200	1,100	1,400	2,252	Separate tanks
						1,400	1,260	2,852	Common tank
	20	65,000	90,000	47,000	270	1,530	1,260	2,852	〃
Three phase	10	55,000	76,000	65,000	125	1,700	1,300	2,720	〃
	15	55,000	76,000	65,000	190	1,700	1,300	2,720	〃
	20	55,000	76,000	65,000	250	1,700	1,300	2,720	〃
	30	55,000	76,000	65,000	380	1,920	1,420	2,720	〃

Note: 1) By condenser loading.
2) By rated current resistance loading.
3) "Separate tanks" means that the transformer and the rectifier have each own tanks. "Common tank" means that a common tank contains the transformer and the rectifier.

THE ELECTRIC SPEED GOVERNOR FOR LARGE CAPACITY WATER TURBINE GENERATORS

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The conventional type mechanical speed governor, which has been widely used up to now, has a mechanism in which the speed variation is detected and amplified by means of a pressure oil transmission through a primary pressure distributing valve and actuates servomotors; then the large guide vanes are moved. The speed detector and all control mechanisms, which are the dominant parts of this system as a speed governor are all made to work mechanically. For instance, the speed variation detector: it is formed of a set of fly balls and springs. The control mechanism is formed of a set of dash pots and a very complicated set of links, including also a fairly long lever. All these components are made in absolute precision, but it is unavoidable to become deviated from several causes such as the loss of inertia, looseness, variation of friction, deterioration of characteristics of springs and lubricants. Also there is a limit in the sensibility, accuracy, speed and performance. It, however, is noted that the connection from the speed detector to a prime mover shaft is usually made electrically. This is a simple electrification replacing the mechanical transmission and yet it has made a considerable benefit to engineers.

In the electric speed governor, the essential part