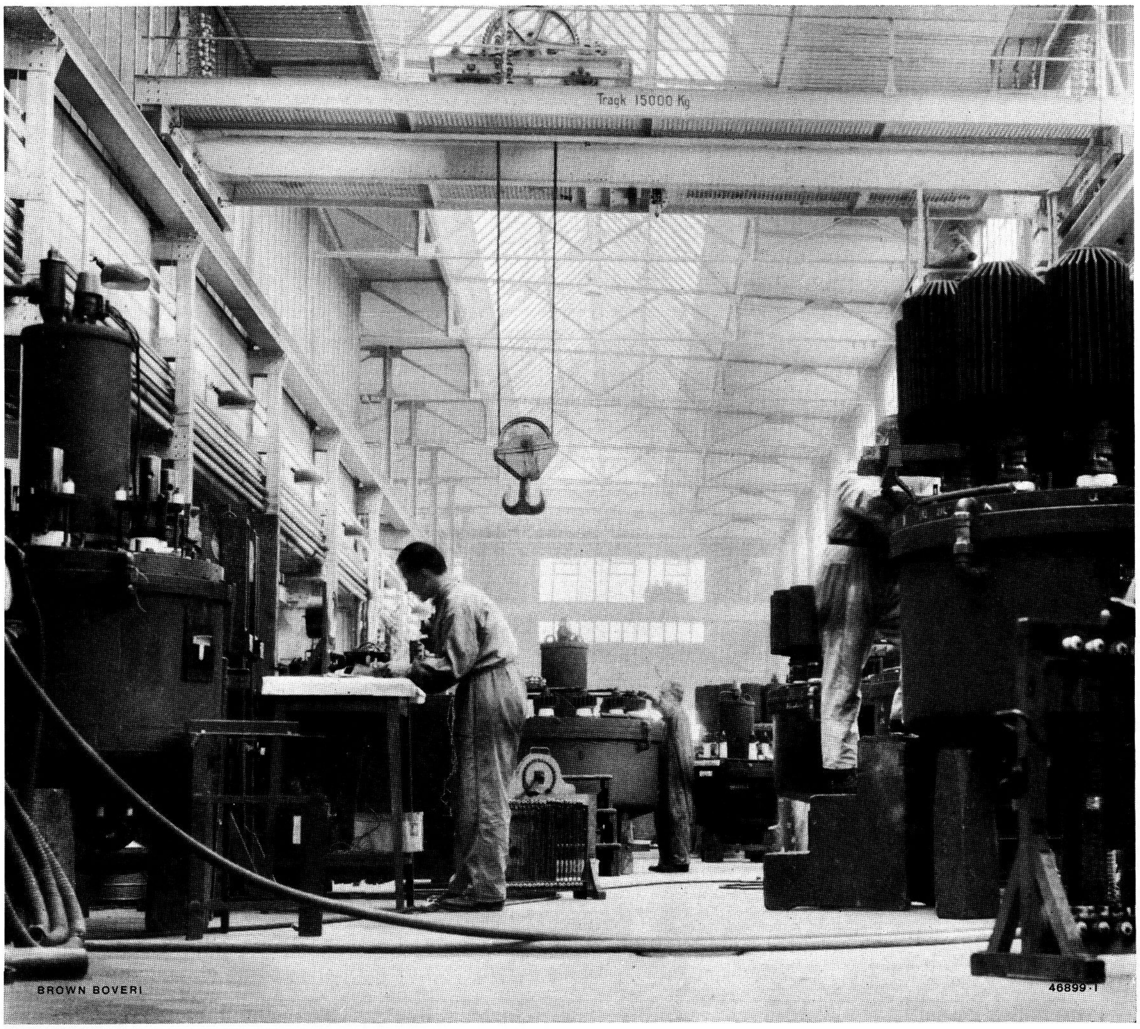
VOL. XXV MAY/JUNE, 1938 (DOUBLE NUMBER) No. 5/6

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

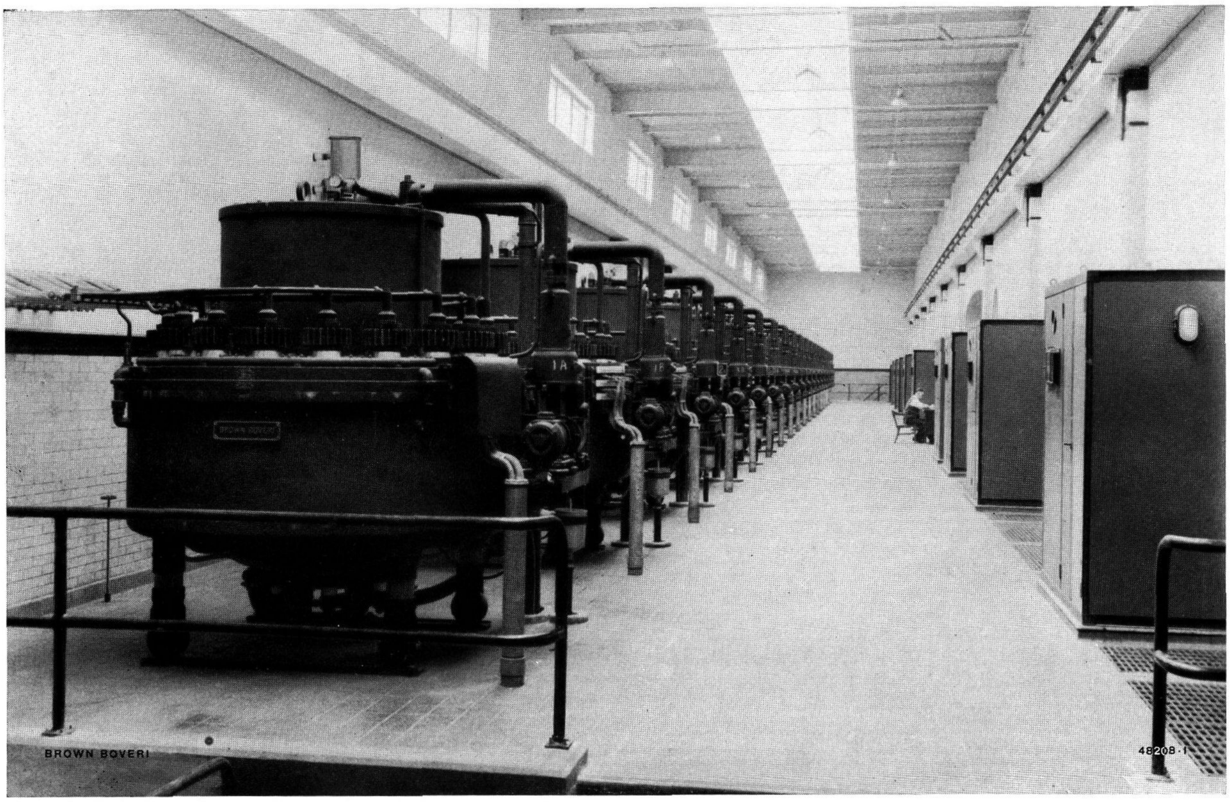


THE MUTATOR SHOP, BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND). VIEW FROM THE FORMATION END.

25 Years

OF THE BROWN BOVERI MUTATOR

Printed in Switzerland.



Mutator plant Arvida of the Aluminium Company of Canada.

18 Brown Boveri mutators with a total of 94,700 A at 575 V, output 54,450 kW. Plant ordered in May 1937 and all units already in service by April 1938.

Among the big mutator substations ordered from Brown Boveri for supplying aluminium furnaces in the year 1937, some of the most important were put into service in the first months of the present year. The illustration given below shows part of a plant of this type. The total current delivered by the Brown Boveri mutator sets put to work between January and April 1938 in aluminium works attains the impressive figure of 328,000 amperes.

This is a record. It is a striking proof of the productive capacity and good name of the firm and maintains Brown Boveri in the position they have always held at the head of mutator manufacturers.

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THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. XXV MAY/JUNE, 1938 No. 5/6

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25 YEARS OF THE BROWN BOVERI MUTATOR.

Decimal index 621. 314. 65.

IN the spring of the year 1913, exactly 25 years ago, Brown Boveri started building mercury-vapour mutators with metal tanks. It, therefore, seems fitting to devote a little space to the survey of this first and — it may be claimed — most successful development phase of the mutator and to combine this survey of past efforts and achievements to a series of articles devoted to the latest progress made in the same field. This is done here and offered to our reader in the form of this special number of our house journal.

For many years, the problem of a stationary converter of A.C. into D.C. exercised the minds of electrical engineers, in all countries. It can, even, be asserted that, from the discovery of the electro-dynamic principle in the year 1867, this problem remained one of primary importance, for approximately 20 years, until it was realized that a purely electro-dynamic solution of the problem was a physical impossibility. On the other hand, the invention of the transformer (1885) and the discovery of the electro-magnetic rotary field (1885/86) followed by the successful transmission of power from Lauffen to Frankfort on Main marked the decided victory of alternating over direct current, for the time being, at any rate. Thus, the problem of converting A.C. to D.C. in a stationary apparatus was relegated to the background during the nineties of the last century and during the first years of the present one. D.C. required for town systems and tramways was generated, when required, directly or in rotary converters or motor-generator sets and, sometimes, in cascade-connected converters. However, as early as the beginning of the century, a change in this trend could be discerned. The general utilization of carbon brushes and of commutation poles with, in extreme cases, of compensation windings on D.C. machines solved satisfactorily the problems inherent to commutation and made possible the practical application of D.C. at high voltages for traction purposes. To generate currents of this kind, however, there was only the very uneconomical motor-generator set available, because the rotary converter, as far as voltages of 1500 V are concerned, only appeared much later — it being, also, a Brown Boveri product. The electro-chemical industry was also interested in higher voltages, for certain processes. This industry was, however, above all anxious to find some more economical form of power generation than heavy-current D.C. generators, as part of motor-generator sets, this for electrolytic plants to produce aluminium and zinc, which call for big amounts of current at low voltages. This requirement was all the more insistent as the said machines were not always satisfactory for continuous day and night service.

The mercury-vapour mutator or rectifier, as it was first termed, was invented or, rather, discovered by an American, Cooper-Hewitt, by accident, in the year 1902, when he was investigating mercury-vapour lamps. Not only did Cooper-Hewitt discover the mutator but, as early as the period in question, he pointed out the possibility offered through a displacement of the moment of anode ignition of regulating the voltage. Despite this, Cooper-Hewitt's invention did not meet with any sustained success, at the beginning, in America. It is true that some laboratory mutators were built in which the electrodes (anodes) were let into a glass chamber which was then exhausted of air. These glass mutators like incandescent lamps had a limited length of life. Efforts made by big American firms to develop a static industrial A.C.—D.C. converter with a metallic tank from the laboratory apparatus and in which the electrodes would have to be insulated and have a gas-tight fitting, met with no success, at that period. The failure was due to the lack of a satisfactory seal. The result was that the construction of an industrial mercury-vapour mutator with metallic chamber was given up in America about the year 1912.

This was the condition of things when Messrs. Hartmann & Braun of Frankfort a. M. began building mercury-vapour mutators with metallic tanks, in the year 1911, this on the initiative of Dr. B. Schaefer. The latter used mercury to seal the joints between the electrodes and the bushing insulators and between the latter and the tank.

The first mutator plant built to this design was for the Eisengiesserei J. F. Mack, in Rödelheim near Frankfort a. M. It had two mutators giving together about 80 kW and supplied a large number of D. C. motors, being itself fed from the municipal single-phase system of Frankfort. There were also two other mutators put in as spares. The next plants were built in 1912, one a charging station of 20 kW output on the Strassburg electricity supply system and one a 300 kW plant in the Maschinenfabrik Heinrich Lanz in Mannheim. However, the interest evoked by this new type of converter was still very slight, as is proved by the modest number of mutator plants put up during the said period. These plants did not suffice to provide that solid basis of practical experience which was essential to the development of mutators for higher outputs and voltages and for starting manufacture on anything like a large scale. Further, Messrs. Hartmann & Braun, being essentially instrument makers, were disinclined to launch out in the acquisition of the necessary plant for big scale manufacture. For this reason, they sold their manufacturing rights on mutators to Messrs. Brown, Boveri & Co., Ltd., Baden, in 1913 and so Brown Boveri were, really, *the first* firm to take up the systematic development of the mercury-vapour mutator, a development extending from small beginnings, through the original function of the mutator as an A.C.—D.C. converter to the present-day stage of recognition of the mutators as a universal converter holding possibilities for the future, which were unthought of in earlier days. The various articles contained in this number will give information on this subject. It is worthy of note that this fundamental expansion work did not take place on the territory of a big industrial state with ample raw materials and other natural facilities, but was exclusively carried out in little *Switzerland* which, thus, once again took a leading part in an important development of electric power engineering.

SUMMARY OF PAST ACHIEVEMENTS AND FUTURE DEVELOPMENTS.

Before giving a short, fragmentary summary of the past achievements in the mutator field, a few general remarks will not be out of place, here, the first being on the designation "Mutator" introduced by us. As long as the Hg vapour valve was utilized exclusively for converting A.C. into D.C., the expression rectifier was a very good and understandable one. But when these valves began to be used for other kinds of conversion and came more and more to the fore for these purposes, such, for example, as the conversion of D.C. into A.C. or A.C. into A.C. of the same or another number of phases or of different frequencies, the name "rectifier" no longer sufficed. In nearly every language different designations cropped up to cover the various applications of the mutator, some good, others quite incomprehensible, but all with the same weakness that they could not be translated, simply, into other languages. Now as an exporting firm, we had the greatest interest in remedying this state of things and we took the initiative of giving the apparatus the general name of "mutator". By adding thereto A.C.—D.C., for example, or D.C.—A.C. or again A.C.—A.C., the kind of conversion work carried out, in each case, is made plainly clear, and is, above all, easily translatable into other languages. The Swiss Comité Electro-Technique proposed this designation as an international one to the C. E. I. but, unfortunately, without success, up till now. It is remarkable that opposition to the suggested reform came from circles not conversant with the requirements of practical engineering. We are, therefore, all the more pleased to see the designation "mutator" being used more and more frequently in the technical press. We have been using it, now, for a number of years and intend retaining it. All unprejudiced readers, going through the various articles which make up this number, will be struck by the simplicity of the said designation. This will be made still clearer by comparing the German and French editions of this number with the English one.

Some further remarks of a fundamental nature should be made on the subject of the scientific research work which was carried out.

The development of the mercury-vapour valve of big output means the successful solution of very difficult and complicated problems. The processes of which the vapour-filled valve is the seat are more difficult to follow and unexpected in their action than is the case for high-vacuum valves. Many problems have been entirely cleared up, to-day, but others await solution. We are still far from the point where we can design the valves from a physical and constructive point of view so perfectly that satisfactory results can infallably be predicted. These difficulties are especially evident in mutators called on to work in the upper limit ranges of current and voltage such, for example, as those for currents of over 10,000 A and voltages between 30,000 and 50,000 V.

Much trouble and pioneering work will be called for before the construction of high-power, mercury-vapour filled valves has reached the stage of scientific development already attained by standard electrical machinery. Nevertheless, it can be asserted that the mutator attained its present-day stage of perfection quicker than the most audacious designer dared to hope for. Here, as elsewhere, practical experience has been ahead of theory. This should be all the more stressed, here, as the designer found himself, in all his work and for the first time in close contact with very modern problems of physical science.

It should be added that Brown Boveri had already studied very thoroughly the possibilities of using the mutator as a universal converter, long before it was found possible to equip the valves with grid control. The fundamental connections put forward as early as 1913 by Jonas with the object of controlling the arc by means of blocking electromagnets are also valid for grid-controlled mutators. The analogy and basic equivalence of the two kinds of control (the one electro-magnetic, the other electrostatic) were recognized by the electro-technical world and find mention in technical articles of the period. On this subject, Brown Boveri patents DRP 317598, 318288, 331708 and ✙ 107466 are worthy of note, the first of these gives the principles of the connections for converting D.C. into single or multi-phase A.C. by using controlled discharge cells (D.C.—A.C. connection). Here the regulating field is composed of a D.C. component blocking the track of the arc and of an A.C. component freeing the track of the current periodically and which can be regulated in magnitude and phase.

It is satisfactory to be able to assert, in conjunction with the problems brought up in the present number, that even the most difficult ones can be and are solved when an unswerving will to that end is applied to the task and when the manufacturing firm gives the necessary moral support to pioneering efforts, a support which is far more vital than a purely financial one.

When a start is made in the opening up of such a new and unexplored field, where surprises can be expected at every step and unsolved problems have to be met, simplicity in reasoning processes and straightforwardness in argument are important factors, over and above the will to succeed and the courage thereto. In all unexplored fields where considerable speculative reasoning is called for, it is necessary to make sure of all results attained and to strive to reach a real understanding of the complete phenomenon being investigated. If this is not done, development is hampered and finally comes to a stop.

Another important point which can be deducted from what has just been said and which cannot be too strictly adhered to in carrying out research is the following:— In all problems which have not been entirely solved, the investigator should never wilfully place restrictions on his own investigations. The specialist working year in year out in the same field is very liable to make this error. After much labour he finds to his great satisfaction that he has, finally, got a basis according to which the difficulties he has been struggling with can be explained. Then he gets so accustomed to his own theoretical basis that he begins to consider it as an incontrovertible fact and, however astonishing this may appear, forgets that it originated from purely subjective speculation. Many good investigators have fallen victim to this weakness and we know of many similar cases within the scope of our own experience.

Striving to adhere to the above sound principles, we took up the construction and development of the mutator, and venture to assert to-day that we have maintained our leading position in the whole field covered. The vapour-filled valve for converting purposes is an American invention, but one which has been developed in Switzerland after the failure of many earlier and expensive attempts made elsewhere.

When our firm took over the manufacturing rights in 1913, for the building of power valves, this was carried out by a separate company designated as the "Gleichrichter Gesellschaft, Glarus". Manufacture was carried out to orders for this company in our own shops and scientific investigation was pursued in a separate department of our works. Construction and investigation took place under the management of the new company, but sales were looked after by the Brown Boveri selling organisation. Fig. 1 shows the first mutator plant in Switzerland, dating from the year 1914.

The work of investigation being carried out at that period in this new experimental laboratory seemed to all of us extremely mysterious and the laboratory earned the popular name of the "witch's kitchen". As a matter of fact, the investigations in question were of an extremely laborious nature and progress was, consequently, slow. After some years, the whole development work threatened to come to a standstill, perhaps, in part, on account of the non-observance of the fundamental principles enumerated in a previous paragraph.

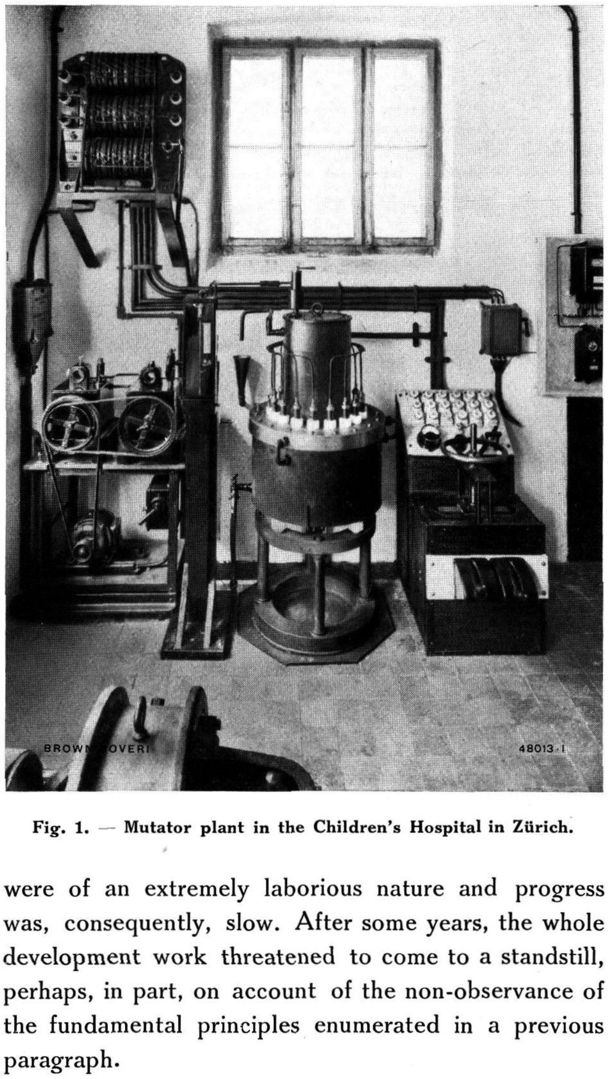

Fig. 1. — Mutator plant in the Children's Hospital in Zürich.

In the year 1919, Brown Boveri took over, themselves, design, manufacture and research. New men were put on the job, who were not hampered by the knowledge of earlier difficulties and, though less cognizant of the new material they had to deal with, possessing the great advantage of a more objective estimation of the whole problem. They were free of traditional lines of thought and filled with good will and unshakable optimism that the problems presented to them could and would be solved.

When we, ourselves, took over the further development of the metal-tank power valve, this static apparatus had more a physical than a sound constructive design. We must, however, render due hommage here to the courage shown by the first pioneers in entering this new field, and consider their unswerving determination as a fine thing, especially in view of the numerous and costly failures already experienced, in other quarters, in this domain of mutator development.

After having worked for a long time on this apparatus, we had to recognize that a number of fundamental questions still separated us from a quick and satisfactory solution of the mutator problem. Above all our knowledge of the physics, inherent to the inner process, proved to be poor and most elementary, indeed. At that time, we had no idea of which influences were of vital and which of secondary importance. The determination of the pressure of the residual gas and its significance, the meaning and importance of gas emissions from the anodes, that of impurities and of ignition substances in the tank and on the closed mercury circuit, the question of the pressure of Hg vapour in general and particularly in front of the anodes, the phenomenon termed mercury sputtering and many other questions were still unexplained. At the beginning, it took us years to reach the point where we were sure that check tests made in our own shops could be reliably repeated, because we did not properly grasp all the factors just enumerated. The recognition of what remained to be explained caused us to form a scientific research body or group to look into the purely physical side of things and get analytical explanations of the phenomena observed. This group quickly got good results and helped developments, considerably. In place of suppositions and assumptions better fundamental factors emerged.

The weak points of mutator design were recognized by us, at a relatively early date. The shape of the various components in these designs was dictated alone by the knowledge of the physics of the mutator available at the period. Hardly any attention was paid to whether the various materials utilized could really stand up, reliably, to the stresses they were subjected to. In this respect we would refer to Figs. 2 and 3. On the other hand materials were made use of which, on account of the physical phenomena, alone, made reliable, continuous operation impossible. All this called for complete redesigning, at least as far as ceramic materials were concerned and certain other materials used as well. The fundamental design was not altered; this is very well shown by a comparison between the old type in Fig. 4 and the new one in Fig. 5.

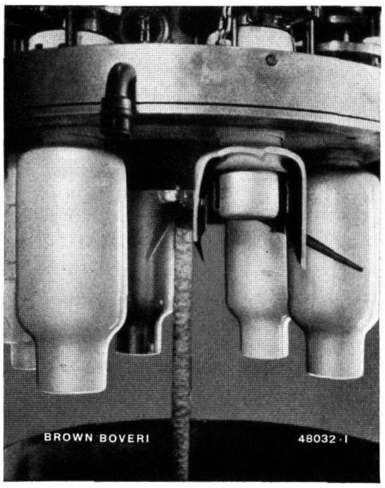

Fig. 2. — Anode sleeves made of porcelain, 1913 design.

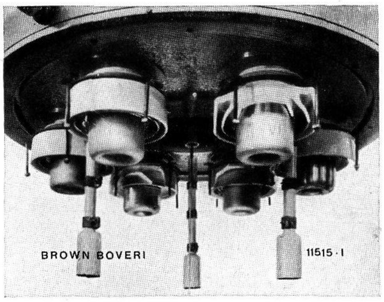

Fig. 3. — Anode insulator, 1917 design.

We were surprised, ourselves, to find what considerable improvement these changes made in the functioning of the mutator. This led us to form a purely technical research group to work along with the scientific one. Contrary to the latter body, which was practically free in its work, the new group was bound by a much more closely-defined programme. Finally, a third group was formed for shop testing, only. To-day, we are sure that we have attained the aim set, thanks to these three groups of workers and their harmonious collaboration.

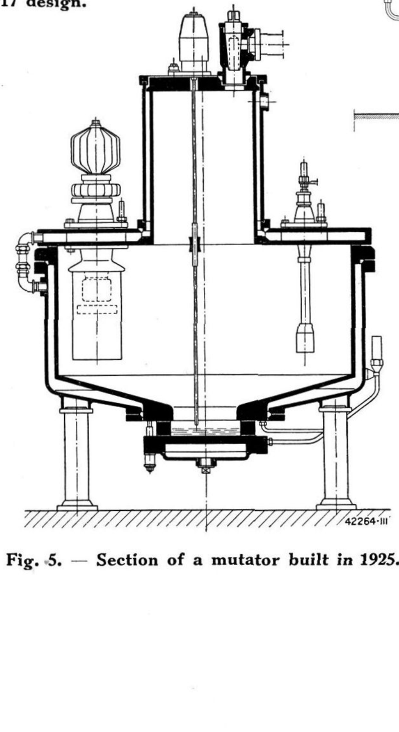

Fig. 5. — Section of a mutator built in 1925.

This is shown especially clearly by the following:— The amount of unsolved problems confronting the scientific group caused it to lose heart after several years of effort. Things went so far, that the leader of the said group suggested to the management to hold up manufacture, for the time being, as it would be a waste of money to continue it. On the other hand, the group working on technical research got so far that it was able to record good progress and hold out hope for future expansion on a big scale; part of this success — however strange it may sound — was due to the work already done by the scientific group.

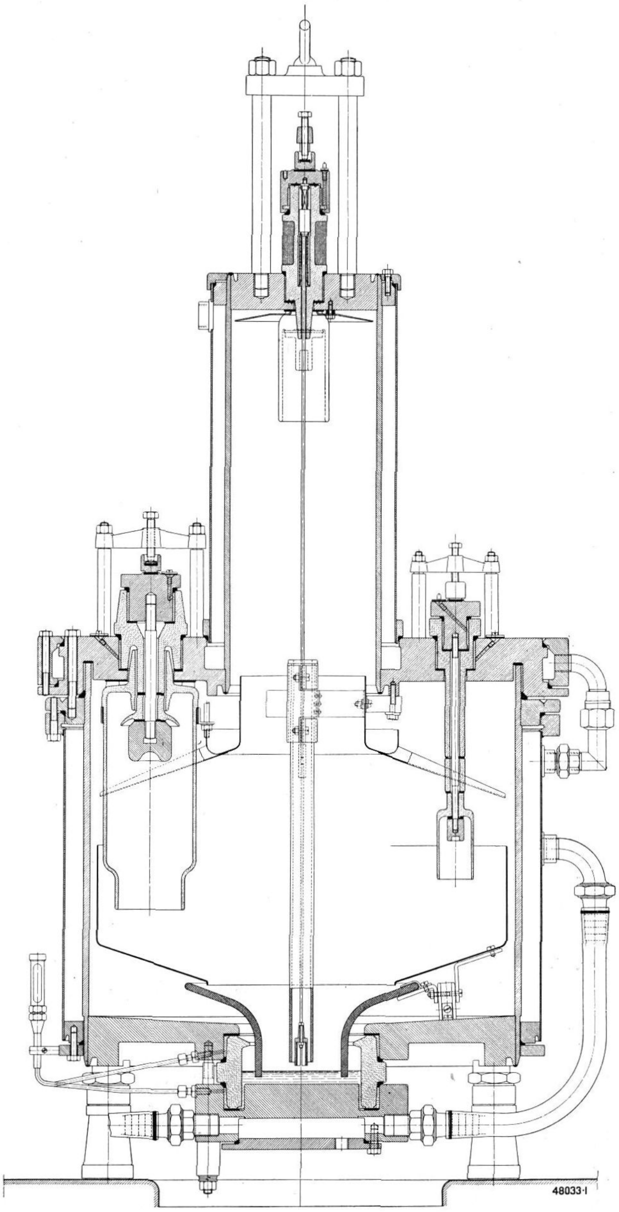

Fig. 4. — Section of a mutator built in 1915.

Thanks to the powerful moral support given by the management of that period, and also by the sales and estimating department and its head Mr. Niggeler, this dangerous crisis was overcome. This happened in the spring of 1924.

The scientific research group was reformed and started work again with fresh courage and zeal. The technical research group overcame innumerable constructive difficulties. Thus, the time of formation for mutators which, even for small units, used to last several weeks, was reduced successfully to one or two days. How right we were to retain our faith in a promising future is confirmed by Fig. 6. This shows, clearly, that the beginning of development on a real business basis dates from just about this period. It is interesting to note that, to-day, mutator plants built to our designs account for far over 100,000,000 Swiss Francs of business.

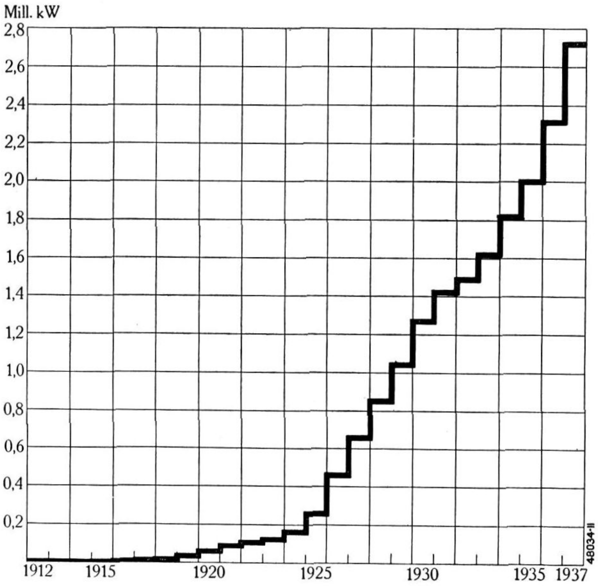

Fig. 6. — Total output of Brown Boveri mutators delivered in the years 1913—1938.

As soon as this progress had been consolidated, attention was turned to bringing out a quite new design and to increasing the range of standard types in the sense of bigger outputs. Obviously, increasing attention was paid to the question of operating reliability under every kind of service condition and overload and the same applies to the attainment of economical operation and to simplicity. So much work and trouble went to the attainment of these objects that a volume could be devoted to the subject. Figs. 7 and 8 show, approximately, the difference in design between the mutator of 1915 and that of 1925.

With the development of the mutator for heavy currents, a series of new problems had to be tackled. Again new materials had to be sought. The voltage drop in the arc showed a great increase as the current became heavier, to our very great surprise and disappointment. Up till then we had believed with the physical experts that the voltage drop in the arc was a constant magnitude independent of the strength of the current. Now, it was clearly shown that the density of the Hg vapour in front of the anodes had a strong influence on the service reliability and on the voltage drop in the arc. These two points are in an undesirable opposition one to the other; if the first was improved the second got bigger and vice versa. However these difficulties were, finally, overcome.

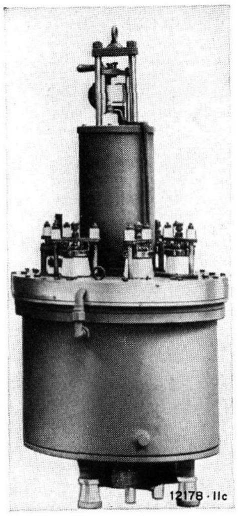

Fig. 7. — Mutator built in 1915.

Some of our friends may have been surprised that the heavy-current type brought out in 1927 and built for 16,000 A, was never used in practice. The reason was a much too big voltage drop in the arc which, as already said, surprised us so much. In the type in question with its big dimensions there are two reasons for the big drop in the arc. One is because of the big current, the other because of the length of the arc column which is too great. As this heavy-current type would be used for chemical plants solely, that is for low-voltage plants, this big voltage drop in the arc makes the whole service impossibly un-

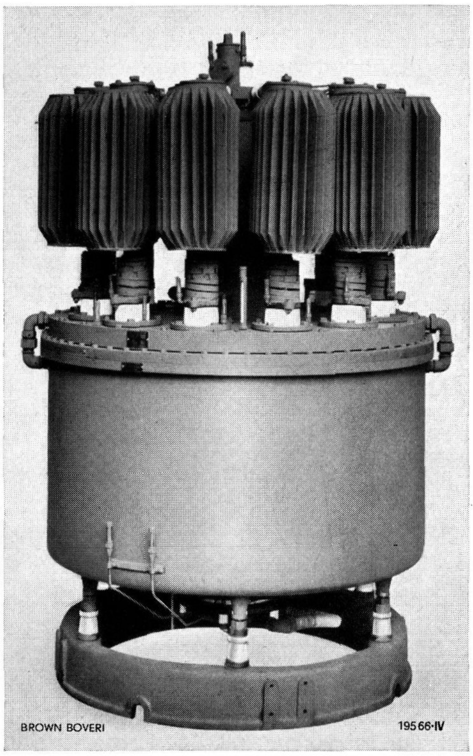

Fig. 8. — Mutator built in 1925.

economical. Further, we must admit that, in 1927, the backfire problem and others were giving us a great deal of trouble. To-day, all these other difficulties could be overcome, but that of the drop in the arc is much the greater trouble. The solution of this problem has not been shelved, its solution is only retarded. The development and present-day position of the types on the market in function of current and years of development, is shown in Fig. 9.

In the year 1925, we began developing grid-controlled mutators and brought out, as early as 1926, our Mr. S. Widmer's most important backfire and short-circuit protective equipment. Without it, reliable operation of heavy-current mutators is hardly to be thought of. At that time, grid-controlled valves were already known but were all very small apparatus. The development of grid-control for heavy-current types was, thus, an entire novelty and, like everything else connected with mutator design, not easy to realize. For this reason, we were about three years at work on grid control for mutators, of over 1000 kW output without making much progress and then, suddenly, the solution of the whole problem was made clear.

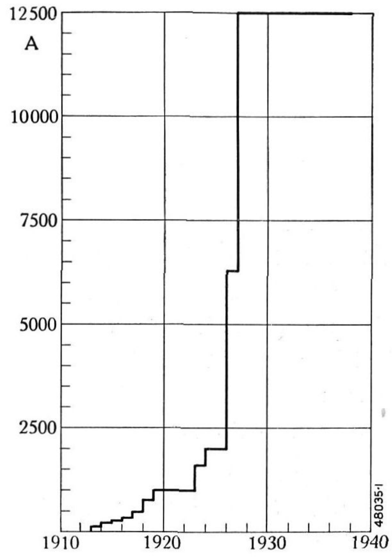

Fig. 9. — Increase in rated current delivered per mutator, during the development period 1913—1938.

After each solution of a difficult task, a time of peaceful development is hoped for. But the demands of practical service generally grant but a short pause to the investigator, especially so in developments in which the initiative has been taken. The stresses in the valves due to short-circuits and backfires are relatively simple, the conditions pertaining to full or to a considerable range of voltage regulation are much more complicated. In conversion from D. C. to A. C., conditions are still more difficult and even more so in the three-phase—single-phase mutator for 50 and 16 $^2/_3$ cycles, used as a system-interconnection converter. The same applies to the high-frequency mutator to feed high-frequency furnaces. All these problems are solved, to-day, as regards testing results and from the point of view of technical mastery of the subject or, if not, they are in process of being cleared up.

New tasks and severe demands had to be faced in designing all the various rotating and static control organs. Step by step progress was made, here, every step being the solution of a separate problem. The mutator with its multiple field of application is a very unique apparatus full of possibilities for the technical world, even though it is often the seat of trouble to the designer.

After having built types of big output up to 4000 V, in 1922/23, the year 1927 saw the appearance of high-voltage types for wireless transmission up to 30,000 V at about 1000 kW. Satisfactory results were obtained, fairly quickly, up to the 15,000 V range, but, above that range, unexpected difficulties were encountered, which, fortunately, are solved to-day. All the factors entering into high-voltage technology had now to be applied to a mutator design and, of course, specially studied to that end. As the field of direct current power transmission at high D. C. voltages always seems to us a most promising one, we continue our efforts in this direction with tenacity and, indeed, all our efforts have not been too much. Despite untiring work, developments remained stationary for three years at the 30,000 V mark. This was, then, a similar position to that we found ourselves in with the development of grid control on heavy-current mutators and, just as in the latter case, success came here suddenly, as well, allowing us to go up to 60,000 V, practically at once, and to attain an output of about 2000 kW.

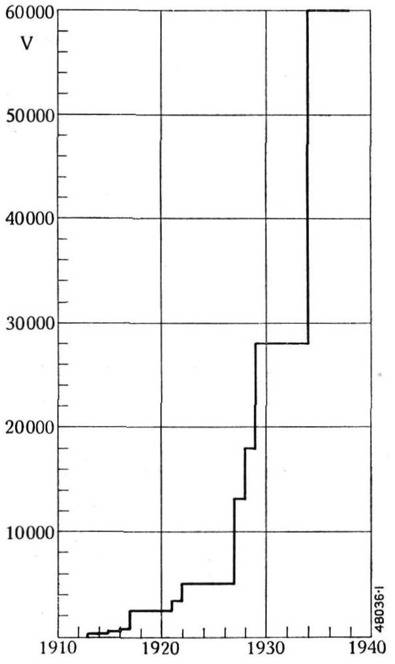

Fig. 10. — Increase in the D. C. voltage per mutator during the development period 1913—1938.

Anyone who has been closely connected with research work will understand the pleasure which is felt by the research personnel when a long-sought for aim is finally reached. All the troubles and disappointments experienced are quickly forgotten. We think it is no exaggeration to say that an inner joy is experienced here equal to that of an artist who sees his labours crowned by the creation of a masterpiece.

The voltage range of 60,000 V which was reached with our mutator was limited by the insulation. Fig. 10 gives an interesting illustration of the development of mutators according to voltage. To-day, we are convinced that 60,000 V is far from being the highest voltage attainable. However, there will be great difficulties to be overcome when it is desired to increase the output up to what will be a necessary minimum of from 15,000 to 20,000 kW per mutator, at these voltages. Such developments and increases cannot be attained yet, either in calculation or otherwise. A great deal of analytical and, unfortunately, empirical work as well will have to be done. The more is known and understood the more modest becomes the investigator; the more the points of view held by others are given due consideration, the easier it is to dominate any false sense of superiority resulting from real or supposed successes. If, as has been done so far, we are successful in keeping up the keenness of our collaborators, while fostering a sense of self-criticism as well, this last big problem like many others will certainly find a solution, in due time.

In the preceding paragraphs, we have given a short summary of the development of the mutator as followed in our works. Intentionally, all details have been left out. It may, however, interest those readers who take an interest in what might be termed historical retrospect to learn the manner in which the constructive development took place. To this end, the various mutator designs of the years 1913—1938 are reproduced in Fig. 11. This summary is interesting as it shows how, in the last 25 years, the fundamental design, that is the characteristic lines, of the Brown Boveri mutator has been maintained. Fig. 11 shows, further, that our mutator passed through three development stages. The first stage, Fig. 11 a, in the years 1913—1919 with units up to 1000 A, then, in the years 1920—1927, the second and big step forward, Fig. 11 b, with mutators up to 12,500 A; finally the third step, Fig. 11 c, that is the present-day mutator as remodelled in 1935 and incorporating every improvement based on shop, laboratory and practical experience gained up till the present time.

The development of the mutator accessories will, now, be touched on, very briefly.

As the mutator should work with a minimum of residual gases, deaerating and measuring apparatus is essential.

Early, that is to say in the first development period, a vacuum-measuring instrument of a quite new type was brought out. It has been described in the Brown Boveri Review, in detail[1]. This was a very valuable innovation and of considerable importance.

A first, rotary and reciprocating pumps were used to evacuate the mutators, these being with or without a sealing liquid. As tanks became bigger this solution proved unsatisfactory. The qualities of the high-vacuum mercury-vapour pump, which had been brought out in the meantime, were quickly recognized. Our own high-vacuum pump, as built to-day, is based on the original one, a great deal of development work and painstaking research going to this task. In connection, herewith, we designed a preliminary vacuum pump. Together these pumps form the complete device for evacuating all cylinders and they have been perfected so that they meet every requirement. [1]

As a further accessory, the devices for the cooling of the mutator should be touched on. There were no separate problems to be solved, as regards the different methods of cooling. The most important point is the distribution of temperature in the mutator tank, itself. As cooling systems, fresh-water cooling or closed-circuit cooling making use of fresh water as cooling agent or of an artificial air draught are all used, each according to local conditions.

It may be of interest to mention that, for a few years past, we have been building small metal-clad mutators with air cooling only, that is without water. There are many plants working to-day with these new air-cooled mutators of small output. They have been developed up to 1600 A; examples are given in Figs. 12 and 13. Air-draught cooling, only, is used both for the static pump and for the mutator, itself, in these new units.

As regards mutators without pumps, we have given our full attention to this question. There can be no question that the small mutator without a pump is an apparatus offering a certain interest. For mutators of bigger output, we hold, however, that the plant without pumps is an error. Even for small units, the future must decide which is best: — poor utilization of available mutator material and no pumps or highest possible degree of material utilization and intermittent

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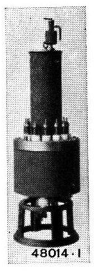
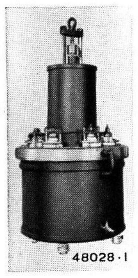
[1] See reference list of publications.

Figs. 11a, b, c. — CONSTRUCTIVE DEVELOPMENT OF THE BROWN BOVERI MUTATOR TYPES IN THE YEARS 1913—1938.

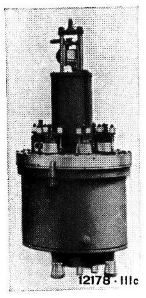
ig.
1a.



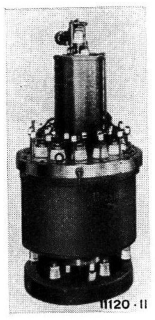
1913
150 A



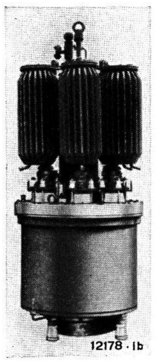
1914
200 A



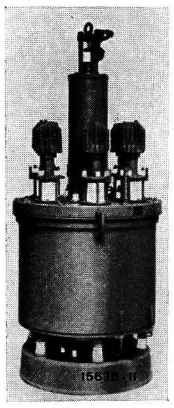
1915
250 A



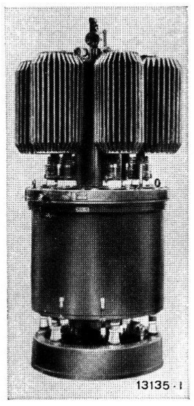
1916
400 A



1917
500 A

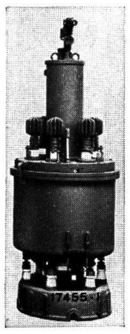


1918
750 A

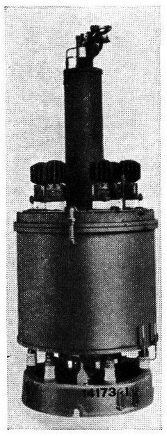


1919
1000 A

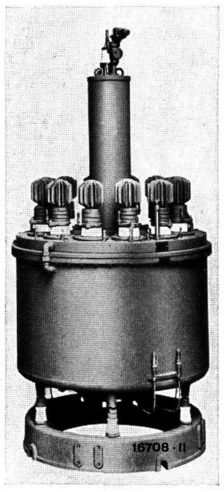
ig.
1b.



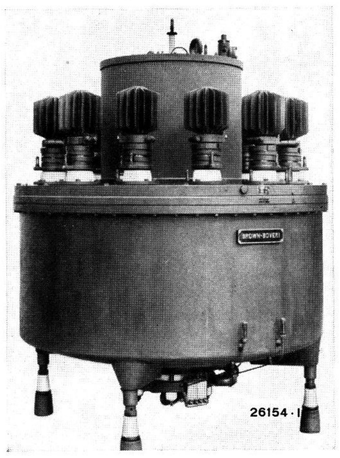
1923
500 A



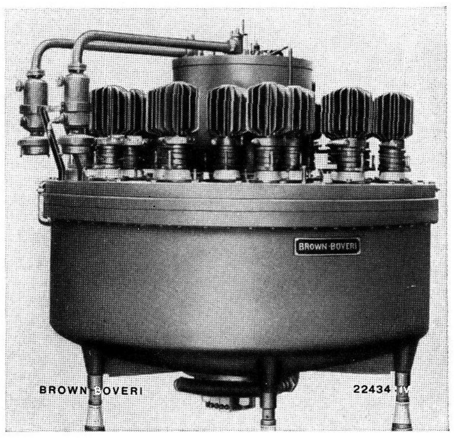
1920
750 A



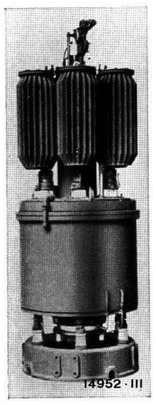
1923
1600 A



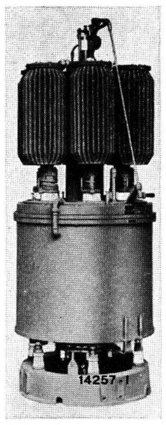
1926
4000 A



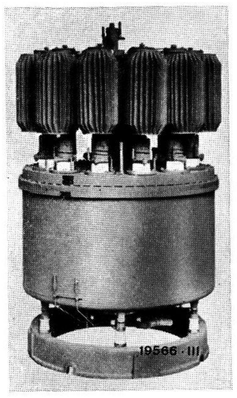
1927
8000 A



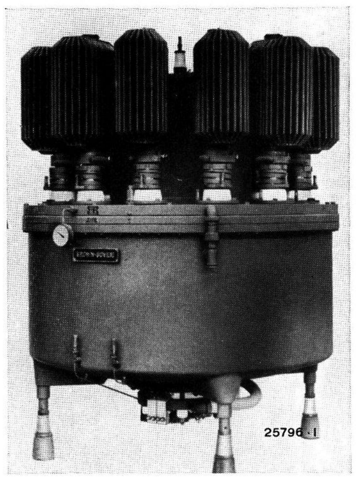
1921
600 A



1920
1000 A



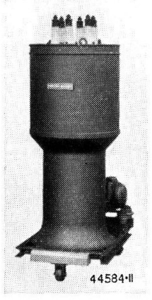
1924
2000 A



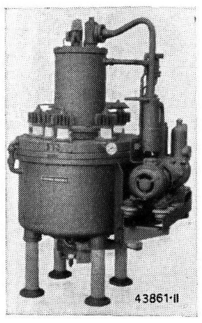
1926
6300 A

1927
12500 A

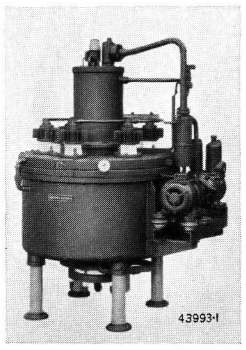
ig.
1c.



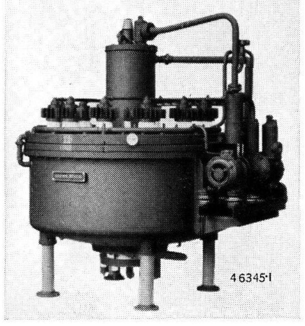
1935
400 A



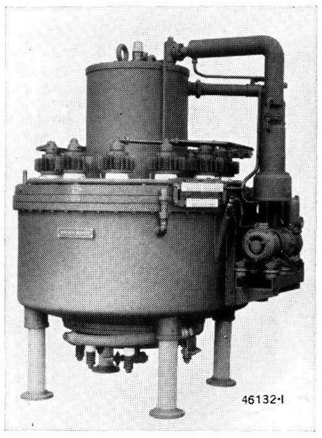
1935
800 A



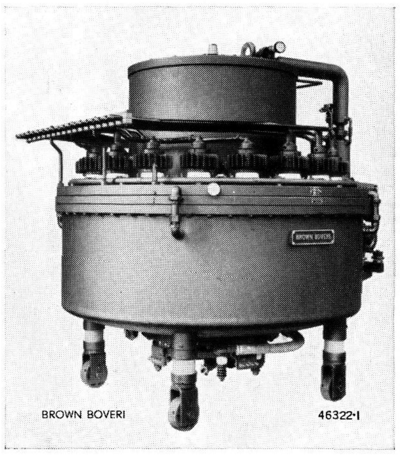
1935
1250 A



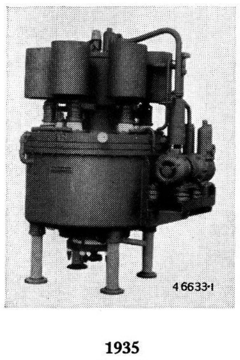
1935
2000 A



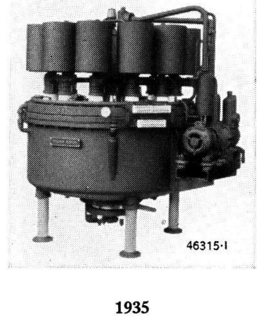
1935
4000 A



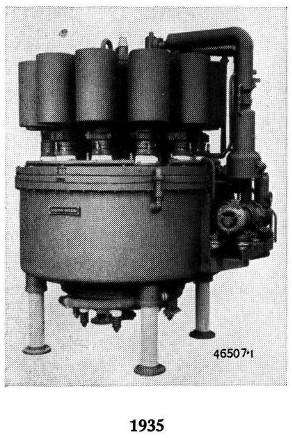
1935
6300 A



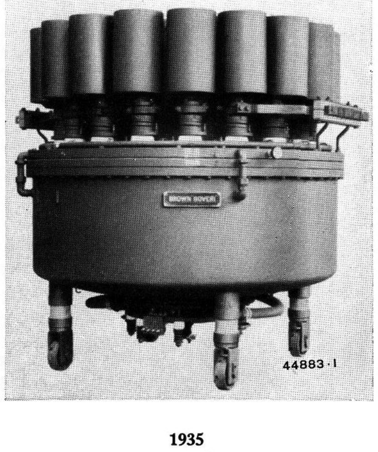
1935
1600 A



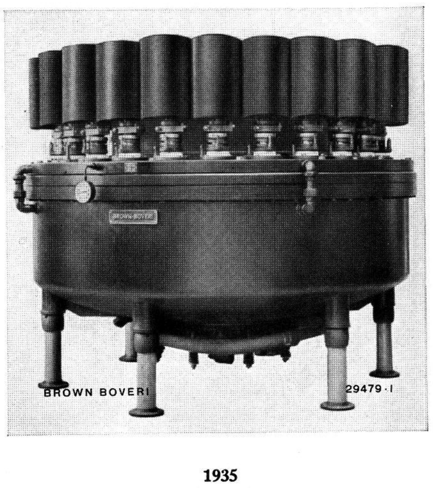
1935
3150 A



1935
6300 A



1935
8000 A



1935
12500 A

Supplement to The Brown Boveri Review No. 5/6, 1938.

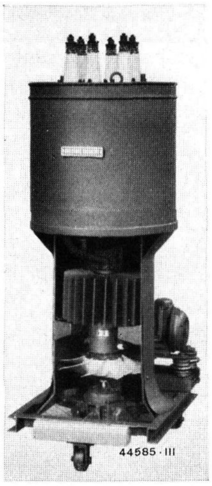


Fig. 12. — Mutator Type A 06, of 1935 design.

pump service; in other words low first costs or high first costs.

The transformer plays a big part in mutator plants. At first, there were certain difficulties encountered, inherent to calculation and design, but these were overcome, relatively early. Our collaborators did some exceptionally ingenious work in this field. We would only mention, here, J. Kubler's brilliant idea of introducing an absorption choke coil which acts so advantageously on the D. C. voltage drop and on the power factor. It is a matter of great satisfaction to see how well our mutator transformers have behaved in practice. In spite of the relatively numerous backfires at starting up the first mutators built for big outputs which all had to work without grid control, not one transformer proved defective: a splendid testimonial to the transformer designers.

A modern heavy-current mutator plant transformer is a real work of art. A convincing proof thereof is furnished by Fig. 14, which shows a relatively simple mutator transformer design.

The automaticity of mutator-plants did not offer any special difficulty. The problems to be solved were, mostly, those of choosing the most suitable connection and construction. Every kind of mutator service can be rendered automatic.

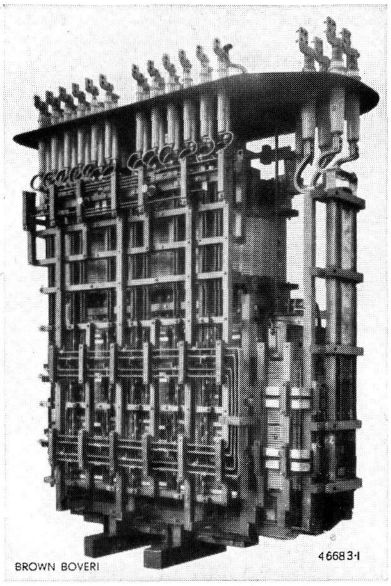


Fig. 14. — Transformer for heavy-current mutator set.

Having touched on the development of the important parts of a mutator plant, it will be of interest to see what mutators have done for the various branches of industry and traction where they have been utilized.

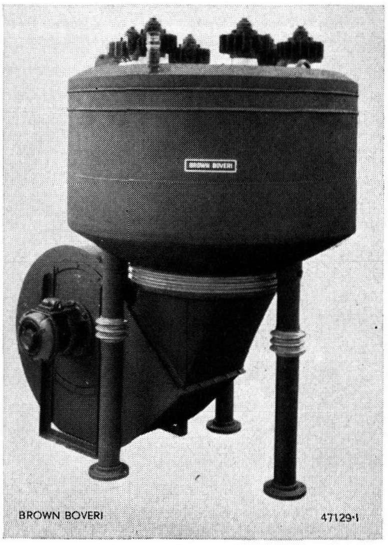
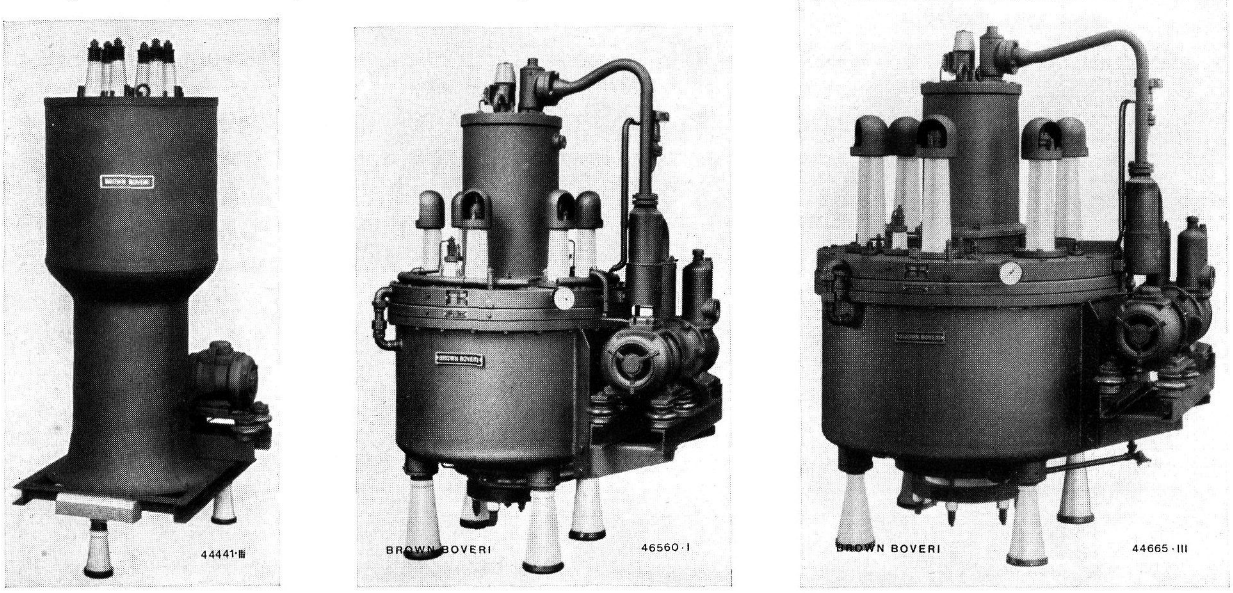


Fig. 13. — Mutator Type AL 36, of 1938 design.

Above all, and in many countries, they have been the prime factor in accelerating *standard-gauge railway electrification.* This even applies to countries having their own rich coal deposits. The Southern Railway of England is a case in point. It has well over a hundred mutators of the Brown Boveri type in operation and traffic has increased considerably since electrification was inaugurated, and most satisfactory financial results have been recorded, according to the publications of the railway authorities. In many other countries such as Italy, in particular, and in France, Holland, Australia, South Africa, etc. railway electrification by D. C. has been greatly furthered thanks to the mutator. The possibility of being able to utilize the frequency used in industry, the elimination of a second network over the country, the convenience of being able to connect up to the available power supply system are all great advantages of D. C., the use of which was first made economically advantageous by the mutator. It is astounding how clearly the former co-founder of our own firm, Dr. W. Boveri, prophesied all these developments, as early as 1915 during the discussions on the electrification of the Swiss railways. In so doing, he was well ahead of the stage of technical development reached at the period at which he spoke. All the requirements of traction service are entirely fulfilled by the mutator. Maintenance of voltage, compounding, recuperation, etc. have all been mastered and put into practical use, by us, for a considerable period, now, and all this for the handling of big outputs. The magnitude of the voltage used is no problem at all, to-day:— the higher the better. All overload problems are solved, as well. It is impossible to think of a better and more economical traction converter than the mutator. It is a pleasure to be able to state that, in every case where we were called on to collaborate in big electrification schemes, the plants delivered by us were never *only* experimental ones, but were usually followed by repeat orders. Brown Boveri mutators are to be found everywhere and we are continually being favoured with repeat orders. In various cases, one and the same railway system will have more than a hundred Brown Boveri mutators, a very satisfactory testimonial to the pioneer work accomplished.



Figs. 15a, b and c. — Standard types of high-voltage mutators.

There is no doubt that mutators have conquered or are in process of conquering the industrial chemical field, to-day. As early as 1917, we made a very modest beginning with an electrolytic plant. Further experiments followed; a very daring step, considering how matters stood at that period, was the 16,000-A mutator plant of the year 1927, for the Chippis station of the Aluminium Industrie A.-G. in Neuhausen (Switzerland). We gained our first experience with heavy-current mutators in this and in another plant of the same company and finally brought the problem to a successful solution. We desire to say here that the sympathy and patience manifested by the staff of the above-mentioned industrial enterprise have proved of the greatest assistance to us in our efforts to develop the high-current mutator and we would like to express our profound recognition of this, here. To-day, there are more than two dozen electrolytic plants built or on order with Brown Boveri mutators, each with a total current of between 20,000 and 105,000 A; we can also point to double and triple repeat orders for mutators in this field of application. In the space of a single year, heavy-current mutator plants with a total output of 240,000 kW were put into service, of these two are quite exceptional plants in Canada, that is to say stations put up at many thousands of kilometres from Baden. One of these was a repeat order and the other was a consequence of the excellent results attained with the first plant. These orders are a recompense for the time and care lavished on the development of the electrolytic mutator.

The high-voltage mutator for wireless-transmitting stations is less remarkable on account of its size than because of its technical significance (Fig. 15). Brown Boveri were far ahead of other firms in this field when they first put in mercury-vapour filled mutators and they have installed by far the biggest of these units as far as voltage and output goes. Many of the best-known transmitting stations have Brown Boveri mutators. The greatest service rendered to us by this development, however, was to keep our attention on the development of high-voltage D.C.

The following table shows the deliveries in kW outputs, made up to date, of Brown Boveri mutators for various fields of application.

Traction	1,680,000 kW
Chemical plants . .	650,000 kW
Light and power . .	410,000 kW
Wireless stations . .	40,000 kW
Total	2,780,000 kW

A fine result when the doubts expressed in many quarters, at the beginning of mutator developments, are remembered. It is amusing to read again, to-day, all the prophesies made and points of view expressed 15 or 18 years ago, in the discussions which always followed our lectures on mutators delivered in Europe and the United States. Very prominent men in the technical world were blind to the great possibilities and importance of the mutator. This makes the successful development of the apparatus a matter of still greater significance to us; it shows that good pioneering work demands courage and a proper measure of audacity.

The mutator has now gained a recognized position in industry. It is making its position still more secure, to-day, and, in recent times has found a field of application in mining and metallurgical plants. Here it tends to replace the Ward-Leonard machine. This presents no difficulties from a technical point of view and the question is a purely economical one. In the place of the D.C. motor with commutator in the Ward-Leonard circuit, a valve-motor without commutator can be put in. All these possibilities have been thoroughly tried out in our testing department. The heavy wattless power called for is, perhaps, the biggest hindrance.

The three-phase - single-phase mutator is another interesting industrial application used for supplying a coreless induction furnace and for similar chemical and metallurgical objects. Here, it is a question of converting three-phase current at ordinary, industrial frequency into single-phase current at 1000 to 20,000 cycles. A plant of this kind is now under test operation.

An application of the mutator, of considerable importance is the static interconnection of systems. We and others have expended an enormous amount of thought on this complicated problem. From the start, we gave up the idea of double conversion and found that the best solution was to be sought in a single mutator, both for three-phase — single-phase and three-phase — three-phase interconnection. Only one plant of this kind has been put into service, so far. It is on trial operation for the flexible interconnection of a balanced three-phase, 50-cycle system and a sinusoidal single-phase $16\,{}^2/_3$-cycle system. All fundamental assumptions have proved correct in this plant, but some slight improvements will be necessary, before it gives entire satisfaction.

A flexible three-phase — three-phase system interconnection plant is building, on order. We consider this application of the mutator as one of the most important ones. The independence of large power stations decreases with increasing interconnection, but can be restored if the flexible three-phase — three-phase method of interconnection is resorted to.

Finally, mention must be made of high-voltage D.C. transmission. It was already touched on when we spoke of the development of the high-voltage mutator and said that voltages of 60,000 V and more would, certainly, be reached. We think that mutator units of 50,000 V and about 300 to 400 A could be taken as standard types, to-day, if the question of D.C. power transmission were considered. Six of these in series with earthed middle point would form an interesting installation and would mean a transmission line carrying 90,000 to 120,000 kW. As has been said earlier, the conversion, at the receiving end, from D.C. into A.C. offers no new difficulty. This is no utopian idea, to-day, but is one for which only an opportunity is awaited to allow of practical experiment. For the moment, however, the chances of such an opportunity presenting itself appear extremely remote. We require about 20,000 kW with about 22,000 kVA. We may find one of our clients who is sufficiently interested to collaborate with us in these tests. For the moment we are building a plant on these lines but to small scale for The Swiss National Exhibition of 1939. Distance 25 km, D.C. voltage 50,000 V, power 500 kW. Rather a small plant but, certainly, a pioneering effort.

We now come to the end of these rather fragmentary retrospective notes. We can truthfully say that we have always held a leading position in mutator developments, that is in the development to higher outputs and voltages, in the introduction of controlled grids, and utilization of grid-controlled apparatus. We trust that we shall not be thought the less of for having sung the praises of the mutator, and for having stressed our own particular performances in this field. These paragraphs have been written as a sincere expression of satisfaction on a successful achievement and as one of thanks to all our collaborators who have supported our efforts.

Our hearty thanks go to our mutator clients, as well, especially to those who gave us support and confidence in the period of first development and helped us by their understanding of difficulties and by their many concessions, to develop the mutator. It is a real satisfaction to see the pioneering spirit alive, as ever, in the technical world.

(MS 610) *Schiesser. (Mo.)*

SOME FUNDAMENTAL PHYSICAL CHARACTERISTICS OF THE MUTATOR.

Decimal index 621. 314. 65.

The rectifying action of the arc is described in this article and an explanation is given of why mercury is used as material for the cathode. The rectifying action is caused by the electrons being able to pass over from the gas of the arc to the electrode, but, in general, not being able to make the transition in counter sense. The use of mercury as material for the cathode is due to the fact that this material must be in a fluid state so that it can flow back to the cathode after condensing on the cooling (condensing) surfaces.

THE object of this article is to discuss two questions:—

1. What is the rectifying action of the arc?
2. Why is mercury chosen as cathode material?

1. RECTIFYING ACTION OF THE ARC.

The current conductivity of an arc is chiefly due to the electrons and is, thus, similar to that of a metallic conductor. As regards the passage of the current from the metallic conductor to the arc and vice versa, there is, however, a fundamental difference between metal and gas. While, on the one hand, the current carrying electrons pass without hindrance from the gas to the metal when they impinge on the surface of the latter, they do not pass from the metal to the gas, under ordinary conditions. The latter passage is only possible when certain conditions are fulfilled on the surface of that electrode from which the electrons should pass to the gas — that is to say the cathode. Thus, for example, the cathode must be at a high temperature or else a cathode spot must be created. The emission of the electrons from the cathode due to high temperature (thermionic emission) is a phenomenon very similar to the giving off of molecules of steam from the surface of a liquid, that is to say evaporation, which is, also, much helped by increasing the temperature. The thermionic emission of the electrons from the cathodes is made use of in the hot cathodes of radio tubes and in hot-cathode mutators. The cathode spot is a strongly pronounced and very luminous concentration of the arc at the spot where the current passes from arc to cathode. It has not been absolutely determined, so far, what the quality of the cathode spot really is which causes the electrons to be emitted by the cathode. The temperature of the cathode, however, is not an essential point here, because the emission of the electrons from the cathode spot also takes place when the cathode is cold, as, for example, in the case of a mercury cathode. In mutators having a mercury cathode, the emission of the electrons from the cathode takes place with the help of a cathode spot. If an alternating-current voltage is applied to two electrodes of a discharge chamber such, for example, as a mercury-arc mutator and if the emission of the electrons from one electrode is made possible by means of the creation of a cathode spot constantly maintained, or else thermally with the help of a high temperature, while no such measures are applied to the other electrode, the current can only flow through the apparatus in one direction and a rectifying action takes place. In a standard-type mutator, with several anodes and a mercury cathode, a cathode spot is only ignited on the mercury cathode and kept up by means of an excitation arc. Thus, the anodes are able to take up electrons but are unable to give any off, which means that they can only carry current when they are at a more positive potential than the cathode. The rectifying action of the mutator is not, thus, based on a special property of the mercury vapour but on a general dissymmetry in the transition of the electric current between a gaseous and a solid or fluid conductor.

2. PARTICULAR SUITABILITY OF MERCURY.

The phenomena of which the cathode spot is the seat cause active sputtering and evaporation of the cathode. The result of this is that, on the one hand, cathode material is used up and, on the other, the walls of the chamber become covered with cathode material. Therefore, the cathode must be in a fluid state in order that the sputtering and vaporized cathode material may flow back, constantly, to the cathode, from which it issued, and does not remain deposited, in ever thickening layers, on the walls of the chamber. On the other hand, the material of which the cathode is made must be an element and not a chemical compound because, in the latter case, it would decompose chemically in the arc. Now, mercury is the only material which satisfies both conditions; it is fluid at the usual room temperatures encountered and it is a chemical element. Further, the vapour pressures of mercury under the usual temperatures encountered on the walls of a mutator chamber are in a very advantageous range as regards the formation of the electric arc (0·001 to 0·1 mm Hg). Both at higher and lower gas pressures, the voltage drop across the arc, and, therefore, the losses in the mutator, would be higher. Thus, it is not necessary to cool the mutator below the room temperature in order to keep down the pressure of the gas, nor is it necessary to add a filling gas apart from the mercury vapour, which would, obviously, be a complication.

(MS 591) *R. Risch. (Mo.)*

SOME TESTS ON THE INFLUENCE OF THE DENSITY OF THE Hg VAPOUR BEFORE THE ANODE, ON THE VOLTAGE DROP ACROSS THE ARC AS WELL AS ON THE BLOCKING EFFECT OF THE GRIDS, IN THE CASE OF MERCURY ARCS.

Decimal index 621. 314. 65.

The results of tests, set forth in this article, show that the voltage drop in the mercury arc depends on the density of the mercury vapour in the area enclosed by the sleeve and, notably, in proximity to the grid and to the anode. The temperatures of the saturated vapour, of the anodes, of the grids and of the sleeves exercise an influence on the voltage drop across the arc and also influence the blocking effect of the control grids.

OTHER articles in this number show that the density of the mercury vapour in front of the anodes of mutators plays an important part in the tendency of the said mutators to backfire. Further, other tests carried out show that the density of the mercury vapour has a decisive influence on the blocking effect which is exercised by the grids, in the case of mutators equipped with controlled grids. Both in the interest of attaining great security against backfires and efficient blocking effect of the anode grids, it is advisable to try to attain as low a mercury-vapour density as possible in the area near the anodes and grids. The tests described in this article show, however, that it is not admissible to reduce arbitrarily the density of the mercury vapour in the area enclosed by the sleeve and, notably, in proximity to the anode and grid, this because the voltage drop across the arc is considerably increased when the vapour density is greatly reduced.

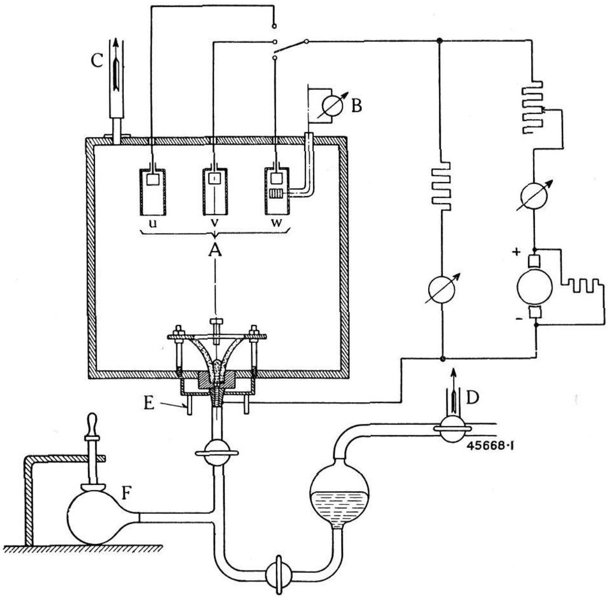


Fig. 1. — Layout of testing equipment and diagram of connections.

A. Anodes.
B. Thermo-elements.
C. To the pump.
D. First-stage vacuum.
E. Cooling.
F. Rubber bulb.

The testing equipment. An anode plate, carrying three anodes arranged on the arc of a circle is cemented on to a glass cylinder. One of the three anodes is equipped with a controlled grid, according to Fig. 2. The grid is insulated from the anode sleeve and has an incoming lead with special bushing passing through the anode plate. The anode sleeve, itself, is equipped with a heating spiral of chronin wire (chromium nickel wire) in order to allow of heating up the sleeve by any additional amount desired. The heating coil is provided externally with a cylinder of nickel sheeting as protection against radiation. The temperature of the grid is measured by thermo-elements. The other two anode sleeves have neither grids nor heating winding but are, otherwise, of exactly the same dimensions as the first one. As is seen in

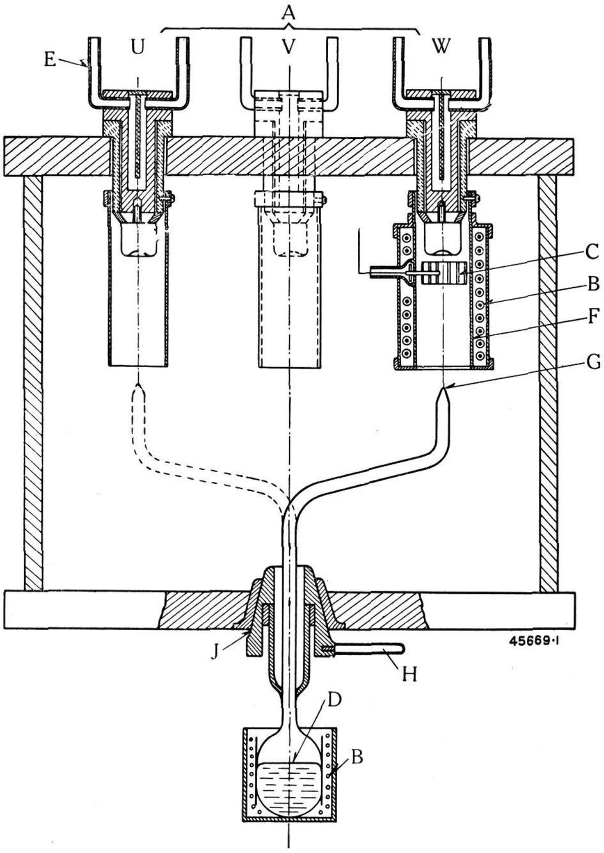


Fig. 2. — Anodes, grids and inlet nozzle for Hg vapour.

A. Anodes.
B. Heating coil.
C. Grid.
D. Mercury.
E. Cooling.
F. Sleeve.
G. Nozzle.
H. Handle.
J. Ground-in fitting.

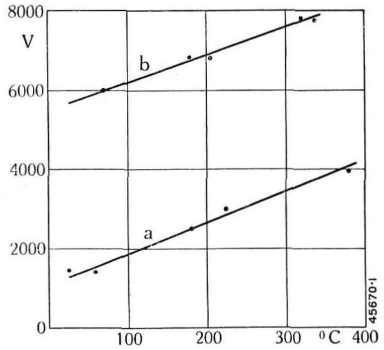


Fig. 3. — Ignition voltage of the anode W in the case of a negative grid voltage of 50 V, in function of the grid temperature.

(a) With injection of Hg vapour.
(b) Without injection of Hg vapour.

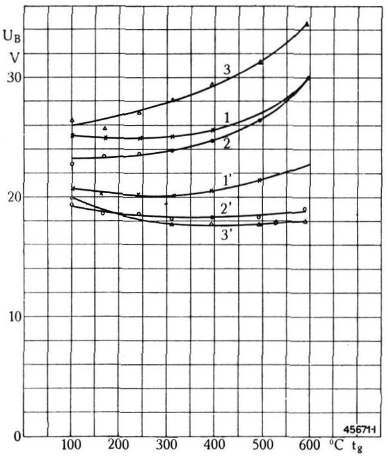


Fig. 4. — Voltage drop across arc in the case of anode W, with fixed cathode spot, with and without injection of Hg vapour, for various anode currents, in function of the grid temperatures.

1. Anode current 10 A
2. „ „ 20 A } without injection of Hg vapour.
3. „ „ 30 A

1′ Anode current 10 A
2′ „ „ 20 A } with injection of Hg vapour.
3′ „ „ 30 A

Fig. 1, the cathode is composed of a piece inserted and hollowed out conically with an insulator fitted over it, which allows the cathode spot either to remain fixed or to move freely in the quarz hollow, according to the level of the mercury. Further, as seen in Fig. 2, there is a nozzle, which can be moved round and which is mounted beside the cathode. The object of this nozzle is to allow of injecting mercury vapour into the anode sleeves, the said vapour being drawn from an electrically-heated vapour boiler. This layout allowed of carrying out the following tests:—

(a) Observations and measurements regarding the blocking effect exercised by the control grid, either with or without injection of mercury vapour into the cold and hot sleeve.

(b) Measurement of the voltage drop in the arc with D. C. applied to the anode equipped with a grid, this at various grid and sleeve temperatures, with moving or fixed cathode spot and with or without injection of mercury vapour through the nozzle.

(c) As under (b) but on the anodes which have no grids.

The results of the measurements carried out according to (a) are reproduced in Fig. 3, and those carried out according to (b) and (c) are given in Figs. 4, 5 and 6. As Fig. 3 shows, the anode current ignites under a negative grid voltage of 50 V, constantly maintained, at increasingly higher anode voltages the higher the temperatures of the grid and sleeve are maintained. If vapour is injected into the sleeve by means of the rotary nozzle, the anode current ignites, in the whole range of temperatures investigated, under very much lower anode voltages. In Fig. 4, the voltage drop across the arc is shown in function of the grid temperature, in the case of the anode equipped with a grid, and this with or without injection of mercury vapour. This measurement shows the influence of the temperature of the grid to increase the voltage drop in the arc along with the influence of the injection of mercury vapour to reduce the said voltage drop, this for arc-current strengths of 10, 20 and 30 A and for a fixed cathode spot. The reduction of the voltage drop in the arc by injection of mercury vapour is shown in Fig. 5 in function of the arc-current strength with the grid temperature as parameter. In order to illustrate the part played by the grid in the increase of the voltage drop in the arc, an anode without grid was experimented with at various sleeve temperatures, with and without injection of mercury vapour. Fig. 6 gives the results obtained.

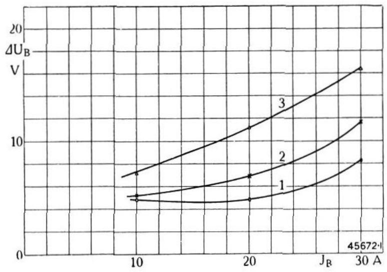


Fig. 5. — Reduction of the voltage drop across the arc, in the case of anode W, by means of injection of Hg vapour into the sleeve, for different grid temperatures in function of the arc current.

1. Grid temperature 200° C.
2. „ „ 400° C.
3. „ „ 600° C.

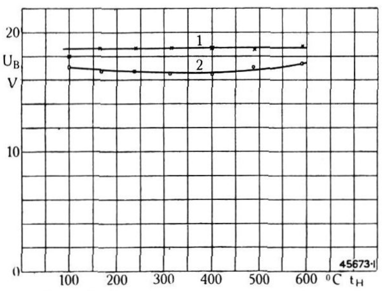


Fig. 6. — Voltage drop across the arc in the case of anode V, with fixed cathode spot and in function of the temperature of the sleeve.

1. Without injection of Hg vapour.
2. With injection of Hg vapour.

Conclusions drawn from these tests. By artificial injection of mercury vapour into the space within the anode sleeve, it was possible to prove that increasing grid temperatures act to reduce the density of the mercury vapour, this is proved because the influence of the grid temperature on the voltage drop across the arc was equalized by injecting mercury vapour. This fact is important as regards the blocking effect of the grid because a hot grid blocks more strongly than a cold one. As is shown by other tests carried out with the same apparatus, the automatic glow discharge, which builds up between grid and anode under high anode voltages, can be substantially suppressed by means of correspondingly high grid and anode temperatures. On the other hand, in the case of low temperatures in the mutator tank, that is to say low mercury-vapour densities, with high grid and high anode temperatures, the vapour densities in the control area can be so low that the anode current goes on burning momentarily with an increased voltage drop in the arc.

(MS 593) *E. Kobel. (Mo.)*

SOME CAUSES OF BACKFIRES AND THEIR SUPPRESSION.

Decimal index 621.314.65 : 0046.

Some of the causes of backfires are examined in this article as well as those conditions pertaining to the anodes and anode sleeves which are of importance to the operation of a mutator.

WHEN backfires occur, which is a rare occurrence in mutators, to-day, they no longer cause any practical trouble to service, because they are so quickly extinguished by the grid protection devised by Brown Boveri that service interruptions are impossible. However, mutators are being constantly developed in the shops, for bigger outputs and higher voltages, and it is natural under these circumstances that the frequency with which backfires occur in these new experimental units tends to increase to a degree which cannot be tolerated in practical service. The discovery and suppression of the causes of backfires is, thus, still one of the most important subjects of investigation. The backfire phenomenon itself is well known and it is summarily described, here, taking as example what occurs on a mutator with two anodes (Fig. 1). During one half wave of the transformer voltage U_u, the cathode spot 3 being ignited, the current flows from 0 to 2—3—4—5 and back to 0, during which time a mercury-vapour arc burns between positive anode 2 and cathode spot 3, which arc contains per volume unit about as many electrons as ions (quasi neutral state). Electric particles are emitted by the arc and stray in all directions so that they also appear in the sleeve 6′, where a break-up takes place in front of anode 2′, in such a manner that the positive ions accumulate in front of the said anode while the electrons are repulsed and prevented from passing over the dotted limit line. There is twice as much voltage between 2 and 2′ as between 0 and 2 and it is a particularity of this electric valve that this entire voltage, named blocking voltage, is concentrated on the positive electric layer. Speaking generally, this so-called space charge forms an insulating layer with very steep potential gradients (up to more than 100 kV/cm). Thus, anode 2′ practically blocks the passage of current, entirely, under ordinary conditions, only allowing some mA to pass, the latter being caused by diffused positive ions. These ions are accelerated by the blocking voltage between the limit layer and the anode and impinge at high velocity on the said anode. When a backfire occurs, the intensity of this minute and fairly evenly distributed return current I_R can swell up to a short-circuit value of some ten thousand amperes, this when a cathode spot is formed on 2′, for any reason. If, now, the mutator is not cut out within a few thousandth parts of a second, the effect on the backfiring anode may be disastrous. The possible causes of this short circuit which arises suddenly are many in number. We will consider, here, a few of these causes. Under ideal conditions the following are the factors to be considered:— there are several anodes made of iron or graphite, chemically pure and exhausted of all gases, these are each surrounded by an iron sleeve 6 (Fig. 1). The whole is lodged in a vacuum chamber containing a very rare mercury vapour, the tension of which is determined by the coldest condensing surfaces. (1 . . . 100 10^{-3} mm Hg corresponding to 20 . . . 85° C). All foreign gases such as oxygen, nitrogen, water vapour, etc. have been exhausted by the vacuum pumps; their residual gas tension is below 10^{-3} mm Hg. The backfire voltage in this limit case is above 150 kV, assuming a low thickness of ion layer before the blocking anode, because with cooling surfaces at 50° C, corresponding

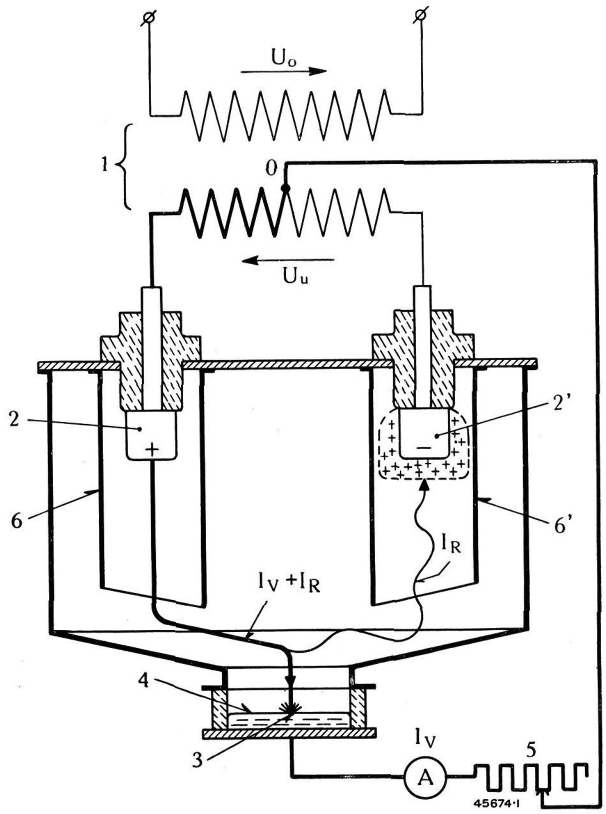


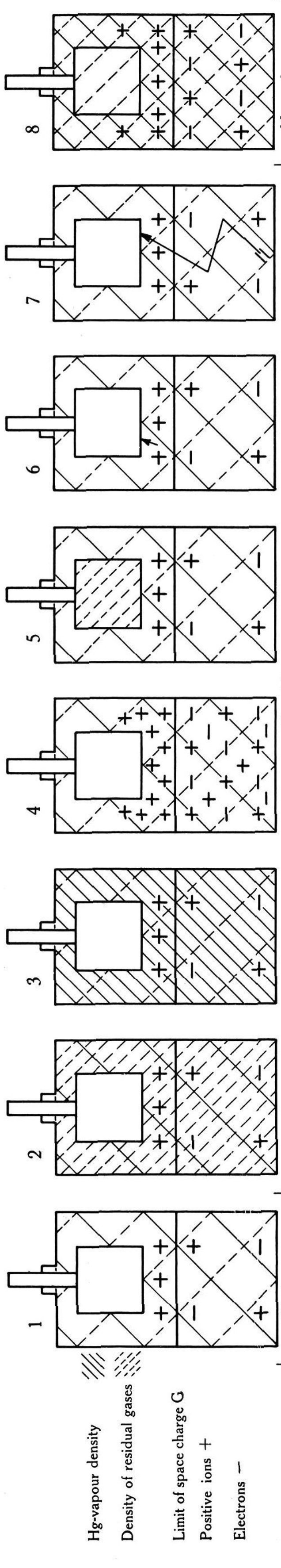
Fig. 1. — **Diagrammatic section of a mutator.**

1.	Transformer.	6,6'.	Anode sleeves.
2,2'.	Anodes.	Uo.	Primary voltage.
3.	Cathode spot.	Uu.	Secondary voltage.
4.	Cathode.	Iv.	Current in forward sense.
5.	Charging resistance.	IR.	Current in reverse sense.

to 10^{-2} mm Hg, Brown Boveri mutators have been operated for hours without trouble with blocking voltages of over 100 kV. If, now, backfires occur at lower voltages than these, they represent practical conditions which differ considerably from the ideal conditions assumed. The magnitude of the backfire voltage is determined by the density of the Hg vapour, by the density of the residual gases and the degree of ionisation in front of the blocking anode; but the gaseous content and impurities in and on the anode, as well as the design of the valve, play a part in the phenomenon, also.

The illustrative and tabular summary of Fig. 2 has the object of determining qualitatively the backfire resistance of an anode valve taking the ideal valve as starting point and only taking a few influences into account which are met with in practice (the list of the said influences can be increased). Based on the many individual tests we have carried out in our laboratories and in the test rooms, it would be possible, to-day, to give the experimental proof of the influences in question. This, however, would take us well beyond the scope of this article. A preceding article in this number is a good example of individual research in this field. The table allows of recognizing, easily, what the right measures are which must be adopted to make a mutator reliable in practical service. Care must, therefore, be taken that the anodes used are free of gas and of pure material. Then, the tension of the residual gas must not much exceed 10^{-3} mm Hg. With the service temperatures of the mutator chamber and valve parts met with, the density of the Hg vapour before the blocking anodes must not be too great. High ionisation densities, especially combined with high densities of residual gas and of vapour is also a dangerous factor. Where impurities increase the emission of electrons from the anodes, conditions get still worse. Further, drops of Hg which reach the hot, blocking anode may set up backfires; they cause a localized and inadmissible increase of the vapour density. Finally, even if all ideal conditions are complied with, an exceptionally high atmospheric super-voltage which attains the blocking anode may ignite a cathode spot on its surface and, thus, bring about a backfire.

(MS 592) *A. Gaudenzi. (Mo.)*



	Ideal case	Trouble case						Normal case
	1	2	3	4	5	6	7	8
Conditions of anode	free of gas and pure	as 1	as 1	as 1	big gas content, pure	as 1	as 1	moderate gas content
Hg-vapour density	low	"	very great	"	as 1	"	"	usual
Hg-vapour tension	$<10^{-3}$ mm Hg	"	$>0{,}2$ mm Hg	"	"	"	"	$<30\ 10^{-3}$ mm Hg
Density of residual gases	low	very great	as 1	"	"	"	"	usual
Tension of residual gases	$<10^{-3}$ mm Hg	$>0{,}2$ mm Hg	"	"	"	"	"	10^{-3} mm Hg
Density of ionisation	low	as 1	"	very great	"	"	"	big
Add. troubles	none	none	none	none	none	glow emission	atmospheric super-voltage	practically none
Backfire strength	maximum	≪ than 1	≪ than 1	less < than 1	≪ than 1	less < than 1	as 1	practically very big
Backfire voltage	>150 kV	< 1 kV	< 2 kV	—	—	—	> 150 kV	10...100 kV

Fig. 2. — The strength of the mutator to resist the setting up of backfires in function of the various physical factors which come into play in mutator operation.

THE IMPORTANCE OF UNCONTROLLED AND OF CONTROLLED GRIDS IN MUTATORS.

Decimal index 621. 314. 65.

This article explains how the uncontrolled and the controlled grids of a mutator act and also the possibility offered by the controlled grid of extinguishing backfires and short-circuits on the D. C. side of mutators within less than a cycle. This process provides an efficient shield and protection of the mutator as well as of the D. C. system and three phase system from the consequences of backfires and short-circuits. The diversity of uses to which the mutator can now be put, thanks to the introduction of controlled grids, is also made clear.

EVER since mutators were built, the key problem has, always, been how to overcome backfires. A backfire takes place when the anode loses its valve property during the period when it should be blocked. Then, an ignition takes place, that is to say a cathode spot appears on the anode in question. A current now flows to the backfiring anode from those anodes which are positively charged with regard to the backfiring one, and, subsequently, from all the other anodes which become positive with regard to it. As the resistance of this circuit is very low (it is only composed of the impedance of the mutator transformer and of the resistance of the arc), the current flowing to the backfiring anode is very high and can attain a maximum of 10 to 15 times the rated D. C. value. Thus, a backfire is comparable to a short-circuit on the transformer. In Fig. 1 it is assumed that the arc is rotating in clockwise sense and that anode 3 backfires. Arrows indicate the direction of the currents at the moment of the backfire. As the anodes 4 and 5 are at the same, or at lower potential, than anode 3, the former will only be involved subsequently in the short-circuit. If the transformer phases had no reactance, the backfire would cease when the e. m. f. of the backfiring phase became higher than that of all the other phases and this would happen within about $^{1}/_{2}$ to $^{3}/_{4}$ of a cycle.

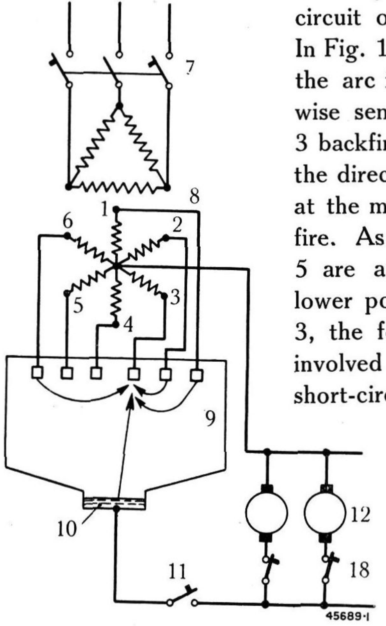


Fig. 1. — Behaviour of the currents in a mutator when a backfire occurs.

1.—6. Mutator anodes.
7. Transformer circuit breaker.
8. Mutator transformer.
9. Mutator.
10. Cathode of mutator.
11. Reverse-current breaker (polarized).
12. D.C. system.
18. Over-current breaker (feeder breaker).

The backfire current of a duration of several cycles is an undulating direct current, the minimum value of which is nearly zero. Fig. 2 shows a backfire current of this nature, as well as the D. C. voltage, taken from an oscillogram. As backfires are accidental phenomena and are, therefore, rarely recorded on an oscillograph, artificial means were made use of in this case, an anode being connected by a conductor to the cathode externally to the mutator, and the current in this connection lead being oscillographed. Here, the mutator was only loaded by an ohmic resistance. Now, experience has shown that, in the case of natural backfires, other anodes get implicated therein, owing to the strong ionisation and rise in the pressure of the Hg vapour; this means a reinforcement of the short circuit. The short circuit will persist until the transformer is cut out which may take one to several tenths of a second with the ordinary type of circuit breaker. If the mutator is working in parallel with other sources of current or feeding an electrolytic plant, then, when a backfire occurs in the mutator, a reverse current flows from the D. C. system over the Hg cathode to the backfiring anode and then through the phase winding to the neutral point of the transformer, that is to the negative pole of the system; see Fig. 1. This reverse current must also be cut out by a breaker which is best done by means of a reverse-current high-speed breaker. However, this breaker must be designed so as to function under very low reverse currents, so that it is sure to trip even if the machines running in parallel are at a considerable distance (for instance in neighbouring substations) so that the reverse current set up is weak, on account of the long lines. If this is not the case, this current can well cause the destruction of the backfiring anode and, possibly, of the phase winding as well; this is because, although the transformer breaker has

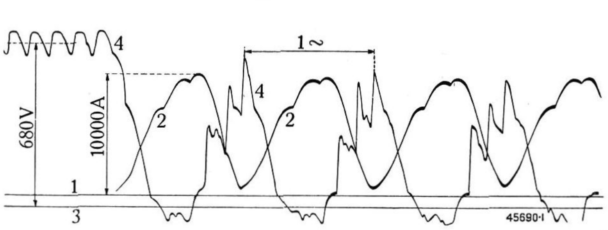


Fig. 2. — Behaviour of the current on the backfiring anode, and of the D. C. voltage, when a backfire occurs in a 6-phase mutator, which is supplied by an 800-kVA transformer delta-connected on the primary side and star-connected on the secondary side *.

1. Zero axis of current on backfiring anode.
2. Current on backfiring anode.
3. Zero axis of D.C. voltage.
4. D.C. voltage.

tripped, the reverse current continues to flow. Every backfire current, according to its strength and duration, has a more or less powerful sputtering (pulverising) effect on the anodes and sleeves and a covering of dust from this pulverization settles on anodes and insulators. This results in a certain ageing of the mutator.

Some of the causes of backfires are:—

Considerable residual ionisation in front of the anodes under the effect of heavy current loading;

Periodic flow of ionized mercury vapour into the sleeves and in front of the anodes, after the momentary extinction of the respective anodes, because a vacuum is created due to the sudden cooling of the mercury vapour;

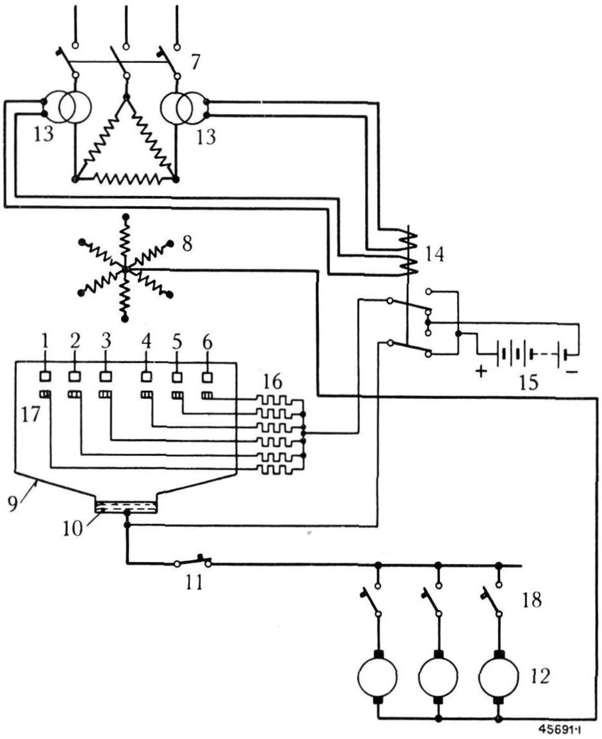


Fig. 3. — Diagram of mutator plant with backfire and short-circuit protection by means of controlled grids.

1—6. Anodes.
7. Transformer breaker.
8. Mutator transformer.
9. Mutator.
10. Cathode.
11. Reverse-current breaker.
12. D.C. system.
13. Current transformer.
14. Grid relay.
15. D.C. source of current for grid relay.
16. Grid resistances.
17. Anode grid.
18. Feeder breaker.

Too high mercury-vapour pressure;

Impurities in the material of which the anodes are made;

Covering of anodes and insulators by the products of pulverization;

Excess-voltages between anode and cathode possibly originating from excess-voltages in the primary or secondary systems, or which may be created by sudden heavy loading of the mutator when it is cold.

A certain number of these causes can, easily, be guarded against by proper supervision and protective devices. Others, and the most important among them, can be suppressed, nearly entirely, by using the anode grids introduced, in 1926, by Brown Boveri. By means of these grids and during the blocking period, the space before the anodes, and the mercury vapours flowing periodically into the sleeves and before the anodes, are very rapidly and, practically, entirely deionized. Further the grids get very hot in service, and their temperature rises with the strength of the anode currents. The heat radiating from the grids maintains the mercury vapour inside the sleeves at a high temperature, which causes the density of this vapour to diminish and this further increases the backfire-proof qualities of the mutator. The installation of grids was an enormous improvement for mutators, so that the output of standard sizes could be considerably increased; the building of mutator units of very considerable output dates from this time. Further, the grids allowed of modifying the mutator design, so that the track to be followed by the arc was considerably shortened. This meant a smaller voltage drop across the arc that is to say much lower losses in the mutator.

A further and most significant improvement introduced by Brown Boveri to mutator design and to mutator service, and one which opened up unhoped, for possibilities for the mutator, was the introduction of controlled grids to metal-clad mutators. As early as 1926 and 1927, Brown Boveri made two fundamentally important discoveries, namely:— the extinction of backfires inside the mutators and of short-circuits on the D. C. side of mutators by means of controlled grids. As early as the year 1927, a large number of mutators located in different plants were so equipped and put into service. The device in question consists in putting the control grids under a voltage which is negative as compared to that of

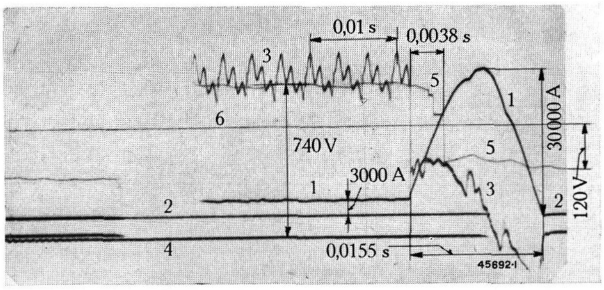


Fig. 4. — Oscillogram of a short circuit on the D. C. side, extinguished by grids.

Mutator transformer 5000 kVA with absorption choke coil, mutator Type A 712.

1. Direct current.
2. Zero axis of direct current.
3. D. C. voltage.
4. Zero axis of D. C. voltage.
5. Grid voltage.
6. Zero axis of grid voltage = cathode potential.

the cathode, immediately after a backfire or a short circuit has begun. The anodes which are not burning at the moment, are prevented from igniting afresh and those which are already burning in the proper sequence will not ignite again after they have gone out in the natural way. Thus, the mutator is extinguished in less than one cycle. A positive space charge forms round the grids of the anodes which are not burning, which then prevents the electrons from reaching the anodes when the latter get a more positive potential than the cathode; in other words, no new ignition of the anodes takes place. Fig. 3 shows the diagram of a grid-controlled mutator set. The grid relay 14 is supplied by two current transformers. The setting of the grid relay 14 is such that it acts at a given excess current value set for. The relay is so designed that its time lag is very short being only some thousandth parts of a second. This time lag is the shorter the steeper the current increase and the bigger a multiple of the rated current the relay current is. Fig. 4 shows an oscillogram of the extinction of a short circuit on the D. C. side by means of a controlled grid. The mutator used in this test is Type A 712 with a current rating of 3600 A at 720 V. At the initiation of the short circuit, the D. C. voltage was 740 V and the D. C. current 3000 A. After 0·0038 s, from the initiation of the short circuit, the grid relay charged the grids negatively and the short circuit was extinguished within 0·0155 s. The maximum value of the short-circuit current attained 30,000 A. Owing to the impedance of the short-circuit loop, the phase voltage of the last anode to burn, is even negative towards the end of the short circuit, in other words, at this period, the mutator works on the system as a D. C.-A. C. mutator. When a short circuit occurs, the total current flows to the cathode and causes the generation of an enormous quantity of mercury vapour which is projected up into the chamber proper of the mutator. This means that the inner organs and the grids must be designed with great care in order to assure proper functioning of the grid protection under these exceptional conditions. Should a short circuit arise on any one feeder, the short-circuit impulse causes the grid relay to act and the feeder breaker also trips; as, however, extinction of the mutator caused by the grids is, usually, quicker than the opening of the breaker contacts, there will be no arcing on the breaker at all when it trips. If, on the other hand, the breaker contacts open somewhat earlier as happens in the case of quick-acting breakers, the ruptured load will nevertheless, be handled for the greater part by the grids and the breaker will, thus, be shielded from too heavy duty. The grid relay is designed for a reset time lag of about $^{1}/_{10}$ s, that is to say that after this time has elapsed positive voltage is impressed on the grid, and then, the D. C. voltage appears again. Within $^{1}/_{10}$ s, however, any standard type of breaker has had time to trip so that no new short circuit occurs. In the case of a straight bus-bar short circuit, where, usually, there is no over-current breaker inserted between mutator and bus-bars, the short circuit would start again, regularly, after the elapse of $^{1}/_{10}$ s, allowing that the point of short circuit had not burnt out or the short circuit been eliminated in some other manner. To meet these difficulties, an additional device is added to the grid relay so that after the short circuit has started again three times the transformer breaker itself is tripped.

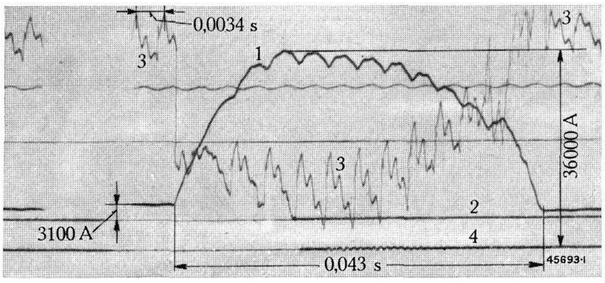


Fig. 5. — Oscillogram of a short circuit on the D. C. side of a mutator, ruptured by breaker (control grids put out of action).

Mutator transformer 5000 kVA with absorption choke coil, mutator Type A 712.

1. Direct current.
2. Zero axis of direct current.
3. Direct-current voltage.
4. Zero axis of direct-current voltage.

The oscillogram of Fig. 5 shows the rupturing of a short circuit by a D. C. breaker under the same conditions as the oscillogram in Fig. 4, with the difference that the D. C. voltage was only 600 V and the current transformers of the grid relay were short-circuited so that the grids were not put under negative voltage at all. Here the peak value of the short-circuit current attained 36,000 A and the duration of rupture 0·043 s. Immediately after the short circuit had been ruptured, the D. C. voltage was re-established at its full value. Despite the lower D. C. voltage, the peak value of the short-circuit current has become, here, considerably higher than in the case of a short circuit mastered by grid control; this is because more anodes are implicated in the short circuit when there is no grid-control.

The extinction of backfires takes place, in principle, in the same way and as quickly as that of short circuits. In this case, however, the arc is created from sound to defective anode and thus, practically, does not cause an increase in the amount of vapour generated. Thus, extinction takes place under more advantageous conditions. If the mutator works on a system with reverse voltage, a reverse current is established when a backfire occurs, which current flows from the system, through the mercury cathode to the backfiring anode. This reverse current has to be broken by a reverse-current quick-acting breaker, as it cannot be broken by the grids. As soon as the rupture of the reverse current has taken place, the reverse-current breaker can be closed again. When there is remote control of the reverse-current breaker, the closing impulse can be imparted to it, through a control circuit closing when the breaker is opened, so that the delivery of current to the system is only interrupted for about 1 s. In so far as the mutators are used to supply aluminium electrolytic plants in which the reverse voltage (voltage due to polarization) only attains $^1/_3$ to $^1/_2$ of the mutator voltage, according to the type of furnace, the D. C. reverse-current breaker can be left out. By means of a simple short-circuiting contactor the furnace series is short-circuited for a moment, automatically, when a backfire occurs, which causes the reverse current from the furnace to be interrupted. This, however, is only made use of in small furnaces.

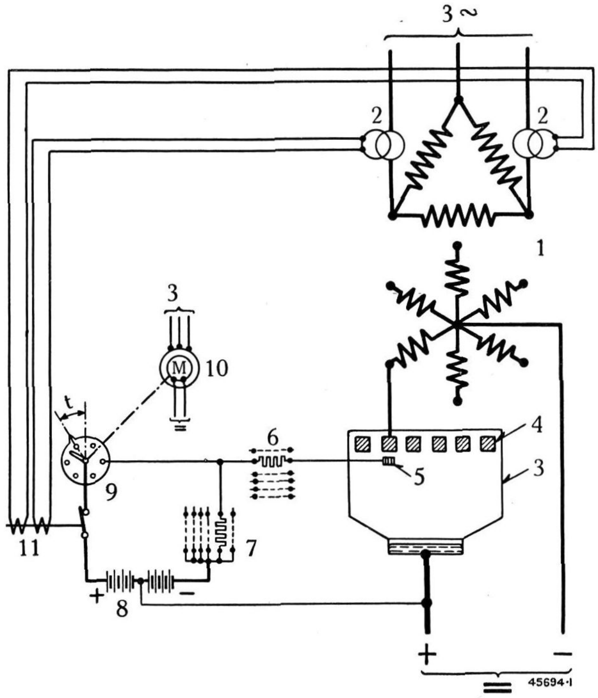


Fig. 6. — Fundamental diagram for voltage regulation by means of grids and backfire and short-circuit protection.

1. Mutator transformer.
2. Current transformer.
3. Mutator.
4. Anodes.
5. Anode grids.
6. Grid resistances.
7. Carry-off resistances.
8. Source of grid current.
9. Distributor.
10. Synchronous motor.
11. Grid relay.

With mutators in which retardation of ignition by means of controlled grids is made use of, with the object of regulating the voltage, see Fig. 6, or for other purposes, the grids are kept constantly under negative voltage as compared to the cathode and they are, then, only subjected for a moment to a short positive impulse, when the brush touches the respective contacts of the distributor, causing the respective anodes to ignite when they are positive as compared to the cathode. In the case of backfires or short circuits, grid relay 11 only suppresses those ignition impulses. Therefore, in this kind of control, and assuming that the grid relay acts instantly, only those anodes are short-circuited which are already ignited just before the backfire or short circuit takes place. The short circuit is, thus, less violent and lasts a shorter time than with control as per Fig. 3.

The backfire and short-circuit protection is used, to-day, on mutators, for all sorts of purposes, from mutators built for the lowest voltages up to those for the highest voltages and from the smallest to the biggest outputs, it is also used for frequency conversion from three-phase to single-phase, for system coupling three-phase to three-phase, for high-frequency furnaces, for high-voltage D. C. transmission, etc.

In mutator plants in which the D. C. circuit presents big reactances, such, for example, as happens in broadcasting plants (wave-smoothing choke coils) a short-circuit on the D. C. circuit (rocky point on transmitting tubes) is put out only after several cycles, because the energy stored in the choke coil keeps up the short circuit. However, Brown Boveri succeeded in eliminating this disadvantage. When the short circuit begins, the positive ignition impulses are so displaced in time, thanks to the action of the grid relay, that the mutator is switched over to D.C.—A.C. operation, and then the energy stored up in the wave-smoother coils is pumped back into the three-phase system and the short circuit extinguished within about one cycle. In high-voltage mutators, this kind of short-circuit extinction is the only possibility of rupturing a heavy D. C. current because there are no breakers available for such high D. C. voltages.

To summarize, it can be said that thanks to the introduction of deionizing grids to mutators, the service reliability of the latter has been enormously increased, their outputs raised and their efficiencies improved. Further, the controlled grids and the backfire and short-circuit protection have, practically, eliminated the destructive effects of this kind of trouble in the mutators themselves as well as their undesirable reactions on the D. C. and A. C. systems; these devices have allowed the utilization of mutators for certain purposes where they could, otherwise, not have been considered at all. The deionizing and control grids have made it possible to build reliable mutator types of the size turned out to-day, which would, otherwise, have been impossible. Further, these devices have opened up new and wide fields of utilization to the mutator.

(MS 598) *S. Widmer. (Mo.)*

THE STATIC CONTROL AND REGULATION OF MUTATORS.

Decimal index 621. 314. 65. 07.

A static control device, which combines the advantages of the well-known mechanical control device with an amplifying feature, can be made so sensitive that the mutator can be supervised, in service, by a new kind of astatic electronic-tube regulator.

I. INTRODUCTION.

THE introduction of controlled grids to mutator design has allowed of extending the fields of utilization of the latter very considerably. It has become the generally-recognized static converter, which can carry out functions previously unthought of. The chief characteristic of grid control is the possibility it offers of retarding the moment of ignition of the anodes, at a very slight expenditure of power, indeed. To this end, positive voltage impulses, in relation to the cathode, of as steep fronted character as it is possible to attain, are impressed on the grids at the moment when the respective anodes should ignite.

Under the word *control* is understood the apparatus which generates the ignition impulses for the grids and which allows of a displacement of the moment of ignition. Under *regulation* is grouped the apparatus which actuates the control, in accordance with definite laws, a quick-acting regulator is an example of this.

The control as well as the regulation can either be, purely, mechanical or it can be electrical that is to say on the static principle. Mechanical control and regulation has the great advantage of being simple and easy to supervise; its working can be checked at any time, easily. As regards the service man, static control and regulation is also easy to look after, because he is already familiar with the mechanical devices and with the secondary phenomena related to control. He knows what points want watching and thus gets easily acquainted with static control devices. In the following paragraphs describing the static apparatus the corresponding mechanical devices will be compared to the static apparatus in question, in order to facilitate comprehension.

Brown Boveri has developed several systems of static control for mutators. Only one of these will be described here; it is one presenting interesting advantages as regards regulation.

II. STATIC CONTROL DEVICES.

Fig. 1 shows the comparison of a mechanical control device I with its distributor and of a static device II with control tube. The battery B shown in connection I imparts negative voltage to the grids of mutator MR through resistances R_2 and R_1. Positive voltage impulses are imparted to the grids in proper sequence and through resistances R_1, these impulses coming from the positive pole of the battery B and being distributed through distributor K, the brushes of which are driven by synchronous motor M_1.

In order to advance or retard, simultaneously, the moment of ignition of all the grids and anodes respectively, the contact track of the distributor K, or the magnetic axis of the synchronous motor can be displaced. When a short circuit or a backfire occurs on the mutator, the current transformer D actuates a quick-acting relay (the grid relay) which opens the switch S. When this takes place, the positive voltage impulses cease and all grids get negative voltages through resistances R_2 and R_1, so that the anodes are prevented from reigniting.

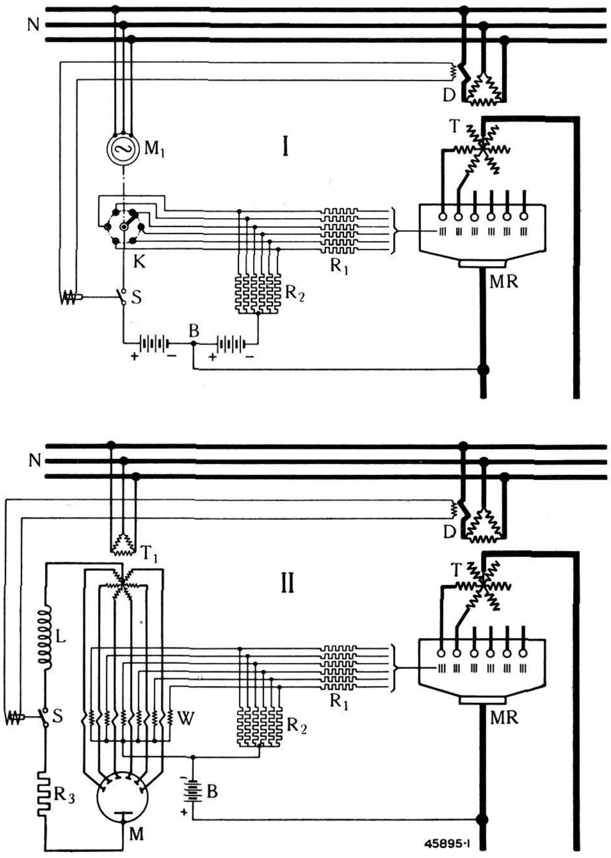


Fig. 1. — **Comparison between a mechanical and a static control device for an A. C. — D. C. mutator.**

I. Mechanical control with distributor.
II. Static control with control tube.
N. Three-phase system.
D. Current transformer.
T. Main transformer.
T_1. Transformer for the control tube.
MR. Mutator.
M_1. Synchronous motor.
K. Distributor with rotating brush.
S. Switching contact of grid relay.
B. Battery.
R_1 R_2. Grid resistances.
R_3. Load resistance of control tube.
W. Current transformer.
L. Smoothing choke coil.
M. Control tube.

Now, in the case of connection II, the grids get negative voltage from the battery B through resistances R_1 and R_2. In place of a distributor with rotating brush, there is a control tube M with a rotating arc. The individual anodes of this tube carry current in the phase sequence of the secondary voltages of the transformer T_1. The control tube delivers current through resistance R_3 and the choke coil L smooths out the current of the control tube. The anode currents of the latter are, practically, rectangular in character and they produce currents and voltages respectively in the secondary coils of the current transformers W, working on the resistances R_2, which have the same character. These rectangular voltages reach the grids of the mutator through the resistances R_1. The time displacement of the ignition impulses can be produced, for example, by means of an induction regulator inserted before transformer T_1, which induction regulator is not shown in the drawing. The switch S of the grid relay which is caused to trip through current transformer D, when a short circuit or backfire occurs, opens the current circuit of the control tube; the latter is now deprived of current and the current transformers W deliver no voltages to the mutator grids. Thus, the grids are fed from battery B and receive negative potential, therefrom.

The static control, just described, can be used for all applications of the mutator as well as for the coupling of systems. The rectangular, that is steep-fronted control impulses, are advantageous. The magnitude of the said impulses is determined by the ratio of the current transformer W. This system of control has not only the advantage of being static, it is also simple, reliable and easy to supervise.

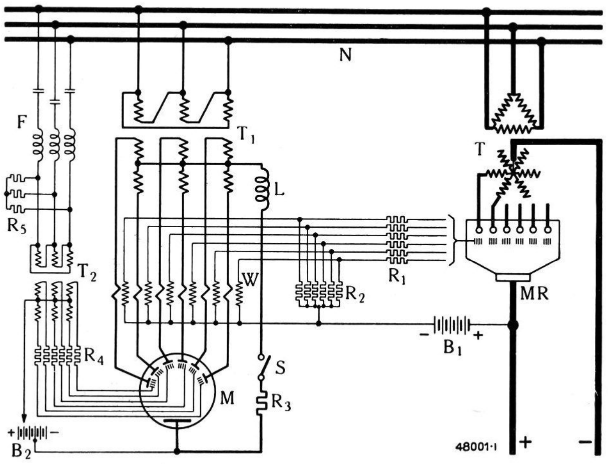


Fig. 2. — Static control of an A. C. — D. C. mutator with adjustment by means of the control-tube grids.

N. Three-phase system.
MR. Mutator.
T. Main transformer.
T_1. Transformer for the control tube.
T_2. Control transformer.
F. Filter.
L. Smoothing choke coil.
W. Current transformer.
M. Control tube.
R_1 R_2 R_4. Grid resistances.
R_3. Load resistance of control tube.
R_5. Basic load of filter.
S. Switch of grid relay, not shown here.
B_1 B_2. Batteries.

Quite special advantages are enjoyed when the control tube, itself, is equipped with control grids, as is shown in Fig. 2. The control tube now works as a kind of amplifier as it can be controlled with an expenditure of a minute quantity of power. According to Fig. 2, the grids of the control tube are controlled, according to a well-known principle, from transformer T_2 through resistances R_4 with the aid of a battery B_2, the voltage of which can be varied by hand. This latter control causes a modification of the phase position of the anode currents of the control tube as referred to the voltage of transformer T_1 and, therewith, a displacement of the control impulses for the grids of the mutator. The regulated D. C. voltage taken from battery B_2 can be modified either by an ordinary mechanical regulator or, as will be explained, further on, by an electric regulator. In order to make the control apparatus independent of possible voltage distortions in system N or from repercussions coming from the mutator, the supply of the grids of the control tube takes place through a filter F. The resistances R_5 give a basic load to the filter in order that it may work independently of the grid currents of the control tube.

III. FUNDAMENTAL FACTORS IN MUTATOR REGULATION.

If a mutator is controlled statically, it is logically correct to carry out the regulation statically, as well. The instantaneous-reaction regulation of mutators also permits of solving problems which cannot be solved by mechanical types of regulators. As the system of control described can be actuated by very low currents, it is quite feasible to carry out regulation with the help of ordinary electronic tubes such as are used in wireless receiving sets.

In the following paragraphs, a regulator working with these electronic tubes will be described, which has the advantage of working astatically and which can be used, generally, for any regulating purpose.

However, before going into the question of the "electronic regulator", it will be helpful to discuss some fundamental methods of regulation with the aid of mechanical examples for the purpose of comparison. For the investigation, the voltage regulation of a D. C. generator will be taken as an example. Fig. 3 shows the three possible cases, namely:— I. compounding, II. static regulation, III. astatic regulation. It will be assumed that the regulating duty consists in attaining that the generator maintains as constant voltage as possible, from no load up to full load.

The compounding (Fig. 3I) works, practically, to instantaneous reaction and has the advantage for it of simplicity. It is very difficult, however, to build the machine so that it really maintains constant voltage from no load to full load. Generally, a

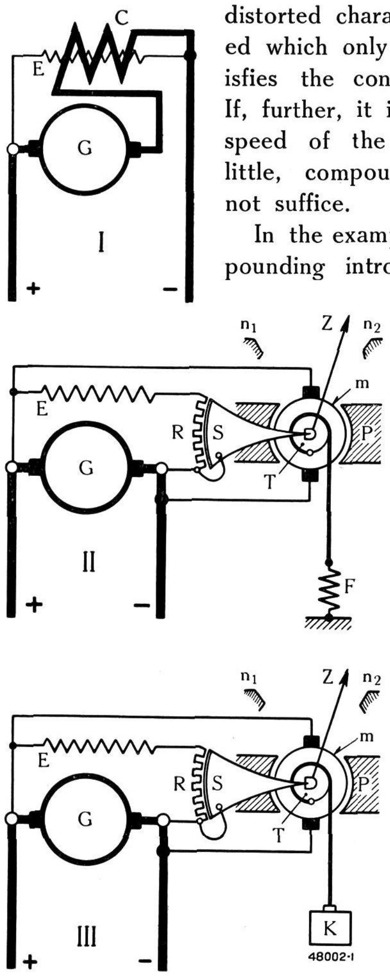


Fig. 3. — Fundamental methods of regulating the voltage of a D. C. machine.

I. Compounding.
II. Static regulation.
III. Astatic regulation.
G. D. C. generator.
E. Shunt winding.
C. Compound winding.
R. Excitation resistance.
S. Rolling sector of quick-acting regulator.
m. Rotary system.
P. Magnet poles.
T. Drum.
F. Spring.
K. Weight.
Z. Indicator.
n_1 n_2. End-travel stops.

distorted characteristic is obtained which only approximately satisfies the condition laid down. If, further, it is assumed that the speed of the machine varies a little, compounding, alone, will not suffice.

In the example taken, the compounding introduced consists in modifying the relation between current and voltage, which results from the design of the shunt-wound machine, by an additional factor.

In regulation, on the contrary, the magnitude to be regulated is compared, directly or indirectly to a fixed and desired magnitude. The difference of the two magnitudes is utilized to actuate a regulating organ.

The simplest case is a static[1] regulation in which a torque proportional to the magnitude to be regulated (voltage) is compared to the torque exercised by a spring (desired or master magnitude). In Fig. 3_{II}, m indicates the armature of a small motor, which is carried on bearings and is free to rotate between two permanent magnets. The armature of the motor is connected up direct to the terminal voltage of the machine. There is a drum T rigidly coupled to the armature; a thread connects this drum to the spring F. If, now, the electric torque and the torque of the spring are equal, they balance each other and the armature is immobile. Let it be assumed that this armature actuates a rolling sector S, for example, as shown; this sector short-circuits a part of resistance R and thus maintains a constant excitation of the machine, when the armature is immobile. Pointer Z gives the momentary position of the regulator. If the terminal voltage of the machine drops, the torque exercised by the spring gets stronger than the electric torque, the pointer moves round towards the right with armature, drum and sector and a part of resistance R will be short circuited. This means increased excitation and the voltage across machine terminals will increase. This correction takes place quite independently of the current delivered or of the speed of the machine. It is effective within the range limited by the stops n_1 and n_2.

The astatic regulation is similar to the static one, but in our example, given in Fig. 3_{III} the spring F is replaced by a weight K.

The difference between static and astatic is that, according to the position of the regulator (i. e. according to whether the spring F is more or less tightly stretched) the pull of spring F varies, while in the astatic regulator the torque is constant and independent of the position of the indicator. This small difference, in itself, has a great influence on the regulating process. The condition of equilibrium of the static regulator Fig. 3_{II} calls for a different electric torque for every position, in other words the voltage adjusted to by the regulator is different in each position. With the astatic regulator, Fig. 3_{III}, on the contrary, the voltage adjusted to is always the same and independent of the position of the regulator.

The regulator methods summarized, here, with the help of a mechanical example can also be applied to the static regulation of mutators. We will confine ourselves to the description of the voltage regulation of an A. C.—D. C. mutator.

IV. COMPOUNDING AND STATIC REGULATION OF A MUTATOR.

The compounding of a mutator can be achieved from the primary, alternating current or from the secondary, direct current. Fig. 4 shows a mutator with static control and compounding by means of the primary current. A D.C. voltage proportional to the system currents of current transformers W is generated across the resistance r, through the metal oxide rectifier n; this voltage is smoothed by the choke coil b and the condenser c. The regulating voltage thus obtained is impressed between the neutral point of the transformer T_2 and the cathode of the control tube M. The handle provided on the resistance r allows of modifying the magnitude of the compounding factor. If the current delivered by the mutator increases, the voltage across resistance r also increases, the potential of the neutral point of transformer T_2 is raised as

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[1] The designation "static" is used considerably in technology. In the chapter under consideration it was found unavoidable to use it for the two following cases:—
1. "Static" as opposed to "mechanical" control and regulation.
2. "Static" as opposed to "astatic" regulating characteristic.

compared to the cathode of tube M and the point of ignition of the control tube will be advanced. In this way, the point of ignition of the mutator is, also, advanced and its voltage drop is compensated by an increase in voltage. There is, here, a fixed relationship between the setting of the control and the mutator current, because to every current strength corresponds a given grid voltage in the control tube and, therewith, a given phase position of the control. Changes in the voltage of the three-phase system are not regulated out by the compounding. The mutator could be compounded to constant current with, practically, the same connections.

Fig. 5 is an example of static (as opposed to astatic) regulation of an A. C.— D. C. mutator. The value to be adhered to, and to which the voltage to be regulated is compared, is battery B_2, which is assumed to give constant voltage. The difference between the voltage of the mutator and that of the battery, the so-termed "error", is taken up on resistance R_6. If the error is positive, that is to say if the D. C. voltage is too high, the control must be displaced in the lagging sense. To this end, it would be possible to connect the voltage across resistance R_6 between the neutral point of transformer T_2 and the cathode of the control tube M. In order to attain as sensitive regulation as possible, it is, however, recommendable to lead the voltage across R_6 to an amplifier V and then to influence the control with the increased regulating voltage. In this way, the slightest variation of the mutator voltage from the value desired, given by the battery, is able to produce a considerable influence on the control.

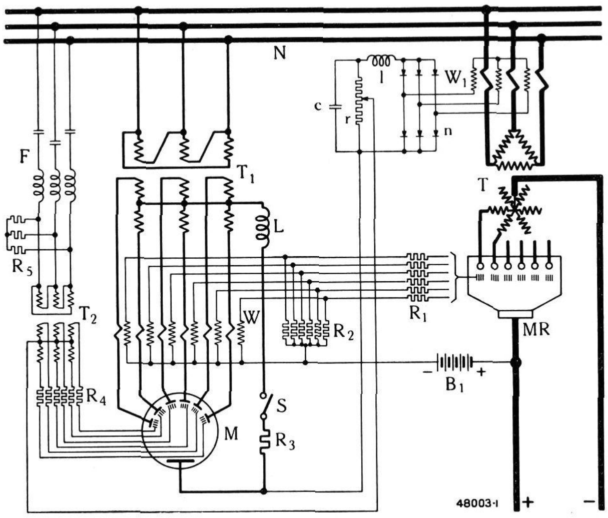


Fig. 4. — Compounding on the three-phase side, in the case of an A. C. — D. C. mutator with static control.

N. Three-phase system.
W W$_1$. Current transformers.
T. Main transformer.
T$_1$. Transformer of control tube.
T$_2$. Control transformer.
MR. Mutator.
F. Filter.
L. Smoothing choke coils.
c. Smoothing condenser.
M. Control tube.
r. Resistance.
R$_1$ R$_2$ R$_4$. Grid resistances.
R$_3$. Load resistance of control tube.
R$_5$. Basic load of filter.
S. Switch of grid relay, not shown here.
B$_1$. Battery.
n. Metal oxide rectifier.

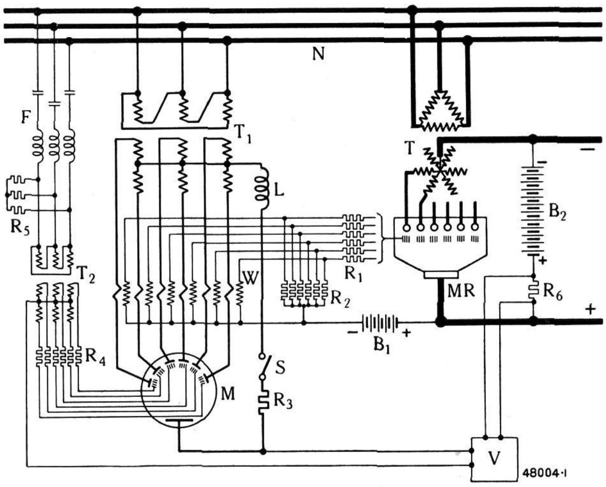


Fig. 5. — Static voltage regulation of an A. C. — D. C. mutator with static control.

N. Three-phase system.
T. Main transformer.
T$_1$. Transformer of control tube.
T$_2$. Control transformer.
MR. Mutator.
F. Filter.
L. Smoothing choke coil.
W. Current transformer.
M. Control tube.
R$_1$ R$_2$ R$_4$. Grid resistances.
R$_3$. Load resistance of control tube.
R$_5$. Basic load of filter.
R$_6$. Resistance.
S. Switch of grid relay, not shown here.
B$_1$. Battery.
B$_2$. Constant-voltage battery.
V. Amplifier.

Despite the amplification just mentioned, this is a static regulation, because a quite definite setting of the control corresponds to each value of voltage measured across resistance R_6. Assuming that the voltage of the mutator should fall below the value of the voltage desired, a voltage appears across R_6 proportional to the error. This voltage acts to produce a definite correction through amplifier V and the control, so that the mutator voltage increases again. This, in turn, makes the error voltage across R_6 smaller and part of the correction through amplifier and control is eliminated. Equilibrium is finally established at a voltage which is slightly below the desired voltage. The more the error is amplified by V the smaller is the difference between the voltage re-established and the value desired, but, nevertheless, the static characteristic of the regulation is evident.

V. ASTATIC VOLTAGE REGULATION WITH ELECTRONIC TUBES.

In order to pass from the static to the astatic regulation, the characteristic of the amplifier V, in the layout of Fig. 5, would have to be so altered that the voltage between the neutral point of transformer T_2 and the cathode of the control tube M also remains at the correct magnitude when the voltage on resistance R_6 is zero, in other words an error voltage across resistance R_6 must exert an influence on the regulator up to the moment when it vanishes. This means that the setting of the control must only be dependent on the sense but not on the magnitude of the voltage across R_6. The error voltage across R_6 must only give an impulse to the regulator but must not influence the amplitude of the movement of the latter.

In Fig. 6, a connection is shown with two electronic tubes which meets the regulating conditions called for. The curve of Fig. 7 shows the behaviour of the anode current J_a of the tubes G_1 and G_2 at constant anode voltage in function of the grid voltage e_g. It is assumed that the two tubes work on point C of the characteristic with the anode current OB and the grid voltage OA. These grid preliminary voltages are tapped from the anode resistances R_1 and R_2 of Fig. 6 between the common cathode and points P_1 and P_2, respectively. The two batteries B_1 and B_2 give the requisite anode voltages. The fundamental principles laid down on the basis of constant anode voltage remain also correct, but in a somewhat modified form, when the voltage drops in the resistances R_1 and R_2 are taken into account.

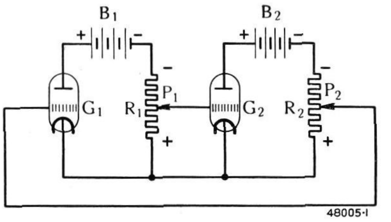


Fig. 6. — Fundamental diagram to explain the astatic characteristic of electronic-tube regulation.

G_1 G_2. Electronic tubes.
B_1 B_2. Anode batteries.
R_1 R_2. Resistances.
P_1 P_2. Handle for manual adjustment.

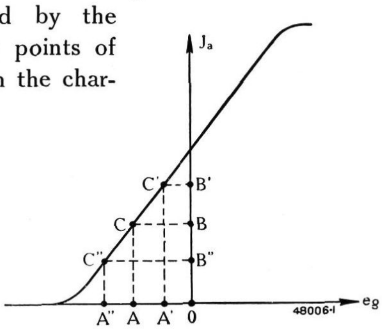


Fig. 7. — Characteristic of the electronic tubes of the regulator.

e_g. Grid voltage of electronic tubes.
J_a. Anode current.

Let tube G_1 be considered and let it be assumed that its working point is advanced, as a result of a momentarly slight impulse, towards C′ in Fig. 7. The anode current now increases from OB to OB′; the voltage drop of resistance R_1, Fig. 6, increases and the grid voltage of tube G_2 increases from OA to OA″, so that the point at which it works is displaced along the characteristic from C to C″. The anode current of the tube G_2 drops from OB to OB″ and the voltage drop across resistance R_2 also decreases. The grid voltage of tube G_1, tapped on this resistance, also drops and this exactly to the value OA′, if the connections are suitably adjusted. It will be seen that the layout is in equilibrium when tube G_1 works on point C′ and G_2 on point C″. As the characteristic of the tube is a straight line, there is an infinity of such positions of equilibrium.

The connections of Fig. 6 are, now, used for the astatic voltage regulation of a mutator, according to the layout of Fig. 8. The error voltage across terminals u v is impressed on the grid circuit of tube G_1 and the necessary voltage for the control of control tube M will be taken from terminals U and V. If, to begin with, it is assumed that the mutator has exactly the desired voltage, then the voltage across terminals u v is zero and the regulator is in the condition of Fig. 6, that is to say the voltage can be zero across U V or there may be a voltage the indication of which is determined by the position of working points of tubes G_1 and G_2 on the characteristic of Fig. 7. Therefore, even if the error voltage is zero, there may be different voltages between the neutral point of the transformer T_2 and the cathode of the control tube M.

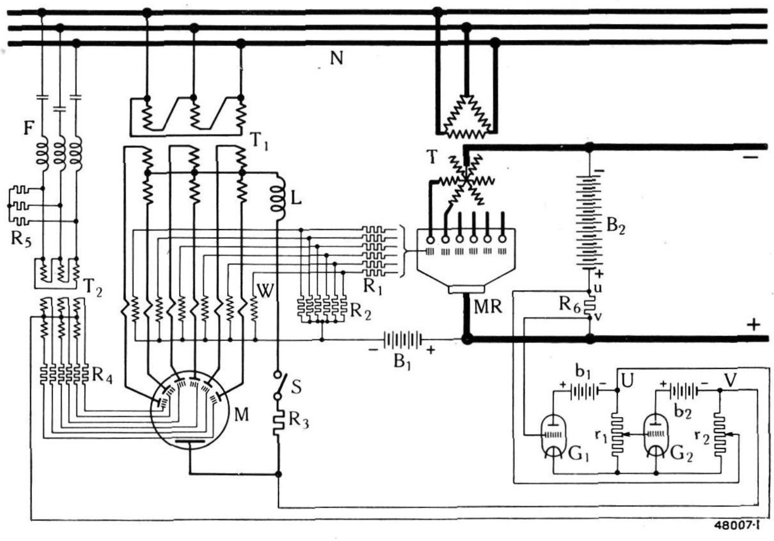


Fig. 8. — Astatic voltage regulation of an A.C. — D. C. mutator with regulation by electronic-tube regulator.

N. Three-phase system.
T. Main transformer.
T_1. Transformer of control tube.
T_2. Control transformer.
MR. Mutator.
F. Filter.
L. Smoothing choke coil.
M. Control tube.
R_1 R_2 R_4. Grid resistances.
R_3. Load resistance of control tube.
R_5. Basic load of filter.
R_6. Resistance.
r_1 r_2. Resistances with adjusting handles.
S. Switch of grid relay, not shown here.
B_1. Battery.
B_2. Standard battery of constant voltage.
b_1 b_2. Anode batteries.
G_1 G_2. Electronic tubes.

Assuming that the working point of both electronic tubes is on point C, for example, of the characteristic of Fig. 7 and assuming an error voltage appears across terminals u and v in Fig. 8, an additional grid voltage will appear in the grid circuit of tube G_1 which will give an impulse to the regulator. The regulator will seek another point of equilibrium on the characteristic until the error across u v has disappeared. If it was the case that in the arrangement shown in Fig. 6, the regulator was in equilibrium in any position, this is no more valid for the arrangement shown in Fig. 8, because another condition of equilibrium has appeared, namely that the error voltage across u v must be zero. It is seen that the electronic-tube regulator is perfectly astatic, because, it goes on working until the error has disappeared and because the setting of the control of the control tube M is independent of the magnitude of the error and can have any value. Only the sense of the error and not its magnitude influences the regulator.

In Fig. 8, the comparative voltage is supplied by battery B_2. However, it is very easy to replace the battery by another instantaneous-reaction device.

Just as in the example given of a voltage regulation of a mutator, the "error" utilized to actuate the regulator is created by a comparison between the real magnitude and the desired magnitude, it is possible to proceed on the same lines in order to attain current regulation. This is done by actuating the regulator through the influence of an error voltage produced by the difference between the real current and its desired value. Thus, it becomes possible to use one and the same astatic regulator for various regulating duties:— voltage, current, output, frequency, speed, etc.

In many cases, it is considered desirable to impart an artificial static characteristic to the regulator, such, for example, that, instead of regulating to constant voltage, it produces increased voltage with increasing load. The regulator described can accomplish this, easily, by displacement of points P_1 and P_2 in Fig. 6. The astatically-balanced connection is then made dependent on the error voltage, in one sense or the other, as, for example, according to a straight-line characteristic. It is, thus, possible to adjust the static feature of the regulator, as desired.

If this regulator can be termed of the instantaneous-reaction type, there is, nevertheless, a limit to its speed of regulation, which depends on the inherent-oscillation periodicities of the various circuits. Many regulating duties call for a retardation of the regulator action and for imparting what may be termed a dynamic characteristic to it. Small modifications in the connections allow of producing whatever dynamic characteristic is wanted.

VI. PRACTICAL EXAMPLES OF VOLTAGE REGULATION OF AN A. C. — D. C. MUTATOR.

Very thorough tests were carried out on a regulator designed as shown in Fig. 8. The results obtained showed the suitability of the layout. This regulator allows of imparting a falling or rising character to the external characteristic of the mutator. The test to maintain the voltage of a mutator at 600 V, gave as result, from no-load to full-load, that being 1000 A cathode current, deviations of less than 0·5 %.

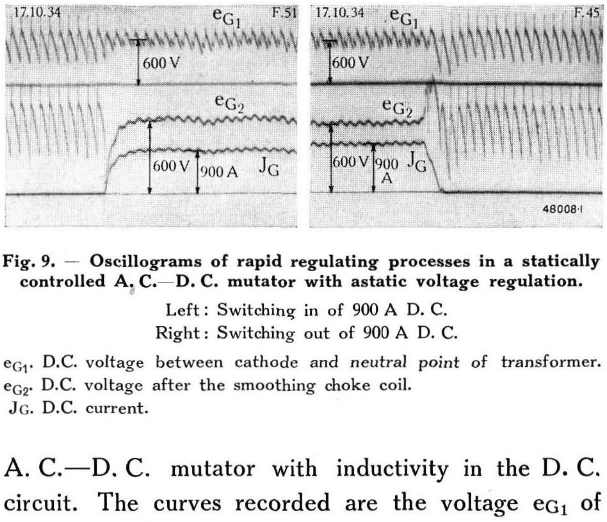


Fig. 9. — Oscillograms of rapid regulating processes in a statically controlled A. C.—D. C. mutator with astatic voltage regulation.

Left: Switching in of 900 A D. C.
Right: Switching out of 900 A D. C.

e_{G_1}. D.C. voltage between cathode and neutral point of transformer.
e_{G_2}. D.C. voltage after the smoothing choke coil.
J_G. D.C. current.

Especially remarkable is the speed at which regulation takes place. The oscillogram of Fig. 9 shows a switching in and switching out operation on an A. C.—D. C. mutator with inductivity in the D. C. circuit. The curves recorded are the voltage e_{G_1} of the mutator between cathode and neutral point, the D. C. voltage e_{G_2} after the choke coil and the D. C. current J_G. The curve e_{G_1} shows that the average value of the D. C. voltage follows the curve of the D. C. current J_G closely. When the tests were made, not even a jump was noticed on the D. C. voltmeter needle (moving coil instrument) when the D. C. circuit was closed or opened. The oscillogram of Fig. 10 was recorded during a closing operation, starting from the basic load of 100 A. The curve e_{G_2} shows that the smoothing influence of the choke coil is still not sufficient at 100 A.

The adjustment of the dynamic characteristic of the regulator must, under certain circumstances, be made to suit inherent-oscillation periodicities of the

D. C. circuit. The oscillogram of Fig. 11 shows the regulating process under sudden loading of an A. C.—D. C. mutator with wave smoother. The curve e_{G_1} is the D. C. voltage between cathode and neutral point of the transformer, that is to say before the wave smoother. On account of the capacity of the wave smoother this curve is still quite smooth, at no load. When the D. C. circuit is closed, it takes on the usual indented shape as compared to the smoothed shape of the voltage after the wave smoother, which is not recorded here. The necessary characteristic requisite for this special case, that is to say the regulator time constant, can be seen from the counter-sense flow of the currents in the two regulating tubes. It corresponds to the well-known characteristic of mechanical regulators with over regulation and damping. The whole process lasts about three to four cycles of the basic frequency.

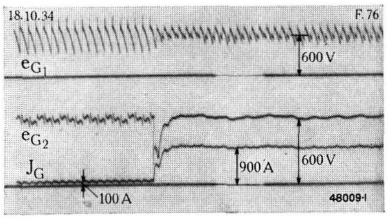


Fig. 10. — Rapid equalizing regulation of a load fluctuation of a statically-controlled A. C.—D. C. mutator having astatic voltage regulation.

e_{G_1}. D. C. voltage between cathode and transformer neutral point.
e_{G_2}. D. C. voltage after the smoothing choke coil.
J_G. Direct current.

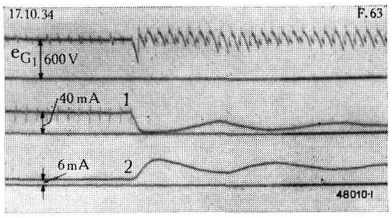


Fig. 11. — Process taking place in regulator under sudden loading of a statically-controlled A. C. — D. C. mutator with wave smoother and astatic voltage regulation.

e_{G_1}. D. C. voltage between cathode and neutral point of transformer.
1. Current in regulating tube 1.
2. Current in regulating tube 2.

The voltage e_{G_1}', measured before the wave smoother, is only smoothed when the mutator is not loaded.

It was shown that the static control of mutators and their regulation by electronic tubes eliminate ordinary service oscillation, practically, instantaneously. There is a possibility here of being able to dominate, in the same way, abnormal phenomena, such as short circuits, in such a rapid manner that they can cause no trouble. The electronic tube which has been so excellently developed for high-frequency purposes can become a useful instrument in the technology of power engineering. With its help, problems which it was difficult to solve, up till now, find an elegant solution,

(MS 606) *Ch. Ehrensperger. (Mo.)*

MUTATOR PLANTS FOR ELECTROLYSIS.

Decimal index 64. 314. 65: 621. 35.

Big quantities of electric power under the form of direct current are required for making aluminium, zinc, hydrogen, chlorine, caustic soda, etc. This power is mostly produced by converting three-phase current into direct current. Mutators of big output are being increasingly used for this purpose because they are superior to rotating converters both from the economical point of view and from that of reliability in service.

I. D.C. POWER STATIONS VERSUS CONVERSION OF THREE-PHASE POWER.

THE laws discovered by Faraday, according to which the same quantities of electricity disassociate quantities of substances which are proportionate to their chemical equivalent weights and that to dissolve a gramme-equivalent 96 540 Coulombs are necessary, will make it clear that big amounts of current are required for electrolytic processes when the latter are on an industrial basis (production of aluminium, magnesium, hydrogen, zinc, copper chlorine and caustic soda). Therefore, these processes are forcibly bound up with the possibility of getting cheap electric power. With a few exceptions, metallurgical plants — and especially those for the electrolysis of aluminium — are supplied from hydraulic power stations.

It is an interesting fact that the site from which the ore is extracted and the site of the metallurgical plant itself are, often, thousands of kilometres apart and, despite this, the process is a paying one because the electric power can be got at very advantageous

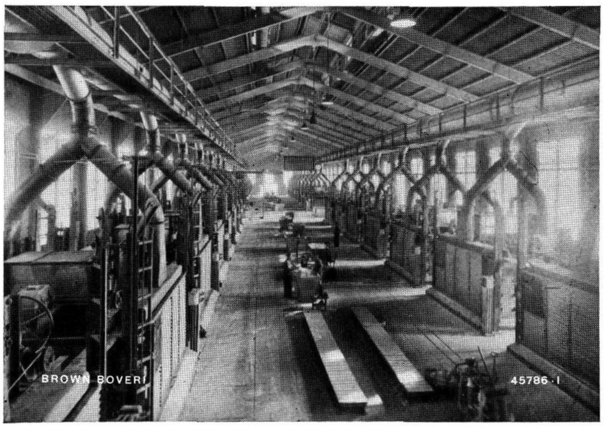


Fig. 1. — Furnace room in an aluminium works with Soederberg furnaces each of 32,000 A.

prices (Norway, Canada). As is generally known, D.C. is required to disassociate metallic salt solutions, as it separates the electrolytes into positive metallic ions (cathions) and into negative anions. The metallic ions are neutralized on the cathode giving up their positive charge and being deposited thereon as a metal deposit while the anions wander to the anodes and are subjected there to determined chemical reactions, giving up their negative charge in the process.

As, now, the electrolytic processes of disassociation require that D.C. power should be available, it seems obvious that direct generation of D.C. power is called for. The fact that it is exceptional to find that D.C. generators have been built, even for the biggest electro-metallurgical works put up so far, seems a strange thing at first sight. The fundamental reasons advocating against the direct generation of D.C. power may be summarized as follows: —

The D.C. generating plant must meet the requirements of the metallurgical plant both as regards strength of current and voltage. In the case of a short or prolonged shutting down of the process the generating plant must also be stopped. In all probability the generators cannot be used for another purpose, this especially so if the power has to be carried over a long distance. For big electrolytic plants, the first costs of a D.C. power station are considerably greater than those of a three-phase plant of the same output, because in D.C. generation practice the generators are much smaller and this means putting in a larger number of them. If turbo-generators are being used, then there are reduction gears also wanted, on account of the high speed of standard steam turbines. To this it must be added that the auxiliary services of the whole plant require the putting in of an additional three-phase set and this for a total three-phase power requirement which may attain several thousands of kW.

Fig. 1a. — Hydrogen electrolytic plant, on left Fauser cells, on right Knowles cells, supplied by grid-controlled mutators 20,000 A, 650 V.

As opposed to this, the engineer laying out the plant is able to plan a suitable three-phase power station on lines of great service reliability combined with economy of operation. He can base his calculations on the most advantageous speed and output as well as voltage for his generating units and can make his plant one which works to the best possible efficiency at the lowest possible capital outlay. If business slumps should occur, in the field of the electrochemical production under consideration, forcing the management to close down part of, or all, the plant, the three-phase generators of the power station can be used for other industrial purposes, as they offer easy possibilities as regards power transformation and transmission. At the much lower capital outlay called for with three-phase power station an overall efficiency is attained including the losses due to conversion from A.C. to D.C., which is fully equal to the overall efficiency to be expected from the direct generation of D.C., unless exceptionally unfavourable conditions for the conversion have to be reckoned with.

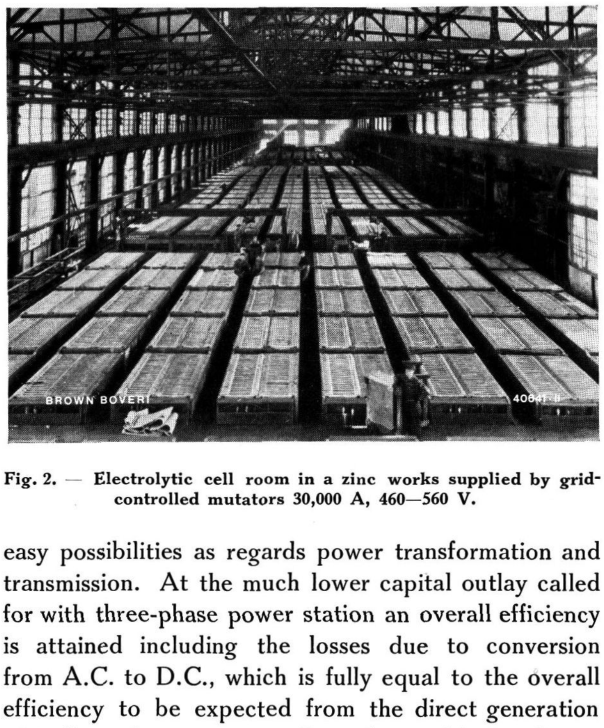


Fig. 2. — Electrolytic cell room in a zinc works supplied by grid-controlled mutators 30,000 A, 460—560 V.

As, now, the outlay for electric power forms the major part of the cost of production in electrolytic processes and this, especially, where aluminium is concerned, and as the three-phase generator units in the power station can always be chosen so as to give the best possible efficiency, all efforts of the projecting engineers will be bent on obtaining the biggest possible production at the lowest cost by using the most economical type of A.C. — D.C. converter on the market. This is the case when the industrial chemist works hand in hand with the electrical engineer in laying out the electrolytic equipment of the plant and when both are animated with the desire to build a plant giving electric power at lowest first costs and lowest upkeep and running charges.

In this respect, the Brown Boveri mutator for large outputs opened up new possibilities. In the short

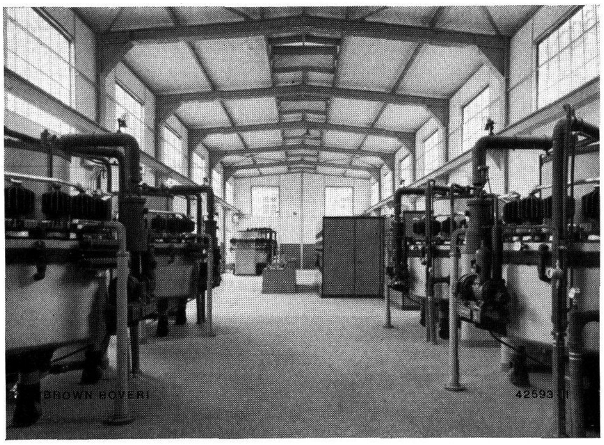


Fig. 3. — Mutator plant for an aluminium works; four double sets of, each, 11,000 A, 600 V, total 26,400 kW.

space of less than 10 years, the mutator has definitely dislodged the rotating converter from the place it held in industrial electrolytic plants, this thanks to the qualities of economy and reliability in service which characterize the mutator.

II. THE CHOICE OF THE BEST ELECTROLYTIC VOLTAGE.

Before the choice has been made of the type of converter to be used, the engineer laying out the electrolytic plant has to decide on the fundamental factor of the best voltage for the electrolysis baths, basing his decision on a given yearly production; he also has to decide what type of converter will be the cheaper supposing the yearly production has to be stepped up and that the plant has to be enlarged, in consequence. If the engineer desires to base his calculations on the point of view of lowest conversion losses, he often comes up against the distaste of the chemist for working with unusually high electrolytic voltages. There may be rooted prejudices to be overcome in this respect. As a matter of fact, statistics show that the number of accidents occurring in big electrolytic plants working at voltages up to 800 V, is rather lower than in low-voltage plants in which the question of insulation has not been sufficiently gone into; this, of course, provided that the first-mentioned plants have electrolytic halls built strictly to the regulations generally adhered to in electric practice as regards insulation of parts under voltage and as regards earthed part. The following table shows the highest voltages used to-day for various electrolytic processes, for which Brown Boveri mutators of large output have been used.

Electrolysis of aluminium . .	800 V
„ „ zinc	820 V
„ „ chlorine . . .	800 V
„ „ water	830 V

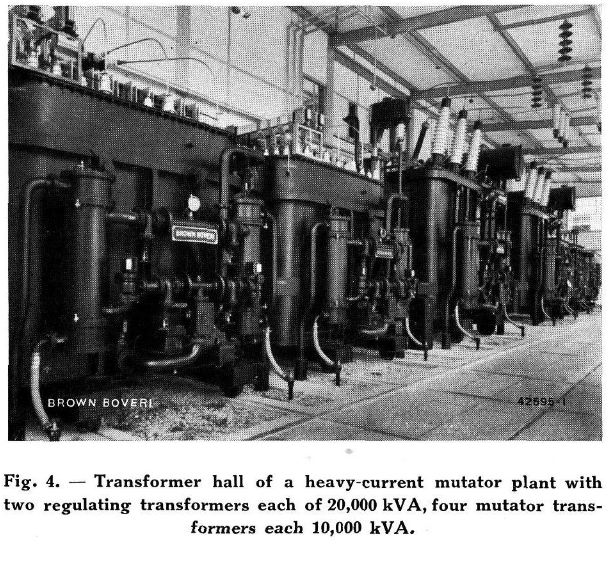


Fig. 4. — Transformer hall of a heavy-current mutator plant with two regulating transformers each of 20,000 kVA, four mutator transformers each 10,000 kVA.

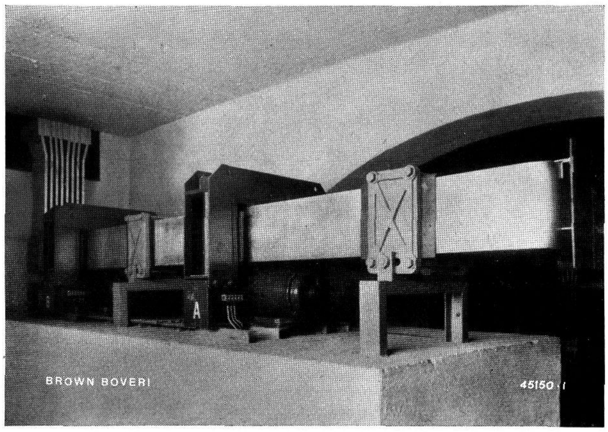


Fig. 5. — D. C. measurement by means of D. C. measuring transformers in a big electrolytic plant.

III. CONSIDERATIONS OF ECONOMY.

The well-known fact that the efficiency of a mutator set is chiefly dependent on the voltage drop in the arc of the mutator and that the latter is independent of the D.C. voltage and varies between 20 and 30 V according to the size of the mutator tank, shows that the overall efficiency of a mutator plant increases rapidly with the electrolytic voltage and that, for voltages such as those just given of up to 800 V, it may attain values which no rotating converter can, even, approach. In industrial electrolytic plants, working day and night, at full load, small improvements in the efficiency, of the order of 2 to 3 %, mean big savings of power. If a concrete example is taken from an existing big aluminium electrolytic plant, the following conditions are attained:—

mutator plant 60,000 kW at 800 V

(a) overall efficiency of mutator plant 94·8 %;

(b) overall efficiency of a corresponding motor-generator plant 91·3 % without intermediate transformation.

As, now, a big metallurgical works is, usually, connected to the high-voltage transmission line of the power station supplying it, there are additional losses for the transformation of the three-phase power to be reckoned with, in case (b), of at least 1 %.

Annual number of operating hours 8500
kWh rate 1 centime.

Annual saving in power cost in francs:—

$$8500 \text{ h} \times 60{,}000 \text{ kW} \frac{4\cdot5}{100} \times \frac{1}{100} = \underline{\text{Fr. } 229{,}000}$$

Leaving the factor of interest out of account, it is seen that with mutators over two millions of francs will have been saved, on power cost, within the space of ten years.

As, however, the opportunity of supplying mutator plants of the size just considered is very rare, while smaller ones, which generally work to lower D.C. voltages according to their yearly production, have been put up in considerable number during recent years, it should be of general interest to determine what the lowest voltage limits are at which mutators can be used to advantage. If the question of profitable exploitation is considered only on the basis of first costs for machinery and apparatus with that of the efficiency of conversion without considering the additional outlay for buildings, cranes, ventilation plant and upkeep, then about 300 V can be taken as the lowest limit. A mutator plant, generally, requires only a light reinforced concrete building or one of steel framework with brick masonry. Special foundations and heavy cranes are, generally, not required; further, the staff needed is considerably reduced in a mutator plant, which brings down running charges appreciably when working with three shifts, so that, even when operating at voltages below 300 V, mutators may be put in advantageously, in many cases. This is, especially, the case when there is a good chance of the annual production being increased, shortly, with simultaneous increase in the electrolytic voltage. Another advantage of mutators is that fouling or dust depositing by graphite or clay on the vital parts of the mutator or decomposition through the action of air containing acid fumes (zinc electrolysis) need not be feared because the mutators themselves work under vacuum in gas-tight tanks and the transformers are in enclosed oil baths.

If, for example, a small mutator plant for an aluminium works is built for an initial annual production of 1500 t and for a future production of double that figure, the cost of the transformation to higher output will only be 15 %, because the three-phase and direct current switchgear plant as well as the mutators themselves can carry and deliver twice the output without being rebuilt.

To summarize, it can be said, that the lowest voltage limit at which mutators can be used, advantageously, for electrolytic purposes is not fixed absolutely. It depends on a number of factors which must be examined and weighed in each particular case under consideration.

IV. THE DIAGRAMMATIC LAYOUT OF AN ELECTROLYTIC MUTATOR PLANT.

As regards the foundamental layout of a mutator plant for a big electrolytic metallurgical works, reference is made to Fig. 6. Usually, the power under form of three-phase current is carried to the plant through a high-voltage transmission line.

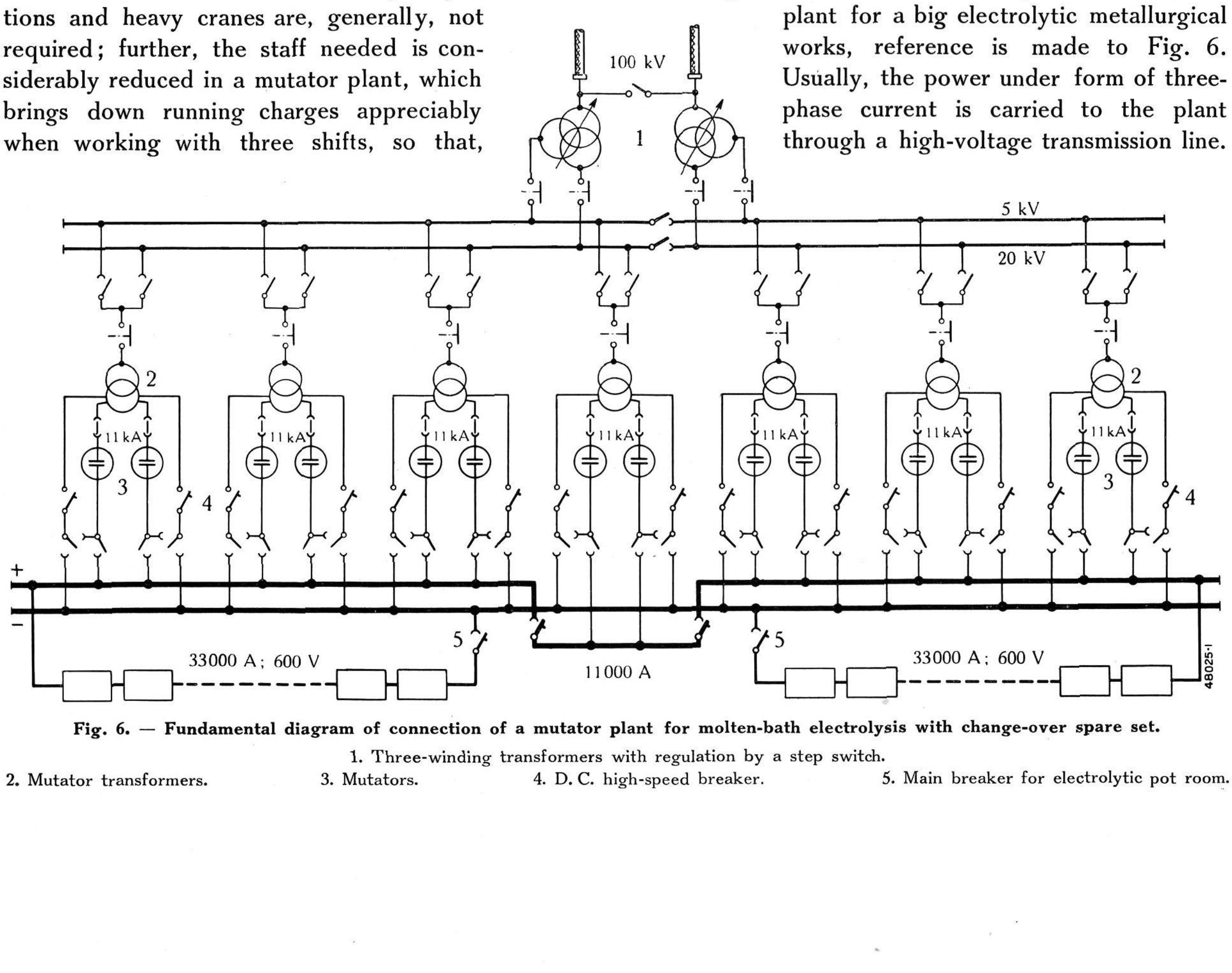


Fig. 6. — Fundamental diagram of connection of a mutator plant for molten-bath electrolysis with change-over spare set.

1. Three-winding transformers with regulation by a step switch.
2. Mutator transformers.
3. Mutators.
4. D. C. high-speed breaker.
5. Main breaker for electrolytic pot room.

Step-down transformation of the three-phase voltage first takes place in a substation, which, according to local conditions, is either combined with the mutator plant or put up separately. The voltage stepped down to is a suitable average one of 10 to 20 kV and the mutator transformers are supplied at this voltage. If current is being supplied to two furnace series or two electrolytic-bath series, for example each for 30,000 A to 40,000 A, two main transformers for the two furnace sets will be put in, in order to secure as independent operation as possible; these form mutual spares and are also designed as regulating transformers with a third winding. This third winding is utilized for the formation of the mutators and for the supply of auxiliary services in the plant. Power is supplied from the regulating transformers to the various mutator transformers which, on their part, each feed two mutators in parallel and the number of which depends on the size of the plant.

Such subdivision of power as that shown in Fig. 7, for big electrolytic plants, is not understandable to those unacquainted with this kind of plant. It seems logical to suppose that fewer and bigger units would be a cheaper solution. Unfortunately, there are narrow limits imposed, here, on the engineer projecting the plant. As most of the mutators used in electrolytic plants work at voltages between 300 V and 800 V, the voltage drop in the arc plays a very important part in calculating the overall efficiency. If, for example, the rated current of a mutator is raised from 6000 A to 10,000 A, the voltage drop in the arc increases. On the other hand, the loading gauge of the railway line puts a limit to the dimensions of the mutators. Contrary to rotary converters, which can be dismantled for transport, mutators are already formed under vacuum before despatch and go as a complete set. A subdivision of the mutator tank into several parts would raise considerable constructive difficulties and would mean complicated work of erection on site, requiring much time.

For electrolytic plants, the twelve- and eighteen-anode mutators according to Figs. 8 to 10 for 4000 A to 8000 A rated current, which have been thoroughly developed, to-day, and have many years of satis-

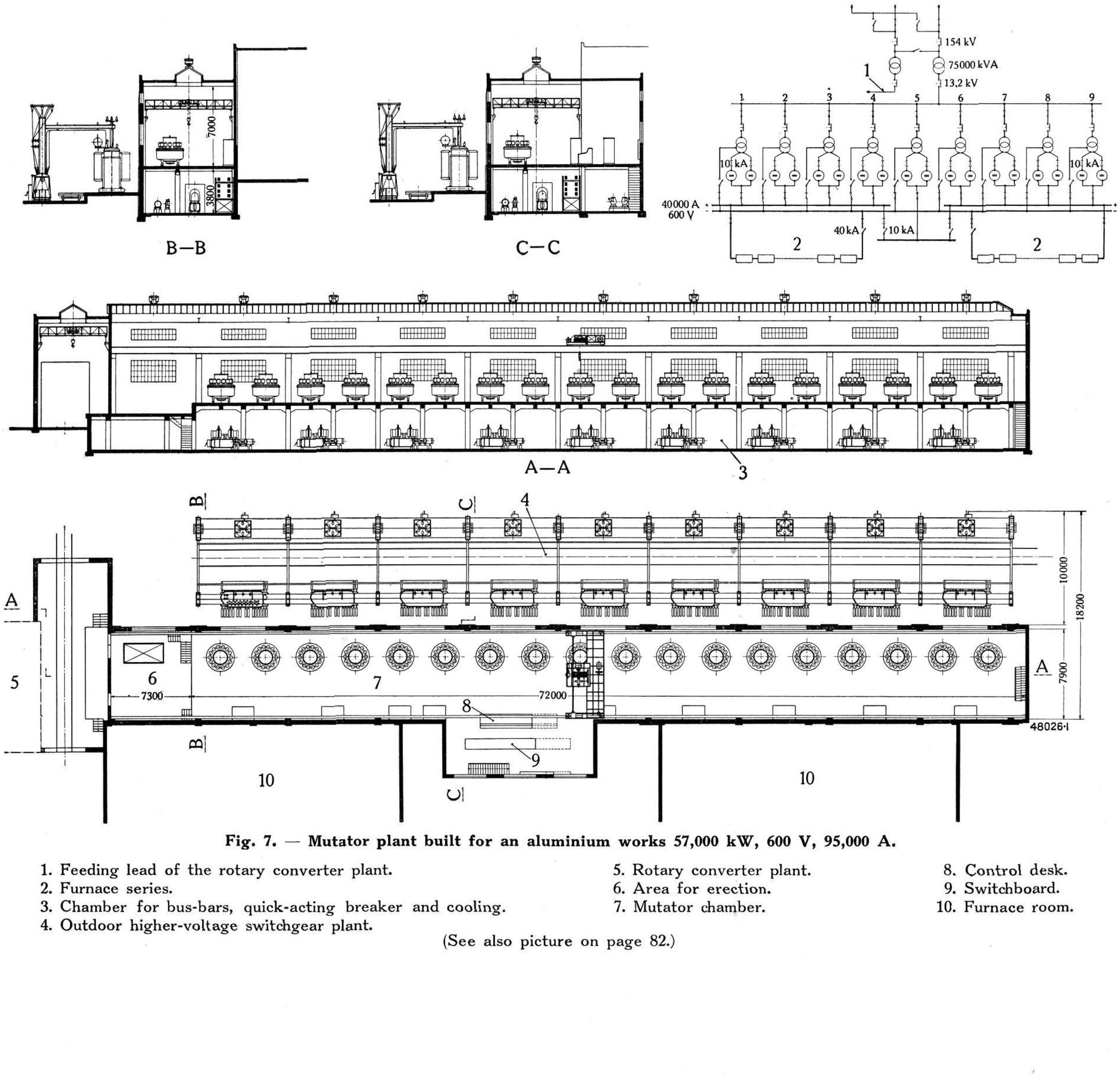


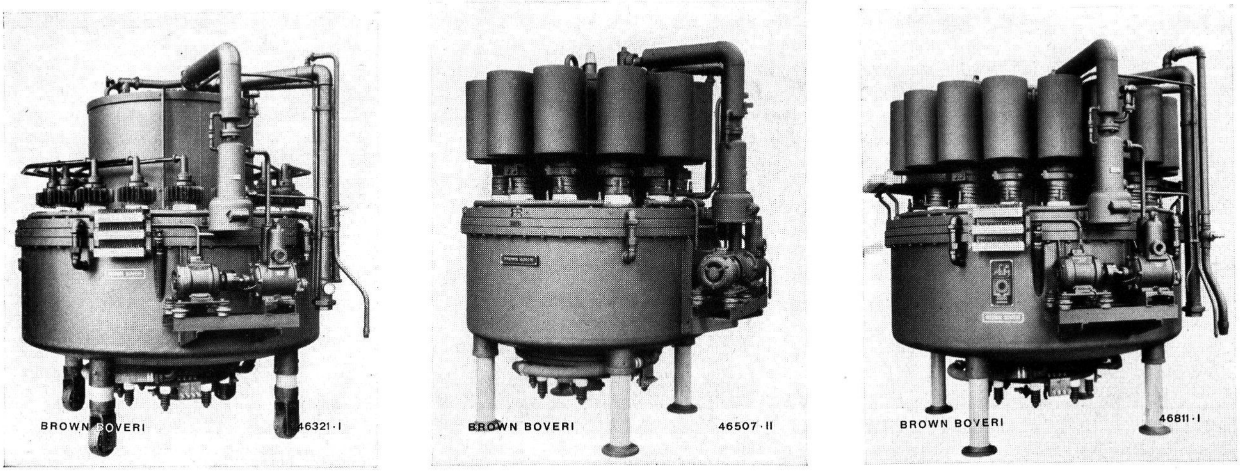
Fig. 7. — Mutator plant built for an aluminium works 57,000 kW, 600 V, 95,000 A.

1. Feeding lead of the rotary converter plant.
2. Furnace series.
3. Chamber for bus-bars, quick-acting breaker and cooling.
4. Outdoor higher-voltage switchgear plant.
5. Rotary converter plant.
6. Area for erection.
7. Mutator chamber.
8. Control desk.
9. Switchboard.
10. Furnace room.

(See also picture on page 82.)

factory service behind them, form the standard mutator types for this purpose.

It may also be asserted that the mutator transformers, as built to-day for the distribution of the A.C. power to the various anode valves of the mutators and which are designed as 2 × n × 6 - phase transformers to simplify the bus-bar plant (in varying from 1 to 4) are, often, masterpieces of modern transformer work. Apart from the ordinary conditions, these transformers have two other important conditions to fulfil. The equal loading of the 24 to 48 anodes demands — apart from the great subdivision of the secondary winding into 24—48 phases — an exact calculation of reactance conditions and an intermingling of the various systems to bring about the desired result, carried out according to a special diagram of connections. Further, the design of this much subdivided secondary winding must be such that the transformer can stand up without damage to the heavy short-circuit forces which are created when backfires take place and this even when the short circuits are repeated. Reliable working of the plant depends fully as much on good transformer design as on using a mutator design tried out by years of service in other plants.



Figs. 8, 9 and 10. — Mutators for electrolytic plants with twelve and eighteen anodes for 4000 A to 8000 A, with built-on vacuum-pumps and fittings for indirect fresh-water cooling, thermostat and terminal board for the auxiliary services.

The connection of the different mutator sets to the main bus-bar is through the D.C. breaker on the negative pole in connection with disconnecting switches on the + and — pole.

The service spare sets which consist of one or two double sets, according to the size of the plant, can be switched on to the bus-bars of one or other of the furnace series through special D.C. automatic switches. The different series of furnaces or baths are either connected up to the bus-bar system through simple bus-bar disconnecting switches or through special main circuit breakers built for rated currents up to 50,000 A.

V. THE INFLUENCE OF THE UNDULATIONS IN THE MUTATOR CURRENT ON THE ELECTROLYTIC PROCESS

and the reaction of the mutator plant on the primary three-phase supply and on possible rotating converters working in parallel, as regards higher harmonics and wattless current.

As both these questions are always coming up again when new electrolytic plants are built and as the influencing of the three-phase supply system by the mutator load of big electro-chemical works has been the subject of lengthy articles in the technical press, it is interesting to summarize, here the experience gained in the course of the last decade in numerous plants with mutator loads of up to 60,000 kW and more.

In none of the 50 big plants equipped by Brown Boveri have any deleterious effects, due to higher harmonics of the mutator current, been recorded in the electrolytic process. According to the oscillographic records made in a number of important plants,

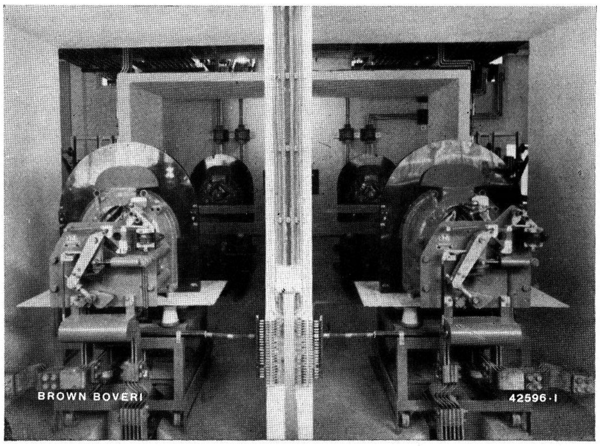


Fig. 11. — D. C. quick-acting circuit breaker and disconnecting switch cells of an electrolytic mutator plant; switch units for 6400 A, 600 V.

the connecting bars between the different sets as well as the main bus-bars between the mutator plant and the electrolytic-process building provide a sufficiently big reactance to smooth out, practically entirely, the D.C. delivered by a six-phase mutator plant, provided the said bars are suitably laid out. In aluminium works, it has been shown that the residual undulations in the mutator current give a welcome additional heating of the furnaces and, thus, provide better utilization of the current absorbed. Not the slightest influence on the purity of the metal in either aluminium or zinc production has been detected. Further, in nitrogen works where mutators have been used for nearly ten years for the preparation of hydrogen by the aqueous process no reduction in the purity of the gas, at all, has ever been noticed. These practical results prove that the six-phase mutator plants which are best suited to rough metallurgical service have no deleterious influence, whatsoever, on the electrolytic process.

As regards the reaction of the mutator plant on the primary three-phase supply and the possible synchronous motor generator sets or rotary converters, running in parallel, this very complicated problem is best answered by the statement that of the 50 plants built within the last decade by Brown Boveri, only one gave trouble of this kind. By rewinding a part of the transformers, the undesirable reaction on parallel operating rotating converters and on the system was satisfactory suppressed.

The six-phase connections developed by Brown Boveri with a two-legged absorption choke coil was the one which first gave an economically satisfactory utilization of the electrolytic mutators and their transformers. It is used generally to-day. If the total mutator load forms a considerable part of the system load of the plant delivering power, the load on the generators chiefly due to the additional load from the fifth and seventh current harmonics can be somewhat reduced. In such cases, the harmonics in question and, therewith, the undesirable influencing of the generators, can be eliminated by simple means. The suppression of the fifth and seventh current harmonics carried out by an artifice in the transformer connection and one which costs very little, will probably be increasingly utilized. Up till now, there have been no cases recorded of resonance phenomena between the capacities of the system and inductivities, created by additional higher harmonics of the mutator load. If the residual higher harmonics should lead to resonance with the inherent frequency of the system, there are means available to eliminate trouble of this nature.

Fig. 12 shows the type of transformer most often used, to-day, in electrolytic plants. This transformer allows of suppressing the fifth and seventh higher harmonics, which would, otherwise, charge the three-phase system unprofitably. The design also allows of making the transformer very resistant to the effects of short circuits even when designed as a regulating unit, as well, a quality which is often required of transformers in electrolytic plants. Sets A and B work in parallel on the same series of furnaces. The phase position of the four six-phase star-connections of both transformers is displaced by 30° by means of a ± 15° displacement of the zigzag-connected primary winding. In this way the secondary six-phase systems of both transformers form a quadruple twelve-phased star connection corresponding to the 48 mutator anodes. As Fig. 12 shows, the fifth and seventh higher harmonics, which are present in the primary current of the two transformers, are so displaced with regard to their fundamental curve by the 30° rotation that they compensate one another in the total current of the system. There still remain the eleventh and thirteenth higher harmonics and the multiples thereof.

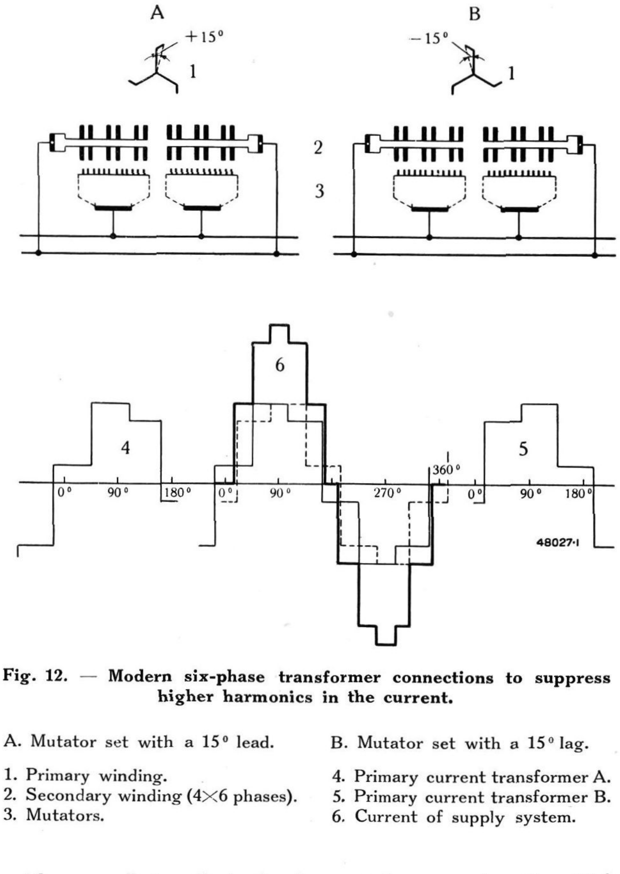


Fig. 12. — **Modern six-phase transformer connections to suppress higher harmonics in the current.**

A. Mutator set with a 15° lead.
B. Mutator set with a 15° lag.

1. Primary winding.
2. Secondary winding (4×6 phases).
3. Mutators.
4. Primary current transformer A.
5. Primary current transformer B.
6. Current of supply system.

Now, if it be desired to go a step further and attain the twelve-phase state in the primary current of each transformer, the latter must be designed with two separate primary windings displaced as to phase position by 30°. From the technical and constructive point of view these transformers are so complicated that, usually, it is considered better to give preference to the units with simpler windings, this both from the point of view of reliability in operation and of cost.

VI. PROTECTION AGAINST BACKFIRES AND SHORT CIRCUITS.

The control grids, which work so reliably, really brought the first satisfactory solution of the short-circuit problem, this in the present-day design and combined with over-current and back-current protection (DRP 537901 and DRP 536535).

The exceptionally satisfactory results attained with grid protection have done much to further the development of the mutator of big output for use in all branches of industrial-scale electrolysis. The experience gained in years of practical operation with grid controls of fundamentally different kinds in big plants, has shown that the principle factor is simplicity in design and absolute reliability in continuous service, this much more than the method of operation of the various systems (control by contact distributors running synchronously, control by phase rotation, control by electronic tubes). Recognizing that every addition piece of apparatus is an additional complication, Brown Boveri have worked out a series of connections based on simplicity, as far as possible. Other articles in this number give explanations of how these backfire and short-circuit protective devices work.[1]

The oscillogram of Fig. 13 shows how the grid control built into the mutator is able to extinguish faultlessly a D.C. short circuit (40,900 A) in a 17·3/1000 of a second.

VII. THE PROBLEM OF VOLTAGE REGULATION.

A characteristic feature of all electrolytic processes is the necessity of being able to adapt the D.C. voltage generated so that it suits the various electrolytic processes. The following conditions make it necessary that it should be possible to regulate the electrolytic voltage, as continually as is feasible within a narrow or wide range.

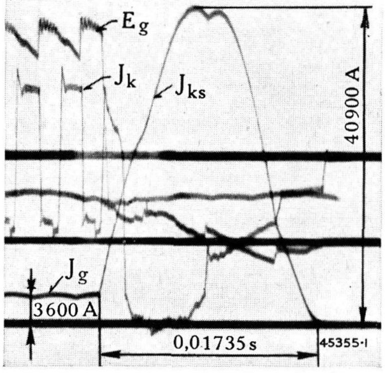


Fig. 13. — **Clearing of a short circuit on a mutator type Agg 918, with the help of built-in controlled grids.**

E_g. D.C. voltage.
I_g. Direct current.
I_{ks}. Short-circuit current.
I_k. Grid current.

1. The chemical changes which take place in the electrolytes and the rapid changes in resistance of the furnaces and baths which are a consequence thereof (anode effect of molten-bath electrolysis, sludging of the diaphragms in the electrolysers).
2. The cutting out of individual furnaces or baths or electrolysing sets when defects develop in the electrodes or when diaphrams break (poor electrolytic efficiency and impure gas).
3. The adaptation of the production to the market requirements and to the amount of power available from the power supply station.
4. The putting to work for the first time of a new electrolytic plant with as continuous increase of the electrolytic current as is possible from zero up to the rated value and the starting-up again of the electrolytic process after a short or long stoppage.

If, now, the electric supply plant has got to satisfy all the conditions enumerated a minimum regulating range is required which is between the highest service voltage and the value of the voltage of polarization of the electrolytic cells in question of the plant.

Generally, coarse regulation is carried out on the regulating transformer by means of the built-in neutral-point step switch, this manually or automatically. Continuous, close regulation is carried out by the controlled grids in combination with a quick-acting regulator or oil-pressure regulator. The combination of step switch and grid control was first developed in 1932 by Brown Boveri for a big aluminium electrolytic works. Since then, this regulating method has been generally adopted for big mutator plants.

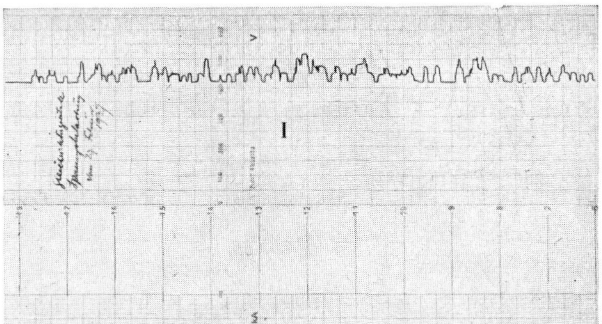


Fig. 14. — **Behaviour of current and voltage in an electrolytic aluminium plant when the mutators supplying the plant are under regulation to constant current by means of grid control.**

I. Total D.C. voltage of the electrolysis.
II. Total D.C. current of the electrolysis.

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[1] See article on page 99.

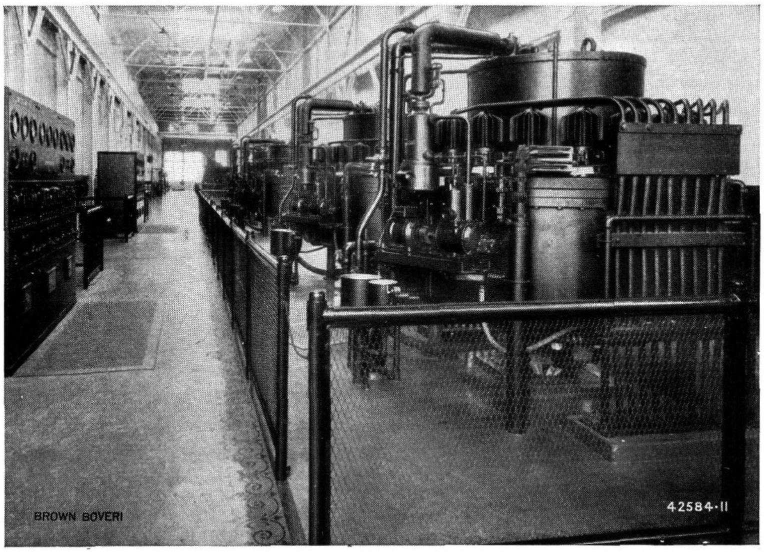


Fig. 15. — Cons. Mining & Smelting Co., Warfield (Canada). Mutator plant for the fertilizing plant. In the background four mutators each of 5000 A, 670 V (1931); in the foreground four mutators each of 5000 A, 830 V (1936).

VIII. PLANTS ALREADY BUILT.

Thanks to the economical and technical qualities of the mutator and to the progress made in the development of controlled grids, which allowed of developing absolutely reliable electrolytic plants, it was possible to introduce the mutator to every field where aqueous electrolysis and molten-bath electrolysis were applied. The following table gives some data on mutators delivered for electrolytic purposes.

	Output in kW	Current in A
1. Aluminium .	442,900	716,000
2. Zinc . . .	71,800	109,500
3. Water . .	76,400	119,200
4. Chlorine and caustic soda	60,300	98,500
Total . .	651,400	1,043,200

A comparison between this table and the figures published in the December 1934 number of The Brown Boveri Review, shows that Brown Boveri succeeded in quadruplicating the 1920 to 1934 figures in the course of three years and in participating to the extent of about 500,000 kW in the enlargements of existing plants and establishing of new ones in Europe and America.

(MS 596) *A. E. Danz. (Mo.)*

THE TESTING OF HIGH-VOLTAGE MUTATORS IN RECUPERATIVE SERVICE, CONSIDERED AS FUNDAMENTAL TESTS FOR HIGH-VOLTAGE D.C. TRANSMISSION.

Decimal index 621. 314. 65 : 315. 051.

This article shows that, to-day, a most satisfactory standard of reliability in service and under continuous loading, as well as perfect clearing of short circuits has been attained. The investigation of voltage relationships shows that the stressing to which D.C.—A.C. mutators and A.C.—D.C. mutators are subjected is essentially different, but that this problem has been entirely mastered. The results of the investigation hold out great promise for future developments.

I. INTRODUCTION.

THE progress made and the improvements introduced to mutator design and to mutator-control devices, in the course of recent years, have resulted in this apparatus becoming, to-day, a universally recognized static converter. Brown Boveri have already delivered a large number of mutators for the transmitting stations of broadcasting companies, where they are used to supply the anode current for high-capacity transmitting valves. The experience gained with these mutators has been most satisfactory. The grid control for regulating the voltage and suppressing short circuits on very inductive circuits, works so reliably that trouble occurring such, for example, as short circuits in valves, flash-overs in the transmitting apparatus, and backfires are, always, cleared, perfectly and in a minimum of time.

The satisfactory experience gained with mutators working on recuperation service in traction plants, at 3000 V D. C. justified high expectations for the development of high-voltage mutators for high-voltage D. C. transmission, as well. Continuous development work on these mutators was crowned by most satisfactory results in D. C.—A. C. service. This signifies that the mutator is, now, a perfect converter for the highest voltages. The development of the mutator means that a big step has been taken towards the realization of power transmission by means of high-voltage mutators.

II. THE FUNDAMENTAL TESTING CONNECTIONS.

In order to test the mutator on A. C.—D. C. service, the converted D. C. power was consumed in resistances, up till now, in accordance with the arrangement shown in Fig. 1. Now, these resistances made of oil-cooled metallic resistor elements, or glass tubes with water flowing through them, required both a certain amount of supervision and a considerable supply of cooling water. These on-load continuous tests were very expensive and it was, therefore, most desirable to find some way of recuperating the power converted *into* D. C. This reduces the cost and also supplies valuable results in D. C.—A. C. service. Apart from these on-load continuous tests in A. C.—D. C. service with unregulated voltage, the regulated-voltage and short-circuit tests with controlled grids showed that a high degree of service reliability had been attained after long and painstaking development work in the field of the high-voltage mutator. The short circuits were produced straight between the cathode and the neutral point of the transformer. In this test, and as seen in Fig. 1, a sparking tip is inserted in series with the short-circuit device, which has such a short gap that the tip flashes over when the short circuit is initiated. In this way, a luminous effect is produced corresponding to the volume of current passed, when a short circuit takes place and this effect could be used to judge the rupture. Even under the heaviest short-circuit currents of 1800 A at 12·5 kV D. C. voltage, according to the oscillogram of Fig. 2 a, or 550 A at 50 kV, according to the oscillogram of Fig. 2 b, the extinction of the mutator takes place absolutely reliably without a subsequent backfire occurring. The oscillograms of Figs. 3 and 4, with the photos of the arc across the sparking gap show, convincingly, the great difference between a short circuit cut by means of grid control and one by means of oil circuit breaker, the grids being, of course, cut out in the latter case. The arc photos are all taken from the same position so that the lighting effects can be directly compared, Fig. 4 also shows the excellent short-circuit strength of the mutator within the time necessary for the oil circuit breaker to clear the short circuit. These few oscillograms suffice to show clearly the great advantages of a controlled mutator like this which is not only indestructable under these stresses but which takes over, in itself, the function of a breaker. Mechanical breakers for D. C. voltages and currents of these magnitudes and with high breaking speeds are not yet developed. In a mechanical breaker, the current is forcibly reduced when a rapid break takes place so that high excess voltages must be generated across the inductivities. But when the break is brought

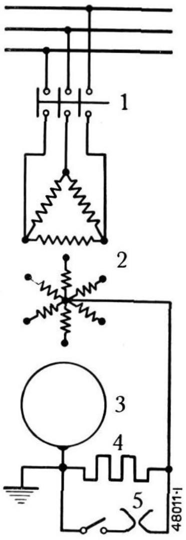
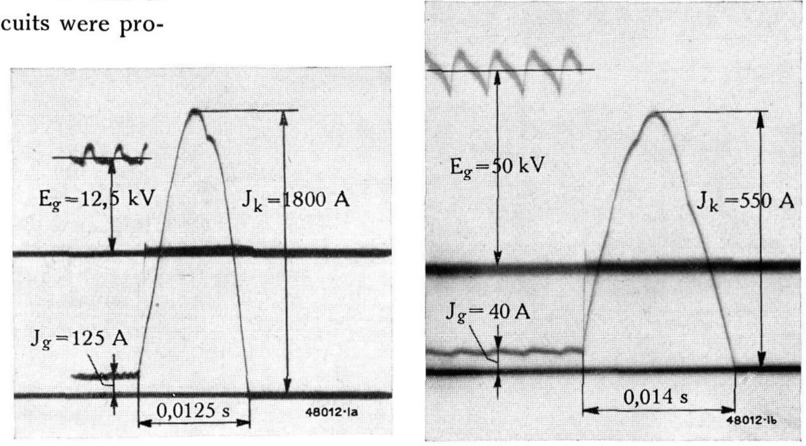


Fig. 1. — **Diagram of connections for load tests on ohmic resistances.**

1. Oil circuit breaker.
2. Mutator transformer.
3. Mutator.
4. Load resistance.
5. Short-circuit device.



Figs. 2 a and b. — **Short-circuit clearing tests by means of grid control, according to the connections of Fig. 1.**

E_g. D. C. voltage. J_g. D. C. current. J_k. Short-circuit current.

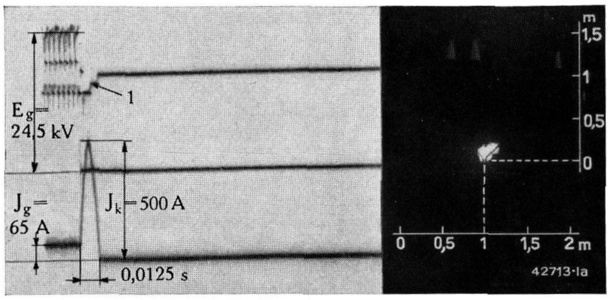


Fig. 3. — **Short-circuit clearing test by means of grid control, according to the connections of Fig. 1, with arc photos.**

E_g. D. C. voltage. J_k. Short-circuit current.
J_g. D. C. current. 1. Grid current.

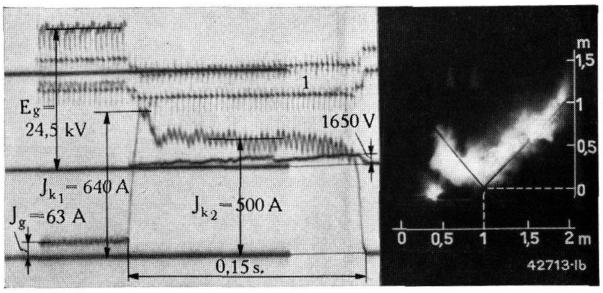


Fig. 4. — **Short-circuit clearing test by oil circuit breaker, according to the connections of Fig. 1, with arc photos.**

E_g. D. C. voltage. J_{k1}. Initial value of } short-circuit current.
J_g. D. C. current. J_{k2}. Constant value of
1. Grid current.

about by controlled grid, the current is brought down to zero by the transformer voltage so that no excess voltages are created in circuit breaking of this kind.

The regulating tests show an increased stressing of the valve. If the point of ignition of the anodes and the control grids, respectively, is gradually displaced in the retarding sense, it is seen that, under constant current, the time of overlapping gets gradually smaller while the commutating voltage between the two phases taking over from one another gets gradually bigger. In this way, the negative voltage step or jump to which the anode just extinguishing is subjected gets constantly greater, while the residual ionization in the anode space is, also, greater at this moment. Both influences cause a considerable supplementary stressing of the valve as regards the initiation of backfires. Further, the capacities and inductivities of the windings play an undesirable part, as they lead to high-frequency oscillations when the voltage steps occur, which stress the valve additionally. The greatest stressing occurs when the D. C. voltage is regulated to about zero. Continuous tests with direct short-circuiting of the cathode and transformer neutral point at 45-kV phase voltage have shown that the grid-controlled mutator is able to stand up to even this high stressing. This shows that, at rated voltages of this magnitude, the mutator can withstand continuous voltage regulation over a wide regulating range. If the point of ignition is retarded still further, the mutator requires an external driving voltage to keep the current up; in other words output and voltage have reversed their sense. In this way, conditions are more favourable again as regards backfires, because the commutating voltage is again lower and the time of overlapping bigger. But, here, the valve must be able to block a higher positive voltage. In this state of operation, the negative anode and positive sleeves and grids of A. C.—D. C. operation interchange their roles in D. C.—A. C. service, i. e. grids and anode sleeves are negative and the anodes positive. In the first case, backfires may take place on the anodes, in the second case, on sleeves and grids. If the mutator is called on to carry out both kinds of service, greater demands are made on the design of the valve.

The tests with the A. C.—D. C. mutator and with the D. C.—A. C. mutator were so carried out that the cathode of the A. C.—D. C. mutator and the neutral point of the D. C.—A. C. mutator were connected to earth potential while the cathode of the D. C.—A. C. mutator connected to the neutral point of the A. C.—D. C. mutator had to show the full D. C. voltage to earth, as is seen in Fig. 5. For this reason, all the auxiliary apparatus for the mutator under voltage, such as the ignition, vacuum and control gears had to be insulated against earth for the corresponding D. C. voltage. All these auxiliary devices were supplied by an insulating transformer and mounted in an insulated switchboard. A choke coil was inserted in the D. C. circuit, in some tests, its duty being to take up the higher harmonics generated by the two mutator sets. In the recuperating tests for 50 kV D. C. voltage and 20 A load current as well as 12·5 kV and 75 A excellent results were obtained. The load was limited by the transformers available.

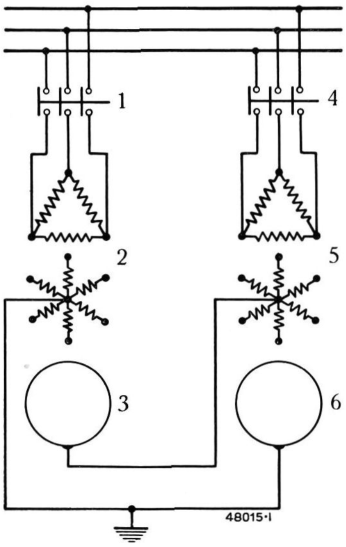


Fig. 5. — Diagram for recuperation tests.

1, 4. Oil circuit breakers.
2, 5. Mutator transformers.
3, 6. Mutators.
1-3. D. C. — A. C. mutator set.
4-6. A. C. — D. C. mutator set.

III. THE BEHAVIOUR OF THE VOLTAGE ON THE MUTATORS.

If a choke coil is inserted on the D. C. circuit, the inductivity of which coil is very large as compared to that of the transformers, the D. C. voltages have the usual shapes, while the choke coil absorbs the voltage difference produced between the two mutators. Fig. 6, curve 1 shows the D. C. voltage generated in an A.C.–D.C. mutator, for a particular case and curve 2 shows the voltage demanded by the D. C.—A. C. mutator. The shaded surface 3 is the voltage appearing across the choke coil. If the phase

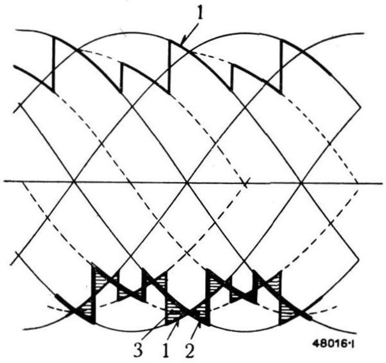


Fig. 6. — Voltage shape across choke-coil when the A.C. — D.C. and the D.C. — A.C. mutator transformers have the same phase and the same voltage.

1. D. C. voltage of A. C. — D. C. mutator.
2. D. C. voltage of D. C. — A. C. mutator.
3. Voltage difference between 1 and 2 = voltage across choke coil.

position of both mutators changes, for example in such a way that the two systems show a displacement of 30° el., then the voltage across this choke coil also changes. Fig. 7 shows this case. It is seen that the higher harmonics of the voltage of six times the system frequency are strongly marked again while they had almost disappeared in Fig. 6. When the choke coil is not inserted conditions are different. Fig. 8 a shows the behaviour of the D. C. voltage and Fig. 8 b that of the anode-cathode voltage for a determined load drop. The D. C. voltage appears quite exceptional but corresponds to the average value of the D. C.—A. C. and A. C.—D. C. voltages. The oscillogram of Fig. 9 confirms the exactitude of these drawings. Naturally, the phase voltage contains deformations caused by overlapping and by the higher current harmonics due to the inequality of momentary voltage magnitudes of the two mutators. The voltage between anode and cathode gets increased higher harmonics, on this account, and also voltage jumps which the valve stood up to in A. C.—D. C. as well as in D. C.—A. C. service.

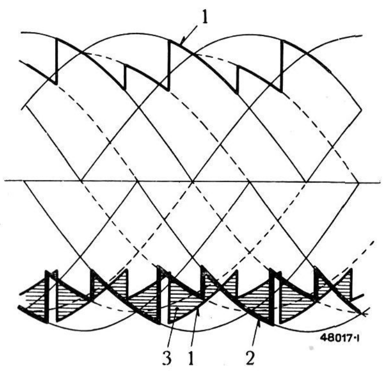
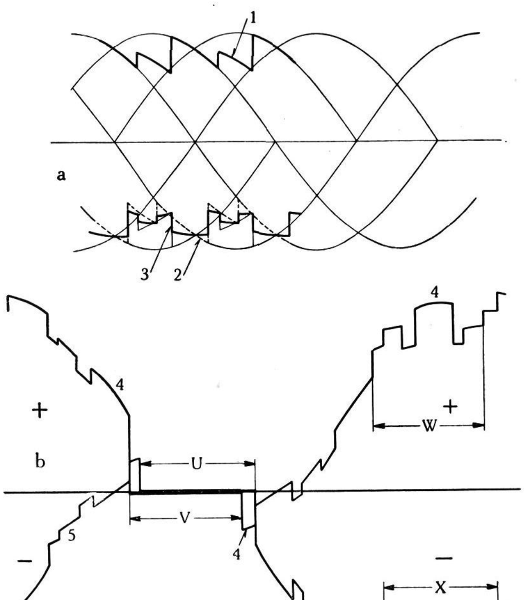


Fig. 7. — Voltage shape across choke-coil when the A. C.—D. C. and the D. C.—A. C. mutator transformers have the same voltage but phases displaced by 30 el. degrees.

1. D. C. voltage of A. C.—D. C. mutator.
2. D. C. voltage of D. C.—A. C. mutator.
3. Voltage difference between 1 and 2 = voltage across choke coil.



Figs. 8 a and b. — Behaviour of voltage during recuperation test at 50 kV and 20 A.

1. Theoretical D. C. voltage on A. C.—D. C. mutator.
2. Theoretical D. C. voltage on D. C.—A. C. mutator.
3. Actual D. C. voltage on both mutators.
4. Anode-cathode voltage of D. C.—A. C. mutator.
5. Anode-cathode voltage of A. C.—D. C. mutator.

U. Time of burning of A. C.—D. C. anode.
V. Time of burning of D. C.—A. C. anode.
W. Time of burning of D. C.—A. C. counter anode.
X. Time of burning of A. C.—D. C. counter anode.

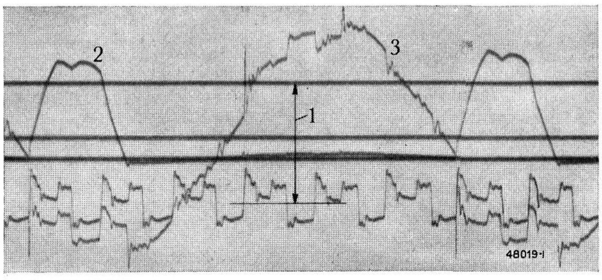


Fig. 9. — Oscillogram for load tests in recuperation service according to connections of Fig. 5.

1. D. C. voltage. 2. Anode current of the 6-W mutator.
3. Anode-neutral point voltage of the 6-W mutator.

The switching-in of these A. C.—D. C. and D. C.—A. C. mutators took place by first putting the D. C.—A. C. mutator under voltage. Its ignition point was chosen about equal to that of the load voltage desired. The ignition point of the A. C.—D. C. mutator was so set that voltage zero was obtained. After the switching in of the A. C.—D. C. mutator, its ignition point was successively displaced in the voltage increasing sense. If, now, the ignition impulse of both mutators is very short, say 1° el., a current voltage characteristic b in Fig. 10 is obtained, in other words it is impossible to set the D. C. current below a certain value. As long as the duration of the positive voltage charge of the grids of six-phase mutators is less than 60° el., in stability of this characteristic

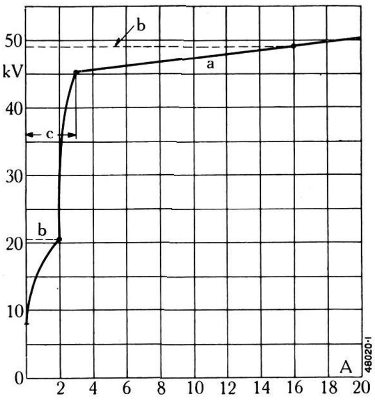
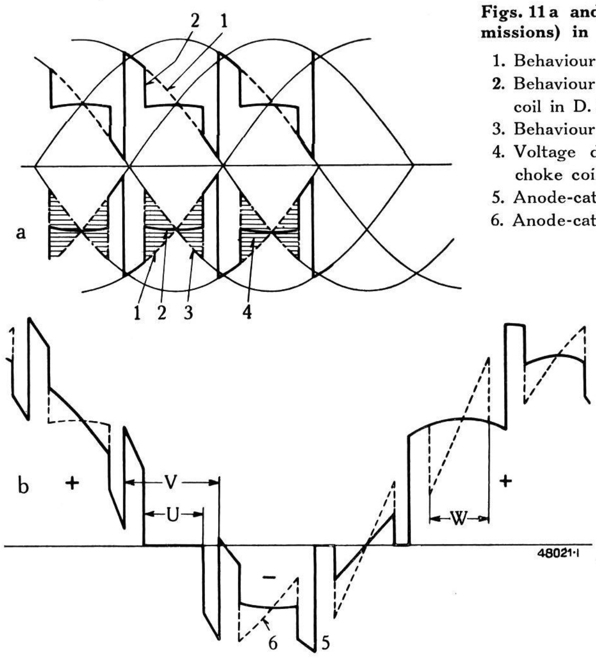


Fig. 10. — Current-voltage characteristic of the A. C.—D. C. and D. C.—A. C. mutators for various grid burning durations.

a. Current-voltage behaviour when the duration of grid burning is 60 el. degrees.
b. Current-voltage behaviour when the duration of grid burning is only 1 el. degree.
c. Range of the intermittent current (with intermissions).



Figs. 11 a and 11 b. — Behaviour of voltage for an imperfect current (with intermissions) in the recuperation tests with 50 kV and 20 A, at 32 kV D. C. voltage.

1. Behaviour of voltage on A. C.—D. C. mutator with choke coil on D. C. circuit.
2. Behaviour of voltage on A. C.—D. C. mutator and D. C.—A. C. mutator, without choke coil in D. C. circuit.
3. Behaviour of voltage on D. C.—A. C. mutator with choke coil on D. C. circuit.
4. Voltage difference between D. C.—A. C. and A. C.—D. C. mutator as long as the choke coil is inserted.
5. Anode-cathode voltage on D. C.—A. C. mutator without choke coil on D. C. circuit.
6. Anode-cathode voltage on D. C.—A. C. mutator with choke coil on D. C. circuit.

U. Time of burning of D. C.—A. C. anode.
V. Time of burning of A. C.—D. C. anode.
W. Time of burning of D. C.—A. C. counter anode.

must be reckoned with. If, however, a duration of grid burning of 60° el. is adjusted to, then the current voltage characteristic of curve a is obtained.

The voltage fluctuations on the mutators, appearing when the current characteristic shows intermissions, are exceedingly big and cause great stressing of the valves. Fig. 11 a shows a certain case of voltage characteristic for the D. C. voltage with an intermittent current. During the current interruptions, the D. C. voltage is dictated by the A. C.—D.C. mutator voltage. Fig. 11 b shows the anode-cathode voltage of the D. C.—A. C. mutator. The whole system between the mutators, insulated from earth and under voltage has to follow these voltage jumps. The many load and regulating tests carried out showed that the valve can stand up to these increased stresses. Short circuits produced on the transmission line were cleared both completely and perfectly and in the shortest time, that is within a half cycle, by the A. C.—D. C. mutator; this, thanks to the quick-acting negative charge of the grids by the grid relay.

(MS 607) *H. Keller. (Mo.)*

THE INTRODUCTION OF D.C.—A.C. MUTATORS TO PRACTICAL SERVICE, FROM THE POINT OF VIEW OF THE TRANSITION FROM A.C.—D.C. TO D.C.—A.C. SERVICE.

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There are various ways of connecting up a D. C. — A. C. mutator unit in traction plants. Connecting it in parallel to an A. C. — D. C. mutator is more advantageous than having a single mutator unit which can be switched over to either service, this from the point of view of flexible service under rapidly fluctuating station load. This arrangement creates a spare for peak load periods.

SINCE the introduction of grid control, the mutator can carry out the functions of a D. C. — A. C. converter. For a number of years, mutators working to this principle have been operating in various plants of considerable outputs and voltages. The practical results recorded fulfil all expectations and widen the field of utilization open to the mutator in traction plants, as it is now able to meet every requirement — including recuperative braking — which can be demanded of a converter for traction purposes. The present article gives a short description of some mutator plants of this type.

To begin with, attention is drawn to the characteristics of an A. C. — D. C. and of a D. C. — A. C. mutator, as shown in Fig. 1, for various ignition angles. This shows, at once, that it is not possible to have smooth transition from one service to the other, without certain measures being taken. This is the factor which played a great part in the problem of introducing the D. C. — A. C. mutator to practical service, in cases where it had to fulfil both functions under the best possible conditions of utilization.

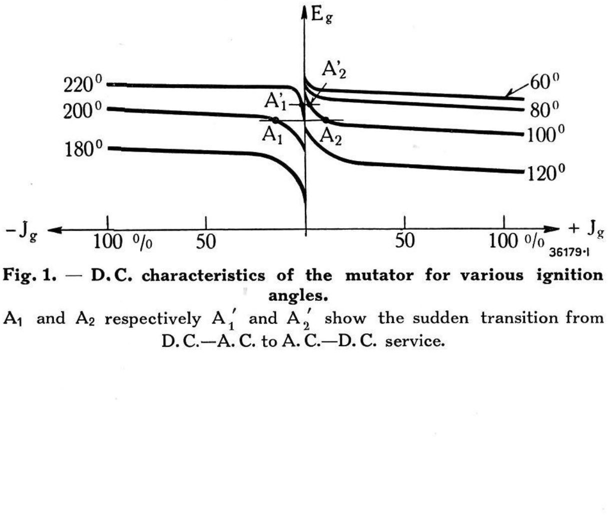

Fig. 1. — D. C. characteristics of the mutator for various ignition angles.

A_1 and A_2 respectively A'_1 and A'_2 show the sudden transition from D. C.—A. C. to A. C.—D. C. service.

If now, for example, two curves are considered, which show the same voltage at the passage of the current through zero, such as in Fig. 2, curve 1, a smooth passage from one characteristic to the other is attained but it is seen, immediately, that the difference in the character of the D. C. voltage between D. C. — A. C. and A. C. — D. C. operation is very great indeed, and would be inadmissible in practice.

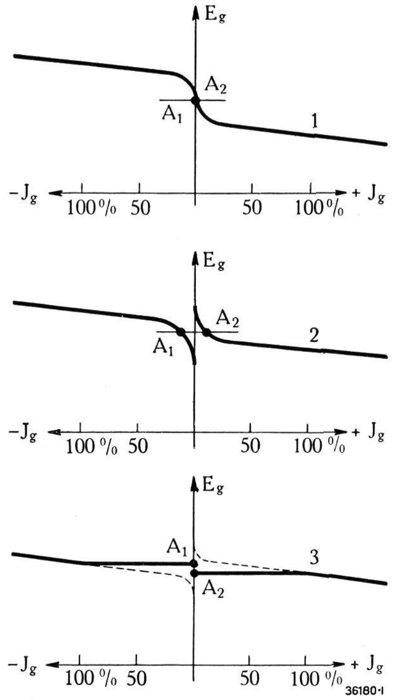

Fig. 2. — Different possibilities for changing over from D. C. — A. C. to A. C. — D. C. service.

1. Both characteristics have the same passage of the current through zero.
2. Both continuous characteristics with reference to ordinary service show a big voltage difference when passing from one service to the other.
3. Both characteristics are regulated to practically the same voltage just before the change-over region is attained.

A much more advantageous choice, as concerns the nature of the two characteristics for D. C. — A. C. and A. C. — D. C. service, is reproduced in curve 2 of Fig. 2. Let a switching over from D. C. — A. C. to A. C. — D. C. service be assumed at a voltage between points A_1 and A_2, it is perceived, immediately, that the operation must be accompanied by a decided current surge, which could not be tolerated in practice.

Therefore, the solution as illustrated in curve 3 of Fig. 2 remains, in which automatic displacement of the ignition point regulates out artificially the marked bend of the characteristic, this down to a very slight voltage difference, just sufficient to actuate a differential relay, which initiates the switching operation.

Thus, the advantages and disadvantages of these connections are shown, purely theoretically, and a practical example can be briefly described, now, to allow of a better estimation of the possibilities of utilization, theoretically and practically.

One of the first applications of a D. C. — A. C. mutator on a full-gauge railway was carried out by Brown Boveri in the South African traction substations of Van Reenen and Colworth (Fig. 3) which have, now, been working for several years, entirely satisfactorily. In this case, there is a D. C. — A. C. mutator continuously in parallel service with an A. C. — D. C. mutator. Both characteristics are so chosen that when the plant is under no load there is a very low current flowing between the two mutators, the losses caused by which can be disregarded as the power in question is restored to the primary system. This circulation current has, also, the advantage that both mutators are always under a very light load, even during long periods where no main load is carried, so that, at any moment, they are ready to handle the heaviest loads and overloads, occurring, without trouble. Further, this arrangement has the advantage that no change-over mechanism is required for the D. C.—A. C. mutator and that even the most sudden change-over from A. C. — D. C. to D. C. — A. C. service takes place perfectly flexibly and without the slightest current surge. This fact has proved very advantageous when the recuperative load is entirely consumed by shunting trains so that the station load fluctuates so frequently that if there were a change-over D. C. — A. C. mutator installed it would have to be constantly going over from one service to the other, and the surges would succeed each other so rapidly that it would be impossible to change-over with the necessary rapidity. Thus, practical results showed that the arrangement adopted meets every requirement whatever service conditions may be and whatever the kind of load to be handled, no special measures being called for on the locomotives. Further, the control of the D. C. — A. C. mutator is so made that, if necessary, this D. C. — A. C. unit can be used as an A. C. — D. C. one, by arranging that, in this

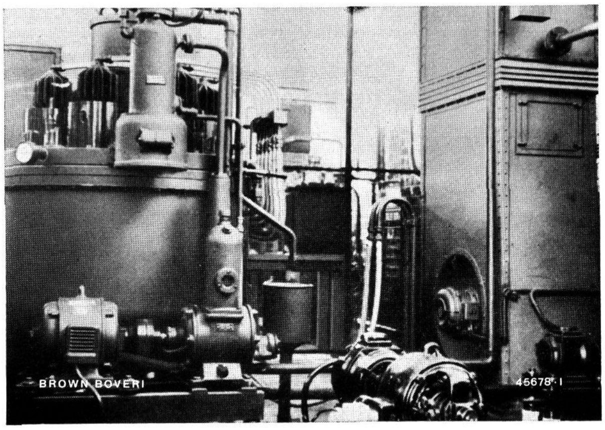

Fig. 3. — Van Reenen mutator plant, South Africa, for D. C. — A. C. and A. C. — D. C. service.

case, the mutator be connected to the transformer winding of the A. C. — D. C. mutator and, thus, serve as a spare for the A. C. — D. C. mutator, as well.

A further application of the D. C. — A. C. mutators by Brown Boveri is to be found in the S. Viola-Bologna railway plant (Italy) Fig. 4. The conditions in this plant are as follows: there are two three-phase systems, one A with a frequency of 50 cycles and the other B with a frequency of 42 cycles and these are connected to the contact wire of the railway through mutators. For metering reasons, a constant amount of power should be drawn from the three-phase system A while, on the other hand, system B cannot deliver any power but, generally, requires power. Therefore, so long as all the power from A is not consumed on the railway system, the surplus should be supplied to B through a D. C. — A. C. mutator. There is an output regulator influencing the grid control of the A. C. — D. C. mutator in such a manner that the power passing through it is constant. This layout was subjected to experimental running for a long period and it gave full satisfaction.

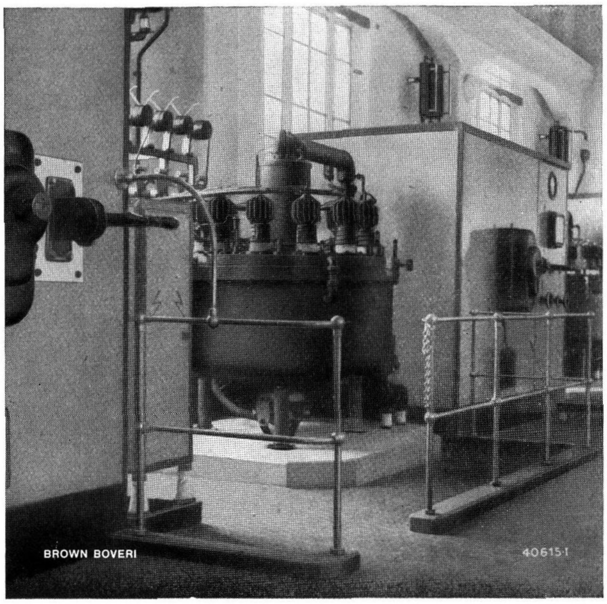

Fig. 4. — D. C. — A. C. mutator plant S. Viola-Bologna of the Italian State Railways.

Another very interesting plant is the automatic change-over D. C. — A. C. mutator in the Cava dei Tirreni substation (Italy) Fig. 5. Under ordinary conditions, this D. C. — A. C. mutator works in parallel with two A. C. — D. C. mutators and has all the advantages already enumerated for the South African substations. If, now, the station load reaches very high values, the D. C. — A. C. mutator is automatically switched over to A. C. — D. C. services and then helps to cover the peak-load requirements in A. C. — D. C. operation. If, on the contrary, the station load falls to so low a value that the said load can be taken care of by the two A. C. — D. C. mutators, the third mutator switches over again automatically to D. C. — A. C. service and is ready at any moment to work back on the primary system, when the total station load gets negative. Under these conditions, changing over takes place without current surges, the switching round to D. C. — A. C. service being carried out in proper time and the D. C. voltage being maintained constant by the parallel A. C. — D. C. mutators during the changing-over process. During no-load periods, the D. C. — A. C. mutator also carries a low circulation current. Therefore, here the advantage is enjoyed that the D. C. — A. C. mutator can also be used as an A. C. — D. C. spare at any time.

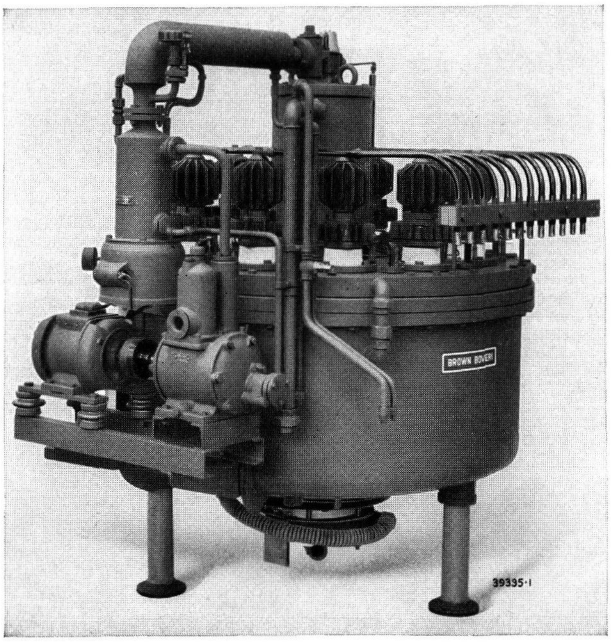

Fig. 5. — Reversible mutator in the Cava dei Tirreni plant (Italy).

In order to prevent the short-circuit point being attained at about ordinary service conditions, in D. C. — A. C. operation, it is necessary that the transformer phase voltage be somewhat higher than for A. C. — D. C. operation, that is to say, when the mutator is designed for automatic change-over service, from D. C. — A. C. to A. C. — D. C., the D. C. voltage in the latter case must be regulated downwards by means of the grid control.

Successful tests were carried out in this plant, as well, in which a separate line for supplying and recuperating was fed from one mutator only. Therefore, according to needs, this mutator was switched over by a relay to A. C. — D. C. or D. C. —A. C. service. The time required for switching was less than 1 s and all these switching operations were, practically, without surges. The change-over of the mutator from one service to the other was actuated by a differential voltage relay working in function of the ratio of system voltage to transformer phase voltage. In service of this kind it was necessary, however, that the motors on the locomotive be excited by a small converter set during recuperation so that the voltage on the contact wire did not become zero during the change-over processes. These tests were most successful and, to-day, the problem of the reversible mutator as used on small railways, for example, is solved.

Of course, as said before, there is the disadvantage, here, that in A. C. — D. C. service the mutator is relatively highly regulated and that the power factor on the three-phase side is lowered. This could be remedied if when changing over the D. C. side of the mutator, primary tappings on the mutator transformer were changed over, simultaneously. This would mean rather expensive apparatus as these change-over operations have to take place under oil.

Of course, there are other ways of carrying out the change-over from D. C. — A. C. to A. C. — D. C. service, such, for example, as parallel switching of a very small D. C. — A. C. or A. C. — D. C. mutator which is always in operation, in order to stabilize conditions at changing over; these solutions will not, however, be gone into here as, in practice, and particularly with big outputs they will never be used to the extent of the other layouts described and which have given such good results.

To summarize, it is seen that Brown Boveri have solved the difficulties in the way of using the D. C. — A. C. mutator in all the principal fields of application, this both under test and in practical service. In so doing all the advantages and disadvantages of the various designs have been investigated and there is no longer any difficulty in choosing the best possible solution for any problem set. As it has been found possible to confer on the D. C. — A. C. the same degree of practical reliability enjoyed by the A. C. — D. C. mutator, there should be a wide field of application awaiting the former apparatus.

(MS 602) *A. Leuthold. (Mo.)*

THE CONTROL AND REGULATION OF THE MUTATOR IN THE CASE OF THE FLEXIBLE INTERCONNECTION OF TWO THREE-PHASE SYSTEMS.

Decimal index 621. 314. 65 : 621. 311. 161.

The mutator offers the means of flexibly interconnecting two three-phase systems, whatever their respective frequencies may be. Special conditions must be adhered to for the control of mutators of this kind. Some fundamental connections used for the control are described in this article. The best regulating methods are, also, described for maintaining constant output, with the help of mechanical regulators and with the aim of attaining the lowest wattless output possible.

I. INTRODUCTION.

THE problem of the flexible interconnection of two three-phase systems comes up when it is desired to make an exchange of active power between systems, the respective frequencies of which should remain independent of one another. The deviations of the frequency of a system from its mean value and the relationship between the two frequencies of the systems to be coupled together played a considerable part in the dimensioning of the machine sets utilized, up till to-day, for the purpose of linking two systems. The development of the mutator naturally brought with it the idea of carrying out the interconnecting of independent, three-phase systems by converting the alternating current of the primary system delivering power, to begin with, into direct current and of then supplying the power to the secondary system through a D. C.—A. C. mutator. The uniformity of the flow of power between the systems, brought about by the rectification and by the smoothing out of the current and also by the number of phases utilized leads to an exchange of power which, as desired, is independent of the respective frequencies. Apart from these desirable properties, this static method of system interconnecting shows much lower conversion losses and, therefore, works to better efficiency. The Brown Boveri Review of December 1934 described the fundamental power-exchange process in question. That description is completed here by details on the control and regulation of the three-phase—three-phase mutator.

II. CONTROL.

The control of a system interconnection of this kind is explained best with the help of a two-phase transmitting element, according to Fig. 1. This element feeds four of the twelve mutator anodes, according to the six-phase design of the complete set and it allows the exchange of power from one phase of the primary system to one phase of the secondary system. The three elements necessary in all for the complete interconnection of the systems are identical in design. The four anodes are connected to the ends of two phase pairs placed on the same column of the transformer of one system, while the middle points of these phase pairs are connected to the ends of a pair of phases of the other transformer. Under the assumption that the latter winding is on the transformer belonging to the primary or power-supplying system (termed, here, the ingoing transformer), then each half of this pair of phases plays the part of an A. C.—D. C. mutator during a half wave of the respective system frequency, which mutator delivers power during every half wave to the respective pair of phases of the other transformer (termed the outgoing transformer) working as D. C.—A. C. mutator.

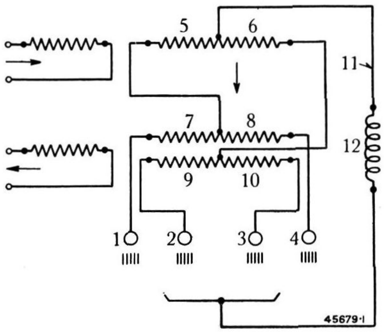

Fig. 1. — Fundamental diagram of connections of a two-phase A. C.—A. C. mutator element.

1—4. Anodes of the mutator.
5, 6. Secondary windings on the incoming transformer.
7, 8, 9, 10. Primary windings on the outgoing transformer.
11. D. C. conductor.
12. Smoothing choke coil.

Transition from one phase to the other of the A. C.—D. C. system 5, 6 takes place in the manner known and independently of the magnitude and direction of the voltage in the windings 7, 8, 9 and 10, because the additional electro motive forces in the windings 7, 8 and 9, 10 counterbalance one another on account of their equivalence as regards the commutating circuit which gets short-circuited during the period of commutation of current. The commutation of the current within the phase pair of the D. C.—A. C. mutator system 7, 8 and 9, 10 takes place in the known way, and without this current commutation being troubled by the alternating operation of these two pairs of windings. Thus, if, for example, anode 1 works first of all, a change of sense of the voltage in system 5, 6 causes anode 2 to take over from anode 1. Here it is seen that the electro motive forces in the windings 7 and 9 of commutating circuit 1-7-5-6-9-2-1 balance each other and do not influence the passage of current between the anodes 1 and 2. The current commutation within anodes 1 to 4 always takes place between anodes in adjacent cyclic order; here 4 and 1 are cyclic neighbours. Now, as is known, the insertion of controlled grids in front of the anodes allows of displacing i. e. retarding the moment of commutation, as may be desired, within the positive range of the commutating voltage. This causes a reduction of the average value of the voltage during the ignition time and thus allows of reducing the D. C. voltage. In this way, it is easy to bring about the requisite equality and opposition of the two D. C. voltages generated by winding systems 5, 6, respectively 7, 8, 9, 10, which equality is necessary for the balancing of the voltages.

Now, let it be supposed that there be a similar system to that of Fig. 1, not for direct supply of the anodes themselves, but for that of the control grids, with the characteristic difference that, according to Fig. 2, there is an ohmic resistance 12 in the D. C. conductor 11, which carries a, practically, constant D. C. as a result of the presence of choke coil 13. The current commutation between the grids always takes place on the initiation of a change of one of the two voltages, that is to say always when the commutation voltage, i. e. the voltage difference between an extinguished and the burning grid is positive. If the supply of the double system is carried out, as is shown in Fig. 2, similar to that of the double system of Fig. 1, by the two systems coupled, the similarity of the conditions comprises the frequency as well and, therefore, also the duration of ignition of the grids as compared to that of the anodes. As, now, the ignition of an anode of positive voltage as compared to the cathodes takes place simultaneously with the ignition of the respective control grid, it is possible to obtain, in this way, and with the A. C.—A. C. mutator connection under consideration, the proper play of the anode arcs, with the help of the controlled grids and of a system of control transformers, which corresponds, externally, perfectly with the connections of the main transformers supplying the anodes. By suitable choice of the phase position of both the voltage triangles of the grid system as compared to that of the anode system it is possible to adjust to the requisite ignition angle for the A. C.—D. C. and D. C.—A. C. mutator operation of the anodes. The control system is, really, nothing else than a two-phase mutator system with two A.C. voltages in series of any frequency, and

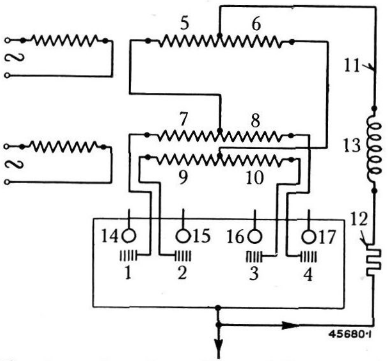

Fig. 2. — Superimposition of the control impulses for the control of the A. C.—A. C. mutator.

1—4. Control grids on mutator.
5, 6. Secondary windings of the control transformer on primary system.
7, 8, 9, 10. Secondary windings of the control transformer on secondary system.
11. D. C. conductor.
12. Auxiliary resistance.
13. Auxiliary choke coil.
14-17. Anodes of mutator.

where the D.C. voltage generated across resistance 12 is equal to the sum of the components of the D. C. voltages generated by rectifying action.

Thus, the system represents a further development of the well-known control with sine-wave A.C. voltage but for the special case of an A. C.—A. C. mutator. While, however, in the control system for the grids under consideration, as shown in Fig. 2, the mutual taking over (or commutation) of the windings working takes place in the natural points of intersection of the voltages and the two D.C. voltages are added as a result thereof, the ignition of the anodes in Fig. 1 as compared to the voltage of the secondary system no longer takes place at the natural point of intersection of the voltages but does so under the influence of the controlled grids, according to Fig. 2. This alteration effected in the ignition of the arc of the mutator has as result that, when the angle of displacement of the ignition is 180°, the D.C. voltage generated by the secondary system works against that of the primary system, so that the output delivered by the primary system is not delivered to the D.C. system but is transferred to the secondary system.

In the control system just described, the negative blocking voltage of the grids is composed of the practically sine half wave of both system voltages. While there is a danger of faulty ignition (cross ignitions) on the anodes when the blocking voltage on the grids is too low, a too strong blocking voltage on the grids creates a tendency to backfiring on the grids themselves. Further, the ignition of the grids and, therewith, that of the anodes is all the more exact, the steeper the passage of the positive-control impulses through those values which are critical for the ignition. Thus, it is advantageous to maintain the blocking voltage on the grids, as far as is possible, at a value which changes little and lies between the faulty-ignition zone and the backfiring zone; with other words, the grid voltage should have a rectangular or trapezoidal character.

In the following paragraphs some possible solutions are discussed for imparting to the control voltage a character approaching the most advantageous one. According to the explanation given, a grid must only ignite first — but must then ignite — when the two component superimposed anode voltages added together which form the control voltage and which are delivered by both systems, become positive, that is when they act in grid-cathode sense. Therefore, the components of the sum of the control voltage during the period of the ignition in question of 180°, as a result of the mutual displacement of the two voltages, must be always ready for action. For this reason, the allowable shortening to any degree desired of the positive control impulse which can be carried out on the A. C.—D. C. and D.C.—A.C. mutator is no longer allowable on the A.C.—A.C. mutator. On the contrary, the duration of the positive ignition impulse of each of the two components forming the sum of the control voltage must attain 180°.

The nearest way to obtain a control-voltage curve of rectangular character and of the desired ignition duration of 180° is based on the well-known fact that the anode-current curve of a two-phase A.C.—D.C. mutator is, itself, rectangular in character when the D.C. current is smoothed out. The pressure drop generated by a current of this kind in an ohmic resistance, according to Fig. 3, gives the rectangular shape which is looked for. The fundamental diagram of connections given in Fig. 3 refers to the control of a standard two-phase A. C.—D. C. mutator. The overlapping between the two control impulses is lowered by maintaining the stray-reactance in the A.C. circuit at a low value, by inserting condensers in parallel with the control transformer or, finally, by retarding the ignition of the anodes in the auxiliary A.C.—D.C. mutator with the help of controlled grids.

At the same time, these controlled grids offer an excellent auxiliary means of carrying out the regulation of the output of the A. C. — A. C. mutator, according to any programme laid down, with a very small expenditure of power, indeed. In Fig. 3 half-wave currents of rectangular shape flow over the primary windings of current transformers 2 and 3, over the auxiliary rectifiers 13 and 14; these flow back to the neutral point of the secondary winding

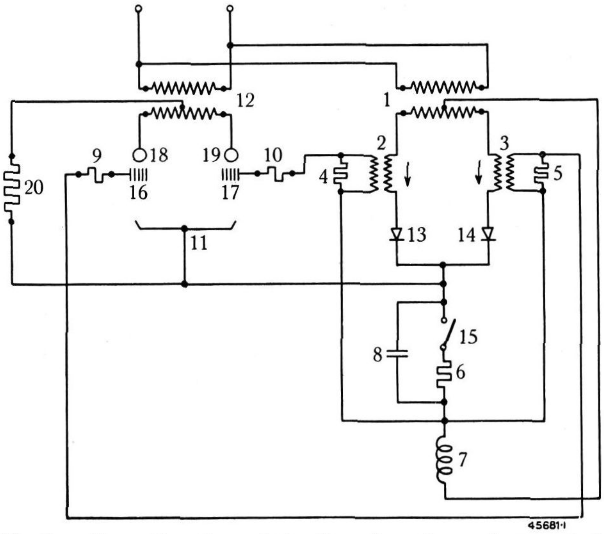

Fig. 3. — **Generation of a control voltage from the anode current of an auxiliary mutator.**

1. Control transformer.
2, 3. Current transformers.
4, 5. Resistances.
6. Auxiliary resistance.
7. Choke coil.
8. Extinguishing condenser.
9, 10. Grid resistances.
11. Mutator cathode.
12. Main transformer.
13, 14. Auxiliary valves.
15. Excess-current relay contact.
16, 17. Control grids.
18, 19. Anodes.
20. Loading circuit.

of the auxiliary transformer, through resistance 6 and smoothing choke-coil 7.

The rectangular voltage impulses generated in resistances 4, 5 in the secondary circuit of the current transformers are then led, in series with the negative bias voltage across resistance 6 to the mutator grids, as is shown in Fig. 3, which is an example of a standard A.C.—D.C. mutator. In the A.C.—A.C. mutator, the rectangular control voltages obtained, in the way explained, from the two systems, are superimposed in the series connection shown in Fig. 2 and then led to the control grids of the mutator.

Another method of obtaining a rectangular control voltage is shown in Fig. 4, also taken from the example given of a two-phase A.C.—D.C. mutator. If the control transformer 2 is connected to the voltage available in synchronism with the anodes of mutator 12 to be controlled, through a relatively big unsaturated choke coil 5, and if a secondary winding 4 of the control transformer is connected, through valve 14, as a mutator, in six-phase connection, to an auxiliary resistance 6, a rectangular voltage appears on windings 2, 3, 4 of the control transformers. This is because the sum of the six sine half waves appearing in the winding halves of the secondary windings 4 of the control transformers and which are rectified in the valves 14, is a, practically, constant D.C., with the slight higher harmonics of a six-phase mutator. This D.C. current generates a D.C. voltage of the same shape in the auxiliary resistance 6. In the same way, the voltage on the control transformer 2 is an alternating voltage, with rectangular and almost vertical half waves which intermingle. Here, the current in the primary winding of the control transformers is sine-shaped on account of the choke coil 5. The time displacement of the control impulses for regulating purposes must be carried out by corresponding displacement of the voltages led to the system.

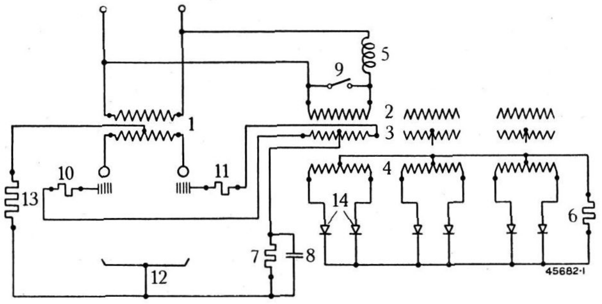

Fig. 4. — Generation of the control voltage by choke coil and auxiliary mutator.

1. Main transformer.
2. Primary winding on control transformer.
3. Tertiary winding on control transformer.
4. Secondary winding on control transformer.
5. Control choke coil.

6, 7. Auxiliary restistances.
8. Extinguishing choke coil.
9. Contact on excess-current relay.
10, 11. Grid resistances.
12. Mutator.
13. Loading circuit.
14. Auxiliary valves.

The necessary bias voltage for blocking the grids during short circuits or backfires can be taken from resistance 6 of the auxiliary rectifier system, according to Fig. 3, or from a resistance 7 through which a grid D.C. current flows, according to Fig. 4. A condenser 8 of sufficient capacity is connected in parallel to the said resistance. The extinction of the mutator when excess currents occur is then carried out, in simple fashion, by suppressing the positive control impulses either by opening the D.C. circuit in the auxiliary system (contact 15, Fig. 3) or by short-circuiting the control transformers (contact 9, Fig. 4).

III. REGULATION.

In general, the problem in system interconnection will be to attain and maintain any desired output, or else to adjust the output transmitted as some prescribed function of, for instance, the frequency of one of the two systems or that of both frequencies and independently of the other electric conditions. When the point of ignition is fixed and when the ratio of the transformer is fixed, also, the current in the A.C.—A.C. mutator is only dependent on the voltage of both systems but is, practically, independent of the two frequencies.

For the purpose of regulation, there are, fundamentally, mechanical regulators and regulators based on the electronic tube principle available. The electronic-tube regulator has great advantages as compared to the mechanical one. It may be of interest to mention that, even in the present case of system interconnection, where it would seem the obvious solution to use the electronic-tube regulator, the mechanical regulator produces quite satisfactory results. As the utilization of electronic-tubes for the control of mutators has been gone into in other articles in this number, the regulation by mechanical regulator, alone, will be reported on, here.

In the control system shown in Fig. 3, the displacement of the point of ignition takes place either (when controlled auxiliary mutators are used for generating the ignition impulses) in the most simple way by superimposing a D.C. voltage which can be regulated over a sine-shaped control voltage of the grids of the auxiliary mutators or else (when uncontrolled auxiliary mutators are used and also in the case of control as shown in Fig. 4) by displacing the voltage led to the control by means of rotary transformers or multi-phase ohmic or inductive potential dividers with choke-coils premagnetized by D.C. current, as shown in Fig. 5. The latter solution is advantageous when the regulation has to be constantly in action in order to maintain the amount of power transmitted at a constant figure, despite variable voltage. In all cases, the regulating magnitude proper can be traced back to a D.C. voltage or D.C. current which must be adjusted by the regulator in function of the electric conditions of the *mutator*. The primary windings 2 of the six choke coils shown in Fig. 5 are delta-connected between points 4, 5, 6 of the auxiliary supply. The reactance of the choke coils can be modified with the help of D.C.-magnetizing windings 3. In each two choke coils connected between two angles of the triangle 4, 5, 6 the magnetizing D.C. current will be strengthened in one and weakened in the other when the contact sector moves over the resistance 1. As a result thereof, the distribution of the voltages of points 7, 8, 9 between points 4, 5, 6 changes (this because the reactance conditions of the choke coils have been modified) and therewith, the phase position of the voltage triangle 7, 8, 9 which supplies the control apparatus proper.

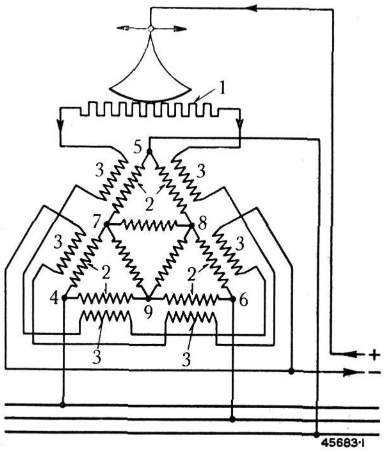

Fig. 5. — Fundamental diagram of connections of a static voltage-phase regulator.

1. Current divider on quick-acting regulator.
2. Choke coils with variable inductivity.
3. *D. C. windings for pre-magnetizing.*

4, 5, 6. Connecting points on auxiliary system.
7, 8, 9. Connecting points of control system to be regulated.

That condition at which both system voltages have their desired magnitudes on the A.C.—A.C. mutator and, therefore, that the moving organ of the regulator remains in its medium position under the rated load is taken as starting point. Now, let it be assumed that the voltage ratio increases, that is the ratio between the voltage on the mutator side of the incoming transformer and the voltage on the mutator side of the outgoing transformer, either because the voltage on the *primary system* has gone up, or because that of the secondary system has gone down, the result would be that the output transmitted would increase, assuming that the regulator does not act. Now to bring back the output transmitted to the value it should have there are two methods available. Either the voltage of the A.C.—D.C. mutator system can be lowered by a suitable retardation of the point of ignition or else the counter voltage of the D.C.—A.C. mutator system can be increased by retarding the point of ignition, i. e. reducing the ignition advance. While the first solution is easily attainable, the second one requires that the ignition advance of the D.C.—A.C. mutator corresponding to ordinary service should have the requisite angular reserve for the ignition advance, which reserve must be called on in the present case of a voltage ratio exceeding the rated one, and utilized for increasing the counter voltage of the D.C.—A.C. mutator. The permanent increase in the phase lead of the current delivered to the secondary system which is a necessary condition for having a reserve of ignition advance ready *is identical with an increase* in the wattless power drawn from the secondary system. The aim followed of operating the mutator with the highest power-factor possible, in the secondary system, as well, corresponds to operation with the lowest ignition lead, that is to service in the limit region of instability that is to say the pull-out point. An increase in the counter voltage of the D.C.—A.C. mutator by a decrease in the ignition advance by means of the quick-acting regulator is now no longer allowable because of the danger of pulling-out occurring. As the *retarding* of the ignition point on the D.C.—A.C. mutator, through the action of the quick-acting regulator, in order to balance an increase in the voltage ratio, means continuous additional wattless loading of the secondary system, the requirement that these should be a minimum of wattless power in the secondary system is contrary to the demand for even a transitory increase of the D.C. voltage in the D.C.—A.C. mutator. Thus, from this point of view, a retardation of the ignition point on the A.C.—D.C. mutator, in the case of an increase of the voltage ratio above the standard value, is certainly more advantageous than a similar retardation in the D.C.—A.C. mutator. A consideration of the other case, namely, a decrease in the standard voltage ratio between primary and secondary systems, leads to the corresponding result, that is to say when a decrease in the voltage ratio below the rated value occurs, it is advantageous to advance the ignition point of the D.C.—A.C. mutator, alone. To summarize, from the point of view of a minimum demand for wattless power for both systems, the quick-acting regulator must satisfy the following condition:— when the moving organ of the regulator leaves its medium position, in one sense (excess of power above quota set for) it is only the ignition point of the A.C.—D.C. mutator which should be retarded; when it is displaced in the other sense (decrease of power below quota set for) it is only the ignition point of the D.C.—A.C. mutator which is to be advanced. The desirable freeing of both systems from the wattless load taken by the mutator is helped most effectively by the automatic control of the step switch by means of the *quick-acting regulator*, which is described herewith.

A modification of the wattless power tapped from one or the other system always occurs when there is a change in the position of the ignition point. If the deviation of the voltage ratio from the rated value, in one sense or the other, attains big values, the wattless load tapped may reach an undesirable magnitude. Thus, in many cases, it becomes desirable to counterbalance deviations of the voltage ratio of long continuous duration by acting on the step switch instead of by means of grid control. In such cases, it is advantageous to let the automatic quick-acting regulator take care of the step switch operation, in such a way that a displacement of the step switch occurs after a certain minimum displacement of the quick-acting regulator has occurred and been maintained, during a certain minimum time.

In this operating method, a displacement of the quick-acting regulator in one sense must cause an increase in voltage and a displacement in the other a decrease in voltage by the step switch. By means of this automatic control of the step switch the voltage modifications of long duration occurring on the systems are, practically, counterbalanced and, thus, the necessary ignition point displacement, on both systems, is brought near to its minimum point again. This control of the step switch should only work after a deviation of the voltage ratio from the desired figure of long duration and, therefore, it is caused to act through a device which only transmits the switching order impulses of the quick-acting regulator after the lapse of a determined period, which can be adjusted.

Now, consideration must be given to those increases of the voltage ratio which, on account of their magnitude, bring the D.C.—A.C. mutator system close to or, even, beyond the pull-out point and which also, are too steep in character to allow the mechanical regulator to follow them, on account of its mechanical inertia. Rapid voltage fluctuations of this kind are due to the connecting-up or cutting-out of sections of the system, or big consumer plants and also to short circuits. Unless special measures were taken, a sudden increase in the voltage ratio say in the range of 20% would mean a considerable increase in the current and, therewith, an infringement of the pull-out point limit (see The Brown Boveri Review, December 1934, page 229). Apart from the electronic-tube regulator, a simply method for keeping up service, even in this case, is to extinguish the mutator, by the control grids, through the intervention of a relay acting under excess currents, in order to bring the quick-acting regulator, in the meantime, to its position of lowest power delivery, by special means after which the blocking of the mutator will be removed and service started again. Naturally, this extinguishing process is not initiated for every steep change in the voltage ratio but only when the said change exceeds a certain value and gets so big that the danger of pulling-out arises.

Fig. 6 shows the fundamental connections of the regulation of an A.C.—A.C. mutator based on these principles. The diagram shows that quick-acting regulator 13 only influences one or other of the two control systems 10 and 11 when it is displaced from its medium position. Further the connection between the remote control 12 of the step switch on transformer 7 and the quick-acting regulator, which passes through time relays 15, 16 is also shown. Resistances 20 and 21 on the quick-acting regulator correspond to resistance 1 shown in Fig. 5. While one sector of the quick-acting regulators rolls over one of these resistances and in so doing influences control 10 or 11, the other sector — after a certain displacement on the quick-acting regulator — carries the current flowing from the sector through one of the two time relays 15, 16, which causes the step switch 12 to carry out the order given by the quick-acting regulator after the elapse of a certain period, and the desired voltage ratio is re-established.

The interlock between excess-current relay 14 and the quick-acting regulator 13 is also indicated. If an excess current occurs resulting from a sudden and big rise in the voltage ratio, the transmission of power is instantly stopped by the blocking of all the mutator anodes with the help of the blocking relay 14 which acts under excess currents. The re-

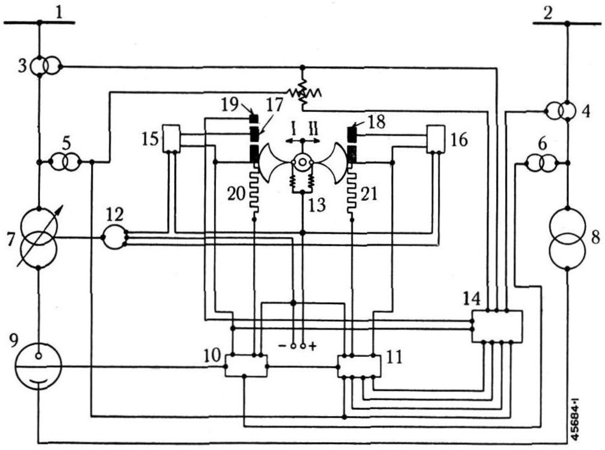

Fig. 6. — **Fundamental diagram of connections for regulation by mechanical regulator.**

1. Primary system.
2. Secondary system.
3, 4. Current transformers.
5, 6. Voltage transformers.
7. Incoming transformer.
8. Outgoing transformer.
9. Mutator.
10, 11. Control.
12. Tap switch remote control.
13. Quick-acting regulator.
I. Rising.
14. Excess-current relay.
15, 16. Time relays.
17, 18. Control contacts on the quick-acting regulator for the tap switch.
19. Blocking contact on quick-acting regulator for the excess-current relay 14.
20, 21. Regulating resistors on quick-acting regulator.
II. Falling.

gulator would then rotate to its position corresponding to the lowest voltage of the D.C.—A.C. mutator system and would cause an excess current to begin again whenever the relay 14 returned to its normal position. To prevent this, relay 14 must remain blocked until regulator 13 is brought to the position corresponding to the lowest voltage of the A.C.—D.C. mutator system which is done by an auxiliary current from relay 14, led to the moving organ of the regulator. After this displacement of the regulator, relay 14 is freed again by the auxiliary contact 19 on this position and the regulator re-establishes the rated output. The whole process causes no trouble on the service, worthy of mention, because it takes place very rarely and when it does, it takes up very little time.

If the regulator has to govern the amount of power transferred as a function of the frequency of one of the two systems or of both systems, this is easily arranged for by introducing to the quick-acting regulator an additional torque depending on the frequency or else by an influence of the current or of the voltage fed to the quick-acting regulator which influence has to be dependent on the frequency.

(MS 601) *E. Kern. (Mo.)*

A THREE-PHASE — SINGLE-PHASE MUTATOR FOR SUPPLYING A HIGH-FREQUENCY CORELESS INDUCTION FURNACE.

Decimal index 621. 314. 65 : 621. 365. 5.

A comparison between the supplying of a coreless induction furnace from a three-phase industrial supply system by means of a rotating converter or by means of a mutator is in favour of the mutator both as regards a better efficiency and as regards a simplification of the furnace operation.

I. INTRODUCTION.

IN the high-frequency coreless induction furnace an alternating field is used in order to induce a strong eddy current in the charge being melted. In essential, the furnace is composed of a circular, fire-proof crucible, round which is placed the cylindrical furnace coil, which is, usually, water-cooled. Both crucible and coil are mounted in a common framework while a tilting device allows of pouring off the melted charge, in the simplest way possible.

The furnace coil is supplied with A. C. current the frequency of which differs according to the nature of the charge and the size of the furnace. The frequency range goes from some hundred cycles to 10,000 cycles, the frequency being the higher the smaller the furnace.

The designation "high-frequency" furnace is not a happy one, because, to-day, under high-frequency are classed frequencies up to the order of one million cycles. It would be better to base the designation on the design of the furnace and to call it a coreless induction furnace.

The most advantageous operating frequency depends on the depth of penetration of the eddy field, on the inductivity of the furnace coils which are, usually, of one layer thickness and also on the mechanical eddy swirls set up in the melted charge by the action of the eddy currents.

The coreless induction furnace is a refusion furnace, by means of which definitely defined combinations of different metals (alloys) are produced. It has the advantage that the purity of the alloy is neither affected by hot gases, nor by products of the combustion of electrodes.

Up till now, furnaces of this type of big outputs were fed by specially-designed high-frequency machine sets, the low efficiency of which had to be taken into account. The current passing through the furnace coil has a low active and high reactive component. In order to relieve the machines of this reactive current, a condenser battery is used which compensates the whole reactive current of the furnace coil.

For the conversion of industrial current into high-frequency current, it is natural that recourse should be had to the mutator, that static converter with the highest efficiency which has conquered so many fields where formerly the rotary converter alone held sway.

Brown Boveri have built a furnace plant, for clients, for 600 kg, supplied through a three-phase — single-phase 300-kW mutator with single-phase current at 1000 cycles.

II. THE PROBLEM OF INCREASING THE FREQUENCY.

The conversion of three-phase current of one frequency into single-phase current of another with the help of a mutator was studied at an earlier date and very thoroughly.[1] However, it was not known, then, if it would be possible to attain a frequency of 1000 cycles by means of a standard mutator without special extinction grids. To attain the aim in question, the de-ionizing period of the mutator (that is to say the time from the moment of extinction of an anode until the moment where the respective grid has attained its full blocking effect) must be only a small fraction of the duration of a half wave of the high-frequency current. For a given design, the de-ionizing time depends, essentially, on the strength of the anode current, on the value of the negative grid voltage (and grid current) and on

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[1] See The Brown Boveri Review of June 1934.

the temperature of the mutator. By choeosing higher anode voltages and correspondingly low anode currents, it was found feasible to reduce the de-ionizing time so much that the mutator became perfectly controllable at 1000 cycles and more.

The excessive stressing of the mutator which reduces its immunity from backfires, owing to the sudden voltage steps which appear in the regulation by grid control, is accentuated at high frequency. Useful data has been collected while investigating these phenomena which go to show how far a mutator can be stressed at high-rated frequencies.

III. THE CHOICE OF CONNECTIONS.

The operating process of the three-phase — single-phase mutator for high frequency is best understood when a case of ordinary system coupling is studied first. Fig. 1 shows two possible systems of connection applicable for the coupling of a three-phase system N_1 to a single-phase system N_2 when one, single mutator is used. As regards the three-phase system, both connections are three-phase, they can, for example, be increased from three to six phase, without any difficulty, when it is desired to reduce the deformation of the curve of the three-phase supply current. The well-known connection I, with the three-phase transformer T_1, the single-phase transformer T_2, the voltage-smoother L and the current smoothers C_1 and C_2 respectively, as energy accumulators, results in a symmetrical load on all three phases of the three-phase side, this allows of delivering sine-shaped single-phase current to the system fed. The indications of the somewhat less common connections II coincide with those of I. Both connections work in the same way, in principle, the difference is only in the switching sequence of the two transformers T_1 and T_2. Starting from the cathode, in connection I over the voltage smoother L, a winding of T_2 is first passed through and then the windings of the three-phase transformer T_1. In the case of connection II, T_1 is first encountered and then the windings of the single-phase transformer T_2. In connection I, the secondary winding is subdivided at T_1 while with connection II it is subdivided at T_2.

However, there are two fundamental differences between the two connections, which show up when the frequencies of systems N_1 and N_2 differ much from one another. If, firstly, it is desired to reduce to a minimum the inductive voltage drops and the additional losses, care must be taken that the higher frequency currents only flow through one transformer. Therefore, the high-frequency currents must only appear in that transformer connected to the system of the higher frequency. Secondly, the stressing of the transformer insulation by the higher frequency is, also, to be limited to that transformer connected to the higher-frequency system.

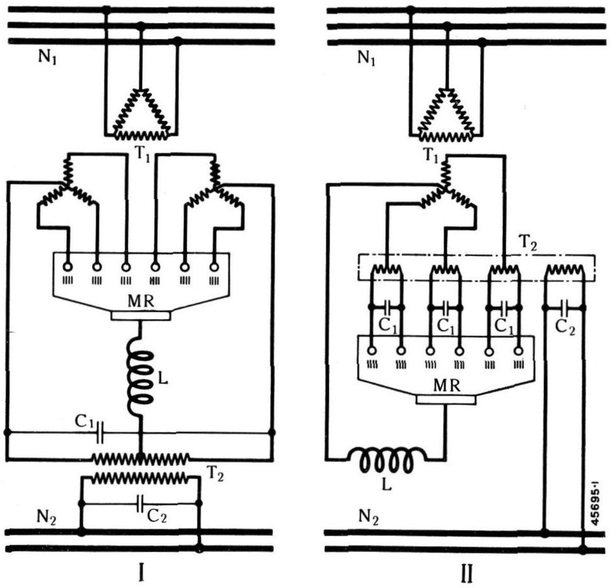

Fig. 1. — Fundamental possibilities for the connections of a mutator used to connect a three-phase system to a single-phase system.

Connection I:— frequency of system N_1 bigger than that of system N_2.
Connection II:— frequency of system N_2 bigger than that of system N_1.
T_1. Three-phase transformer.
T_2. Single-phase transformer.
MR. Mutator.
L. Voltage smoother } energy accumulator.
C_1, C_2: Current smoothers

If these two fundamental principles are applied in the choice between connections I and II, of Fig. 1, it will be seen that, according to the frequency of the systems connected, one or other of the two connections is the best one to be chosen.

If, for example, the frequency of the three-phase system N_1 is higher than that of the single-phase system N_2, then connection I of Fig. 1 will be chosen. The two secondary windings of transformer T_1 then each works independently at the frequency of the three-phase system and carry current alternately and in measure with the lower single-phase frequency. The insulation of the two three-phase windings will be additionally stressed by the voltage of the lower frequency, while the winding insulation of the single-phase transformer is not stressed by the voltage of the higher frequency.

If, on the contrary, the frequency of the single-phase system is higher than that of the three-phase system, then the connection II of Fig. 1 is the better one, according to the above considerations. Each primary winding of the single-phase transformer T_2 now works at the higher frequency, as long as the corresponding phase of the three-phase transformer carries current. No high-frequency current now flows in three-phase transformer T_1; further, the insulation of the three-phase transformer will only be stressed with the voltage of the lower frequency.

In order to ascertain what the connection should be for the three-phase — single-phase mutator utilized to supply a coreless induction furnace, let it be assumed that the single-phase system N_2 of connection II of Fig. 1 has been replaced by a powerful resonance circuit. As is shown in Fig. 2, this will comprise the inductivity L_2 of the furnace coil and the condenser battery C_2 which is necessary to compensate the reactive current. As the reactive current in the furnace coil, as already said, is considerably stronger than the active current delivered by the mutator through the single-phase transformer T_2, the resonance circuit behaves like a powerful system. The static control apparatus S of the mutator, only indicated in the drawing, is directly fed by the resonance circuit in such a manner that each modification of the resonance frequency of the oscillation circuit influences the control directly. The flexible coupling of the three-phase system N to the independent high-frequency resonance circuit L_2 C_2 makes the latter quite independent of the frequency of the three-phase system, an advantage which will be referred to in the next chapter. In other respects, the connection of Fig. 2 corresponds to connection II of Fig. 1, only the three-phase transformer is connected in zigzag on the secondary side, in Fig. 2, in order that the unilateral magnetizations, due to the D. C. current component of the secondary current, may be able to compensate one another, mutually.

IV. FREQUENCY AND POWER FACTOR.

The inductivity of the furnace coil changes during the melting process because of the changes taking place in the charge. If, for example, steel is being melted, the latter is magnetic in its cold state, which causes the furnace coil to have a certain inductivity. When the steel reaches a glow point it looses its magnetic properties and the inductivity of the furnace coil diminishes. When the steel begins to melt, the bath forms a kind of short-circuited winding for the furnace coil so that its inductivity diminishes still further. Thus it happens that, in practical furnace operation, it must be reckoned with that the reactive current consumption of the furnace coil will be subjected to continuous changes.

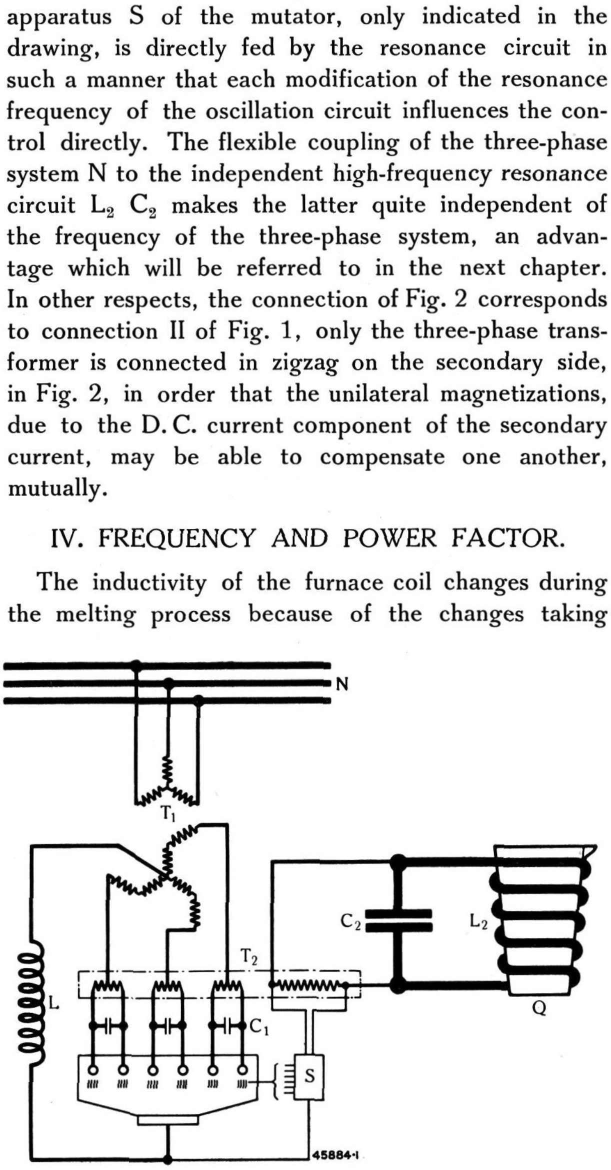

Fig. 2. — Fundamental connections of a three-phase — single-phase mutator for supplying a high-frequency coreless induction furnace.

N. Three-phase system.
T_1. Three-phase transformer.
T_2. High-frequency transformer.
L. Voltage smoother.
C_1. Current smoother.
C_2. Reactive-load battery.
L_2. Furnace coil.
Q. Crucible.
S. Static control apparatus.

An induction furnace supplied from a high-frequency machine thus calls for continuous regulation of the capacity of the reactive-load battery in order to meet the changing inductivity of the furnace coil. As the power factor of the furnace coil is, generally, about $0 \cdot 1$, a slight change of its inductivity corresponds to an additional reactive current which is of considerable magnitude as compared to the active current delivered by the generator. In this case, it is not only a question of getting the power factor of the high-frequency generator as close to unity as possible, but the regulation is indispensable in order that the generator should not be overloaded by reactive current.

The conditions are quite different when the high-frequency furnace is being supplied from a mutator, according to Fig. 2. As, here, the frequency of the furnace current is determined by the resonance condition, every change in the inductivity of the furnace coil will be followed by an automatic adjustment of the frequency of the furnace current. The inductivity L_2 of the furnace coil and the capacity C_2 are constantly in resonance with the frequency of the furnace current. In other words, this means that the reactive current through the coil is constantly compensated by the reactive-load battery C_2. As the mutator works flexibly, this change in frequency remains without direct influence on the active load delivered to the furnace. For this reason, in the present case, the regulation of capacity which is indispensable with supply from a machine, is completely eliminated, an advantage which the service operator will appreciate at its true value.

V. PRACTICAL SERVICE RESULTS.

It may be of interest to note that no complicated manoeuvres are called for when the plant is started up. When the main breaker on the three-phase side is closed, a current surge passes through the mutator and both transformers. The resonance circuit swings up to its standard voltage at this current surge and this means that furnace operation has been initiated. The furnace power input can be adjusted to by means of a tap switch on one of the two transformers or with the help of the grid control.

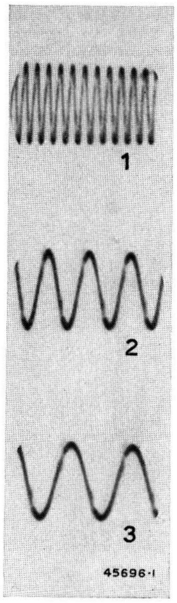

Fig. 3. — Behaviour of the 1000 cycle furnace voltage.

The three curves 1, 2, 3 are records taken with various time scales.

The trial operation carried on with the complete plant on the test bed showed an efficiency of 93% at 300 kW, that is to say at full load. Some oscillograms will help to illustrate the working conditions of this three-phase—single-phase mutator. Fig. 3 shows the voltage recorded on the furnace with the Braun tubes, at 1000 cycles and this with three different time scales. The regularity of the individual curves will be noted and the satisfactory sine shape of the voltage. Fig. 4 allows of deducing the behaviour of the phase voltage 2 on the three-phase side, of the furnace voltage 1 and of the current 3 of one anode. It is interesting to note how the latter shows up in rhythm with the frequency 50 and how it is interrupted in rhythm with the 1000 cycles per second. If a comparison is made between the sections repeated at rhythmic intervals, it will be noted that they are not absolutely identical. This is a characteristic of the flexibility of the mutator which can operate at any frequency conditions. Fig. 5 shows the same features as Fig. 4 with another time scale which allows of clearer observation of the details of curve 3 of the anode current. Curve 2 of Fig. 6 shows the voltage of an anode as compared to the cathode which is obtained by the superimposing of a 50-cycle and a 1000-cycle phase voltage respectively. The steep voltage peaks with which the mutator is stressed will be noted.

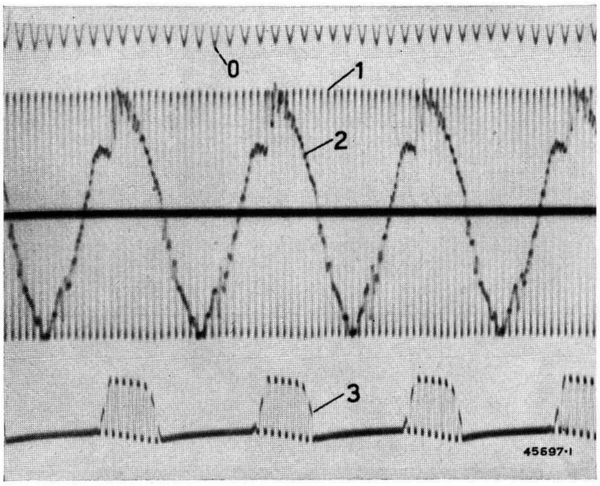

Fig. 4. — Current and voltage conditions of a three-phase — single-phase mutator with generation of single-phase current at 1000 cycles.
0. Calibrating frequency 500 cycles.
1. Furnace frequency 1000 cycles.
2. Phase voltage on three-phase side.
3. Current of one anode.

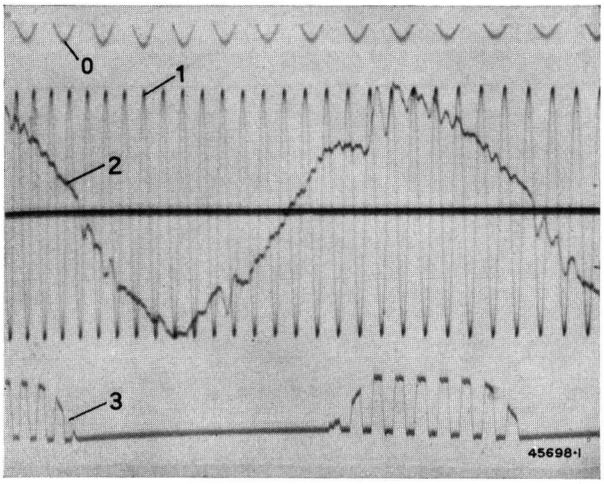

Fig. 5. — Current and voltage conditions of a three-phase — single-phase mutator with generation of single-phase current at 1000 cycles.
0. Calibrating frequency 500 cycles.
1. Furnace frequency 1000 cycles.
2. Phase voltage on three-phase side.
3. Current of one anode.

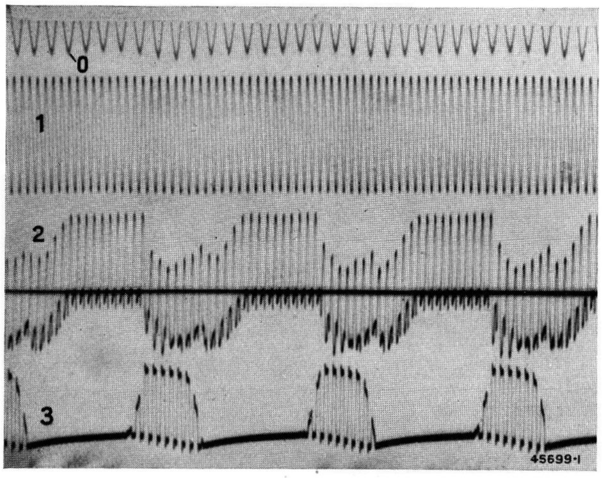

Fig. 6. — Stressing of the mutator under high-frequency service.
0. Calibrating frequency 500 cycles.
1. Furnace frequency 1000 cycles.
2. Voltage between an anode and the cathode.
3. Current of an anode.

Thus, the well-known advantages of the mutator compared to the rotary converter are, once again, made use of for supplying coreless induction furnaces. To-day, it is possible with a single mutator of standard design to convert three-phase current at 50 cycles into single-phase current at 1000 cycles. Apart from the good efficiency, an important quality is that the high frequency continually adapts itself to the service requirements of the furnace without it being necessary to regulate the condenser battery. Practical results obtained, up till now, fully justify the assumption that a field of development awaits the mutator in this new application.

(MS 605) *Ch. Ehrensperger. (Mo.)*

UNDULATIONS IN THE VOLTAGE AND CURRENT AND INTERFERENCE VOLTAGE IN MUTATORS.

Decimal index 621. 314. 65. 0183

The square of the R. M. S. value of the nth higher harmonic in the D. C. voltage is a linear function of cos $(2\alpha + u)$ in which α is the angle of displacement of the point of ignition and u the overlapping. This function leads to a simple representation of the undulations in the voltage and current as well as of the interference voltage, by means of a family of straight lines with the overlapping u as parameter.

THE object this article is to determine a formula generally valid for the higher D. C. voltage harmonics, which can be expressed geometrically in simple manner and which can be utilized for clear representations of the undulations in the voltage, those in the current and for the interference voltage of mutators.

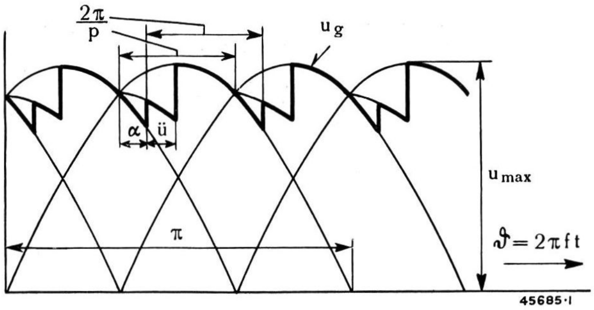

Fig. 1. — D. C. voltage u_g of a p-phase mutator in the case of a displacement of the moment of ignition α and of an overlapping u. Frequency of A. C. system = f.

I. HIGHER HARMONICS OF THE D.C. VOLTAGE.

In Fig. 1 the D. C. voltage of a p-phase mutator is represented by U_g. The mean value of the same is determined by

$$U_{go} = \left(\frac{p}{\pi}\right) \sin\left(\frac{\pi}{p}\right) u_{max} \cos\left(\frac{u}{2}\right) \cos\left(\alpha + \frac{u}{2}\right)$$

from which the following is deduced, in the special case of $\alpha = u = 0$,

$$U_{go} = \left(\frac{p}{\pi}\right) \sin\left(\frac{\pi}{p}\right) u_{max} \quad \ldots\ldots\ldots \quad (1)$$

(no-load voltage for $\alpha = 0$).

Here, the D. C. voltage u_g contains all those higher harmonics (higher harmonics with reference to the frequency of the basic wave of the A. C. system from which the mutator is supplied) the orders of which are multiples of the number of phases p. The R. M. S. value of the nth higher harmonic is

$$U_n = \frac{1}{\sqrt{2}} \sqrt{U_n'^2 + U_n''^2}$$

in which expression U'_n and U''_n are determined according to the Fourier formula:—

$$\begin{matrix} U'_n \\ U''_n \end{matrix} = \left(\frac{p}{\pi}\right) u_{max} \left\{ \cos\left(\frac{\pi}{p}\right) \int_{\frac{\pi}{2} - \frac{\pi}{p} + \alpha}^{\frac{\pi}{2} - \frac{\pi}{p} + \alpha + u} \sin\left(\vartheta + \frac{\pi}{p}\right) \substack{\cos \\ \sin} (n\vartheta)\, d\vartheta \right.$$

$$\left. + \int_{\frac{\pi}{2} - \frac{\pi}{p} + \alpha + u}^{\frac{\pi}{2} + \frac{\pi}{p} + \alpha} \sin\vartheta \substack{\cos \\ \sin} (n\vartheta)\, d\vartheta \right\}$$

The integration for uneven values of n gives

$$\begin{matrix} U'_n \\ U''_n \end{matrix} = (-1)^{\frac{p+2}{2p} \cdot n \mp \frac{1}{2}} U_{go}$$

$$\left\{ \frac{\substack{\sin \\ \cos} (n-1)\left(\alpha + \frac{u}{2}\right) \cos (n-1) \frac{u}{2}}{n-1} - \frac{\substack{\sin \\ \cos} (n+1)\left(\alpha + \frac{u}{2}\right) \cos (n+1) \frac{u}{2}}{n+1} \right\} \quad . \; . \; (2)$$

On the other hand for even values of n:—

$$\begin{matrix} U'_n \\ U''_n \end{matrix} = (-1)^{\frac{p+2}{2p} n + 1} U_{go}$$

$$\left\{ \frac{\substack{\cos \\ \sin} (n-1)\left(\alpha + \frac{u}{2}\right) \cos (n+1) \frac{u}{2}}{n-1} - \frac{\substack{\cos \\ \sin} (n+1)\left(\alpha + \frac{u}{2}\right) \cos (n+1) \frac{u}{2}}{n+1} \right\} \quad . \; . \; (3)$$

and, from this, generally, for any value of p and n

$$\left(\frac{U_n}{U_{go}}\right)^2 = \left(\frac{\cos (n-1) \frac{u}{2}}{\sqrt{2}\,(n-1)}\right)^2 + \left(\frac{\cos (n+1) \frac{u}{2}}{\sqrt{2}\,(n+1)}\right)^2$$

$$- \frac{\cos (n-1) \frac{u}{2} \cos (n+1) \frac{u}{2}}{(n-1)(n+1)} \cos (2\alpha + u) \quad . \; (4)$$

so that $\left(\frac{U_n}{U_{go}}\right)$ can be expressed geometrically as being the third side of a triangle with the two adjacent sides

$$d_{nu} = \frac{\cos (n-1)\left(\frac{u}{2}\right)}{\sqrt{2}\,(n-1)} \qquad s_{nu} = \frac{\cos (n+1)\left(\frac{u}{2}\right)}{\sqrt{2}\,(2+1)}$$

and the opposite angle $(2\alpha + u)$. As will be seen, the ratio of the R. M. S. value of the nth higher harmonic to the no-load D. C. voltage $(\alpha = 0)$ is independent of the number of phases p. According to equation (4) the square of this quotient, when u is maintained constant, is a linear function of cos

$(2\alpha + u)$. As the square of the undulation and of the interference voltage is proportional to the expression $\Sigma\left(k_n \frac{U_n}{U_{go}}\right)^2$ (k_n being a magnitude dependent on the order), these magnitudes are also linear functions of $\cos(2\alpha + u)$.

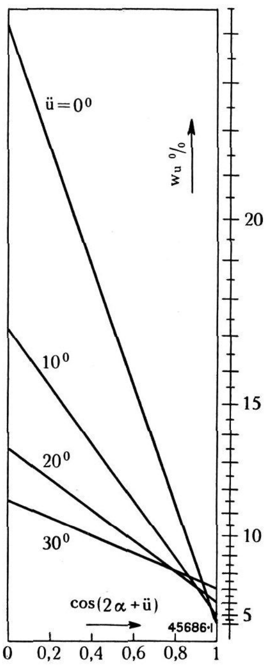

Fig. 2. — Voltage undulations in percent in the case of a 6-phase mutator, in function of cos $(2\alpha + u)$.

- α. **Displacement of the moment of ignition.**
- u. **Overlapping.**
- w_u. Voltage undulations in %.

II. UNDULATIONS IN VOLTAGE AND CURRENT.

We confine ourselves to the consideration of the R. M. S. values of the undulations given by:—

Undulations of voltage w_u:

$$w_u^2 = \Sigma\left(\frac{U_n}{U_{go}}\right)^2 \quad . \; . \; (5)$$

Undulations of current w_i:

$$w_i^2 = \Sigma\left(\frac{J_n}{J_{gN}}\right)^2 \quad . \; . \; (6)$$

here, J_n = R. M. S. value of the nth higher harmonic current. J_{gN} = Rated value of current.

In Fig. 2 the voltage undulations are shown in function of $\cos(2\alpha + u)$ in accordance with equation (4) and (5) and for a number of phases $p = 6$. Here, for $n > 24$ the values $(n-1) = (n+1) = n$ have been put down in the nominators of equation (4). The inexactitude thus introduced can be disregarded.

In equation (6) $J_n = \frac{U_n}{z_n}$ is to be, generally, inserted, z_n being the reactance of the D. C. system for the nth higher harmonic (big inductivities in the D. C. circuit, such as cathode choke coil, bus-bars) then with $z_n = 2\pi f n L$ we get

$$(w_i \, t_g \psi)^2 = \Sigma \frac{1}{n^2}\left(\frac{U_n}{U_{go}}\right)^2 \quad . \; . \; . \; . \; . \; . \; (7)$$

$$\text{with } t_g \psi = \frac{2\pi f L}{\left(\frac{U_{go}}{J_{gN}}\right)}$$

Fig. 3 contains the expression $(w_i \, t_g \psi)$ in function of $\cos(2\alpha + u)$ again for $p = 6$. This allows of determining the current undulation or the inductivity L requisite to obtain a determined current undulation.

In Figs. 2 and 3, we have confined ourselves to the region of $0 \leq \cos(2\alpha + u) \leq 1$. The behaviour of the straight lines shows clearly the influence of the ignition point on voltage and current undulation. Apart from small displacements of the ignition point, the maximum undulation (at constant displacement) is always under no-load ($u = o$).

The numerous intersection points of the straight lines of constant overlapping show the complicated dependence of the undulations on the ignition retardation or on the overlapping u.

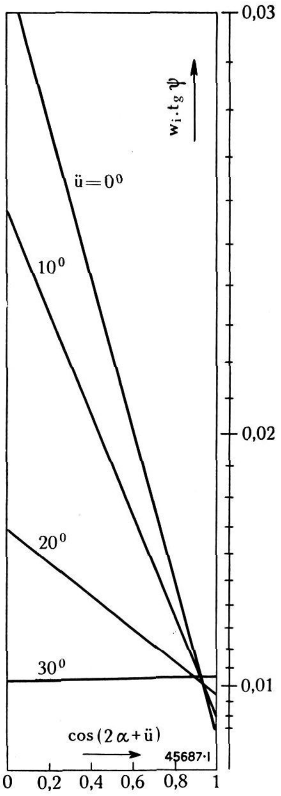

Fig. 3. — Product $w_i \times t_g \psi$ of a 6-phase mutator, to determine the undulations of the current in function of $\cos(2\alpha + u)$

$$w_i \, t_g \psi = \frac{2\pi f L}{\frac{U_{go}}{J_{gN}}}$$

- f. Frequency of A. C. system.
- L. Inductivity of D. C. system.
- U_{go}. No-load voltage.
- J_{gN}. Rated D. C. current.
- α. Displacement of moment [of ignition.
- u. Overlapping.

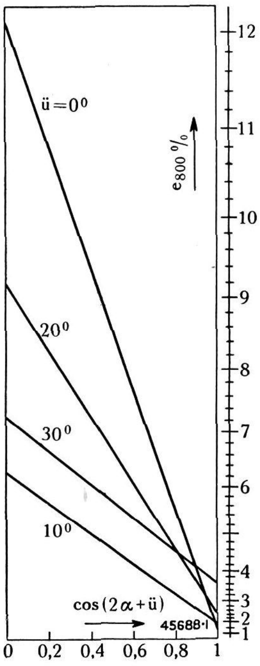

Fig. 4. — Interference voltage in percent in the case of a 6-phase mutator, in function of cos $(2\alpha + u)$ **referred to frequency 800, for an A. C. system frequency of 50 cyc.** (Factors of interference according to CCI 1933).

- α. Displacement of moment of ignition.
- u. Overlapping e_{800} = interference voltage in %.

III. INTERFERENCE VOLTAGE.

In the case of the influence exercised by D. C. circuits supplied by mutators on neighbouring telephone lines, the frequency as well as the magnitude of the individual higher harmonics is important. In order to form an estimation of the disturbance caused by all the higher harmonics together, a knowledge of the interference voltage is useful. It is determined by

$$u_s = \sqrt{\Sigma\left(g_n \frac{U_n}{U_{go}}\right)^2} \quad . \; . \; . \; . \; . \; . \; . \; (8)$$

Here, g_n is the factor of interference of the nth higher harmonics, by which the effects of interference of different intensities produced by the higher harmonics on the human ear, are taken into account. It is so chosen, for the nth higher harmonic, that its multiplication by the voltage magnitude of the said harmonic has an equally strong interference voltage value as the frequency of 800 cycles. Its behaviour in function of the frequency can be taken from the interference curve published by the Comité Consultatif International (CCI).

Under the assumption that the frequency of the mutator-fed system f is 50 cycles, the interference voltage of a six-phase mutator has to be introduced into Fig. 4 according to equations (4) and (8).

The interference voltage can be considerably reduced by using a resonance wave smoother or an impedance wave smoother. Both wave smoothers contain a series choke coil through which flows the total service current. After this choke coil and in parallel to the load there are placed, in the first case, two or four resonance circuits tuned and, in the second case, condensers.

For the interference voltage after the wave smoother we get:

$$u_s = \sqrt{\Sigma \left(f_n\, g_n \frac{U_n}{U_{go}}\right)^2 + \dot{\Sigma} \left(g_n \frac{U_n}{U_{go}}\right)^2} \quad . \; . \; (9)$$

$$\text{with } f_n = \frac{r_n}{2\,\pi\, n f L}$$

Here

r_n = Ohmic loss resistance of the respective resonance circuit,

L = Inductivity of the choke coil in series.

As equation (9) shows, the wave smoother acts in the sense of a reduction of the factor of interference of the higher harmonics on which the resonance circuits are tuned.

In the case of the impedance wave smoother, the choke coil in series and the condenser are tuned to the $\frac{1}{k}$ times system frequency. The interference voltage, after the wave smoother is then given by

$$u_s = \sqrt{\Sigma \left(\frac{g_n}{(k\,n)^2 - 1} \cdot \frac{U_n}{U_{go}}\right)^2} \quad . \; . \; . \; (10)$$

As in Fig. 4, where the voltage of interference before the wave smoother was inserted, the voltage of interference after the wave smoother can be put in, determined according to equations (9) or (10).

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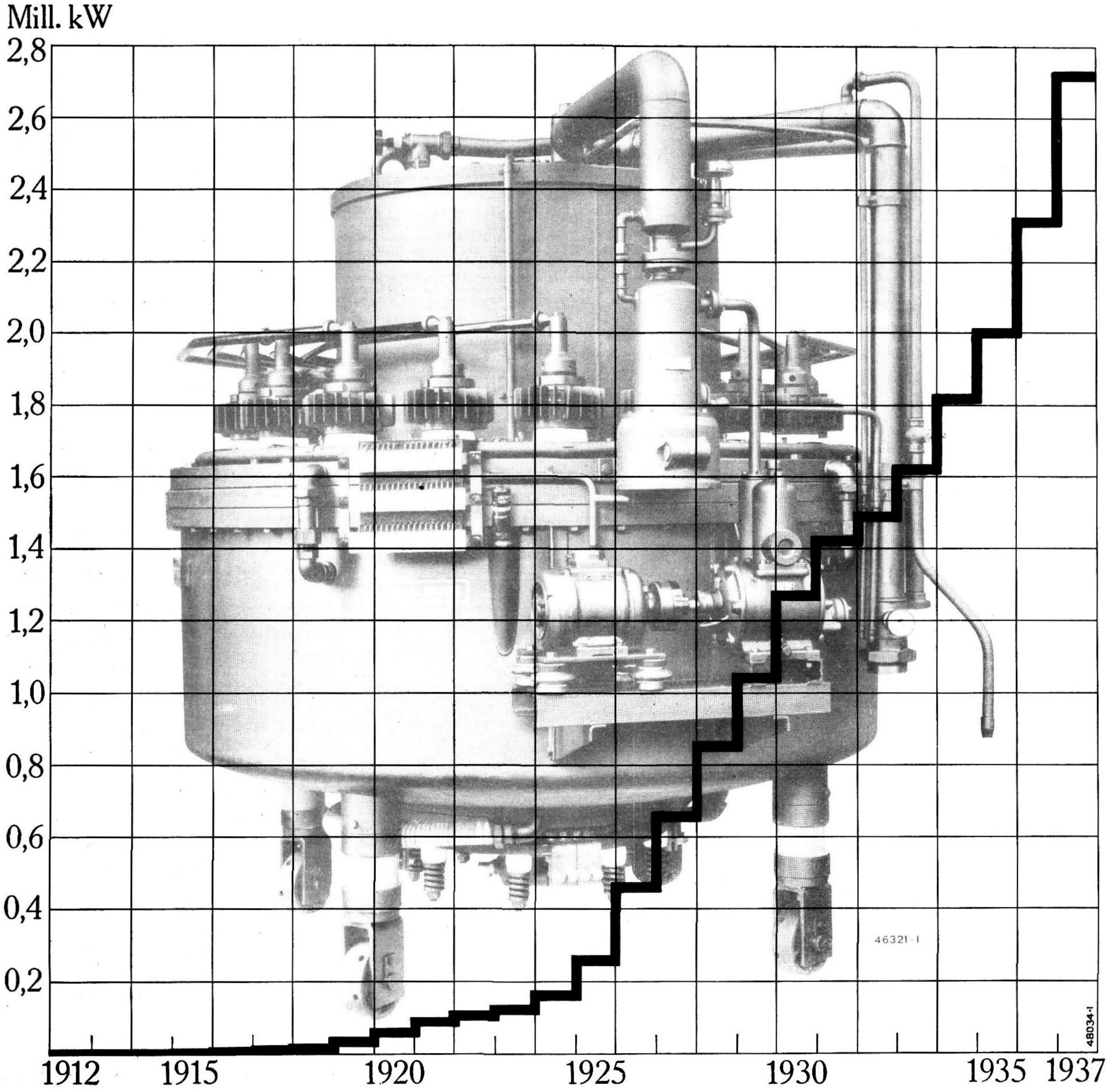

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