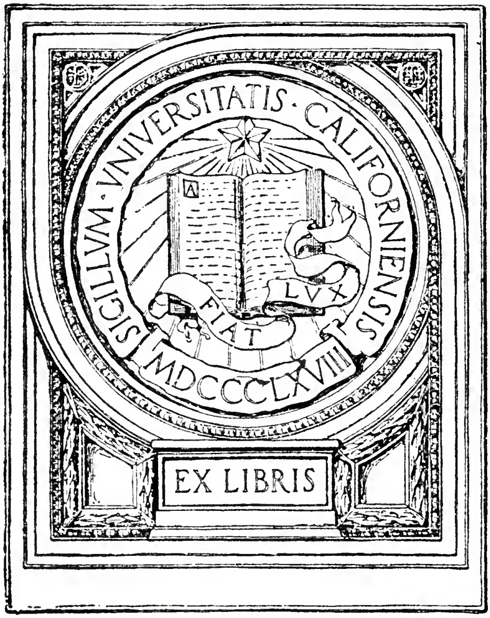
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COMMERCIAL DYNAMO DESIGN

ORIGINAL PAPERS

ON

COMMERCIAL DYNAMO DESIGN

BY

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"*It is not knowledge, but ignorance, that begets confidence.*"

Charles Darwin

"*I hold every man a debtor to his profession; from the which, as men of course do seek to receive countenance and profit, so ought they of duty to endeavor themselves by way of amends to be a help and ornament thereunto.*"

Francis Bacon

INTRODUCTION

Commercial Engineering.—The nineteenth century was notable for the achievements of the engineer, and there is little doubt that the men responsible for this pioneer work were engineers in the broadest sense of the word. They were engineers in their ability to manipulate the forces and materials of nature; but they were also far-sighted and level-headed men of affairs in their appreciation of the economic value of their work, and in the management of their projects. These men, by their genius and enterprise, and by their hard common sense and solid achievement, forced the world to recognize the engineer as destined to play a leading part in the future. Public attention became focussed on the engineer, and numbers of men were attracted to the profession, either through natural inclination or through hope of profit. But as was to be expected, a large percentage of these men were imperfectly educated, and possessed only a specialized talent in certain directions, without any of the broad-minded comprehensive spirit of the pioneers. This change soon reacted on public opinion, and the engineer lost his high standing; so that the public and the world of commerce came to regard him as a specialized "crank," a species of high-grade artisan, who though useful enough in his place, was devoid of any ability to take a sane and comprehensive view of a situation, or to manage an undertaking in which he might be interested. The commercial world, though distrusting the ability of an engineer to manage his enterprises, came to realize more and more their economic value and financial possibilities. The result of this was, that the enterprises which the engineering world proposed, gradually came to be exploited by business men, who had to a greater degree the confidence of the financial powers. These men, who attempted to manage such undertakings, were usually altogether ignorant of the work they took up, and it is not surprising that this development produced indifferent results. Engineers, being effectively cut off from the commercial side of their work, became narrower; while the increasing specialization left the commercial men in still greater ignorance of the products they were handling, and their management became more and more wasteful. The inefficiency of this arrangement has gradually become evident to all, and it is now generally recognized that the executive and commercial head of any large engineering enterprise must posess some engineering knowledge. It is also realized that, given an opportunity for a broader education, an engineer can be readily trained to become an efficient and high-grade commercial executive, while it is almost impossible to instil an engineering knowledge into one whose training has been restricted to the commercial world. As a result of this, engineers are being given opportunities to obtain a broader commercial education, and it is recognized in high financial quarters that in the future they will have to depend on the engineering profession for high-grade operating men in all engineering enterprises. Already we find engineers at the head of a number of the large concerns, and it is probable that the time is not far distant when it will be the exception to find the operation of an engineering undertaking in the hands of any other than an engineer.

Mr. John I. Beggs.—It was my good fortune to work under Mr. John I. Beggs, one of the first and one of the most prominent of the commercial engineering executives in this country, at a time when I was so interested in purely engineering problems that I was in danger of drifting away from broader interests. For twenty-five years in active touch with the electrical engineering industry, as a manufacturer, or as an organizer and operator of public service corporations, obtaining his engineering and commercial knowledge through hard personal experience, Mr. Beggs was pre-eminently fitted to guide and encourage the youthful engineer. Continually improving and rendering commercially practicable much of the apparatus used in connection with electric lighting or railway interests, and doing this with the purpose of obtaining results, rather than of being accorded credit or public recognition, he was one of the first to realize that the engineer was destined to become the dominant factor in large engineering corporations. Giving his young engineers a free hand in all branches of commercial and engineering work, only guiding and checking them where necessary, he developed organizations and men in a way, which, while it made the men his grateful and enthusiastic admirers, established his reputation as one of the foremost organizers in the engineering industry, and left his mark on the methods and apparatus of to-day. In inscribing these few papers to Mr. John I. Beggs, I am only taking an opportunity of expressing my indebtedness, and my appreciation of the education it was to be in touch with him. I have entitled the papers "Commercial" Design, because engineering questions of purely academic interest are made subservient to those broader issues, where design and operation must be considered in their relation to the commercial success and future of the undertaking. It is in this feature of my work that I have to acknowledge the influence of Mr. Beggs, and to state that I have in a great measure to thank him for any small success I may have had.

History of Papers.—These papers, which have been written at different periods during the past six years, are the result of fifteen years' experience as a designing and manufacturing engineer in some of the most important electrical manufacturing concerns in Europe and America. They cover various subjects relating to the design of electrical power machinery, in which I happened to have been interested at different times, and they are reproduced here in the hope that they may be more accessible, to any whom they may interest, than they would be in the proceedings of the various institutions. The student will find there is no lack of treatises on dynamo design by capable men, and this book makes no pretense to be a comprehensive work. It is merely offered as a supplement to such treatises, as a series of articles, which written by one who is actively engaged in practical manufacturing, may cover a few points of special interest to the student or designing engineer, that could not be satisfactorily covered in a more general work.

December, 1910.

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[*Presented before the American Institute of Electrical Engineers, June* 29, 1903.]

COMMERCIAL ALTERNATOR DESIGN

The design of alternators has been treated times without number, but usually the commercial element in the design, *i.e.*, the relation of factory cost to selling price, has been ignored. An engineer has been defined as a man "who can do for one dollar what any fool can do for two," and as this definition applies in connection with machine design, the man who can design the cheaper machine to satisfy a given specification is the better designing engineer.

Speaking generally, there is no type of alternator that will compare with the internal revolving field construction, in which each pole carries a separate field coil of edge-on copper strap. The revolving armature is cheaper for high frequencies and low voltages, the inductor type is good for small 60 cycle high-speed machines, while the disc alternator with no iron in the armature is an excellent machine for high frequencies. But these, though sufficiently satisfactory in their own limited field, do not compare with the revolving field type for general work.

Fundamental Types of Construction.—The revolving field alternator took its present form about 1892 when Mr. C. E. L. Brown designed some alternators which were practically modern machines; while in 1893 Mr. S. Z. de Ferranti * installed some

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*** I understand from Mr. C. E. L. Brown that the Brown Boveri Maschinenfabrik deserve to some extent the credit for the design of the Portsmouth alternators, though Mr. Ferranti was the first to use edge-on copper strap for field magnets.**

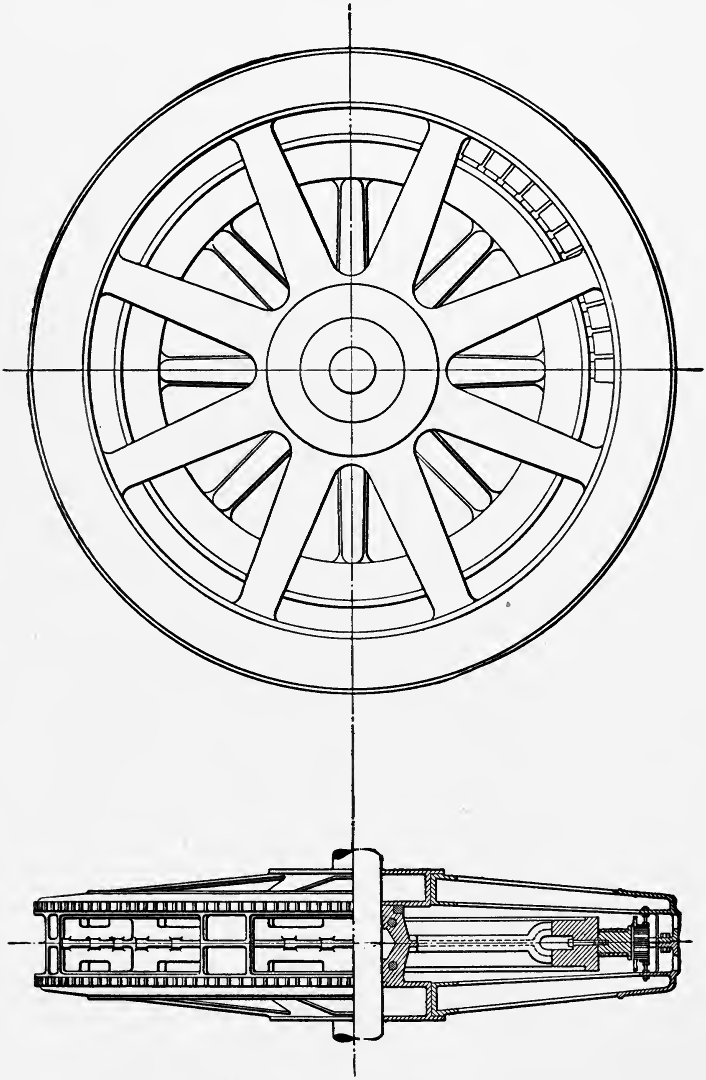


Fig. 1.

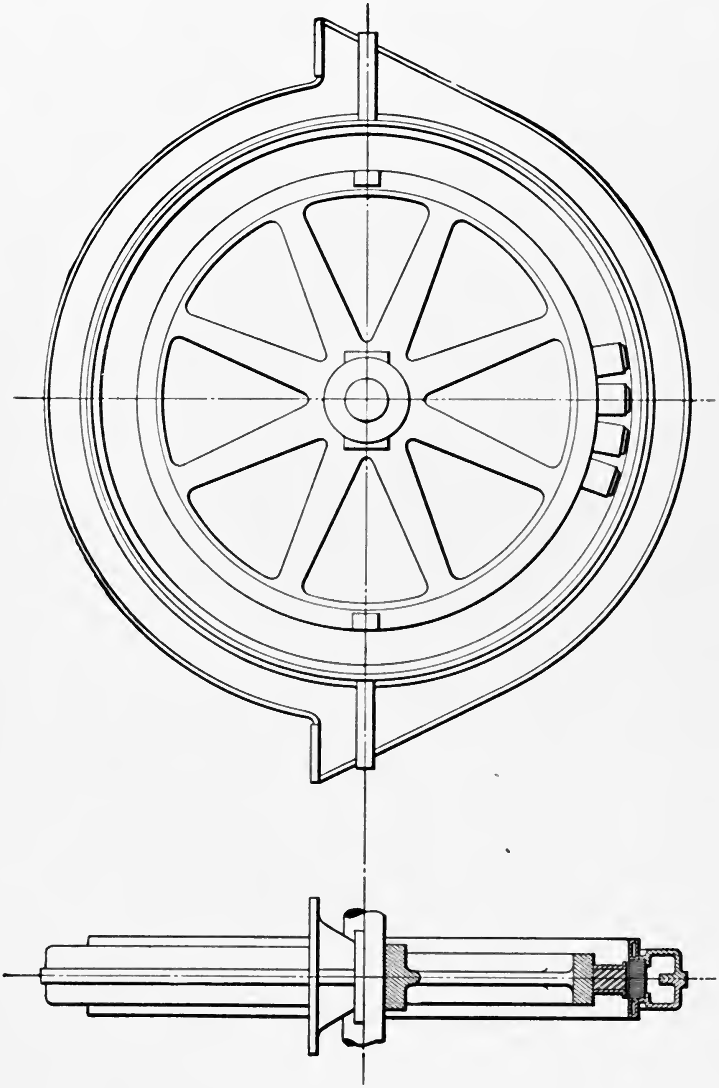


Fig. 2.

210 K.W. alternators at Portsmouth, England, which were of similar design to those of Mr. Brown. Before that date alternators of this type were of a clumsy amateur design, and their performance was, generally speaking, very poor. Strangely enough, these two engineers, after bringing out a high grade design, apparently abandoned further development, and their machines to-day are almost identical with their machines of ten years ago.

It has taken the different manufacturing concerns a long time to recognize the superiority of the Brown and Ferranti type for standard work, and it is practically only during the last three or four years that this type has been generally adopted. The result is that, except for a few minor details, the construction of these alternators has been improved very little since they were first introduced; while the excellence, from a commercial point of view, of the electrical design of Mr. Brown's early machines seems hardly recognized even yet by some engineers; and we have alternators on the market to-day which are for a given performance decidedly more expensive than those which he designed ten years ago.

The armature frame in the Brown type of machine was only a skeleton cast iron frame for clamping the laminations together, and was provided with large ventilating holes; while the ends of the armature coils stood out from the laminations, quite free and exposed to the full windage of the magnet-wheel. The numerous holes gave excellent cooling effect, but they reduced the strength and stiffness of the frame, so that the armature had to be stiffened by a series of tie-rods or struts. This construction, which saves material at the expense of labor, has become standard with German and Swiss firms, though on account of its unsightly appearance it has never found favor in this country. This type of alternator, shown in Fig. 1, has retained practically its original form up to the present time and developments that have taken place have been mostly in the Ferranti type.

American and English engineers have followed the Ferranti

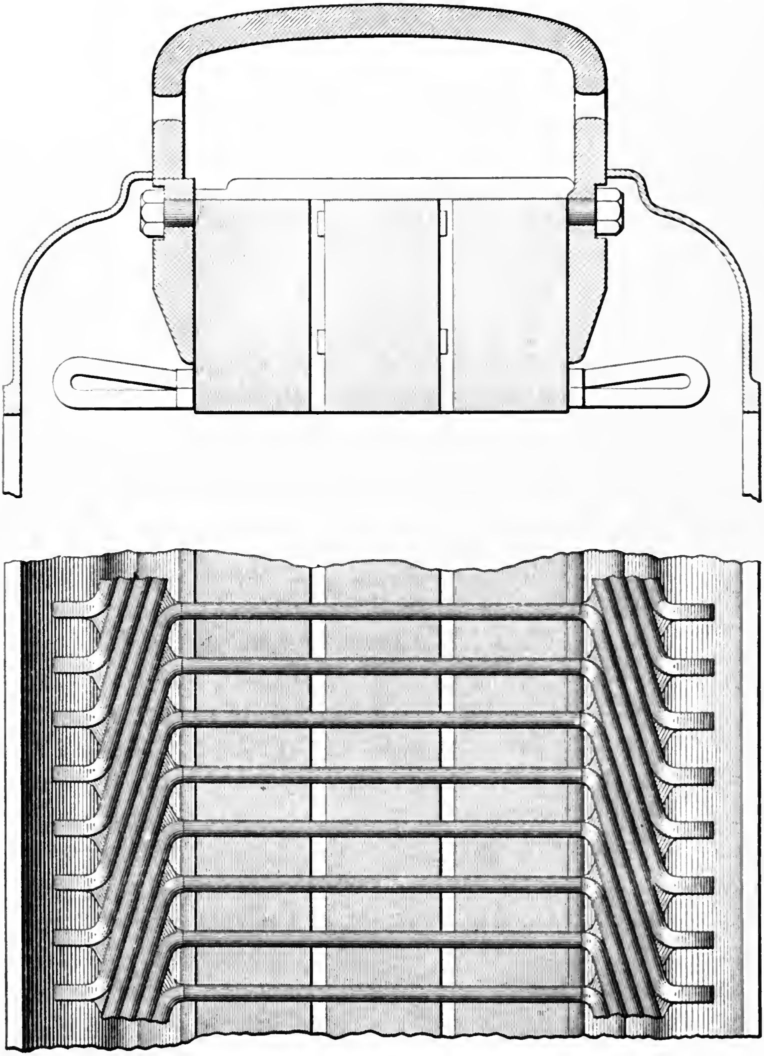


Fig. 3.

type shown in Fig. 2, and made the armature frame stiff enough to stand without bracing. The trouble with this construction was originally the poor ventilation of the armature. Ventilating spaces were either not used, or if they were, there was no proper circulation of air through them. The end connections on the armature winding and the ends of the coils were packed tight together, or were closed in by cover-plates permitting no ventilation. Thus, the armature winding was usually the hottest part of the machine; so that even allowing temperature rises of 45° C., these machines could not be rated as they should, solely on account of the poor ventilation. When American and English engineers took up the revolving field type of alternator, the badly ventilated Ferranti type was adopted, and the great importance of ventilation was not recognized, so that the development of alternator design in America and England has been comparatively slow.

The improvement in ventilation which has recently taken place in this type of alternator is really the greatest forward step that has been made, and it has given the designer immense help in increasing the output of machines.

Fig. 3 shows an old, badly ventilated armature, while Figs. 4 and 8 show a more up-to-date well ventilated machine. In Figs. 4 and 8 it will be seen that where the ends of the armature coils cross one another they are separated by an air space, and that the end covers are provided with ventilating holes, to allow a circulation of air around the coils; thus the armature winding, instead of being the hottest part of the machine, becomes the coolest. The armature core is well provided with vent spaces both at the centre and at the ends, and the air passing through these vents is free to escape at the back of the core. This type of armature coil has the additional advantages that if lightning gets into the machine or a coil is burnt out, the damage is confined to one coil, so that we do not have half a dozen burnt out as usually happens. Also, all the coils on the armature are alike and made on the same former, so that the question of spare coils is simplified. The difference in the cooling effect between

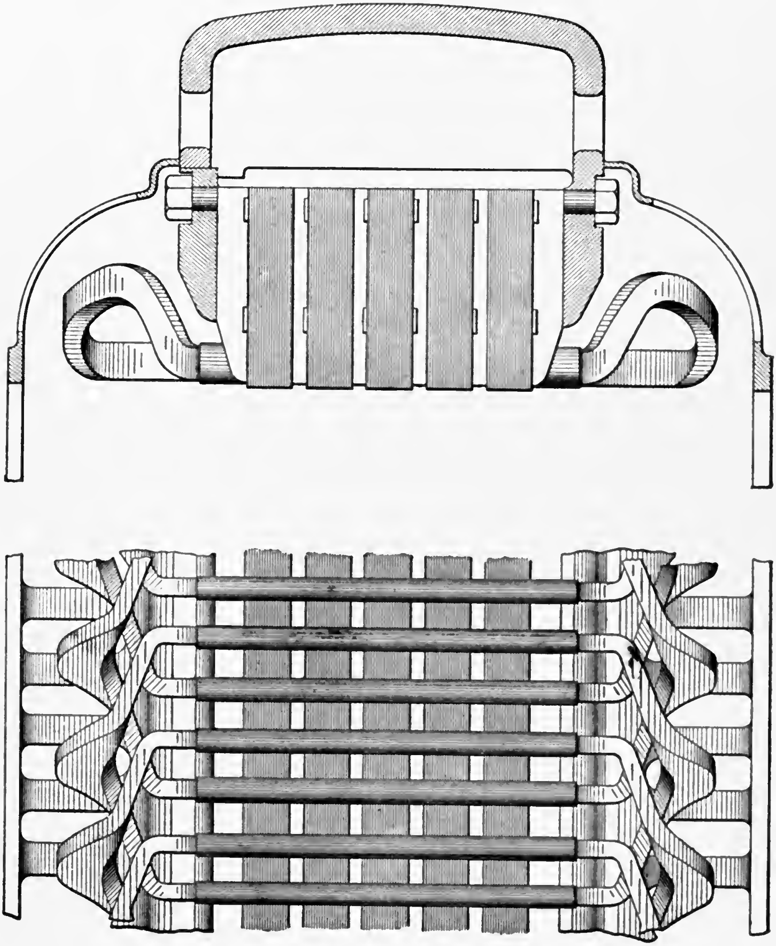


Fig. 4.

these different designs may not seem to be much on paper, but it results in the difference between a temperature rise of 45° and one of 25°, on actual test. It means that we need only take into consideration efficiency and regulation in designing a machine, knowing well that if these are satisfactory we can guarantee a temperature rise of 25°, even on low-speed machines.

When designing any machine we have the choice of taking a large diameter and making the machine short, or of taking a small diameter and making the machine long. The difference in the cooling effect between these two is obvious from Figs. 5 and 6. In Fig. 5 the machine is small in diameter and long, the poles are close together and the winding crowded, while all the heat from the field-coils has to be dissipated from the small exposed surface at the ends of the coils. In Fig. 6 the alternator is large in diameter and short, and practically the whole surface of the field-coil is available for cooling. In addition, the field coils being

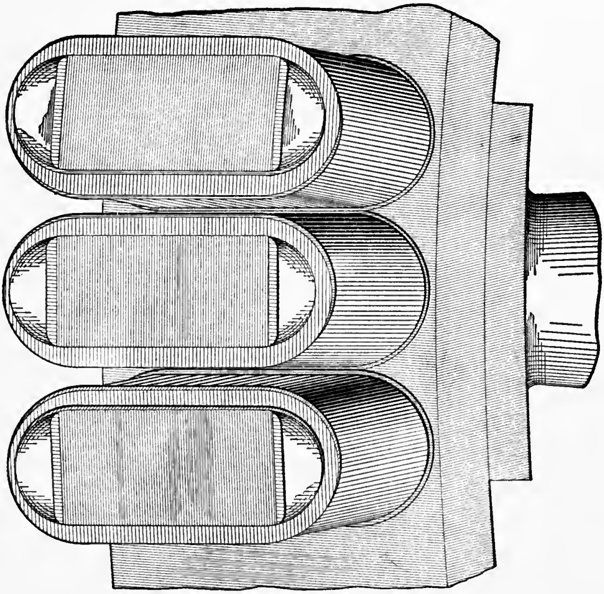


Fig. 5.

separated more from one another and the peripheral speed higher, the cooling effect on the armature is much greater. The machine in Fig. 6, being built on a large diameter, will require heavier castings and present greater difficulties in handling, but the fact that the designer is not restricted by the temperature rise, gives him so much more latitude, that he will easily offset this slight extra expense by a cheaper design generally, and will in addition have a much cooler machine. The difference in cooling effect between a construction with armature and magnets as shown in Figs. 3 and 5 and one with armature and magnets as shown in Figs. 4 and 6 is so obvious, that it is quite surprising to find the poorly ventilated type still on the market. The only inference to be drawn is that the firms building them have not given the subject due thought.

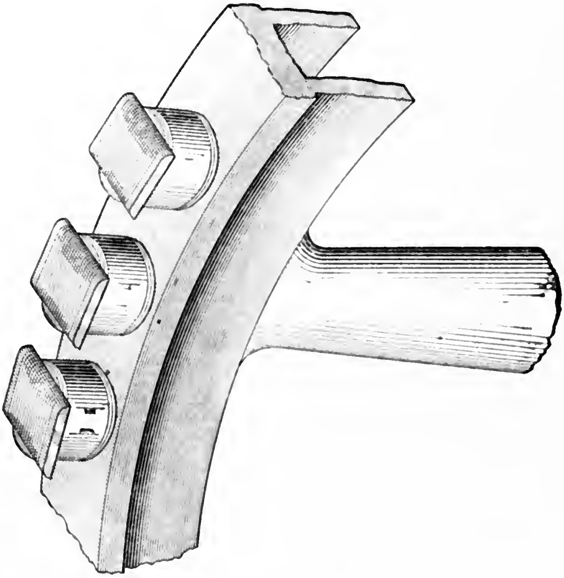


FIG. 6.

Specification.—In the electrical part of the design, the first thing to be decided is the specification to which the machine is to be built. The firm with which I am connected has adopted as standard:

A temperature rise of 35° C. on a continuous full load run;

A temperature rise of 50° C. on 50 per cent over-load for two hours;

A regulation of 5 to 7 per cent on non-inductive load, according to the size of the machine;

And gives a guarantee that all machines will without damage give continuously 25 per cent current over-load at zero power factor.

Detail Design.—Given the specifications, we have next to decide what diameter we shall make the machine. What magnetic densities to take in the iron? What current density in the conductors? What percentage of the pole pitch shall the pole face be? What air gap? Of course, these questions can only be answered off-hand as the results of experience. But generally speaking we can, after a few trials, decide on the best design. We have only to consider the efficiency, the regulation, and the cost; as with a good design the temperature need not be considered.

The efficiency of a machine within ordinary limits practically depends on the magnetic densities in the iron and the current densities in the copper. The higher the densities, the cheaper and the less efficient the machine. The copper loss in the armature is usually between 1 and 2 per cent. Apart from the efficiency this is decided by the regulation, because if we allow only 5 to 7 per cent voltage drop on $P F = 1$, we cannot well have more than 2 per cent of this as $C R$ drop. This means that in low-speed machines with a large number of poles, the current density in the armature is very low, while in high-speed machines with few poles the current density can be much higher. In practice it varies from 1200 to 3000 amperes per square inch. The iron densities do not vary much in standard machines, as the most economical densities are very fairly constant and independent of the speed; and any attempt to obtain higher efficiencies by decreased iron densities will increase the cost rapidly.

The best ratio of pole face to pole pitch is largely a matter of opinion. If it is large, say 70 per cent, then the E.M.F. coefficient (the Kapp coefficient) is reduced, and the total flux of the machine increased and hence the magnets made heavier. On the other hand, with a wide pole face we have more teeth to carry the flux, and for a given tooth-density the machine is shorter. But the armature core-plates are correspondingly deeper, so that the only saving is a slight decrease in the length of mean turn of the armature winding. The larger the percentage of pole face to pole pitch the greater the magnetic leakage, and to a certain extent the less the synchronizing power of the alternator. So that there is little to be gained by much variation of this ratio, and it seems advantageous to keep it low, say between 60 and 65 per cent.

The air gap is decided by the regulation of the machine. An immense amount has been written on various theoretical methods of calculating the regulation of alternators, but broadly speaking the regulation depends on the ratio of the ampere-turns on the armature to the ampere-turns for the air-gap. In an alternator the armature conductors are cut by magnetic lines due to the armature current, *i.e.*, the armature self-induction flux; and by magnetic lines due to the magnet current. But the self-induction of the armature varies with the magnitude of the current in the armature and magnets, and with their relative position; while the useful flux due to the magnets varies with the current in the armature and field, on account of the varying permeability of the iron and the magnetic leakage. So it is obvious the conditions to be taken into account are so complicated that it becomes quite impossible to treat them theoretically, without making so many assumptions that the results, even when obtained, cannot be directly applied. What a designer has to do is to work theoretically through a few simple special cases himself and the results will give him an idea on what lines to work. Then by means of experimenting on a number of machines he can develop an empirical method for calculating the regulation. Afterwards as he gets more and more experience with alternators, he introduces further refinements, and taking the regulation curves obtained by empirical methods he corrects them a little by eye.

Speaking generally from a designer's point of view, an alternator should be calculated for a certain regulation on a low power-factor load, say $PF = 0$. For, if the machine is satisfactory on low power-factors, it will be satisfactory for non-inductive loads, while the converse is not true. Other things being equal, the larger the air-gap the better the regulation on the low power-factors. But the leakage coefficient of the machine is an important factor, and this increases with the air-gap. This coefficient is, of course, taken into account in drawing the no load saturation curve; but we have to remember that on full load of low power-factor the leakage coefficient is much increased (the leakage is often doubled), on account of the additional ampere-turns required on the magnets to overcome the demagnetizing ampere turns on the armature. So that if the leakage coefficient is already high, and if the density in the magnet iron is also high, we run a considerable risk of saturating the magnet circuit so that we cannot obtain the rated voltage on loads of a low power-factor. It was this trouble that caused inductor machines to become obsolete for low power-factor loads, as they are particularly sensitive to leakage and are always worked at high densities. Speaking generally, if the no load leakage coefficient of a machine is higher than 1.25, and if the density in the magnets is greater than 100,000 lines per sq. in., the designer has to be very careful or he will be in difficulties.

The regulation on non-inductive loads is not affected by the length of the air-gap to the same extent as the regulation on low power-factors. So machines which are only intended for lighting or rotary converter work usually can be economically designed with a smaller air-gap and higher densities than machines for motor work.

In Europe practically every alternator sold has to operate motors, so that the regulation either for $PF = 0.8$ or for $PF = 0$ has to be guaranteed. In America, on account of the patent situation, induction motors are used only to a limited extent, and as a result of this it has become standard practice to sell machines on a regulation guarantee for non-inductive, rather than for inductive loads. This is very unsatisfactory. Almost every load that an alternator has to carry is to a certain extent inductive, *e.g.*, arc lamps, transformers on light loads, rectifiers, induction motors, and synchronous motors, unless the excitation is carefully adjusted. And as the regulation of an alternator on $P\,F = 0.95$ is usually about twice as bad as on $P\,F = 1$, it is obvious that a more satisfactory guarantee would be to give regulation on inductive loads. Practically the only exception to this is the case of an alternator for use exclusively for running rotary converters. And even with a compound-wound rotary converter and an inductive line, the power-factor is usually low and the current lagging for light loads; while if the rotaries have to be started from the alternating current side, a generator with poor regulation on low power-factors is very noticeable and may give trouble.

It is extremely difficult to measure the regulation for $P\,F = 1$ on any machine with good regulation, while on a large machine it is practically impossible. The result can only be figured as the difference between two large quantities, and there are so many disturbing features that the result when obtained is not very accurate. On the other hand, it is quite easy to measure the regulation on a very low power-factor by loading on to a second machine running as a synchronous motor, the first one operating as a generator, and varying the excitation of the motor and generator till full load current is flowing at full-load voltage. The power-factor in such a test will be very low and can, with sufficient accuracy, be taken zero.

Alternators can be designed so as to satisfy a close regulation specification for non-inductive loads and yet be almost worthless for carrying loads of low power-factor. So that as such machines can be made cheaper than if they were required to give a reasonable regulation on inductive loads, there is a temptation for manufacturers to take advantage of the fact that the regulation is only guaranteed on $P F = 1$, to install one of these cheaper machines. It is probably this fact which is responsible for the number of alternators having poor regulation on low power-factors, that have been installed in this country. It would certainly be an advantage from the customer's point of view, and probably in the end from that of the manufacturer also, if the regulation were guaranteed for a load of low power-factor. This would make it necessary from the commercial standpoint to alter somewhat the lines on which modern alternators are designed, but the cost of the machines would not necessarily be much increased. A modern alternator gives, say, 7 per cent regulation on $P F = 1$, and 22 per cent on $P F = 0.8$. When operating with a normal power-factor of about 0.85, and a regulation of about 17 per cent, it does not help the station engineer to know that if he had a non-inductive load he would have good regulation. Such a machine could be re-designed on somewhat different lines, so as to have 6 per cent regulation on $P F = 1$, and 12 per cent on $P F = 0.8$, and about one per cent lower efficiency without increasing the cost appreciably. Such a machine would be much more satisfactory for general work and could probably be sold for considerably more than the machine designed only for work on non-inductive loads.

Other things being equal, the regulation of an alternator is better the more saturated the magnet circuit, and this applies to low power-factor loads as well as to high. It can be considered simply as an experimental fact, or the explanation can be accepted that the voltage drop in an alternator is partly due to the reaction of the armature ampere turns, and that the effect of a definite percentage change in the ampere-turns is less when the magnets are saturated than when they are not. Obviously the part of the magnetic circuit to saturate is the magnet core, as the less its cross section, the less its perimeter and the less the weight of the magnet copper. In the type of magnet shown in Fig. 7, it is impossible to saturate the pole core, and the large amount of iron and copper necessary always makes this design needlessly extravagant. It, however, possesses the advantage that the voltage can be raised 25 or 30 per cent, if desired, to compensate for an extraordinary line drop; though usually it is sufficient if an alternator is capable of having its voltage increased 15 per cent when carrying full load.

When designing an alternator for a given output we can adopt either a strong armature and a weak field, or a weak armature and a strong field; and generally speaking, the stronger the armature, the cheaper the machine but the worse the regulation. So to design cheap machines with good regulation, it is necessary to take advantage of everything that will better our regulation, *i.e.*, we must work with a long air gap and we must saturate our poles. But a long air gap results in large leakage, and as I pointed out before, a machine with large leakage and saturated poles is the most difficult machine to design. To make a uniform success of such machines, the designer must have had considerable experience with the type of alternator in question, and must be a very careful worker. In fact, when I first began designing alternators I was told to put plenty of iron and plenty of copper into the magnets, and that if I did this I would be safe. I think for a beginner the advice is good and that he could not do better than commence with a conservative and simple design like that shown in Fig. 7. But for a designer who has had considerable experience, it is well to figure more closely, as there is quite 20 per cent in the cost to be saved by so doing.

Suppose we have decided to adopt a large air-gap and yet wish to keep down the leakage. There are several things which will help us in this, but making the pole pitch large and decreasing the length of the magnet pole are the most important. Adopting a large pole pitch results in making the machine larger in diameter, and shorter. Beyond certain limits this increases the cost; and it is a question to be decided by the designer as to when the advantages obtained from the larger pole pitch are offset by the increased diameter and weight of the castings. Decreasing the length of the magnet pole core reduces the leakage. Decreasing this length also results in decreases the radiating surface, increasing the depth of the magnet winding and hence increasing the length of mean turn of the magnet coil somewhat at the same time. It also slightly decreases the ampere-turns for the magnetic circuit. If we use a large pole pitch, giving plenty of space between the poles, together with a short armature and high peripheral speed, we can easily avoid the increase in temperature due to decrease in radiating surface. So that the limiting factor in reducing the length of the pole core becomes the additional weight of copper due to the increased length of mean turn on the magnet winding, caused by the extra depth of the winding. With good design we can usually reduce the length of pole core to about one inch for every 1500 ampere turns required on full load; so that our leakage coefficient will generally not exceed 1.25, which is not excessive.

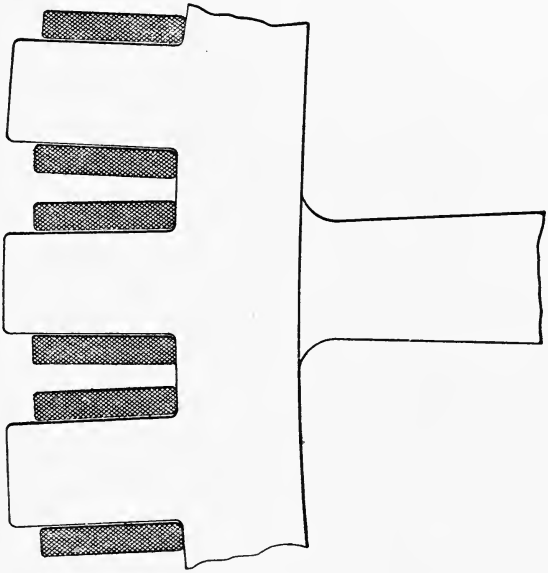


FIG. 7.

To show the effect of these various points on the design of a machine, let us take a definite example.

Output 750 K.W. 60 cycles, 100 R.P.M., 72 poles, 2200 volt. Specification to be:

Electrical efficiency at full load, 95%
Regulation 7% for $P F = 1$
" 16% for $P F = 0.8$
" 25% $P F = 0$

Temperature rise on full load $P F = 1$. Armature 30° C., Magnets, 20° C. This low magnet temperature being adopted so that the temperature will not become excessive with the increased losses which will result when operating on loads of low power-factor.

A is a machine which has a pole pitch and diameter large enough to use round poles, and has saturated pole cores. It has a strong armature and strong magnets.

B has a smaller pole pitch, so that it is a longer machine, and has unsaturated fields. It has a weak armature and field, and the magnet winding is crowded.

	A.	B.	C.
Internal diameter of armature	207″	161″	207″
Length of armature core	6¼″	13½″	6¼″
Pole pitch	9″	7″	9″
Air gap	5/16″	1/4″	5/16″
Peripheral speed. feet per min.	5400	4200	5400
Slots per pole	6	6	6
Turns per coil	5	3	4
Magnet core section	round	rectangular	round
Induction in magnet core, per sq. in.	110000	95000	110000
Regulation $P F = 1$	7%	6.8%	5.6%
$P F = .8$	15.5%	16%	10%
$P F = 0$	24%	25%	16%
Losses magnet C^2R watts	12500	8500	17000
Armature C^2R "	10700	7250	12000
Iron loss "	15200	24000	19300
Efficiency	95.1%	95.0%	94.0%
Temperature rise of armature	22° C.	30° C.	26° C.
" magnets	15° C.	16° C.	26° C.
Weight magnet copper lbs.	1800	3800	2300
" " poles "	1420	4500	1780
" " wheel "	14000	15000	16000
" armature copper "	1425	1200	810
" " laminations "	5500	7500	6600
" " frame "	22000	18000	22000
Cost of above material	$1,645	$2,150	$1,710

So on the principal items that enter into the cost of material, the saving is about 25 per cent, due to the use of strong armature and magnets, large pole pitch, and short saturated magnet cores. Probably the saving of the cost of the complete machine would be about 20 or 25 per cent. The designs of these two machines are a little exaggerated, but they show very well the saving in cost that can be made.

C is the same machine as A, but designed with a weaker armature, so as to have better regulation, especially on low power-factors, at the expense of a lower efficiency. The cost is about the same.

The chief points for a cheap design for an alternator with good voltage regulation on inductive loads are strong, saturated magnets, a reasonably large pole pitch, and as large an air-gap as can be used without excessive leakage. In machines of small output with a large number of poles, it is impossible to get a really economical design. The diameter is decided by the number of poles and little is gained by making the machine less than 5 or 6 inches long, so the cost is not reduced very much with the output. Generally speaking, if the output of the machine is less than 10 K.W. per pole, the design is unnecessarily expensive, while machines in which the length of the armature is about equal to the pole pitch are usually the most economical. It is for this reason that 60 cycle alternators for small outputs, and 120 or 133 cycle alternators of all outputs are usually made belt-driven; the saving in cost by doing this often being 50 per cent. In continental Europe, where 50 cycles is the usual practice, belt-driven alternators have never met with much favor; the universal custom being to direct-connect the alternator to a low-speed engine. The result of this has been that the fly-wheel type of alternator has practically become standard for this work, and the poles of the alternator are simply bolted to the rim of the fly-wheel. This type allows considerable saving in cost in small 50 or 60 cycle machines and possesses so many other advantages that it is being introduced into this country.

Steam Turbine Driven Alternators.—Alternators for direct connection to steam turbines have lately come into prominence; the chief consideration in these machines being, of course, the high speed at which they operate. In order to prevent the length becoming excessive, the diameter of a turbo alternator is made as large as possible, and peripheral speeds of from 12,000 to 20,000 feet per minute are adopted. The mechanical stresses in the metallic parts of the magnets are high, but a conservative factor of safety can be maintained if high-grade materials are employed. The greatest difficulty consists in arranging the mechanical stresses on the insulation of the rotor in such a way that the insulation is not damaged. If this is not done, and if the winding and constituent parts of the rotor are not firmly fixed so that relative motion cannot take place under the influence of the centrifugal forces, continual trouble will result due to changing of balance.

The electrical design of a turbo alternator is much the same as that of a belt-driven machine, except that the speed being very high the efficiency is good; so that the magnetic and current densities in the armature are limited only by magnetic saturation and the difficulty of dissipating the heat in the extremely long armatures used on these machines. The pole pitch and the ampere turns on the armature being large, the magnets are of necessity very strong and the air gap large, so that the question of magnetic leakage becomes important. In turbo alternators just as in low-speed machines, saturated magnets with armature and magnets as strong as can conveniently be adopted, result in economical designs; but as the mechanical conditions are so much more severe, good mechanical design has a more important influence on the cost than is the case in a slow-speed machine.

General Comparison.—When commencing to work out a machine an experienced designer can usually estimate the most economical diameter to adopt; and he knows from experience approximately the number of ampere-turns he can take per inch periphery on the armature for an alternator of given pole pitch and type. This decides the number of turns on the

FIG. 8.—Armature Winding of 275 K.W., 600 R.P.M., 3 Phase, 60 Cycle Generator.

armature and the ampere-turns on the magnets. He then completes the first rough design, and working out the performance curves, he can usually see very quickly in what way to modify it so as to obtain the best design possible under the circumstances. The speed and frequency are the chief factors in deciding the design of a machine, but the voltage, the conditions of operation, the equipment of the factory in which it is to be built, the facilities for obtaining castings and for shipping the completed machine, all are points which affect the design and have to be considered by the practical designer, since the prime object in a commercial design is rather to make profits for the manufacturing company than to produce the most perfect machine. The points which have to be taken into consideration are so numerous and varied that it is impossible to give general rules for practical design. All that can be done is to give general directions and then it is a question of ability and experience until the engineer can produce the best results.

Neglecting for a moment the designs of Mr. C. E. L. Brown, the greatest change in the design of alternators in the last ten years is the improved ventilation and the increased magnet strength. In 1893 we were working with air-gap densities of 25,000 to 30,000 and magnets with 3,500 to 4,000 ampere-turns per pole on full load, while to-day we have air-gap densities of 60,000 to 70,000 and magnets giving anything up to 20,000 ampere-turns per pole on full load, for ordinary belt-driven or engine-type alternators, and up to double this on steam-turbine-driven machines. The change has been made so gradually that it has been hardly noticeable, but the effect can be seen if I give the dimensions on two machines designed and tested, one in 1894 and the other in 1903, this latter machine being shown in Fig. 8. Both the designs are typical of the condition of the alternator design at those dates.

	1894	1903
Output	70 K.W. 3 Phase 50 K.W. Single Ph.	275 K.W. 3 Phase
Speed	600 R.P.M.	600 R.P.M.
Cycles	60	60
Type of magnets	Lauffen Type.	Standard Revolving Field Type.
Internal diameter armature	37″	38″
Length of armature laminations	10½″	10
Armature ampere-turns	1380	1050
Ampere-turns on magnets	4700	7500
Full load efficiency, per cent	90	94
Regulation $P F = 1$	11%	5.5%
" $P F = .8$	Would not give volts	14%
Full load temperature rise of armature	31° C.	23° C.
Total weight of copper, lbs.	730	680
Total weight of machine "	7400	11000
Total cost of material (Two bearing machine and 15c. copper)	$455	$490

The output has been increased about four times and we have a much better machine as regards performance, while the cost is about the same. The older machine having such a low output needs a large amount of unnecessary material, to reduce the losses so as to give a reasonable efficiency. While in the larger output machine we can afford a considerably higher loss without reducing the efficiency, so that the weight of material is little more; and the better mechanical design has made the cost of material in the two machines about the same. Speaking generally, the whole result has been accomplished by using stronger magnets and higher densities throughout, which are possible on account of the improved ventilation.

Alternating current design has rather stagnated of late on account of the limited competition, and most of the recent developments have come from the other side of the water. But I think it has been shown that, from the point of view of dollars and cents, it is certainly worth while to spend time and ability somewhat lavishly in designing alternators.

[*Paper presented before the Northwestern Electrical Association, June* 10, 1904.]

DOUBLE-CURRENT GENERATORS IN THEIR CONNECTION WITH DOUBLE-CURRENT SUPPLY

THE relative advantages of direct and alternating current supply are now tolerably well recognized. The great advantage of alternating current is the ease with which high voltages can be handled, and the facility with which the voltages can be transformed by means of stationary transformers; while the disadvantage is that in the present state of the art it is unsatisfactory for street railway work, and also to a certain extent for elevator or variable speed motors. With direct current, exactly the reverse is the case; it is unsuitable for high voltage work, but gives good results in all classes of motor work. The obvious result of this has been the adoption of double-current supply in situations where both these advantages and disadvantages are important. So that usually in small towns alternating current is supplied for lighting and direct current for traction work while in larger towns direct current is supplied for the down-town districts, where the motor load is important, and alternating current for up-town districts, where the load is almost entirely a lighting one. Thus we very often have both alternating and direct current supply from the same power station.

The question of double-current supply from one station is usually settled by the installation of both alternating and direct current sets, each set generally having its own engine. This solution is hardly regarded as satisfactory because the motor load, having its maximum during the day, and the lighting load its maximum in the evening, the result is that the alternating current sets are idle during the day and the direct current sets are idle in the evening, so that we have only about half the plant in use at one time. It is obvious that a saving in first cost and in operating expense will be made if the two systems are tied together in some way, so that they can help out one another at times of heavy load. This can be done by having both an alternator and a direct-current generator coupled to one engine, or by having double-current generators, or by tying the supply circuits together by rotary converters and motor-generator sets. A modification of the latter method which has recently become popular consists in installing alternating current generators only, and providing rotary converters to transform a portion of the power to direct current.

From the point of view of the station engineer the double-current generator should be the best solution. The efficiency is higher than when rotary converters or motor generator sets are used, and it ought to be considerably cheaper than either of the other methods. The objection to it is that the voltage on the alternating current side of the generator bears a definite ratio to that on the direct-current side, so that one cannot be varied without the other; while the variation of the load on one side affects to a slight extent the voltage on the other. The relative importance of these objections has, of course, to be decided in each individual case. From the manufacturer's point of view the objection to double-current generators is that they are special machines, and usually require new designs and special patterns or tools.

Of course, we can take any direct-current generator, provide it with collector rings, and use it to supply alternating current; but the difficulty is usually that the frequency is unsuitable. An alternator can be built for any commercial frequency, speed, or voltage, without any serious difficulty; but for a direct-current generator, given the speed, voltage, and output, the question of commutation and cost decide within narrow limits the number of poles, and hence indirectly the frequency. If it is necessary to change this number of poles considerably in order to obtain a special frequency, there is often difficulty with the design, which results in increased cost. So if some latitude can be allowed in selecting the frequency and speed for double-current generators, it is advisable to choose them so that, if possible, the generator does not differ very much from some standard direct-current machine.

The following table gives the frequency of the alternating current that could be obtained from standard direct-current generators. The number of poles and the speeds of the machines are taken from those of the National Electric Company, but there is little difference in these respects between the machines of the various manufacturers, so that they can be regarded as applying approximately to all standard makes of generators.

K.W. Rating.	Engine-Driven.		Belt-Driven.		Steam Turbine Driven.	
	250 Volt.	500 Volt.	250 Volt.	500 Volt.	250 Volt.	500 Volt.
25	15	15	40	40	..	..
50	14	14	33	33	90	90
100	14	13	35	35	70	70
250	14	12	27	23	60	60
500	12	10	31	25	75	50
750	14	10	..	..	..	70
1000	15	13	..	..	..	..
1500	20	16	..	..	..	..
2500	22	18	..	..	..	..

Considering as standard frequencies for double-current generators 25, 40, and 60, it is evident that some of these standard direct-current machines could be very conveniently used as double-current generators with only a slight change in speed. A standard 2,500 K.W., 250 volt engine type machine would make a good 25 cycle double-current generator, the only changes necessary being to provide collector-rings, and to increase the air gap and put more copper on the field magnets to make the regulation satisfactory when operating as an alternating-current generator. These changes would not increase the cost of the generator more than 20 per cent. On the other hand, if we took a 500 K.W., 500 volt engine type machine, very radical changes would be required to make this into a 25 cycle double-current generator, as it would be necessary to increase the number of poles from 10 to 24 or 30, which would practically double the cost of the machine. But if we make this 500 K.W. machine belt-driven instead of direct-connected to a slow-speed engine, it is evident from the table of frequencies that a standard machine would be satisfactory for 25 cycles.

Twenty-five or forty cycle machines are not in any way difficult to build—at the most it is a question of special designs and patterns. But with 60 cycle generators we begin to have difficulties with the commutator on account of the high peripheral speed. Sixty cycle, 600 volt, double-current generators and rotary converters can undoubtedly be built, but at the present date they are not such reliable machines as those for lower frequencies, and there is no brush gear now on the market which is quite satisfactory for the peripheral speeds necessary in a 60 cycle, 600 volt machine.

The higher the speed of a standard direct-current machine for a given output, the higher the frequency; thus we would expect that the higher the frequency of a double-current generator the higher the speed at which it should operate; and it appears from the table that the most satisfactory 60 cycle double-current generators will be those driven by steam turbines. Direct current generators for direct connection to steam turbines and suitable for operation under American conditions, are not at present on the market, but in all probability they will be shortly; and it appears probable that this type of machine will solve the problem of 60 cycle double-current generators.

Generally speaking then, 25 cycle double-current generators, if of large size, can be direct-connected to a steam engine, while for smaller units than 500 K.W., they are better belt-driven. Forty cycle machines should always be belt-driven if the cost is to be reasonable, while for 60 cycle double-current generators apparently the only reasonable solution is to have steam turbine driven sets. Of course, double-current generators can be made for any frequency or voltage up to 60 cycle, 600 volts, and at any speed desired, it is only a question of cost; but to obtain a reasonable price or delivery, and to have a unit which will at some time in the future have a second-hand value better than scrap, it would be advisable to consider the above table of frequencies and outputs when laying out a station for double-current supply with double-current generators.

NOTE [*Dec.*, 1910]

In the past three years great improvements have been made in the construction of commutators and brush gear for operation at high speeds; this work having been done in connection with development of 60 cycle rotaries and direct-current turbo generators, which should be as reliable in operation as the corresponding 25 cycle and slow-speed units. The result of this work has been to revolutionize the methods of constructing high speed commutators and brush gears, so that at the present time commutators are being built to operate perfectly, with reasonable attention, at the speeds required by 60 cycle rotaries and direct-current turbo generators. This being the case, the statement above, in regard to the reliability of 60 cycle 600 volt double-current generators and rotary converters should be modified accordingly.

[Presented before the American Institute of Electrical Engineers, May **17, 1904.]**

PREDETERMINATION OF SPARKING IN DIRECT CURRENT MACHINES

Speaking generally, dynamo design did not become an art until after the old two pole smooth-core Siemens and Edison machines came into extensive use for electric lighting. The original design of these machines was more or less guesswork; but after a few machines had been made to operate satisfactorily, the engineer was able to lay out a complete line of machines, designing them partly by his engineering intuition, and partly by some empirical rules, which he decided on as he built successive machines. The armatures were designed more from a mechanical than from an electrical standpoint, their length being limited by the stiffness of the shaft rather than by questions of commutation; while they were unventilated, and in consequence the output was limited by heating. The armatures being of the smooth-core type, the self-induction of the armature coils was usually so small, even with the length of armatures in general use, that it was unnecessary to consider it in connection with the tendency of the machine to spark. It was, however, generally recognized that if the magnets were too weak the machine was liable to spark, so the length of the air-gap was usually determined by some empirical rule obtained by experiment. When slotted armatures were first adopted extensively they were designed along the same lines as smooth-core armatures. They were so badly ventilated that the output was limited by heating to about one-half that of a modern armature; but in spite of this it was found necessary to use carbon brushes to obtain good commutation. To economize in tools several different lengths of armatures were frequently built on the same diameter, while to economize space, the armatures were often built smaller in diameter and longer than they otherwise would be. Experience with these different forms of armature made it very evident that a long armature had a greater tendency to spark than a short one; and this became especially noticeable as the ventilating was improved and the output correspondingly increased on account of the cooler operation.

Previous to this a great deal had been written on the theory of commutation in dynamos, but had been ignored by the practical designers, who had more faith in experimental results. But this bad behavior of long armatures as regards sparking, called attention to the theoretical work, and designers began to consider whether or not the self-induction of the armature coils did not, after all, decide the amount of current the machine would commutate without sparking. In the first attempts to take into account the self-induction of the commutated coil, the self-induction of a one-turn coil was considered as being simply proportional to the length of the armature core; that is, the shape or size of the slot, the number of coils per slot, and the self-induction of the end connections, were all neglected. This gave a very simple formula for the self-induction:

$$L = l\,n^2.$$

Where l = length of armature
n = number of turns per coil,

And the self-induction E.M.F. of commutation (the reactance voltage as it was called), which is an estimate of the difficulty of commutating the current, was given by

$$E = l\,n^2\,i\,f$$

i being the current per coil and f the frequency of commutation.

This formula gave satisfactory results when applied to machines designed along the same general lines. The allowable value of the reactance voltage could be obtained from experiment on one machine, and used in the design of other similar machines. But, if applied to machines which were designed differently, the formula showed wide discrepancies; so it soon became recognized that the formula was at best only a rough approximation.

Early slotted machines were designed with one coil per slot; two coils per slot obviously saved insulation space and were soon tried, but it was found that generally if this were done every other bar on the commutator became badly marked. As it was imperative to save space in car motors, three coils per slot were adopted, and in extreme cases four, or even five coils per slot were used. It was generally found, however, that whenever more than one coil per slot was used some of the commutator-bars were marked, and that it was possible to count the number of coils per slot by the recurrence of the marking on the commutator. This marking was attributed to the inequality caused by using a small number of slots, and so the general rules were adopted to use as many slots as possible and to make small machines with one coil per slot and large machines with only two coils per slot.

It was also noticed that the dead coils necessary in certain multipolar wave-windings often caused some of the commutator bars to be marked. This was naturally attributed to the dissymmetry produced in the winding, and it became generally recognized that anything tending to produce inequality in the commutation conditions, such as few slots, or many coils per slot, or dead coils, tended to make perfect commutation more difficult.

With increased competition came the necessity of cheapening the cost of building these machines; designers then returned to the construction of several coils per slot. In reducing the amount of copper on the armatures to save in the cost of material, it naturally happened that shallow slots were used. And it was found that with these wide and shallow slots it was possible to obtain good commutation with several coils per slot, under conditions where it would be quite impossible with the old deep and narrow slots. Obviously this was due to the lesser self-induction of a wide slot compared to a narrow one, and it was soon acknowledged that the shape of the slot should be considered in calculating the self-induction of the commutated coil.

When designing an armature for small self-induction it would be natural to make it large in diameter and short in length; that is, with a large pole-pitch. But in carrying this to an extreme it was found that it did not give the good results expected. It was suggested that this result was due to the fact that the self-induction of the end connections had been neglected, and that in armatures with large pole-pitch and short length of core, the self-induction of the end connections was comparable with that of the conductor embedded in the slots.

In the light of these experiences it is evident that the design of a direct-current machine in regard to sparking is a compromise between a number of conflicting conditions. It is not possible to obtain a formula which will give a strict measure of the commutating qualities of all machines; but by taking into consideration the more important conditions which affect the sparking, it is possible to obtain one which will give fairly accurate results when applied to machines similarly designed, and which will give some idea of the tendency to spark when applied to machines of widely different design. Such a formula, when it has been applied to numerous machines of different types, so that the allowable values for the sparking constant have been determined, can be taken as a fair working formula, and can be placed in the same category as empirical formulæ for determining the regulation of alternators. Such formulæ are not intended to reduce designing to mere slide-rule work, but are intended simply to give an idea as to the experimental results to be expected from an individual design.

As outlined above, the most important conditions to be taken into consideration are the self-induction electromotive force of the commutated coil, and the inequalities introduced by the conditions of commutation.

Electromotive Force Due to Self-Induction. This is given by the formula: E = Self-induction of one coil × number of coils commutated in series × current in coil × frequency of commutation.

The self-induction of one coil = (self-induction of one conductor embedded in the slot + self-induction of one end connection) × (number of turns per coil)^2.

The self-induction of one conductor embedded in the slot $= l k$. Where l is the length of the core and k is a constant depending on the dimensions of the slot.

By determining the self-induction of a large number of slots we find that this constant k can, with sufficient accuracy, be taken as a function of the ratio r, where

$$r = \frac{\text{Width of slot.}}{\text{Depth of slot.}}$$

A curve can be plotted connecting r and k, determined experimentally from tests on a number of armatures; such a curve is shown in Fig. 9.

The self-induction of the end connections can be taken as = length of end connections × constant c'. And as the length of end connection is approximately proportional to the pole pitch, the self-induction of two end connections can, with sufficient accuracy, be written $= p\,c$.

Hence the self-induction of one coil $= n^2\,(l\,k + p\,c)$.

The number of coils commutated in series, N, is, of course, one in a parallel or lap-wound armature, and equal to the number of pairs of poles in a series or wave-wound armature.

The current per coil i in a two-circuit series or wave-wound armature is equal to one-half the total current in the machine, while in a parallel or lap-wound armature it equals the total current divided by the number of poles.

The self-induction pressure of the commutated coil is then given by

$$V = n^2\,(l\,k + p\,c)\,N\,i\,f$$

Where f is frequency of commutation, and is equal to the number of commutator bars × speed in rev. per min.

The width of the brush is neglected in calculating the frequency of commutation, since it is found by experiment that within the ordinary limits of practice the thickness of the brush has little effect on the operation of a machine, unless the current density is excessive. The probable explanation of this is that a thicker brush gives more time for commutation to take place; but it also means that more coils are commutated at the same time, thus introducing the effect of mutual induction. These two effects apparently counterbalance each other to a great extent.

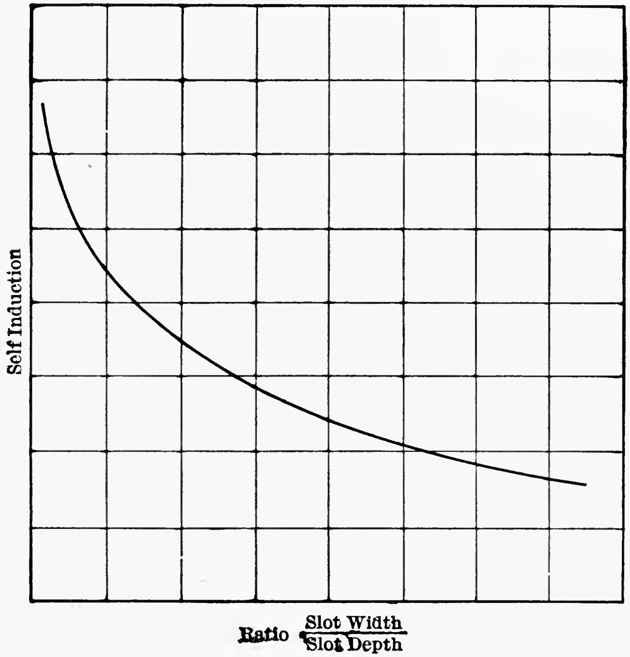


FIG. 9.

Inequalities Due to Conditions of Commutation.—These are due to the use of few slots; more than one coil per slot; and to dead coils.

If there is only one coil per slot the use of few slots does not in itself affect commutation, unless the number of slots is extremely small; for though the slot may move through an appreciable arc while the coil is being commutated, the conditions are exactly the same for every coil when it is commutated. So there is no tendency to inequality in the conditions, and if it is possible to set the brushes so that one coil can be commutated satisfactorily, then commutation will be satisfactory for all the coils. But if the number of slots is extremely small, say less than six per hole, then the coil will move in such a widely varying magnetic field, and will come so close to the strong field under the pole-tip while it is being commutated, that the local currents under the brush are liable to produce marking of the commutator-bars even if the brushes apparently do not spark. Of course this is only important in very low voltage machines and it is unnecessary to take it into account in any constant which is to be a criterion of the tendency to spark. It is sufficient to say that the number of commutator-segments in the polar-gap, that is, the arc between the two pole-shoes, must never be less than two and should generally be three or more.

With more than one coil per slot inequalities are introduced: due to the difference in the value of the self-induction of the various coils; and due to their commutation under different conditions.

The self-induction of all the armature coils will be the same when there are only two coils per slot, as it is obvious that the configuration of the conductors and neighboring iron is the same for both coils. But when there are three or more coils per slot the self-induction of the various coils will vary, as they occupy different relative positions in regard to the iron; the self-induction of the center coil being less than the self-induction of the outer coil. Investigating conditions at the point of commutation in a modern generator by means of a pilot-brush, it is found that commutation usually takes place at a point where there is practically no resultant magnetic field; that is, at a point where the magnetic field of the armature just counterbalances the average field due to the magnets. In other words, there is resistance commutation; the armature current is commutated by the varying resistance of the brush, rather than by a reversing E.M.F., due to passing through a magnetic field. This being the case it is only necessary to consider the self-induction of those coils which have the greatest self-induction. If these are commutated satisfactorily by means of the varying resistance of the brushes, then the coils which have a smaller self-induction will also be satisfactorily commutated. Hence the variation in the self-induction of the coils need not be con-

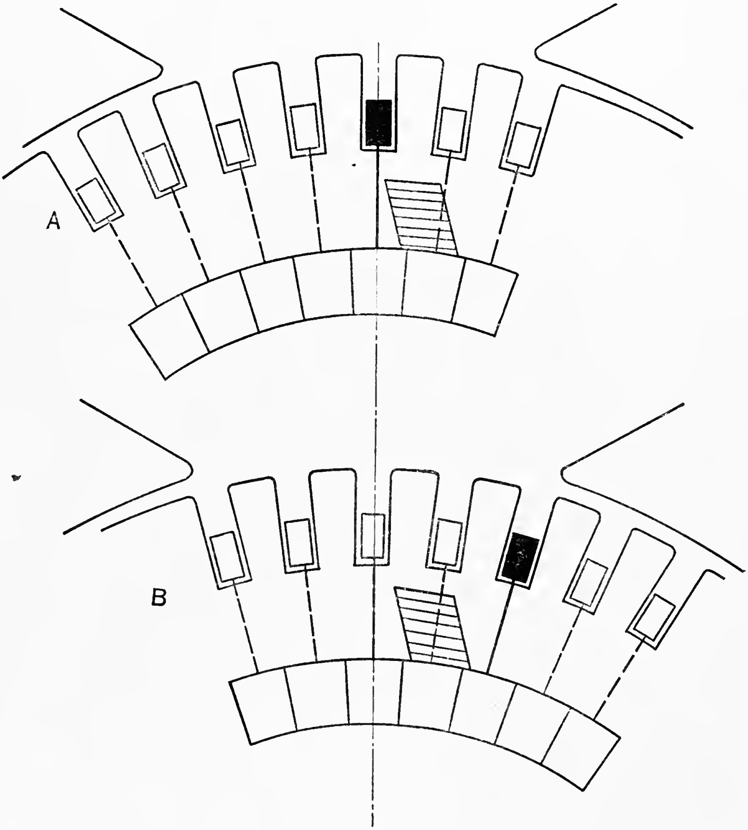


Fig. 10.—Showing Position of Armature at Beginning and End of Commutation Period.

sidered, and in the formula all that it is necessary to consider is the self-induction of those coils which have the greatest self-induction.

The chief inequality introduced into the commutation by the adoption of more than one coil per slot is due to the various coils in the slot being commutated when they are in different magnetic fields. This is evident from Fig. 11, which shows the position of the armature when the first and the last coil in the slot are being commutated. If the brushes are set so that the magnetic field is right for the first coil it will be incorrect for the

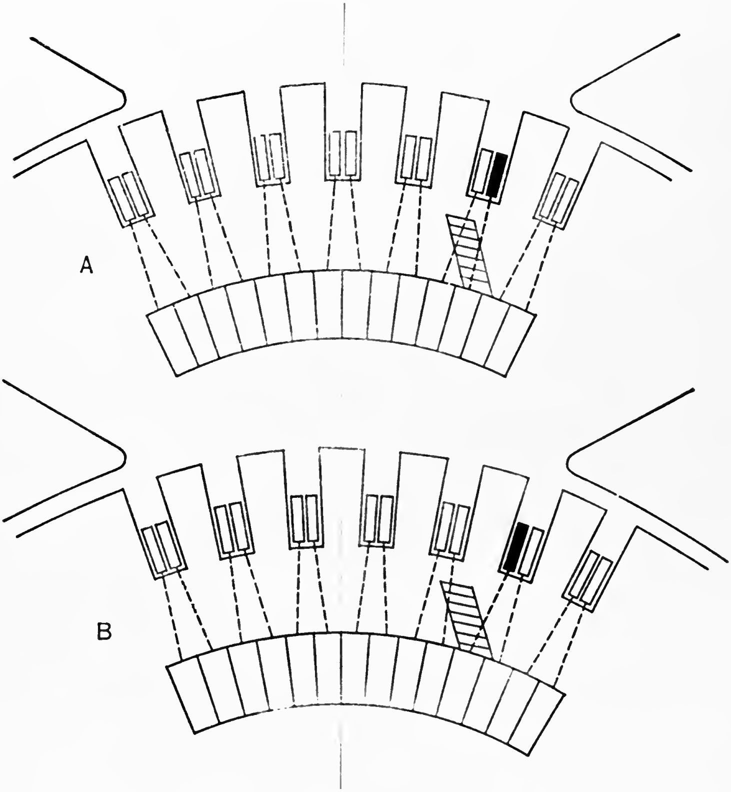


Fig. 11.—Armature with Two Coils per Slot Showing Position of Armature when the Two Coils are being Commutated.

last one, and vice versa. So whenever the machine is loaded to its limit the commutating conditions may be so bad for some of the coils, that in time some of the commutator-bars will become pitted and the well-known regularly recurring marking of the commutator-bars will develop.

The question is how to take this inequality into account in the sparking formula. To do this, we make the assumptions that the magnetic field varies uniformly from the neutral point to the pole-tip, and that in order to obtain perfect commutation it is necessary to move the brushes from a position on the neutral point at no load, to a position half-way between the neutral point and the pole-tip at full load. Calling the distance between the neutral point and the pole-tip 2 d, and assuming the brushes fixed on the line $O\,P$ half-way between the pole-tip and the neutral point, then if any coil is commutated when it is at Q distant "a" from P, the machine will only commutate perfectly a current corresponding to $1-\frac{a}{d}$ of full load.

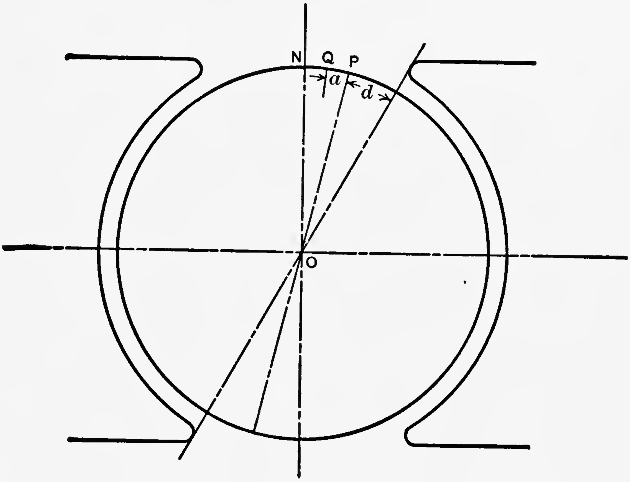


Fig. 12.

Just what this assumption means can be seen from Fig. 13.

Abscissæ represent positions along the polar-gap corresponding to Fig. 12, and ordinates represent E.M.F's. The line $N\,A$ gives the E.M.F. induced at various points by the conductor moving in the field due to the magnets. $C\,P$, the ordinate of the line $B\,B$, gives the E.M.F. necessary to reverse the full-load current I in the coil. If the coil is commutated at the position Q instead of at P then the commutation conditions will be perfect only for a current $\frac{D\,Q}{C\,P}\,I$. Hence we assume that if we have several coils per slot, and that if in consequence of this we have to commutate some of our coils in a position $E\,Q$ and $E'\,Q'$, then the current which the machine will carry without sparking is reduced in the ratio $\frac{D\,Q}{C\,P}$ that is $\frac{N\,Q}{N\,P}$.

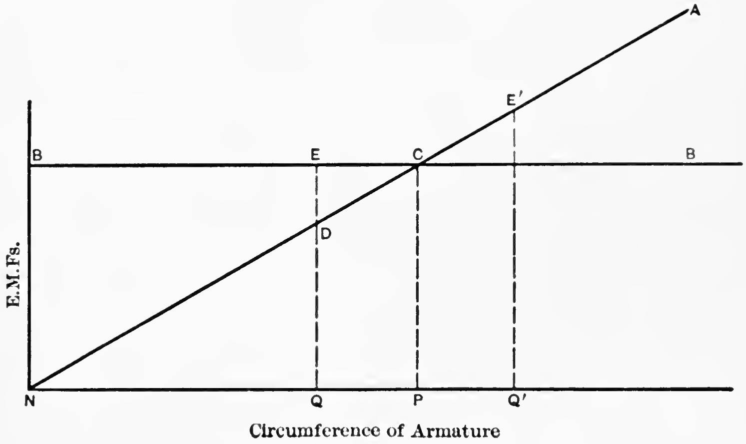


Fig. 13.

It is very easy to figure out what this inequality amounts to in any particular case. Take 20 slots per pole, 3 coils per slot, and pole-face = 75 per cent of pole-pitch. There are 2.5 slots between the neutral point and the pole-tip. Assuming that the conditions are perfect for the centre coil, the outer coils are 0.33 slot pitch distant from this most favorable position. And 1.25

slots corresponding to variation from no load to full load, hence an equality of 0.33 slot-pitch gives an inequality factor $\frac{0.33}{1.25}$ = 0.26; so that the sparking constant should be multiplied by the inequality factor 1.26.

Curves can very easily be plotted for different numbers of slots per pole and coils per slot, in order to facilitate the calculation of this inequality factor. Such curves are shown in Fig. 15. The assumptions on which this calculation is based are to a great extent rational, and though we cannot pretend that the calculation has a rigid basis, yet it is probably as correct as the other sparking calculations, and used with discretion it gives fairly reliable results.

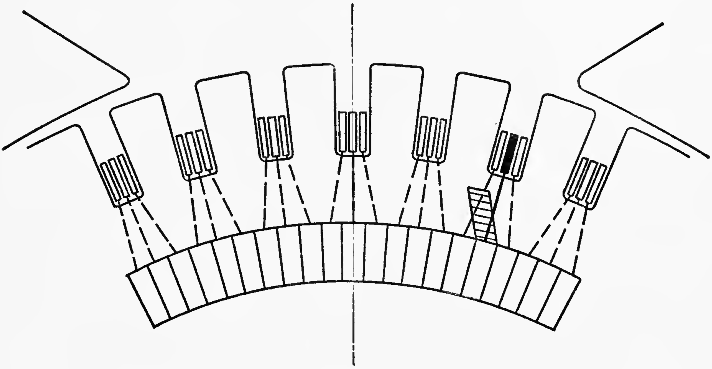


Fig. 14.—Armature with Twenty Slots per Pole and Three Coils per Slot.

The inequality introduced by the use of a dead coil on the armature is similar to that due to several coils per slot. The dead coil produces a break in the uniformity of the winding; and if the position of the brush is correct for commutation of the coil immediately on one side of the dead coil then it will be one segment out of the correct position, for the coil immediately on the other side of the dead coil. The inequality introduced can be calculated, and allowed for, in exactly the same way as we estimate the inequality due to several coils per slot. Assuming that the brush is in a mean position, then it will be half a segment out of position for the two coils which are next in position to the dead coil. So making the same assumptions as before: if there are n commutator-segments per pole, and if

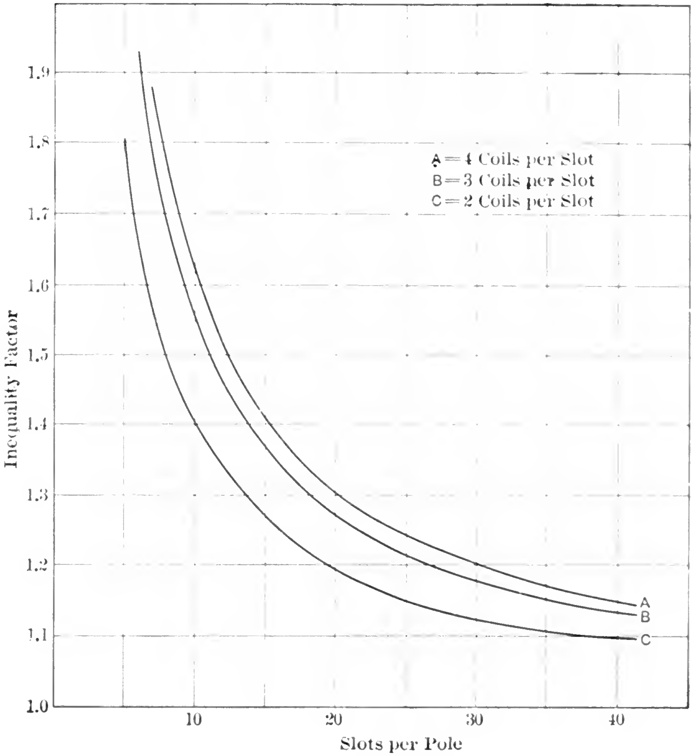


FIG. 15.

the pole face = 75 per cent of pole-pitch, then the inequality is equivalent to $\frac{8}{n}$. Thus if there are 20 segments per pole, a dead coil produces an equality equal to 40 per cent of the load, and the inequality should be introduced into the sparking constant by the factor 1.4. A curve can readily be plotted between the inequality factor and the number of commutator segments per pole. Such a curve is shown in Fig. 17.

General Formula.—Combining all the various factors which affect sparking we get as our complete formula for a sparking constant

$$C = n^2\,(l\,k + p\,c)\,N\,i\,f\,P\,Q.$$

P being the inequality factor resulting from a number of coils per slot, and Q the corresponding factor due to the presence of a dead coil.

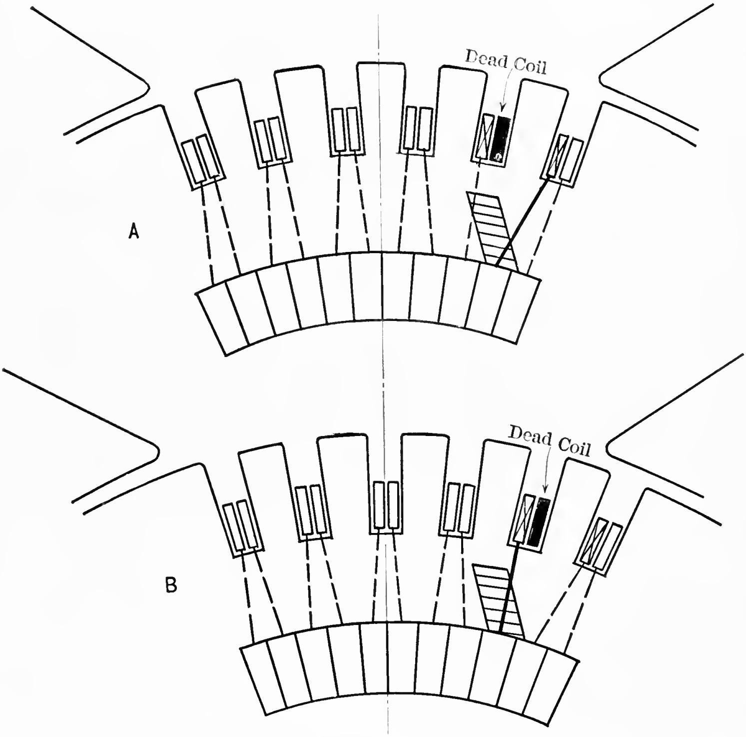


Fig. 16.—Armature with Dead Coils Showing Positions of Armature when the Two Coils Next to Dead Coil are being Commutated.

This formula is not put forward as being scientifically exact, but as an empirical formula which has gradually been built up as the result of experience, different terms having been added to the formula from time to time when it was found necessary to take different conditions into account. As the formula stands it gives good results, when we know the value of C which can be allowed for the particular design of machine considered.

The relative values of C that have been found allowable in different cases are somewhat as follows:

2-pole	20
4-pole, series two-circuit winding	35
6-pole, " " "	50
4-pole, multiple wound	30
6-pole, " "	35
gradually increasing to	
24-pole, multiple wound	50

These relative values, of course, only apply when the machines in each class are designed with similar constants. That is, they should have approximately the same densities in the teeth, and approximately the same ratio of ampere turns per pole on the armature (armature reaction) to the ampere-turns required for the teeth and air gap. If these vary much it is difficult to get consistent results. The brush-gear and the current density in the brushes also play an important part in the sparking. If the brush-gear is weak mechanically, or if the commutator is in bad condition, sparking is sure to take place; while with the average carbon brush, burning will usually take place when the current density reaches 50 amperes per sq. in. The shape of the pole-tips has some effect on the operation of the machine. But as long as they are not too close together, and as long as they are shaped so that the commutation field varies gradually, the exact shape need give us no concern. The density in the armature core (behind the teeth) has also some effect on the allowable sparking constant; and if the core is highly saturated a higher constant can be used than if it is unsaturated.

Assuming that all these conditions are uniform and satisfactory, the variation in the allowable value of C, found in actual practice, shows that the formula does not take into account all the conditions that affect the sparking, so the formula must be used with considerable discretion. It cannot be claimed that it is in any way accurate, but it can be considered an empirical working formula, capable of giving good results when carefully used; and as such it is put forward.

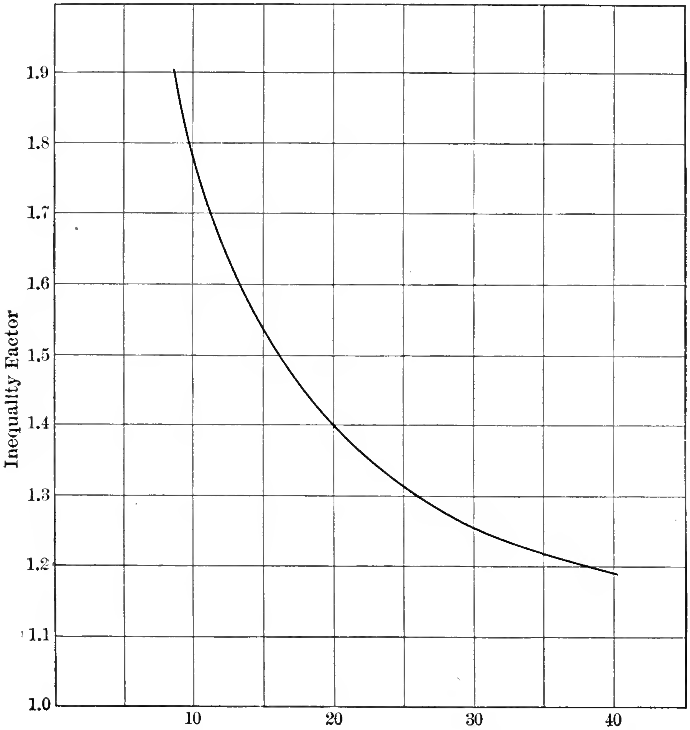


FIG. 17.—Commutator Segments per Pole-pitch.

[*Presented before the American Institute of Electrical Engineers, June* 19, 1905.]

ROTARY CONVERTERS AND MOTOR-GENERATORS

At the present time the alternating current motor in a motor-generator set of 100 K.W. capacity or larger, is usually a synchronous motor; an induction motor is seldom used for this purpose. The reasons for this are, that the lagging current taken by an induction motor renders it undesirable at the end of a long line, that from an operating standpoint the mechanical construction of an induction motor makes it less reliable than a synchronous motor, and that the cost of an induction motor has been heretofore appreciably higher than that of the corresponding synchronous motor. The usual objections to the synchronous motor—that it has a low starting torque and that it requires external excitation—do not apply to the case of a synchronous motor used in a motor-generator set, as a high starting torque is unnecessary and as there is always some way of exciting the motor whether it is coupled to a direct-current or to an alternating current generator. It has thus become practically standard practice to use synchronous motor-generator sets in all sizes except where the output is too small for a standard synchronous motor. This being the case it is only necessary to consider synchronous motor-generator sets in comparison with rotary converters.

Motor-generators and rotary converters can be discussed from two points of view; that of the operating engineer, or that of the designer and manufacturer. As the operating point of view is probably most familiar to engineers, that will be considered first.

Cost and Floor Space.—The main points that concern the engineer when installing transforming machinery are the first cost of the machinery, its efficiency, and its reliability and flexibility of operation. Incidentally, the floor space occupied, and sundry other things have to be taken into consideration. The cost of a motor-generator or rotary converter, or rather the price at which it is sold by the manufacturer, depends upon the output and the speed, and incidentally upon the competition among the firms that are trying to secure the business. The choice of the speed for either machine being usually left to the manufacturer, is as high as is consistent with good mechanical and electrical design. The following table gives speeds in R.P.M. which may be regarded as more or less standard for such machines of different output, frequencies, and voltages.

25 CYCLES

K. W.	Motor-Generators.		Rotary Converters.	
	250 Volts.	600 Volts.	250 Volts.	600 Volts.
250	750	750	500	750
500	500	500	300	500
1000	250	250	187	250
1500	214	214	150	214
2000	187	187	125	167

60 CYCLES

K. W.	Motor-Generators.		Rotary Converters.	
	250 Volts.	600 Volts.	250 Volts.	600 Volts.
250	720	720	720	900
500	514	514	450	600
1000	240	240	225	300
1500	189	189	189	240
2000	150	150	150	189

In comparing the cost of motor-generators and rotaries it may be assumed that it will always be necessary to use transformers with the latter in order to get the comparatively low alternating current voltage required. With motor-generators, on the other hand, the motor can be wound to take the high-tension current without the interposition of transformers, unless the line voltage exceeds 15,000 volts. In estimating the costs of motor-generator sets it is assumed that no transformers are necessary. In general, any table of relative costs of motor-generators and rotary converters should be accepted with a certain amount of reserve; as each individual installation must be considered by itself and the costs of the various items compared. The cost of the switchboard and cables should also be considered, and in this respect the motor-generator is usually cheaper than the converter. The following table gives the cost, efficiency, and the floor space, required for rotary converters and motor-generators of different outputs. The rotaries are assumed to operate in connection with three single phase 6,600 volt transformers, and the motor-generators to operate on 6,600

500 K.W. 600 VOLTS, 25 CYCLES

	Rotary Converter.	Motor-Generator.
Cost	$4500+2700=$7200	$9000
Efficiency 1.25 load.......	91.5	88.
“ 1 “	91.5	87.5
“ 0.75 “	91.0	85.5
“ 0.05 “	88.5	81.0
Floor space.............	60+50=110 sq. ft.	85 sq. ft.

500 K.W. 600 VOLTS, 60 CYCLES

	Rotary Generators.	Motor-Generator.
Cost	$4700+2300=$7000	$8700.
Efficiency 1.25 load	90.5	88.
“ 1 “	90.5	87.5
“ 0.75 “	89.5	85.5
“ 0.50 “	86.5	81.
Floor space.............	70+50=120 sq. ft.	90 sq. ft.

volts without transformers. The efficiencies are the combined efficiencies of the sets; rotaries and transformers in the one case, and motors and generators in the other. In the case of rotaries, under the head of cost and floor-space, the first figure refers to the rotary and the second to the transformers.

1500 K.W., 275 VOLTS, 25 CYCLES

	Rotary Converter.	Motor-Generator.
Cost	$18000 + 6300 = $24300	$21000
Efficiency 1.25 load	93.5	90.5
" 1 "	93.5	90.
" 0.75 "	92.5	88.
" 0.50 "	90.5	85.
Floor space	240 + 125 = 345 sq. ft.	320 sq. ft.

The above are sale prices f.o.b. factory and do not include freight or erection charges. All necessary rheostats and shunts are included, but no induction regulators for the rotaries.

In all three cases it will be noticed that the rotary converter and transformers are the more efficient, the difference in efficiency being about 3 per cent at full load and about 6 per cent at half load. The value of this difference in efficiency has to be decided in each case by the cost of producing the extra kilowatt-hours. In a water-power plant the efficiency is an unimportant feature; in a steam plant, where the cost of fuel is high, it is quite important. The floor space taken up by a rotary converter and its transformers is about 25 per cent greater than that taken up by a two-bearing motor-generator set. The floor space is only of importance in the case of a sub-station in a city where real estate is valuable, and in such cases the transformers could be placed in a gallery over the rotaries if desired. As the rotaries themselves only take up about two-thirds the floor-space of a motor-generator set, the advantage would, with this arrangement, be with them.

Operating Characteristics.—The relative desirability of rotary converters and motor-generators from the operating point of view depends upon the question of their reliability and flexibility of operation. As regards flexibility, the motor-generator is of course by far the better. With motor-generators the power-factor of the motor may be adjusted to unity, or if desired a leading current may be introduced into the line without affecting the operation of the motor, while the voltage on the direct current side may be adjusted within wide limits either by use of the shunt rheostat, or by compounding. Neither of these adjustments can be applied conveniently to a rotary.

In a rotary converter the ratio of the voltage on the direct current side to that on the alternating current side is practically constant; that is, any drop or rise of voltage on the line affects proportionally the direct current voltage of the rotary. In attempting to regulate the power factor of the rotary or to introduce leading or lagging currents into the line by varying the field strength, we are liable to alter the alternating current voltage at the end of the line, and hence to affect the direct current voltage of the rotary. Variation of the shunt current within wide limits is also objectionable, because it often has a tendency to produce hunting.

Theoretically a rotary converter can be compounded or over-compounded, or rather the line can be over-compounded, producing the same effect on the direct current terminal voltage as if the rotary itself was over-compounded. This may be done by introducing an artificial self-induction into the line, and producing by means of a series winding on the converter fields a leading current approximately proportional to the load on the rotary. This leading current will then raise the voltage of the line because of the self-induction present. This compounding is, however, at best a rough method and can be used only on systems in which exactness of voltage is unimportant, as it is somewhat difficult to adjust the self-induction and the series winding to give the required effect. With this method the power factor of the rotary and that of the system are also varied within wide limits as the load varies, and a change of voltage affects all other machinery on the line. So that the cases are limited in which this method can be used to regulate the direct-current voltage on a rotary.

A method of voltage control with rotary converters is used on some of the Edison systems. An induction regulator is inserted in the alternating current circuit between the transformer and the rotary, and is usually controlled from a switchboard by means of a pilot motor. Such a regulator increases the cost of the apparatus about 20 per cent, decreases the total efficiency about 1 per cent, adds about one-third to the floor space required by the transformers, and introduces additional complications into the system. Usually, therefore, the necessity for employing an induction regulator is a strong argument against the use of rotary converters in the particular installation considered.

A rotary converter is more liable to hunt and to flash over on short circuits, and is a somewhat more complicated piece of apparatus than a motor-generator set. On the other hand, a synchronous motor wound for a pressure of over 6,600 volts is not so reliable as a transformer wound for the same voltage. Generally speaking, from the point of view of reliability of operation, there is little choice between 25 cycle rotaries and 25 cycle motor-generators, although in a 60 cycle installation the advantage is decidedly in favor of the motor-generator. There is no doubt that satisfactory 60 cycle rotaries can be made up to 600 volts, but their design is more difficult than that of 25 cycle rotaries, so that it is natural they should require more attention than motor-generator sets.

Motor-generators have another advantage over rotary converters in that they are not so liable to hunt. Of course, hunting can be prevented, but not usually without introducing some corresponding disadvantage. Dampers may be placed on the pole faces, but with the disadvantage of causing some loss in efficiency; or extreme uniformity of engine speed may be obtained at the expense of a heavy fly-wheel; while the small line drop that is usually found necessary for the reliable parallel operation of rotary converters requires considerable expense for conductors. Synchronous motors are not so liable to hunt as rotary converters, and the conditions that are good enough to insure the satisfactory parallel operation of alternators are usually all that are required to prevent hunting in synchronous motors.

From the operating engineer's standpoint, a motor-generator is preferable to a rotary converter in almost every respect, except as to efficiency and cost; and even as to cost a motor-generator is the cheaper for low voltages and large outputs. Consequently, when comparatively cheap medium size units are wanted, and close voltage regulation is unimportant, rotary converters are used. But when large units are desired, and the voltage regulation is important, as in incandescent lighting, motor-generators are employed. This applies to both 60 and 25 cycles.

So far, rotary converters have only been considered for transforming from alternating current to direct current. In regard to inverted rotary converters; that is, rotaries for transforming from direct current to alternating current, almost the same remarks apply. In addition, however, inverted rotaries are subject to another disadvantage: that the power factor of the load on the alternating current side affects the magnetic flux, and in consequence the speed and frequency of the rotary. A heavy inductive load on the alternating current side tends to make the rotary run away. This, of course, can be prevented by an automatic speed limit device; or, to a certain extent, by separately exciting the rotary from an under saturated exciter which it drives mechanically, or by making the armature of the rotary very weak in comparison with its field magnet. But these devices are makeshifts, and none of them can keep the speed absolutely constant under these conditions. And when the speed varies it also causes variation in the speed of all induction and synchronous motors, driven from the rotary, which is highly objectionable. This, combined with its other faults, makes an inverted rotary usually less desirable than a motor-generator.

Design of Rotary Converters and Motor-Generators.—Generally speaking, and within reasonable limits, the higher the speed of a machine the less is its cost, so that it is to the interest of the manufacturer to run at as high a speed as possible. (See *NOTE* p. 64.) The permissible speed for any alternator is limited only by mechanical considerations, while the maximum speed at which a direct-current generator or a rotary converter of a given output can be run is limited by the operating characteristics in regard to sparking. Given the approximate speed at which a direct-current machine will run, the number of poles which it should have, is fixed within narrow limits by questions of sparking and economy of design. As the number of poles and speed determine the frequency, it is easily seen how the choice of speed for which a rotary of given output, frequency, and voltage may be built is limited.

Suppose a 1,000 K.W., 25 cycle, 600 volt rotary is to be designed: to insure the cheapest machine the number of poles must be as few as possible so that the speed can be high. There are 1,670 amperes to commutate; this, to a great extent, determines the number of poles. On laying out the design, it is found that 8 or 10 poles will suffice, but that 12 poles will be more conservative. Let 250 rev. per min. be decided upon. Assuming a pole-pitch of 21 in., we obtain an armature diameter of 80 in., 24 slots per pole, two coils per slot, length of armature core 13.5 in. The slots are comparatively narrow, only 0.4 in. wide, so that solid pole-faces or copper dampers can be used. This makes a very good machine. Fig. 18 shows such a machine.

If a 1,000 K.W., 600 volt motor-generator is to be designed, the most suitable number of poles on the direct current generator can be decided on, and the speed may be made as high as is consistent with good commutation. The speed may be as high as 300 rev. per min., but, as in the case of the rotary, a more conservative machine would result if the speed were kept down to 250 rev. per min. Twelve poles is a suitable number, and as a somewhat better sparking constant is required than in a rotary, the armature is built with a slightly larger diameter. An armature of 86 in. diameter, with 16 slots per pole and three coils per slot, is satisfactory. The width of slot is not limited, as laminated pole-faces are to be used, so that a wide slot can be adopted with its consequent reduction in the self-induction of the commutated coil. This gives an armature length of 10.5 in., and also makes a very good machine.

FIG. 18.—1,000 K.W. 600 Volt, 25 Cycle Rotary Converter.

This is one instance in which we find that the rotary converter and motor-generator will operate at the same speed. In this case, the cost of the rotary and transformers will be less than the corresponding motor-generator set.

Suppose, on the other hand, a 1,500 K.W., 275 volt, 25 cycle machine is to be designed. It is found that the minimum number of poles for a rotary of this output and voltage is about

20. This gives a 20 pole rotary at 150 rev. per min., with an armature 130 in. diameter, 13 in. long, 24 slots per pole, and one coil per slot.

The corresponding generator for the motor-generator set may be run at 250 rev. per min. by making it with 18 poles. This gives: armature 110 in. diameter, 9.5 in. long, 14 slots per pole, and two coils per slot. In this case the cost of the motor-generator will be less than that of the corresponding rotary and transformers, on account of higher speed at which the motor-generator can be run. Such a motor-generator is shown in Fig. 19.

Speaking generally from the designer's standpoint, there is little to choose between the difficulty of designing a rotary converter and that of designing a direct current generator of the same output, speed, and voltage. The design of a rotary is subject to more limitations than that of a direct current generator. The number of commutator segments per pair of poles must be divisible by the number of phases, and the number of slots per pair of poles should preferably be also divisible by the same number. Also the relative dimensions of the slot and air gap are limited by the fact that eddy currents must be avoided in the solid pole-faces, or copper dampers, which are usually employed to prevent hunting. On the other hand, the absence of armature reaction in a rotary converter is a considerable point in its favor as regards tendency to sparking.

Investigating the conditions of commutation in a direct-current generator by means of a pilot brush, when the machine is operating at full rated output with brushes set in the normal position, it is generally found that resistance commutation is taking place; that is, the brushes are advanced just far enough for the armature cross magnetization field to neutralize the direct field due to the magnets at the point of commutation. As the load on the machine is increased, the increased armature-reaction causes the resultant field at the point of commutation to become of the opposite sign to that which would be required for perfect commutation, thus tending to make the brushes spark. At the same time the increased current, which has to be commutated, also has a tendency to make the brushes spark unless the resistance of the brush contact is sufficiently high. Thus assuming the generator is delivering the maximum current that the brushes could commutate by the varying resistance of their contacts if they were in a zero resultant magnetic field, any increase of load on the direct current generator will cause the brushes to spark, for two reasons: first, because of increased armature-reaction; second, because the current becomes too great to be taken care of by resistance commutation, even assuming no armature-reaction.

Fig. 19.—1,500 K.W. 6,600 Volt, 3 Phase, 25 Cycle and 300 Volt D.C. 250 R.P.M. Motor-Generator.

In a rotary converter, on the other hand, the armature-reaction effect is not present, and the brushes may be assumed at all times to be either in a neutral field or in one that is helping the commutation. The result of this is that a direct current machine operated as a rotary converter will carry, as regards sparking, heavier overloads with fixed brushes than will the same machine as a generator. The sparking does not appear to increase so rapidly in a rotary converter when the load is raised. The result of this is that the sparking constant in a rotary is usually permitted to be about 25 per cent higher than in a generator, and in consequence of this a rotary converter may be designed for a lower peripheral speed, and with a longer armature core than the corresponding generator.

There being no resultant armature-reaction in a rotary converter, some manufacturers design such machines with a high armature-reaction and low volts per commutator bar; that is, with a strong armature and weak field. This design requires less material in the construction and tends to lower the cost of the machine. But this saving is not so pronounced as one might think at first sight, as the labor cost is increased quite materially when the number of coils on the armature and the number of commutator bars are increased. In addition, a strong armature is not conducive to good operation in a rotary converter; it tends to make the brushes flash badly or even to flash over when starting from the alternating current side, or when hunting, and it also reduces the synchronizing power of the machine. Considering the question from all points of view, it is usually found most satisfactory to design rotary converters with about the same armature reaction and volts per bar as the corresponding direct current machines.

Rotary Converter Armature Winding.—The copper loss in the armature of a polyphase rotary converter is usually considerably less than in the corresponding direct current generator, so that such rotaries are often designed with a much smaller cross-section of copper than would be used in a generator. This is bad practice. The copper loss in a rotary converter armature is not equally distributed, the loss in the bars nearest the collector leads being usually much greater than in those midway between the leads. And although the difference in temperature at the end of a temperature run cannot generally be detected by a thermometer, the difference is very appreciable in the case of sudden overload at a low power factor. And cases are on record where the armature bars connected to the leads in a large rotary have been fused before the other bars got dangerously hot. For heavy railway work the section of the copper in a rotary armature ought to be at least equal to that in the corresponding generator. As regards heating, six phase rotary converters have an advantage over two or three phase, but as they result in extra complications in the cables and switchboard they are seldom employed except in large units. In any case a six phase rotary may have to operate three phase at some time, so it should be designed simply as a three phase machine with three extra collector rings. This being the case, the remarks before made in regard to the section of the armature copper and heating of conductors also apply to six phase machines.

One advantage sometimes claimed for the six phase rotary is that having a greater number of equipotential connections on the armature than either a two or three phase, there is a greater tendency towards equality in distribution of current between the various sets of brushes on the commutator. This would be true if the collector rings were the only equipotential connections on the armature. But in addition to the collector rings, the armature winding of the modern high speed rotary is usually provided with an equipotential connection for every second slot, while in 60 cycle or large 25 cycle rotaries where the commutating conditions are more severe, one connection to every slot is frequently employed. So it is obvious that, in this respect at least, the six phase rotary as usually constructed presents no advantage over the two or three phase. Undoubtedly the larger the number of phases in the armature winding of a rotary converter, the more accurately and uniformly do the alternating and direct currents in the conductors neutralize one another, and in consequence, the less the pulsation of the armature reaction and the less the variation in the commutating conditions. But with the modern well proportioned rotary converter, this variation and pulsation is not a serious matter, so that it should not influence the choice of the number of phases any more than the necessity for additional equipotential connections should.

An important feature in the design of the armature of a rotary converter is often overlooked, and that is equality or balancing of the phases. If the windings of the different phases on a rotary armature are not all exactly equal, and placed on the armature in an exactly similar and symmetrical position with regard to one another, then the phases will be unbalanced, with the result that the load will not be balanced among the phases, and that there will be a greater tendency to hunting. If the three ammeters in the three phases of such a rotary are watched, the load can be seen changing from one phase to another. This is the reason why rotary converters with series wound armatures are usually unsatisfactory. It is often impossible to balance the phases. A 6 pole, three phase rotary having a series wound armature with 224 coils, must have the rings connected to coils 1–26–51. An 8 pole three phase rotary having a multiple wound armature with 520 coils, must have its rings connected to coils 1–44–86. The phases of both these armatures are unbalanced. To have the phases perfectly balanced the number of commutator bars per pair of poles should not only be divisible by the number of phases, but the number of slots per pair of poles should also be divisible by the same number. The reason for this is that to have the different phase windings all symmetrically and similarly placed on the armature, all the coils that are connected to the phase leads must be in the same relative positions in their slots.

Hunting of Rotary Converters and Synchronous Motors.—Rotary converters are more liable to hunt than synchronous motors. Generally speaking, conditions of operation and design that will enable two alternators to operate satisfactorily in parallel without hunting, will also enable one of them to operate satisfactorily as a synchronous motor when driven by the other machine under the same conditions. A single rotary driven from an alternating current system, will not operate under given conditions quite so well as regards hunting, as a motor-generator. The armature reaction of a rotary converter is considerably higher in proportion than that of a synchronous motor. Therefore, its synchronizing power is less and the fact that the direct current side is so intimately connected to the alternating current side, makes it peculiarily sensitive to hunting. But the main difficulties with rotaries in regard to hunting are experienced when two or more rotaries are running in parallel on the same alternating current system, and feeding into the same direct current system. These difficulties are especially marked when the rotaries are running in parallel upon the same alternating current and the same direct current bus-bars. Under similar conditions motor-generators are no more sensitive to hunting than under the conditions of singly operated units. But the difficulties with rotaries are often so serious, that operating engineers have found it necessary to insist that manufacturers provide damping or anti-hunting devices for all machines intended to be connected in this way, and also to install artificial choke coils between the collector rings and the alternating current bus-bars, in order to limit the interchange of current.

Artificial damping devices of various types and forms have been tried, but the only one in extensive use at the present time is a heavy grid of copper embedded in the pole face. Another construction now in use for accomplishing the same result, consists in solid pole faces so shaped, and with the armature slots and air gap so proportioned, that eddy currents due to the teeth are avoided. As far as can be seen from practical operation, these two methods of preventing hunting seem equally effective. They both enable rotaries to be run in parallel satisfactorily, as long as the variation in speed of the engines and the pressure drop in the feeders is not excessive. As regards the relative effects of a copper grid damper and a solid pole face upon the efficiency under working conditions, it is difficult to speak with any degree of accuracy as so much depends on the uniformity of speed of the engines. But it is probable there is a constant loss in the copper-grid damper, when, as is often the case, it is used with large armature teeth and small air gaps. Solid pole faces require a larger air gap or narrower slot, which in turn demands more copper on the magnets, this being especially the case in 60 cycle converters. On the other hand, from a mechanical point of view it is a nuisance to have to attach auxiliary copper grids or dampers to any pole face, while the cost of the dampers themselves is not insignificant. Generally speaking, then, there is little choice between solid pole-faces and auxiliary dampers, so it would perhaps be best to advise the use of solid pole-faces in all cases, as they are simpler and more mechanical.

Mechanical Design.—Though rotary converters have been used for quite a number of years, yet their detail design seems to have received less care than has been given to generator design. A rotary in a sub-station carrying a street railway or interurban load is usually subjected to rough treatment, and consequently should be of robust design. All parts should be as accessible as possible in order to facilitate repairing.

Two features in the design of rotaries that are often faulty are the alternating current collector gear and leads, and the starting resistance used for starting from the direct current side. The alternating current end of a rotary is often designed similarly to the old revolving-armature alternators; that is, the leads are strap-copper soldered to the armature conductor and attached to the armature end-plate with a few cleats. While the collector-rings are mounted solid upon the shaft, separated and insulated by fiber or wood discs and bushings, the leads being embedded in this insulation where they pass through or are connected to the rings. This construction is shown in Fig. 20, and it is hardly necessary to state that it is unsatisfactory for heavy railway work. Solid copper leads, unless very carefully and solidly cleated to the armature end plates, are liable to break due to vibration, while soldered joints are liable to melt under overloads. Collector-rings mounted solid on the shaft are liable to break down due to warping or cracking of the insulation, and to get hot on overloads due to poor cooling facilities. Also when the rings are insulated by wooden discs projecting between the rings they cannot be easily turned off when they become cut or grooved by the metal brushes. The most substantial construction is probably to use cable for the leads and to connect them to the winding by special lugs riveted and silver-soldered to the armature conductors. The rings should be carried on arms projecting from a spider and should be freely open to the air for cooling, and be easily accessible for turning off whenever they become grooved or uneven from wear. In fact they should be designed exactly like the collector gear of an up-to-date revolving-field alternator. When this construction is adopted a temperature rise of over 15 degrees is rarely attained on normal load. Such collector-rings are shown in Fig. 21.

FIG. 20.—Rotary Converter Armature and Collector-Rings.

Regarding a starting resistance for starting a rotary or a motor-generator from the direct current side, it is often forgotten that such work is much more severe than starting a motor. A rotary or a motor-generator has to be run up to speed and then synchronized, and when synchronizing the speed has to be exact. If the voltage on the direct current system is varying, it often requires several minutes to synchronize, and if it is varying suddenly, the speed can only be adjusted by means of the starting resistance because shunt control is not quick enough. Starting resistances for rotaries or motor-generators should be designed so that the last steps can be kept in circuit

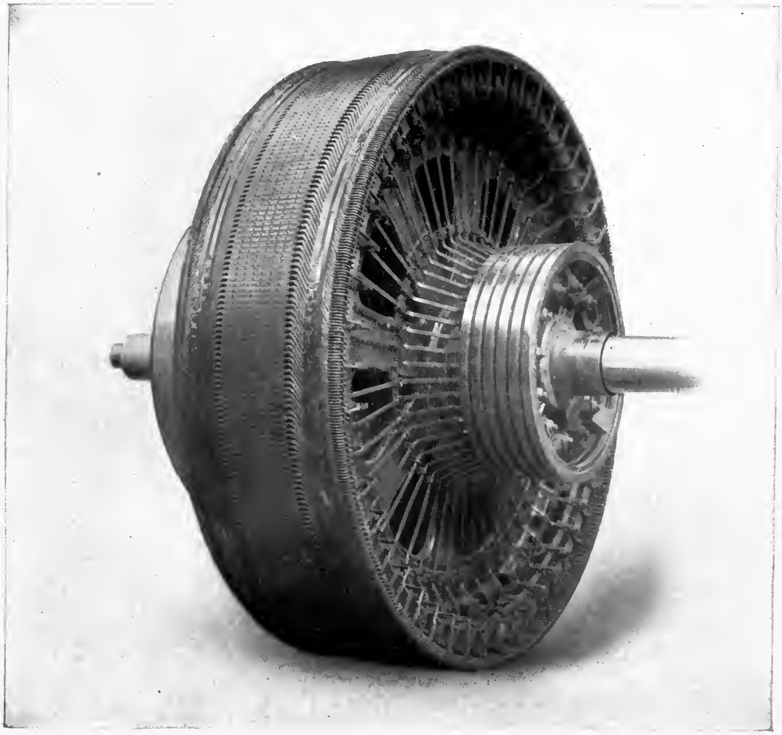


Fig. 21.—A.C. Collector-Rings on Rotary Converter.

for at least five minutes without overheating. An oil-cooled starting resistance that has been designed by the National Electric Co. for this work is shown in Fig. 22. The resistance coils are of iron wire supported on porcelain insulators and brazed to heavy brass terminals. It is designed so that the temperature rise of the oil will be 150° Cent. in five minutes with all the resistance coils carrying their maximum rated current. This type of resistance gives excellent results, and has the additional advantages of being quite cheap and almost fireproof. The usual starting switch, with overload and no-load release, is neither necessary nor desirable for rotary converter work; it is too complicated and expensive and not reliable enough for such duty. A standard multiple-contact switch is all that is required. Such a switch requires very little space and may be mounted on the rotary panel.

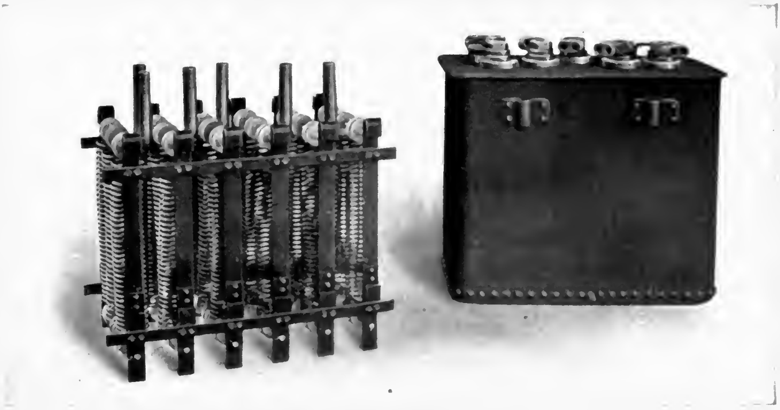


FIG. 22.—Starting Resistance for Rotary Converter or Motor-Generator.

This paper has not been written with the idea of advocating the use of rotary converters instead of motor-generators, or vice versa, but more with the idea of comparing them generally, their advantages and disadvantages, and of pointing out some of the characteristic features of each machine. The question as to which type of machine should be used in any given case can only be decided after every feature of the situation has been duly considered. Broadly speaking, however, the tendency to-day is toward motor-generator sets in lighting systems and rotary converters on traction systems. This seems to be perhaps the most rational conclusion.

Motor-generators and rotary converters, all things considered, are more difficult to design and build than the ordinary standard engine-type generator. They are high-speed machines and usually operate in sub-stations where the conditions of operation and the supervision are not of the best. The question of their reliability in continuous operation should therefore receive the most careful consideration from the designer and manufacturer; and as suggestions and criticisms from operating engineers are of the utmost value they should always be welcomed and investigated, in order to determine whether or not they contain features valuable enough to warrant the modification of standard designs.

NOTE [*Dec.*, 1910]

In the past two years the standard speed for rotary converters and motor-generators has appreciably increased, this being due partly to improvements in mechanical design; partly to the development of commutating poles for direct current generators and to a certain extent for rotary converters; and partly to our increased knowledge of power system phenomena and to the education of power station engineers, which has permitted closer commercial designing. The present commutating pole units require careful adjustment, but, after adjustment are much less sensitive to operating conditions, and require less attention and maintenance.

As stated above, increasing the speed of any unit tends to decrease the cost, though this is true only within certain limits. This is exemplified by the direct current generators which are now built for operation at the very high speed required for direct connection to steam turbines, and whose cost is, on account of the mechanical difficulties of construction due to the high speed, appreciably greater than that of the corresponding medium speed unit. Given the approximate speed at which a direct current generator is to operate, and adopting a commutating pole construction, the number of poles which the machine should have is fixed within narrow limits by questions of cost, efficiency, and mechanical design. If we carefully design a unit of given rating, whether A.C., or D.C. (with commutating poles), for a number of different speeds, and figure the efficiency and cost of manufacture for each design, we find that with increased speed the efficiency improves and the cost decreases till a certain speed, dependent on the rating, is reached; and that if the speed is still further increased, the efficiency is reduced and the cost increased. There is a similar relationship between the number of poles, and the efficiency and cost. The smaller the number of poles, the lower the frequency and, generally speaking, the larger the flux per pole, and in consequence the heavier the magnetic circuit. On the other hand, when the number of poles is excessive, the frequency is high and the

STANDARD ROTARY CONVERTER AND MOTOR-GENERATOR SPEEDS (1910)

25 CYCLES

K.W.	Motor-Generators.		Rotary Converters.	
	250 Volts.	600 Volts.	250 Volts.	600 Volts.
250	750	750	750	750
500	750	750	500	500
1000	500	500	300	375
1500	375	375	214	250
2000	300	300	167	187

60 CYCLES

250	1200	1200	1200	1200
500	720	720	720	900
1000	514	514	514	600
1500	360	360	360	360
2000	300	300	240	240

diameter of the armature becomes very large; while the cost of the armature and field winding, and in a direct current machine, the cost of commutator and brush gear, also increases rapidly. The most economical and efficient number of poles to adopt for any machine of given speed and rating, whether A.C. or D.C., can be readily determined by a few trial designs, and any change in this number usually results in increased cost and decreased efficiency.

FIG. 23.—3,000 K.W., 600 Volt, 25 Cycle Rotary Converter.

Adopting a modern commutating pole design for the D.C.

unit of a motor-generator set of given rating, we can select the most suitable number of poles and speed without any restrictions other than those mentioned above. But with a rotary converter the frequency is fixed, so that the number of poles must vary inversely with the speed. This restriction is more serious the lower the frequency, as we are dealing with a smaller number of poles, so that it is often easier to develop an economical design for a motor-generator than it is for a rotary converter. The recent developments in commutating pole designs for direct current machines have allowed an appreciable increase in speed of motor-generator sets compared with rotary converters, so that at the present time the comparison in cost, efficiency, and floor space, between these two types of units is, if anything, more favorable to the motor-generator than it was in 1905.

[*Presented before the American Institute of Electrical Engineers, May* 28, 1906.]

SHUNT AND COMPOUND WOUND ROTARY CONVERTERS FOR RAILWAY WORK

THE question of shunt or compound excitation for rotary converters has been discussed so much that it is of interest to compare the relative merits of the two. As the shunt winding is obviously the simplest, cheapest, and most convenient way of exciting a rotary converter, it would be well to begin by considering why a compound winding is ever used.

In a direct current circuit it is often an advantage to have a system which is to a great extent self-regulating as regards voltage. This is especially the case where the load changes frequently, and in such cases a compound-wound generator is used. A series winding on the generator field-coils tends to make the voltage at the generator terminals rise as the load comes on the machine, and this rising characteristic is employed to counteract the increasing voltage drop in the feeders and mains due to increasing load. By changing the series winding on the generator the rising tendency of the terminal voltage can be varied to almost any extent.

Compounding of Rotaries.—In a rotary converter the ratio of the voltages at the terminals on the two sides of the machine is approximately constant, and independent of the load or the magnitude of the excitation; that is, when transforming from alternating current to direct current, the direct current terminal voltage bears an almost constant ratio to the alternating current terminal voltage under all conditions. So the only way of varying the direct current terminal voltage is to vary the alternating current voltage supplied to the machine. If the direct current voltage is to rise as the load comes on the rotary, then the alternating current voltage which is supplied must be made to vary in the same way. Assuming that approximately constant voltage is supplied at the generator end of the alternating current feeders, and that the circuit between the generator and the rotary converter contains sufficient self-induction, then the voltage at the rotary converter end of the alternating current line can be raised or lowered by introducing a leading or a lagging current into the system. A leading or lagging current can be introduced into the system by over or under exciting the rotary. So by putting a series winding on the magnets of the rotary the excitation will be increased as the load comes on, and a leading current approximately proportional to the load introduced in the alternating current system. This will tend to raise the alternating current voltage supplied to the rotary and, in consequence, the terminal voltage at the direct current side. By means of this system, a rotary converter can be compounded in a manner similar to that employed for compounding a direct current generator, or rather the line can be compounded so as to cause the voltage at the direct current terminals of all the rotaries on the line to increase as the load comes on.

Here then is a system that gives automatic control of the voltage as the load varies. Such a system is obviously extremely useful and convenient. Unfortunately it presents a number of disadvantages in practice, e.g.—a series winding is required on the rotary magnets; it is practically always necessary to insert artificial self-induction in the alternating current line, so as to bring its reactance up to the required value; and extra switchboard arrangements are required. This results in increased complications and cost, and a loss of efficiency. A compound-wound rotary costs about 5 per cent more than a shunt-wound, and reactance coils usually cost about 5 per cent of the cost of the rotary, while the efficiency of the system is lowered probably 1 to 2 per cent. In addition the system is more complicated, and in consequence more liable to break down, while there is a possibility of troubles in operation, due to the fact that a series field winding on a rotary converter is a source of danger on account of its liability to reversal. When starting a rotary the series fields can be short-circuited, and the danger at that time avoided; but if the attendant forgets the short-circuiting switch, there will be trouble. And if at any time, when the series coils are in use, the alternating current supply fails or is cut off, so that the machine is left connected to the direct current circuit, the series coils will reverse and it is likely to run away; especially if the direct current voltage is varying. A speed-limit device should take care of this, but as automatic devices usually go wrong when they are most needed, the fact must be accepted that a series winding introduces a possible source of serious trouble in any rotary converter system.

Small Sub-Stations.—The automatic compounding obtained by a series winding and reactance coils is not so satisfactory as would be expected, because the compounding of all the rotaries is proportional to the total load on the line, rather than to the load on the individual rotaries. We would expect that the most useful application of this system would be to over compound rotaries in a small sub-station, so as to compensate for a large feeder drop, where the load fluctuates violently. The results in such a case are, however, not always satisfactory. To over compound a rotary, and to change the voltage at the direct current side, requires that the magnetic flux in the field magnets of the rotary must change; as solid steel field magnets or copper dampers are always used in rotaries the magnetism cannot change quickly, and there is therefore often a considerable time lag before the voltage changes to correspond with the change in load. The result of this is that when the load is varying quickly the voltmeter needle is kept wandering aimlessly about the scale, indicating anywhere from, say, 500 to 650 volts, the voltage apparently not having any relation to the load on the machine. However, when the rotary is flat-compounded instead of over or under-compounded the result is more satisfactory, as the natural tendency of the solid poles or dampers is to hold the magnetism and voltage constant. Unfortunately, however, small sub-stations are usually supplied from comparatively small power stations; and with a varying load on the rotaries one of the main effects noticed in the sub-station is the fluctuation of the speed of the engines, and consequently in the speed of the rotaries and the alternating current voltage. The effect of this variation in speed often completely masks all results from the compound winding.

In addition, this method of compounding is often a nuisance. There must be careful adjustment of the series winding and of the reactance-coils at the sub-stations before obtaining the desired effect. Then if the rotaries are changed to another station, or if the line conditions are changed, the adjustment has to be made again. If other compound-wound rotaries are installed in the same sub-station, there is trouble to adjust them so that they divide the load properly at all loads. Equalizer connections are used, but the results are rarely altogether satisfactory. The different characteristics of the rotaries, and the variation in the brush-contact resistance or temperature of the machines all tend to upset the adjustment. If shunt-wound rotaries are not dividing the load properly, varying the field rheostat will quickly adjust the load. And in any case shunt-wound rotaries, like shunt-wound generators, have a much greater natural tendency to divide the load properly than have compound-wound machines. With this automatic compounding, the power-factor of the rotary system varies, and often varies widely, with the load. The power-factor cannot be interfered with, without disturbing the complete system of regulation. A shunt-wound rotary tends to keep the power-factor the same at all loads; and in any case the power-factor can be adjusted by means of the field rheostat without in any way upsetting the regulation. The result of all the complication and disadvantages of a compound-wound rotary with reactance coils is, that, often after the system has been in operation for some time, the series magnet-coils and the reactance-coils are cut out and the rotary operated as a straight shunt machine. It is then more under the control of the operator and less liable to give trouble.

Most Satisfactory System.—Probably the best system for general work is to a have shunt-wound rotary, standard transformers, and no reactance-coils. Somewhat over excite the rotary so as to keep the power-factor a leading one at all times, and then leave the machines to take care of themselves, only adjusting the excitation in case they fail to divide the load properly.

In the case of a large system the feeder drop is small and the fluctuations in load are unimportant, so that the voltage is fairly constant at all times. The only work then for the sub-station attendant is to cut in or out an extra rotary as the load requires it, and to see that each machine in circuit carries approximately its proper proportion of the load.

In the case of interurban systems operating several small sub-stations, the voltage will vary with the load on account of the feeder drop. The direct current voltage will be high on light loads and will fall on full load. For a feeder line with sub-stations at various points this is an ideal condition. When the load is light on any sub-station it will mean that most of the load on the system is being carried by other stations. The voltage will then be high at the lightly loaded stations and lower at the more heavily loaded ones, so that the lightly loaded stations will tend to help out the heavily loaded ones, resulting in ideal conditions:—a tendency to distribute the load proportionately between the stations at all times. The rotaries should be excited so as to obtain either unity power factor or a leading one at all loads, and then the feeder drop will automatically take care of the distribution of load, and there will be tendency always to divide the load proportionately between all the sub-stations.

Thus with shunt-wound rotaries instead of compound-wound machines with reactance-coils, there results a cheaper, more efficient, and less complicated outfit, one less liable to give trouble and one which will give better results both in large and in small stations. It is hardly to be wondered at then that there is at the present time a tendency to make rotaries shunt-wound; and it is probable the time is not far distant when the compound-wound rotary will be considered as a type to be used only to meet special requirements, the shunt-wound rotary being accepted as standard for all railway work.

[Presented before the American Institute of Electrical Engineers, February 14, 1908.]

THE NON-SYNCHRONOUS OR INDUCTION GENERATOR IN CENTRAL STATION AND OTHER WORK

THAT an induction motor could act as a generator and return power to the line when driven at a speed above that of synchronism, has been known for many years. It has, however, always been regarded as more or less of a scientific curiosity, and except in the case of the Swiss three phase mountain railways, where the motors are sometimes allowed to run as generators to brake the train on descending heavy grades, the induction generator has had but few commercial applications. The fact that the characteristics of this generator are such that it must receive a lagging current from the system, the magnitude of which is for a given machine definitely decided by the slip of the generator above synchronism, combined with the fact that when connected to a circuit it has no definite voltage or frequency of its own, make it lack the flexibility of the synchronous generator. In 1895 it was proposed to operate an induction generator in conjunction with an unloaded synchronous motor, the generator to supply the watt component and the motor the wattless component of the current in the system. But though this suggestion caused the induction generator to become a practical machine, it is easily understood that, on account of the lesser flexibility when compared with the synchronous generator, it has not appealed to the central station engineer as a desirable addition to his equipment.

The question as to the advisability of adopting the induction generator for power station work, was decided adversely by engineers at the time when the steam engine and the water turbine were the only practical prime-movers. But to-day we have to deal with the steam turbine and the gas engine, and the introduction of these two new types of prime-mover has altogether changed the situation in regard to the use of this generator for power station work. It often happens in such cases that the real meaning and possibilities of the introduction of types of machinery with such fundamentally new characteristics as the steam turbine and gas engine, are not recognized until they are accidentally forced upon us. This has been the case in the present instance; the question of the use of the induction generator with steam turbines was not seriously considered until it was brought up indirectly.

In 1904 the Baltimore Copper Smelting and Rolling Company was installing a 1,200 K.W., 200 volt, direct current generator for electrolytic work. It was desirable to have the good steam economy on variable loads, the small floor space and reduced maintenance of the steam turbine, and at the same time to generate 200 volt direct current. A 1,200 K.W., 6,000 ampere, 200 volt, 1,800 R.P.M., direct current turbine generator was not considered practical, and an induction generator together with a rotary converter was suggested as an alternative. It was decided to adopt this type of equipment, and a 1,200 K.W., six-phase, 140 volt, 30 cycle, 1,800 R.P.M. generator together with a 1,200 K.W., six-phase, 150 R.P.M. rotary was installed to supply the required 6,000 amperes direct current at 200 volts. A direct current exciter for the rotary was provided, so that the direct current voltage could be varied from 100 to 230 volts without any danger of instability. The exciter is compound wound to give constant voltage on the direct current side of the rotary, and the power-factor gradually rises from about 25 per cent at no load, to about 96 per cent at full load. When starting up the set, the rotary is run up to speed from an auxiliary source of direct current, and the generator by its turbine. They are then thrown together, the generator driving the rotary as a synchronous motor, and the rotary supplying the magnetizing current of the generator. The governor of the turbine decides the frequency of the set, and the slip of the rotary behind the generator is proportional to the load, being about 1 per cent at full load. This equipment has been running now for about three years and operates perfectly. The generator is similar in arrangement to the old open-type turbo-generator, and in consequence is rather noisy, but with the modern enclosed type of generator, the air circulation could be better arranged, resulting in a quieter running machine.

This installation is given in detail, as it is one instance where the adoption of this apparently inflexible type of generator resulted in an installation, which combines the flexibility of the standard direct or alternating current generator, with the heavy overload capacity of the rotary converter, and the reliability and robustness of construction of the induction generator. No other electrical equipment which could have been installed would have given the good results that were obtained. And though the existing conditions rather forced the choice of the equipment in this case, the result so thoroughly met expectations, that engineers began to consider whether the development of the last few years in regard to prime-movers, had not changed the induction generator from a scientific curiosity to a machine offering great advantages for certain conditions of power station work.

General Characteristics of the Induction Generator.—As most engineers are more familiar with the characteristics and performance of the induction motor than they are with those of the commercial induction generator, it will be well to show how the characteristics of the two machines are allied. An induction motor of given characteristics, carrying a certain definite load, runs at a speed fixed relatively to that of synchronism, and it takes a current the magnitude and phase of which are definite. The torque exerted by the motor is proportional to the product of the current induced in the short-circuited secondary, and the magnetic flux. The electromotive force and the current induced in the secondary, and hence the torque, are proportional to the rate at which the secondary conductors cut the primary magnetic field, that is, to the slip of the rotor above or below the speed of synchronism. As the speed of the motor gradually rises to that of synchronism, the current in the secondary, and the torque gradually fall, till at the speed of synchronism they both become zero. If the speed of the machine still continues to increase, the secondary conductors cut the primary flux in the reverse direction, so that the induced electromotive force, the secondary current, and the torque become negative; that is, the machine requires mechanical power to drive it above the speed of synchronism. The machine now returns electrical power to the circuit, and has become a generator. When running as a motor, the current is never in phase with the impressed voltage, for two reasons: (1) the motor requires a certain wattless magnetizing current; and (2) the motor windings, both primary and secondary, have a certain amount of self-induction. This makes the current lag behind the impressed voltage by an angle ϕ, depending on the characteristics of the machine, and on the load it is carrying. When the machine runs above synchronism as a generator, it still takes from the circuit the wattless magnetizing current, and the circuits still possess their self-induction. The result of this is, that as the watt component has reversed in direction, the primary current lags less than 180° behind the voltage impressed by the circuit on the generator, hence the current leads the electromotive force supplied by the generator to the circuit. Thus we have as a fundamental characteristic of the non-synchronous generator, that for a given load, it runs at a certain definite speed above that of synchronism, and that, (*a*) it supplies a watt current which represents the power delivered by the generator to the circuit, and (*b*) it takes a wattless magnetizing current from the system, the magnitude of which depends on the voltage, and on the watt component of the current. Hence this type of generator cannot supply a lagging current to the outside circuit, and can only deliver power to a circuit which is able to provide the lagging magnetizing current required by an induction generator: while for any given speed, the magnitude and phase of the current which the generator will supply is definitely fixed. Also, as the wattless component of the current varies in magnitude when the load of the machine changes, we must have in circuit some apparatus which can supply a variable amount of lagging current, and which will maintain the voltage of the circuit constant. It is these apparently rigid and inflexible conditions that have prevented any extensive use of the induction generator, and it is only because under certain modern conditions these limitations cease to be serious disadvantages, that this generator is now put forward as an important part of a power station equipment.

Usually the load on a power station is either non-inductive, or has a lagging power-factor, so that if this type of generator is used, the lagging current required by the generator, and perhaps also by the outside circuit, must be artificially supplied. There are two ways of obtaining the lagging current required by the induction generator: (1) from a condenser; (2) from a synchronous generator, or an over-excited synchronous motor. It would not be desirable commercially to install a condenser specially to supply the required lagging current, as the cost would be prohibitive; but a large cable system has a considerable electrostatic capacity, and the lagging current supplied by this system will usually greatly reduce the size of the necessary synchronous machine. In any case, however, it is necessary to have a synchronous machine, either a motor or a generator, in the circuit, in order to set the frequency and the voltage. If we have the induction generator operating in parallel with a synchronous unit, the latter machine supplies all the lagging wattless current required by both the induction generator and the outside circuit, while the voltage of the circuit is decided by the excitation of the synchronous machine. The distribution of the watt component of the current between the two machines is decided by the adjustment of the governors on the prime-movers. The load which the induction generator takes, depends on the percentage slip by which it leads the synchronous unit, while the remainder of the load is taken by this latter machine. When additional load comes on the station, it comes first on the synchronous generator, and then, as this machine slows down and allows the slip of the induction generator to increase, part of the load is transferred to this latter machine. In any case, the voltage regulation of the system is that of the synchronous unit, and the voltage of the circuit under any condition of load is decided by the excitation of this machine.

If the induction generator is operating in parallel with a synchronous motor or rotary converter, the same remarks apply. The voltage regulation is that of the synchronous machine, and the voltage of the circuit is decided by the magnitude of its excitation. When the energy load on the two machines increases, the additional load comes first on the synchronous machine, energy being supplied to the system from the momentum of its rotating part; and then as the machine slows down a little, the load is transferred to the induction generator, the synchronous machine supplying only any increase in the wattless component of the external load, together with the additional lagging current required by the generator when carrying the increased energy load. The synchronous machine supplies at all times all the lagging wattless current in the circuit, and the governor of the prime-mover driving the induction generator decides the frequency of the circuit, the synchronous machine slipping behind the generator an amount sufficient to allow this latter machine to supply all the power required by the circuit.

Non-synchronous Generators in Power Station Work.—Obviously the disadvantage of this type of generator for power station work is, that it cannot supply a lagging wattless current, and that it requires an additional lagging wattless current to excite it. The power-factor of the current supplied by such a generator is a direct measure of the amount of wattless current required to excite it under that particular load. The power-factor which can be obtained in designing any induction generator, depends on the size, speed, voltage, and frequency of the machine. Low speed, high voltage, and high frequency, all tend to lower the power-factor which can be obtained.

Table I gives the characteristics of steam turbine and gas engine driven induction generators of from 1,000 K.W. to 10,000 K.W. for 2,200 or 13,200 volts, and for 25 or 60 cycles. The table shows that on high speed 2,200 volt generators, the power factor rises as high as 98.25 per cent, and that we can obtain on

TABLE I

STEAM TURBINE DRIVEN 25 CYCLE INDUCTION TYPE GENERATORS

Kilo-watts.	Rev. per min.	Volts.	Load.						No-load Cur-rent.	Full Load Slip.
			1	0.75	0.50	1	0.75	0.50		
			Efficiency.			Power-factor.				
1000	1500	2200	97.6	97.7	97.5	97.0	97.5	97.0	8.3%	0.75%
		13000				95.0	95.9	96.5		
2500	1500	2200	98.2	98.2	97.9	97.9	97.3	96.4	8.3	0.48
		13000				96.5	96.9	96.0		
5000	1500	2200	98.3	98.2	98.0	98.0	97.7	97.4	8.5	0.46
		13000				96.5	97.0	96.5		
10000	1500	2200	98.5	98.4	98.2	98.2	98.0	97.5	8.1	0.40
		13000				96.8	97.3	97.1		
60 CYCLE										
1000	1800	2200	97.6	97.7	97.5	96.4	96.9	96.4	9.5	0.75
		13000				94.0	95.0	94.5	11.5	
2500	1800	2200	98.2	98.2	97.9	97.2	96.8	96.2	9.5	0.48
		13000				94.5	95.3	94.8		
5000	1200	2200	98.3	98.2	98.0	96.0	97.2	97.0	9.5	0.45
		13000				94.5	95.6	95.5		
10000	1200	2200	98.5	98.4	98.2	97.6	97.6	97.1	9.5	0.40
		13000				95.3	95.6	95.5		
GAS ENGINE DRIVEN 25 CYCLE INDUCTION TYPE GENERATORS										
1000	94	2200	96.7	97.1	97.2	94.0	94.2	92.0	16.5	1.5
		13000				89.3	90.9	88.7	18.0	
2000	83	2200	97.0	97.4	97.6	95.5	95.1	94.0	16.5	1.4
		13000				92.4	93.2	90.7		
3500	75	2200	97.1	97.5	97.7	95.7	95.2	94.2	16.5	1.4
		13000				92.6	93.4	91.0		
60 CYCLE										
1000	93	2200	95.5	95.7	96.0	88.8	88.5	84.6	25.0	1.8
		13000				83.0	81.0	73.3	40.0	
2000	82	2200	96.0	96.3	96.5	89.5	89.2	85.6	24.0	1.7
		13000				83.5	81.8	75.0	38.0	
3500	75	2200	96.3	96.5	96.7	90.8	89.5	87.0	22.5	1.6
		13000				85.0	83.3	77.0	35.0	

such machines a power-factor which averages 97 per cent to 98 per cent, from one-half to one and one-quarter load; while the no-load magnetizing current is less than 10 per cent of the full load current of the machine. This being the case, the fact that these generators require a wattless current to excite them ceases to be a serious objection, and it would appear that the only important limitation of this type of machine is, that it cannot supply lagging wattless current to the outside circuit. The low-speed, 60 cycle machines are relatively poor as regards power-factor and exciting current, so that the use of induction generators would not be advocated under these conditions, unless their other characteristics made them particularly advantageous for the special conditions under which they were to be used. It will also be seen from Table I that another advantage of this type of generator is the extremely high efficiency at all loads that is obtained in high-speed machines. As a result of this, these generators have a low temperature rise at normal rated load, and have a large overload capacity. The normal ratings of the individual machines given in the table were chosen so that their characteristics would be best at from one-half to one and one-quarter rated load. All the machines given can generate from two and one-half to five times their rated output, and as far as general characteristics are concerned could be rated 50 per cent higher. It was stated above that the slip of the induction generator relatively to the synchronous unit must increase from no load to full load, in order that the former may carry its due share of the load. So if it is required that the load always be automatically divided between the two machines, we must adjust the governor of the synchronous prime-mover, so that its drop in speed from no load to full load is equal to the drop in speed of the non-synchronous prime-mover plus the full load slip of the non-synchronous generator. This means that the speed and frequency of the synchronous generator must change with the load, but we see from the slip given in the table that this change is unimportant. The slip varies from 0.4 per cent to 0.75 per cent in high-speed machines, and from 1.4 per cent to 1.8 per cent in low-speed machines, and this is about as close as the governors can be made to regulate in any prime-mover.

The greatest commercial field for the induction generator is undoubtedly in connection with steam turbine driven generators. This type of generator is more suitable both mechanically and electrically for high speed work than any other type of electrical machine. The squirrel cage secondary with heavy copper bars, each bar held in a separate closed slot, and practically requiring no insulation, is an ideal construction mechanically, and is one which can be operated at very high temperature without damage. Comparing this with the rotating magnets of the standard synchronous turbo alternator, the difference is very great. The magnet winding of a synchronous turbo alternator consists of a number of turns of thin strap separated by insulation; while the windings often reach high temperatures due to over load at low-power factors, and are in addition subject to heavy centrifugal stresses and a potential difference of 125 volts to ground. We can see that such a construction does not compare favorably with that of the squirrel cage rotating secondary of an induction generator; and as a breakdown on the field of a synchronous turbo generator usually puts the machine out of commission for a couple of weeks, the commercial advantages possessed by the non-synchronous generator are obvious.

The simplicity in construction and insulation of the rotating parts, the ease with which the centrifugal stresses necessarily present can be taken care of, and the absence of a complicated winding or brush gear, obviously tend to reduce the cost of the induction generator compared with that of the standard synchronous generator. The actual cost of any machine, as distinguished from the sale price, depends on the performance specification to which it is designed, and on how closely it is rated, but it can readily be seen that the induction generator offers facilities for cheaper design and manufacture which are not presented by the synchronous generator.

The Excitation of the Induction Generator.—A synchronous generator requires direct current excitation, while an induction generator requires alternating current for its excitation. The induction generator is excited by a lagging current taken usually from a synchronous machine, and as this synchronous unit requires direct current excitation to produce this lagging current, it can be said that indirectly the induction generator does require a direct current exciter. But on account of the small air gap of this type of generator, it requires much less excitation than a synchronous machine. The actual capacity of the exciters required by a power station consisting of induction generators, depends on the power-factor of the load on the system. The capacity will usually vary from one-quarter to one-half of that which would be required for the corresponding synchronous generators; though if the power station feeds a cable system with high electrostatic capacity, this will supply part of the required lagging excited current, and reduce the size of the required exciter. The charging current of the New York Interborough system is given as about 105 amperes at 11,000 volts, *i.e.*, about 2,000 K.V.A.; and that of the New York Edison system is about 40 amperes at 6,600 volts, *i.e.*, about 450 K.V.A. From Table I it is evident that the capacity charging current of the New York Edison system is sufficient to supply full load magnetizing and wattless current required by a 2,000 K.W., 6,600 volt, 25 cycle turbine driven non-synchronous generator, when running on a non-inductive external load. In the same way the capacity charging current of the Interborough system would be sufficient to supply the wattless current of a 10,000 K.W., 11,000 volt, 25 cycle turbine driven generator. If we had a cable system, such as the Interborough, distributing at 20,000 volts, it would have a charging current of 190 amperes at 20,000 volts, which would be sufficient to supply the wattless component for 40,000 K.W. in 22,000 volt, 25 cycle turbine driven non-synchronous generators. So we can see that the electrostatic capacity of a large cable system will play an important part, when the introduction of such generators into some of the large New York power stations is considered.

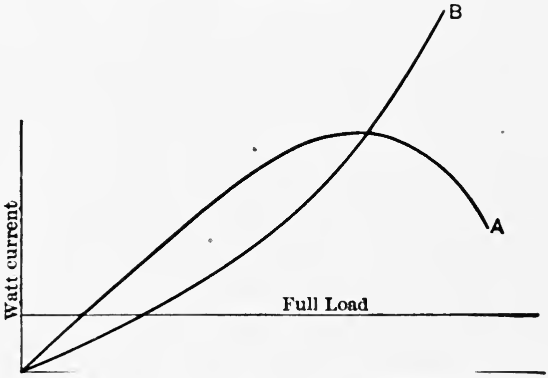
In a system consisting of induction generators supplying power to rotary converters, it is unnecessary to have any exciters or synchronous units in the power station. The first rotary started up, must be brought up to speed from the direct current side and then thrown on the generator circuit, when it will excite the latter, the voltage being decided by the excitation of the rotary. We can see from Table I that the power-factor of an induction generator can be made to remain practically constant from one-half to one and one-quarter load, so that the amount of wattless current taken by the generator throughout its normal working range will be practically proportional to the watt component of the current. Hence, assuming we can neglect the capacity charging current of the cable system; if we have a number of rotaries operating on the circuit, we can adjust the shunt excitation so as to give the correct voltage at no load, while the series excitation can be adjusted to obtain any desired voltage characteristic as the load comes on the system, the rotaries compounding the generators by their series winding. This compounding of the generators as the load comes on any sub-station, affects of course all the other sub-stations fed from the generators; so if we are not regulating for constant voltage, it may be advisable in some cases to introduce artificial self-induction into the rotary feeder circuits, so as to over compound these circuits rather than the generators, and avoid disturbing the voltage on other unloaded sub-stations. In a large system, the capacity current of the cables cannot be neglected, so the wattless current to be supplied by the rotaries will not be directly proportional to the load. Such a system, however, usually requires constant voltage at the direct current terminals, and when such is the case it may be found advantageous to install compound-wound rotaries with automatic voltage regulators to control the shunt excitation. The voltage regulators could then be made to keep the generator voltage constant, while the series winding would serve to compound each individual feeder in order to compensate for the voltage drop in that feeder. In such a system, all regulators controlling the voltage on a given group of generators would be tied together, so that any one regulator could not act before, or act against the others, and make the shunt excitation converters different for the individual rotaries.

Assuming the self-induction is negligible, then if there is no electrostatic capacity in the system, the power-factor of the rotaries is practically the same as that of the generators; but if there is capacity which helps to supply the lagging current, then the power-factor of the rotaries will be higher than that of the generators. Taking once more the Interborough system, and assuming there are 75,000 K.W. of 11,000 volt turbine-driven non-synchronous generators in the power station, and 75,000 K.W. of rotary converters in the sub-station, then the capacity current supplies 13 per cent of the wattless current taken by the generator on full load, and the full load power-factor for the rotaries will be 98 per cent. Such a power station of induction generators, having no direct current exciters and exciting circuits, is much simpler as regards cables and switchboard connections than a similar station with synchronous generators, and is much simpler to operate. There is no necessity for synchronizing the generators; they are run up to speed and thrown on the line in series with a choke coil (to limit the rush of current); the choke coil being then short-circuited, the generators are automatically excited from the rotaries and take care of themselves. The governors of the prime-movers are controlled by pilot motors from the switchboard, and the load can be distributed at will among the different generators without any adjustment of the excitation to keep the power-factor constant, as would be necessary with synchronous generators. This results in an ideally simple station, as there are no auxiliary circuits, and the switchboard is practically limited to the main generator and feeder switches and instruments.

Short Circuits and Resonance.—During the last few years we have heard a great deal regarding resonance and high power surges in large installations with cable distributing systems of high electrostatic capacity. These phenomena can be investigated mathematically in detail, if we choose to make a number of more or less arbitrary assumptions; but on account of the arbitrariness of these assumptions, we are, from the practical engineer's standpoint, justified at the present time in describing these phenomena only in general terms. By a high power surge, is meant the oscillation sometimes set up in a system by a sudden rush of current, such as a short-circuit, and which has usually the fundamental frequency of the circuit. The power represented by such a surge is proportional to the square of the value reached by the current in the first sudden rush, while the rise in voltage is directly proportional to the current surge. Resonance effects cover the extremely high rises of potential which take place in a circuit containing self-induction and capacity, when the frequency of the circuit has a certain critical value dependent on the amount of induction and capacity in circuit. In the usual power systems, resonance cannot generally take place at the normal frequency of the circuit; but there are usually higher harmonics of this normal frequency, introduced by distortion of the fundamental wave-form, and there may be resonance and high voltage due to one of these high harmonics.

This short analysis shows at once why a power station of synchronous generators is so liable to suffer from surges and resonance. Synchronous generators and motors will give a greater sudden rush of current, or surge, in the case of short-circuit than almost any other class of machine. And though they have voltage wave forms which approximate closely to a sine wave on no load, these wave-forms become so distorted by armature reaction on load, and change so much with the magnitude and phase of the current, that there is an excellent chance of introducing such harmonics as will produce resonance. If we were deliberately to try to choose conditions which would be most liable to give trouble from high-power surges and resonance, we could not well choose anything that would be worse than synchronous generators feeding synchronous motors through a cable system of high capacity. The induction generator is a great contrast to the synchronous in this respect, as it tends rather to eliminate disturbances from the line than to originate them. A short-circuit on a system results in the voltage falling to zero, consequently any induction generator on the circuit losing its excitation becomes dead, and does not tend to supply either power, current, or voltage to the short-circuit. Further, the voltage wave form of an induction generator is virtually a sine wave for all loads, and has no tendency at all to introduce higher harmonics which might produce resonance. If the synchronous machines supplying the wattless current in the circuit have a badly distorted wave form, the magnetizing current of the induction generator will also be distorted, but there will be a strong tendency to damp out all harmonics in the voltage wave form of the system; and we can say that, generally speaking, the induction generator acts as a strong damper to remove all harmonics in the voltage wave form of the system, introduced by distortion of the wave form of any synchronous machines. This distortion in a synchronous machine, being due to the armature reaction of the watt component of the current, rather than the wattless, we see that the best conditions as regards freedom from distortion and harmonics are obtained by the use of a rotary converter or unloaded synchronous machine, rather than a loaded synchronous generator or motor to supply the wattless current required to excite an induction generator.

Fig. 24 shows approximately the relation of the watt component to the wattless component of the current supplied by a 2,000 K.W. induction generator, the curve being for its normal rated voltage of 11,000 volts; for a different voltage the values of current, both watt and wattless, should be multiplied by the ratio of the new voltage to 11,000 volts. We can see from this, that the magnitude of the watt current bears a definite relation to that of the wattless, and that the watt current, and consequently the load on the machine, cannot change without the wattless current also changing. Further, for each point on the curve, the slip of the induction generator ahead of the synchronous machine has a certain definite value. This shows that when a short-circuit comes on a system consisting of an induction generator and synchronous generator or motor, the short-circuit will come on the synchronous machine. If the voltage drops to zero, the induction generator will be dead; but if the short-circuit is not severe enough to reduce the voltage of the system to zero, then it may still supply current to the circuit. The amount which it supplies will depend on the way in which the excitation of the synchronous machines is changed by any automatic voltage regulators. But a change in load which can be taken care of by voltage regulators hardly comes under the class of short-circuits, and as these latter effects are the only serious ones, we will consider them alone.



Wattless current (curve A), and slip (curve B).

FIG. 24.

We see from the above that the induction generator takes no part in the sudden surge of current which occurs on a short-circuit, so that this surge cannot be greater than that which is supplied by the synchronous machines in circuit. This sudden surge which takes place when any synchronous machine, whether generator, motor, or rotary, is short-circuited is equal to:

$$\frac{\text{Electromotive force of synchronous machine}}{\text{Total impedance in circuit}}$$

After the current has flowed for an appreciable interval, so that the magnetism of the synchronous machine has had time to change, the armature reaction cuts down the electromotive force generated, and the current falls to the value commonly known as the short-circuit value, this being the value of the current on a continuous short-circuit. The 5,000 K.W., 11,000 volt Manhattan generators will give a continuous short-circuit current about three times full load current, but the instantaneous value of the current on a sudden short-circuit is about seven times this; that is, about twenty-one times normal full-load current. If these generators are supplying rotary converters these rotaries will also supply power to the short-circuit. Operating as generators, the 1,500 K.W. Manhattan converters give about full-load current on a continuous short-circuit on the alternating current side, with the self-induction of the transformers and reactive coils in circuit; and the instantaneous value on sudden short-circuit is about three times this value. So a short-circuit on a system consisting of the Manhattan generators supplying power to rotary converters will give, on sudden short-circuit, a rush of current equal to twenty-four times the total full-load current of the generators in circuit; while after a short period the value of the short-circuit current will fall to about one-sixth of this value. Assuming that we had induction instead of synchronous generators in the power station, the short-circuit current would be limited to that from the rotaries, and the sudden surge would be equal to three times full-load current. The voltage of the system would fall to zero, and the rotaries would supply a gradually decreasing current to the short-circuit, until their rotational energy was expended, and they had come to rest. We see then that with induction generators in the power station, the magnitude of the sudden surge on a short-circuit would be reduced to one-eighth of that which would take place with the present synchronous generators. As a result of this the voltage rise would be only one-eighth, and the power of the surge would be one sixty-fourth. These figures do not need any comment.

There is one point, however, that must be considered when operating non-synchronous generators on a system containing considerable electrostatic capacity, and that is, that the individual generator units are not too small. An induction generator can be excited by the lagging current from a condenser, and the voltage to which it will be excited depends on the size of the condenser. In a system consisting of induction generators and synchronous units, we might, as the result of opening circuit breakers by line disturbances, have one generator and one small synchronous unit left on the line. The capacity current of the cable system would then tend to build up the voltage of the machines until the saturation of the magnetic circuit prevented any further rise. Taking the 2,000 K.W., 11,000 volt induction generator, the current curves of which are shown in Fig. 24; the magnetizing current at 11,000 volts is 9 amperes. If the capacity charging current of the cables is 100 amperes at 11,000 volts, and the synchronous machine is so small as to take a negligible lagging magnetizing current, the voltage of both units would probably build up to double the normal. If, however, the smallest machine on the circuit were a 10,000 K.W. generator, and a 1,500 K.W. synchronous motor or rotary converter, the rise in voltage would not be more than 10 per cent, while if the minimum generator unit had been 20,000 K.W., there would be no rise in voltage; so that this is a condition which can be taken care of when designing the station.

Distortion of the wave form introduces higher harmonics, and may cause resonance or cross-currents. In a synchronous generator or motor, the wave form of the magnetism is usually badly distorted when operating under load, the distortion being greater the higher the power-factor, and the greater the load. This distortion of the magnetic wave introduces higher harmonics into the wave form of the electromotive force generated in the armature conductors; the most important harmonic introduced being the third, though the fifth, seventh, ninth, and higher harmonics are also usually presented. In a three-phase winding, the third harmonic, and also harmonics of this third harmonic, appear in the electromotive force between the neutral and outer terminals, but not in the electromotive force between the outer terminals. They therefore appear in a three-phase, four-wire system, or in a three-phase system with grounded neutral. The other harmonics appear, no matter what the connections are. Though the presence of these harmonics may not cause harm in any individual case, it is always possible that there may, under certain conditions of circuit and load, be harmonics of a frequency sufficiently close to that of resonance to cause serious rise of potential. And if generators of different characteristics operate together, or if there are loads of different magnitude and phase, or different excitation on the synchronous generators or motors, cross-currents are liable to be produced between the machines, this being especially the case when running with a grounded neutral. Rotary converters are very much better than any other class of synchronous machines as regards distortion of wave-form when operating with unity power-factor, as they have practically no armature reaction; so that the electromotive force wave generated under such conditions is approximately a sine. The above remarks on synchronous generators and motors, then, only apply to rotary converters to a limited extent.

Induction generators have no distortion of field due to armature reaction, and as long as the iron in the magnetic circuit is not saturated, the electromotive force wave-form of these generators is virtually a sine wave for all conditions of load. In consequence of this there can be no cross currents between generators of this type, due to difference in wave-form, and no tendency to produce resonance in the circuit. Furthermore, an induction generator acts as the strongest possible damper in a circuit; and if there is any surge, unbalancing of phases, distortion of wave-form or hunting present, the induction generator will tend to damp it out, and to restore the original condition of steady sine wave operation. If we then have a system consisting of induction generators supplying power to rotary converters, it would be as nearly perfect as possible in its freedom from surges and resonance. The rotary converter would give the minimum distortion of any synchronous machine, and the induction generator would tend to damp out any disturbance that occurred on the line. Such a system would certainly be much superior to any one containing synchronous generators and synchronous motors, in regard to liability to disturbances from resonance or surges, and in all probability the engineers of such a system operating with grounded neutral would not be made aware that such phenomena existed.

I have endeavored to show that the induction generator is very much superior to the synchronous from almost every point of view, for the purpose of supplying power to motor generators or rotary converters through an underground cable system; and that rotary converters are less liable to introduce line disturbances than synchronous motors. In some cases it might be considered advisable to install both synchronous and induction generators, or the station might be one in which the units first installed were synchronous while the later extensions were induction generators. In such cases it is readily seen that the advantages as outlined above, are obtained to a degree which depends on the ratio of the capacity in induction units to those in synchronous. It should be remembered that the induction generator and rotary converter give the best combination to insure freedom from line disturbances, and that the synchronous generator and synchronous motor give the worst; combinations of the two systems give results intermediate between these two.

Small Power Stations.—Above we have considered in detail large systems which can easily provide the necessary lagging exciting current for the induction generator, either from the charging current of a cable system or from synchronous motors or rotary converters in the system. With smaller stations which supply power direct to motor and lighting circuits, the conditions are not so favorable to the induction generator, as this type is primarily one for high power-factor loads, and is at a distinct disadvantage in a station where the load is of low power-factor. The advantages of the non-synchronous generator as outlined above are, however, so great, that each particular case should be considered in detail to determine whether its adoption is advisable. Usually the low power-factor load on such a station consists mainly of motors operating only during the daytime, whereas the heavy peak load is the lighting load at night. We can therefore install synchronous generators sufficient to carry the low power-factor day motor load, and induction generators to assist in carrying the lighting load at night. Considering a 60 cycle station having a day load of 2,500 K.V.A., with a power-factor of 70 per cent, and a night load of 4,000 K.V.A., with a power-factor of 95 per cent; and assume further that we have, exclusive of spares, two 1,250 K.V.A. synchronous turbo generators to carry the day load, and two 1,250 K.W. induction generators to assist in carrying the night load. This night load consists of 3,800 watt K.V.A. and 1,250 wattless K.V.A., while the two induction generators require in addition 640 K.V.A. to excite them. We shall then have the two synchronous units carrying a load of 2,290 K.V.A. at 52 per cent power-factor and the non-synchronous machines carrying a load of 2,500 K.W. at power-factor of 96.5 per cent.

It is nearly always more economical to supply wattless current in a power station from unloaded high speed synchronous motors, than from the main synchronous generators. This is more especially the case with steam turbine or very slow-speed units, as such machines cannot be economically designed with the good regulation and the margin on the field magnets necessary to handle satisfactorily a low power-factor load. A machine of either of these types to carry satisfactorily a certain kilowatt load at power-factor 70 per cent will be about double the weight of a unit to carry the same kilowatt rating at unity power-factor. In the station considered in the preceding paragraph, we assumed that the synchronous generators supplied the wattless current required for the induction generators and outside circuit. It would be better, however, to make the synchronous generators 1,000 K.V.A. units with poor regulation, and install also a 1,500

K.V.A. high speed synchronous motor to supply all the wattless current. This would give a cheaper and more flexible installation, as we would be able to run the induction generators without the synchronous units at any time, using the synchronous motor to excite them. The induction units would require no direct current exciters, exciting circuits, or switch panels, while they would probably be cheaper than the synchronous generators, simpler to handle, and less liable to break down. The above is sufficient to show that this type has such important advantages that it should be carefully considered in each individual case before deciding to adopt synchronous generators exclusively.

Other Applications of Induction Generators.—In the above remarks, the non-synchronous generator has been dealt with more especially as a steam turbine driven unit for generating alternating current. This type, however, often presents important advantages for other and more especial conditions; two of the most important of which are gas engine driven alternators, and steam turbine driven direct current units. The advantage of the induction generator for gas engine driven units is that it does not require the extreme uniformity of speed required by a synchronous generator; and the advantage of its application for direct current generation by turbine units is that by the use of an induction generator and rotary converter we can avoid the use of a direct current turbo generator.

Gas Engine Driven Units.—With the modern tandem and twin-tandem gas engines, giving respectively two and four impulses per revolution, gas engine driven alternators can undoubtedly be run in parallel. But to obtain the same kind of satisfactory operation that is obtained with steam engines, large fly-wheels and heavy dampers on the pole-faces of the alternators are necessary. Such fly-wheels result in a considerable increase in cost, and sometimes in the floor space taken up by the engine; and also a loss in efficiency due to the increased bearing friction and windage; while there is necessarily a considerable loss in the dampers on the pole-faces of such a gas engine driven alternator, because the irregularity of speed in a gas engine is usually such that the dampers have to perform heavy work in accelerating and retarding the fly-wheels. We can readily see that there can be easily an increased loss of three to five per cent from these two causes, which would not be detected except in a gas consumption test, when running in parallel with other units. Instead of synchronous units, we can install induction generators, and have high-speed synchronous motors running light, to provide the necessary lagging current for the outside circuit and for exciting the generators. In this case any change in load comes first on the synchronous motors, causing a change in their speed, and as a result a transference of the change in load to the generator. As the voltage of the generator would be decided by the excitation of the synchronous motors, the voltage regulation of the station is that of the motors; so that for constant potential it may be advisable in some cases to control the motor excitation by an automatic voltage regulator. The size of the direct current exciter necessary for the synchronous motors would depend on the power-factor of the load on the station, and would be greater, the greater the lagging current required by the external circuit. Generally speaking, the size of the exciter required would be from one-quarter to one-half of that necessary for the corresponding synchronous generators. The probable arrangements would be a direct connected exciter on each synchronous motor, which could also be used as a starting motor; and one gas engine driven exciter for starting up the first motor.

Taking as the load on such a 2,200 volt, 25 cycle power station, 20,000 K.V.A. at 70 per cent power-factor, we would have four 5,000 K.V.A., 75 R.P.M. synchronous generators, each requiring a 125 K.W. exciter; or four 3,500 K.W., 75 R.P.M. induction generators, together with four 4,500 K.V.A., 500 R.P.M. synchronous motors with 60 K.W. direct coupled starting motor exciters. Each synchronous motor would supply the 1,000 K.V.A. exciting current required by one induction generator, together with 3,500 K.V.A. wattless current for the external circuit. The relative efficiencies on the load of 70 per cent power-factor are as follows:

	Synchronous Generator.	Induction Generator and Synchronous Motor.
Full load.........................	95.7	94.0
0.75 "	95.1	93.6
0.50 "	94.0	92.5

These efficiencies given for the synchronous generator do not take into account the additional losses due to the increased friction of the larger fly-wheel, and the losses in the dampers or solid pole-faces which occur with the gas engine driven synchronous generator. These additional losses will reduce the efficiency of the synchronous generator below that of the induction generator set. The cost of the electrical equipment would not be very different in the two cases, and as the larger fly-wheel, shaft, and bearings, required for the synchronous generator would increase the cost considerably, it is probable that the induction generator equipment would be somewhat cheaper. It must be remembered that this is an extreme case, because the low power-factor of 70 per cent taken for the outside load is very much against the induction generator, and that if the power-factor were higher, the result would be more favorable to that type.

It might be supposed that unless the gas engine was provided with a very heavy fly-wheel, there would be the same trouble with hunting of the induction generator and synchronous motor that we would have with the synchronous generator. But such is not the case. There will undoubtedly be cross currents between the machines, the magnitude of which will depend on the variation in the speed of the gas engine, but it will be practically impossible to break them out of step. The worst effect of this interchange of current between the machines is the heating and losses in the armature conductors, and the pulsation in voltage due to the interchange of wattless current. This pulsation of voltage is diminished by dampers on the pole-faces of the synchronous motor, but it will usually be perceptible when only one generator is running. However, as these gas engine driven units will be used mainly for power work in mills, the slight pulsation of voltage will be unimportant.

It is by no means settled that extremely heavy fly-wheels and powerful dampers are a practical and advisable solution of the parallel running difficulties with gas engine driven synchronous generators. So though induction generators are not put forward as the only solution of the gas engine driven alternator question, they probably offer the most practical solution, and the one which will recommend itself most highly to the conservative power station engineer and manufacturer.

Steam Turbine Driven Direct Current Units.—The other special application of the non-synchronous generator above referred to—which is, to operate with a rotary converter to supply direct current—is to meet the special case in which a steam turbine is desired as a prime-mover in the production of direct current by large units. Minimum overhead clearance, small floor space, poor foundations, objection to the vibration of reciprocating engines, high steam economy required over a wide range of loads, reduced maintenance and supervision, might render the adoption of a steam turbine necessary; and as the direct current turbo generator has as yet hardly established its position as a conservative and reliable machine, at any rate in large units, it would be necessary to use some type of alternating current generator in combination with a motor-generator or rotary converter. Two years ago the Milwaukee Electric Railway and Light Co. wished to install an auxiliary 3,000 K.W., 300 volt direct current steam-driven generating equipment in the basement of their new Public Service Building. As the head-room was limited to about 12 feet, and as the vibration would be objectionable, reciprocating engines were out of the question. They installed two 1,500 K.W. horizontal steam turbine driven synchronous alternators, and two synchronous motor-generator sets. This would have been an ideal case for an induction generator and rotary converter. The rotaries could be started from the direct current system, and when up to speed would excite the non-synchronous generators; no exciters nor exciting circuits would be necessary, the voltage being controlled by the excitation of the rotaries. The equipment which was installed has a combined full-load efficiency of about 88 per cent, while the combined efficiency of an induction generator and rotary converter to do the same work would have a full-load efficiency of about 95 per cent, and in addition it would probably have cost about one-third less.

In comparing a turbine driven non-synchronous generator and rotary with a steam engine driven direct current generator, the former is found to be a more flexible equipment, one which will carry heavier overloads; and is usually cheaper. Any compounding desired can be obtained by means of a compound winding on the rotary; while by use of transformers we can operate rotaries at different voltages and supply different direct current systems. The rotary can be located at a distance and the power transmitted to it at a high voltage, or the equipment can be divided up and arranged as we please, while the efficiency is slightly higher on the induction generator equipment than on the engine type, as can be seen from the following table of full load efficiencies for 270-volt generators.

	1000 K.W.	2000 K.W.	3000 K.W.
Steam turbine driven induction generator.....	97.5	98.0	98.25
Rotary converter	97.0	97.5	97.75
Combined efficiency of induction generator and rotary converter	94.5	95.5	96.0
Engine type generator.....................	93.5	94.25	94.5

There are many indications that the day of the large engine-type direct-current generators is past. The inaccessibility of the brushes, the difficulty of building and maintaining a commutator of large diameter, and the numerous other drawbacks of this type of machine have caused it to be regarded as an undesirable addition to a power station. It is a question whether the steam turbine driven induction generator and rotary converter are not superior to the engine driven direct current generator in almost every case, and this combination should always be carefully considered when any new direct-current station is laid out, or any extensions are added to existing plants.

I have endeavored to show that the one great disadvantage of the induction generator—its inability to carry a lagging wattless current load—should not always prevent its successful adoption; and that the important advantages it possesses in its excellent mechanical construction, high efficiency, good characteristics in regard to short-circuits and resonance, strong balancing and damping action, absence of rotating windings or collector rings, absence of direct-current excitation and exciting circuits, ease of parallel running, facility for control of load by governor, and general simplicity and flexibility of operation, render it in many cases the most advisable machine to adopt. This type of generator suffers from the fact that it was judged and condemned in the early days of electric power stations. At that time there was no real field for this generator; but the introduction of the steam turbine and the gas engine, with the modern development of large power stations, have so fundamentally altered conditions, that the induction generator is no longer an interesting curiosity, but one of the most promising types for power station equipment. At the present time this machine can be considered as having been placed on a demonstrated commercial basis; and while it may have limitations, it possesses so many advantages, and its sphere of usefulness is so extensive, that it must be acknowledged to offer greater future possibilities than almost any other type of power station equipment.

NOTE

The following data on the steam consumption obtained from tests at the Baltimore Copper Smelting and Rolling Co. plant referred to earlier in the paper, are of interest in comparing the efficiencies of the two types of direct current generating equipment. The first column gives the actual steam consumption of the 1,200 K.W. steam turbine driven induction generator and rotary converter, the turbine being run with 140 lb. steam pressure, 28 in. vacuum and 135° superheat. The second column gives the corresponding figures on a Corliss engine and direct connected generator, the steam consumption being based on a minimum consumption of 12.5 lb. per I.H.P. at 80 per cent of full load.

POUNDS OF STEAM PER KILOWATT HOUR AT DIRECT CURRENT TERMINALS

Load.	Steam Turbine Equipment.	Corliss Engine Equipment.
0.5 load	21.2 lb.	23.5 lb.
0.75 "	18.2	19.8
1. "	17.5	20.3
1.25 "	17.5	23.2

[Presented before the American Institute of Electrical Engineers, June 29, 1908.]

MODERN DEVELOPMENT IN SINGLE PHASE GENERATORS

The single phase alternator has been in commercial use now for twenty years, and it may seem surprising that there should be new developments at this late date. However, single phase alternators have been used in the past almost exclusively for lighting work, and in units of comparatively small output and low speed. Recently, on account of the adoption of single phase current for traction work, an important demand has arisen for large, high speed, low frequency, single phase generators; and it is in the design and manufacture of such units that the engineer has had to overcome new difficulties. In these large, high speed machines for 15 and 25 cycles the difficulties met with, are due almost entirely to the large pole-pitch and high armature reaction which it is necessary to adopt. A 500 K.W., 60 cycle, 72 pole, single phase generator would have a pole-pitch of about 7 in.; while a 6,000 K.W., 15 cycle, 2 pole machine would have one one of about 120 in. It is easily seen that the design of these two generators will be radically different.

These difficulties in single phase generators of large pole-pitch are the result of:

1. Pulsation of the armature reaction.
2. Mechanical stresses on the ends of the armature coils, where they are not embedded in the laminated core.

The pulsation of the armature reaction causes hysteresis and eddy-current losses throughout the machine, often resulting in dangerous heating and low efficiency. The mechanical stresses on the ends of the armature coils, due to the current, result in vibration or distortion of the windings, and often in damage to the insulation or complete destruction of the coils; these stresses being particularly serious in single phase railway generators, on account of the sudden variations in load and frequent short-circuits to which these machines are subjected. As the effect of the mechanical stresses on the armature coils, and the losses due to the pulsation of armature reaction, increase approximately proportionally to the square of the pole-pitch in generators of standard design, it is easily seen why such effects which were negligible in the old single phase alternators of small pole pitch have become quite important in the modern steam turbine driven generator. The seriousness of these difficulties when first met with was so great, that even within the last two years responsible engineers have stated it was impossible to build satisfactory low frequency, high-speed, single phase generators of large capacity; and it is only by careful study and experimenting that the modern machine of this type has been developed.

Losses Due to Pulsation of Armature Reaction.—In a polyphase generator the armature current produces a magnetic flux which rotates synchronously with the field magnet. This magnetic flux may result in increased losses in the laminated armature core, but being of practically constant magnitude, causes very little loss in the iron of the magnetic circuit. On the other hand, the armature current in a single phase generator produces a pulsating magnetic flux which is stationary in space, and it is easily seen that this flux will cause hysteresis and eddy-current losses throughout the whole magnetic circuit. The exact effect of the armature reaction flux on the rotating magnets depends, of course, on the relative phase of the armature current and electromotive force; that is, on the power-factor of the load carried by the generator. When the power-factor is unity and the armature current is in phase with the electromotive force, the armature reaction flux is a cross-magnetization; when the power-factor is zero and the armature current is 90° out of phase with the electromotive force, the armature reaction flux is a demagnetization. In the special case in which the rotating field magnet is cylindrical, without projecting poles, the effect of the armature reaction flux on the magnets is more nearly independent of the power-factor of the armature current. But in any case this flux is a pulsating one, and there are important losses in the field magnets, due to their rotation through this cross magnetizing or demagnetizing flux. An estimate of the combined losses in the armature and field magnets due to the pulsating armature reaction, can be obtained in a number of ways.

We can measure the increase of the power required to rotate the field magnets due to normal R.M.S. current in the armature coils, with:

1. Direct current in the armature winding.
2. Alternating current of synchronous frequency in the armature.
3. Armature short-circuited and field excited.

Or with the magnets stationary we can:

4. Send normal frequency alternating current through the armature and measure the losses by a wattmeter.

These methods must all be regarded as convenient tests which are found by experience to give some indication of the magnitude of the losses. Method 4 has the additional advantage that we can vary the relative position of the armature reaction flux and the pole-faces, and thus investigate the variation of the losses in a single phase generator with the power-factor of the load.

The only exact methods of measuring the losses are:

1. As unknown losses in a motor-generator (Hopkinson) method efficiency test.
2. From a comparison of the temperature rises obtained on full load with those obtained with known losses.

Unfortunately, both of these tests are difficult to make accurately, especially on a large machine, and probably in practice they do not give results which are any more accurate than the other more approximate methods. So at the present time we have to acknowledge that though we know a great deal about the relative values of the losses under various conditions, our knowledge of their absolute values is limited.

Pole-Face Dampers.—Losses caused by a pulsating flux in the magnetic circuit are due to:

1. Hysteresis.
2. Eddy currents.

And the relative magnitudes of the two depend on the amount of solid metal in the path of the flux. If the whole magnetic circuit is laminated, then the losses are practically all due to hysteresis. On the other hand, if we have solid cast steel poles there will be eddy currents in these poles which will partly choke back the pulsation of the flux so that the hysteresis loss will be reduced. But in this case there will be eddy-current losses in addition to the hysteresis, and the extent to which the total loss is changed will depend on the proportions and design of the magnetic circuit. If we place a heavy copper damper in the path of the pulsating flux, it will provide a low-resistance path for the eddy currents, so that the pulsating flux and consequent hysteresis loss will be reduced practically to zero, while on account of the low resistance of the damper circuit the eddy loss will not be appreciable. The extent to which the losses and the pulsation of the flux vary according to the presence of eddy currents, can be determined for any particular design, by varying the thickness of the lamination, or by changing to solid poles or the addition of dampers. It is usually found that the losses are greatest with heavy laminations or solid poles; that they are less for thin laminations, and practically zero when heavy low-resistance dampers are used either with solid or laminated poles.

Fig. 25 shows the pulsation of the armature reaction flux in a 500 K.W., single phase, 20-pole generator, as determined by means of search-coils wound on the pole-faces. *C* shows the pulsation for laminated poles, No. 29 gauge; *B* shows the same machine with solid poles; and *A* the same solid pole-faces covered with a $\frac{3}{8}$-in. copper plate. The magnitude of the pulsations in the three cases is about in the ratio of from 30 to 15 to 1; thus the copper plate has practically damped out all pulsations, the armature reaction flux becoming constant. In practice, a copper damper usually takes a form similar to the squirrel-cage secondary of an induction motor. Heavy copper bars are dovetailed into the pole-faces, and short-circuited at the ends by copper rings or discs. Fig. 26 shows such a cage damper on the field magnet of a 6,000 K.W., 2 pole generator.

The question of losses due to the pulsating armature reaction in a single phase generator may be considered in another and possibly a simpler way. The single phase pulsating field is equivalent to, and produces the same effect as, two rotating fields each of half its maximum value, one rotating at the same speed and in the same direction as the generator field magnet, and the other rotating at the same speed but in the opposite direction. The flux rotating synchronously with the field magnet, being constant in magnitude, causes very little loss. The flux rotating in the reverse direction causes losses throughout the whole magnetic circuit due to hysteresis and eddies. If a squirrel-cage damper encloses the field magnets, this damper

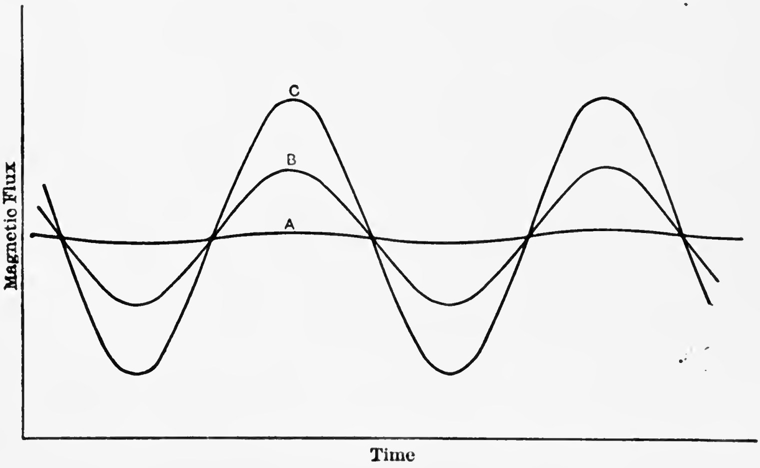


FIG. 25.

system acts in regard to this reverse rotating flux in the same way as the short-circuited secondary of an induction motor or transformer; a current is induced in the damper which produces a field neutralizing the rotating flux. The eddy and hysteresis loss in the iron of the magnetic circuit which would be caused by this rotating flux is thus eliminated, and the only loss is that due to the current circulating in the damper. If we make the conductors forming the squirrel cage of sufficiently low resistance, this damper loss becomes negligible, with the result that the entire loss due to the pulsating armature reaction of the single phase generator is practically eliminated.

To show how serious this matter of losses becomes in high speed, two pole, single phase machines without dampers, the following table is given, showing the loss and full load temperature rise on three turbo generators at full load, both with and without dampers:

TWO POLE, 25 CYCLE, SINGLE PHASE GENERATORS. SAME CURRENT PER ARMATURE CONDUCTOR ONE AND THREE-PHASE, UNDER ALL CONDITIONS, AND ALL LOSSES IN PER CENT OF SINGLE PHASE RATING

Generator Rating.	Type Field.	Three Phase.		Single Phase.			
		Without Dampers.		Without Dampers.		With Dampers.	
		Loss Per Cent.	Temp. Rise, Degrees Cent.	Loss Per Cent.	Temp. Rise, Degrees Cent.	Loss Per Cent.	Temp. Rise, Degrees Cent.
750 K.W.	Solid	0.53	27	3.75	95	0.8	34
1000 "	Solid	0.3	31	3.0	122	0.5	37
1000 "	Laminated	0.2	19	3.8	150	0.3	18

It will be seen that in these three machines, operating single phase, there is due to the pulsating flux an average loss of 3.5 per cent and an average temperature rise of 125° C., without dampers; with dampers the average loss is 0.5 per cent and the temperature rise 30° C. Figures are given only on comparatively small machines on account of the difficulty of measuring losses on large machines. But tests on larger generators up to 6,000 K.W. capacity show that the improvement due to heavy copper dampers is even more striking in large machines than it is in small. So far as experience goes at the present time, it may be said that the use of such dampers is the complete solution of the difficulties due to pulsating armature reaction met with in large, low frequency, two pole, single phase generators.

Mechanical Stresses on Armature Coils.—That it was necessary to mechanically brace the end connections of the armature coils on a direct current machine subjected to sudden loads and short-circuits has been known for many years. But until quite recently additional supports for alternator armature coils were seldom provided. The reason for this was that as the continuous short-circuit current of an alternator is only about two or three times normal, it was not considered that the mechanical stresses on the ends of the small pole pitch coils generally in use were sufficiently great to cause trouble. Only during the last few years has it been demonstrated by experience that coil supports on large pole pitch alternators are not only advisable, but necessary, and that on account of the numerous short-circuits

Fig. 26.—Rotary Field Magnet for 6,000 K.W., 2 Pole, 25 Cycle, Single Phase Generator.

they are particularly necessary on single phase machines operating on traction circuits.

When an alternator is suddenly short-circuited, the first rush of current is limited only by the self-induction and resistance in circuit; and in the case of an alternator of low self-induction, this first rush of current on sudden short-circuit may be 20 to 30 times normal full load current. As the mechanical stress on the end of the armature coils varies with the square of the current, the stress on the armature coils will be 400 to 900 times normal. A 6,000 K.W., 2 pole, 25 cycle, single phase generator has a pole pitch of about 100 in., and the length of the end-connection at one end of one armature coil will be about 180 in. The mechanical stress on the end connections at one end of one armature coil of this machine on a sudden short-circuit is approximately 5 tons; and usually on low-frequency high speed generators of large capacity, the mechanical stresses on the end connections at one end of one armature coil in the case of a sudden short-circuit are from 2 to 10 tons. When it is considered that this results in a sudden mechanical shock to the winding, we can realize the strength of the coil supports required, and can understand the disastrous results sometimes obtained on short-circuits, when such supports are omitted. It is obvious from these stresses that coil supports must be of metal and of heavy cross-section. The difficulty of suitably insulating metal coil supports has caused numerous other materials to be used, but though supports of wood, porcelain, and similar insulating materials have been tried, it is easily understood that they have proved unsatisfactory on machines of large pole pitch. Fig. 27 shows a form of coil support and bracing which has proved very satisfactory for such machines. It consists of a bronze strap which clamps the coils, by means of wood insulating blocks and insulated bronze bolts, to malleable iron brackets, which also serve to support the copper strap connectors between the various groups of coils. The support and its method of application are evident from the illustration; it is placed in position after the machine is wound and is removable in a few

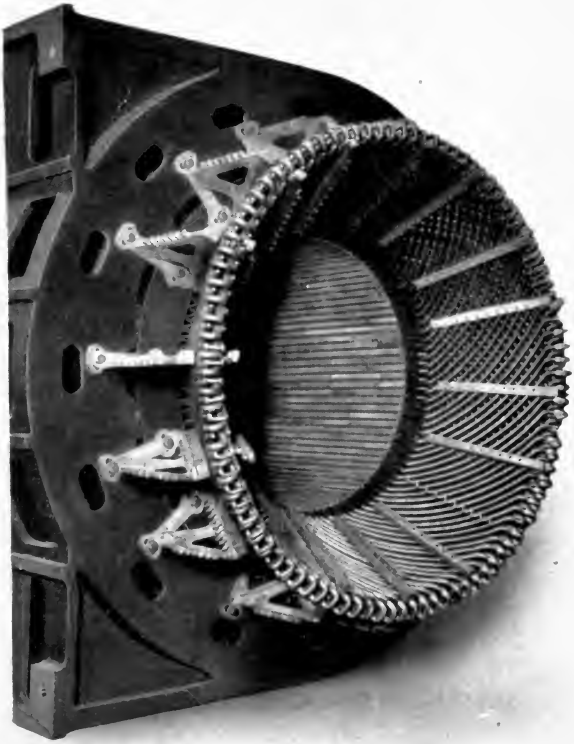


FIG. 27.—Armature Winding of 10,000 K.W., 11,000 Volt, 60 Cycle, 4 Pole Generator Showing Method of Bracing Coils.

minutes at any time. It is not suggested that this is the only satisfactory type of coil support that can be used; it is merely given as a type which has proved successful in actual operation on machines up to 10,000 K.W. capacity, and which has apparently solved the difficulties due to mechanical stresses on the end connecions of large pole pitch generators liable to sudden variations in load or frequent short-circuits.

The two main difficulties met with in large low frequency, high speed, single phase generators, that have been described above, can at the present time be regarded as having been successfully overcome. The use of heavy copper dampers on the pole-faces, and heavy bronze coil supports applied to the ends of the armature coils, in such a way as to take directly the mechanical stresses which develop on short-circuits, has now made such generators a practical success. Like every other new type of electrical machinery, the large turbine-driven, single phase generator has had its period of development, but at the present time it may be said that such generators for 15 and 25 cycle, in units of 5,000 to 10,000 K.W. capacity, can be, and are, built with the same success as that obtained on slow speed polyphase generators.

[*Presented before the National Electric Light Association, June 3, 1909.*]

PERFORMANCE SPECIFICATIONS AND RATINGS

Uniformity of Rating.—The question of uniformity in the rating of generators and motors is in a decidedly unsatisfactory condition at the present time, as almost every manufacturer and every purchaser rates his generators or motors, and specifies their performance in a different way. The result of this is that when an operator decides a new generator is required he specifies as nearly as possible a unit he considers suitable for the work, buys one that the manufacturer estimates will fill his specifications, and then proceeds to test, to find what output he can obtain from it under the conditions that exist in his station. The operating engineer and the manufacturer are both to blame for this state of affairs; the manufacturer because he often designs and builds his machine to take care of some arbitrary theoretical, rather than practical, conditions of operation; and the operating engineer because he does not more closely study the operating conditions of his machinery, and insist that the manufacturer supply generators or motors suitable to his requirements. So long as the mechanical construction of a machine is satisfactory and such that repairs can be easily carried out, no further inquiries are usually made by the purchaser, provided the name-plate carries the nominal rating required. The tendency is to pay altogether too much attention to the figures stamped on the name-plate when buying a generator or motor. The result is that almost every engineer knows examples of units with the same nominal rating, built either by the same or by different

8

manufacturers, some of which under certain operating conditions are capable of carrying 50 per cent more load than others. The remedy for this, of course, is to have some uniform and rational method of rating adopted by all manufacturers, and then to specify and select machines suitable for the work they have to perform.

Temperature and Power-Factor.—The two most important points in which specification and performance guarantees are unsatisfactory seem to be:

1. The temperature rise on alternating and direct current generators or motors; and

2. The power-factor of the load for which guarantees are made on alternating current generators.

The present system of temperature guarantees, which consists in stating the maximum temperature rise in any part of the machine, under numerous different conditions of load and for varying periods, is both unsatisfactory and irrational. The temperature limit of output in any generator or motor is not decided by the temperature rise, but by the absolute temperature of the insulation. At one of the specified loads the armature iron may be the hottest part, at another the field coils, while at a third it may be the armature winding or commutator. As each of these parts has a different limiting temperature to which it can be subjected without damage, it is obvious that such a system of uniform guarantees is misleading. The operating engineer is not practically interested in knowing that the temperature rise of his generator, as measured by a thermometer on the outside of the winding, is 35 degrees on full load for 24 hours, 45 degrees on 25 per cent overload for 24 hours, and 55 degrees on 50 per cent overload for one hour. What he must know is the maximum load he can safely carry continuously, and in some cases the overload he can safely carry for two or three hours. This load depends, obviously, on the room temperature and on the limiting temperature to which the insulation can be subjected without damage. The most rational method of temperature rating is, then, to specify the maximum continuous rating at which the unit can be safely operated with a certain room temperature, *e.g.*, 25 degrees centigrade; and where desirable the safe two or three hour overload, with the same room temperature, can also be given. Usually, in a modern, well ventilated generator or motor, the temperature reaches its maximum after a three or four hour run, so that the two or three hour overload is about the same as the maximum continuous rating. In this case the system of temperature guarantees reduces to a single guarantee of the maximum safe load which the unit can carry continuously, with the specified room temperature; and it should be noted that this maximum load is greater the lower the temperature of the air cooling the machine. This system of maximum rating has been in use to some extent for the past year, and it would seem that the sooner it is adopted universally, the sooner will purchasers have a rational idea in regard to the temperature limitations of the machines they are buying.

Few engineers seem to appreciate the effect of a low power-factor on the operation of an alternator, and few operating engineers consider the power-factor of the load an important point when installing new machinery. When new generators are to be bought, we regularly find 100 per cent power-factor machines specified for a station operating with a power-factor varying from 65 to 85 per cent; and the purchaser becomes suspicious when he is told that a standard 100 per cent power-factor generator would not carry much more than 50 per cent of its rated kilovolt-amperes if operating on his system, or that he ought to buy a more expensive generator which is designed and guaranteed for a 75 to 80 per cent power-factor load. A standard alternator designed for 100 per cent power-factor load (*i.e.*, for rotary converter or synchronous motor work) is usually designed with a comparatively saturated magnetic circuit, and, unless extremely liberally designed, such a machine will not hold up voltage with full rated K.V.A. at 80 or 90 per cent power-factor. If such a machine were required for 80 per cent power-factor, it would be re-designed with an unsaturated magnetic circuit, given a rating of about 75 per cent of its nominal K.V.A. rating at 100 per cent power-factor, and possibly a higher temperature rise specified for the field coils.

Any method of giving alternators a different rating for every operating power-factor would probably be too complicated for practical work. It has, therefore, been proposed to continue to give all machines a nominal rating in kilovolt-amperes at 100 per cent power-factor, and in addition to give the maximum load which they will safely carry at various lower operating power-factors. This maximum load at low power-factors, is decided for some machines by the question of holding up voltage, and for others by the heating of the field coils, so that for cases in which temperature is the limit the maximum load should be referred to a definite room temperature, *e.g.*, 25 degrees centigrade. This method of rating alternators gives for the purpose of comparison a nominal rating at 100 per cent power-factor, and in addition gives the purchaser exact information as to the operative characteristics of the proposed unit under any particular condition of load. If the operating engineer knows the power-factor at which the machine will be required to operate, he should have no difficulty in deciding as to the suitability of the unit for his requirements.

The question of power-factor is equally important in rotary converters and synchronous motors. Generally speaking, the power-factor should always be adjusted to 100 per cent, unless for some special reason, definitely specified and understood at the time the machine was purchased. A case recently came to the writer's knowledge in which a system was operating its rotaries at 90 per cent power-factor, and when the manufacturer protested on behalf of his generators and rotaries, the operating engineer stated that he considered 90 per cent a "mighty good" power-factor. Possibly it would be for induction motors, but for rotary converters it is a "mighty bad" one. Synchronous motors are often used to correct the power-factor of the line, but when they are installed with that intention the maximum kilovolt-amperes at the required power-factor should be specified, exactly as in the case of an alternating current generator. A synchronous motor designed to operate at 100 per cent power-factor, is just as unsuitable for operating at a low power-factor as an alternator would be in a similar case.

Limiting Conditions.—Neglecting the question of efficiency, the limit for operating conditions should, in all cases, be decided by the resultant injury to the machine. The limit of temperature rise is decided by the damage to the insulation, or to the mechanical construction, of the part of the machine considered. Some insulation will not stand continuously a temperature higher than 90 degrees centigrade without deterioration; other insulation will stand 300 degrees safely. The temperature limit on a commutator or collector-rings is usually decided by the shrinkage of insulation or unequal expansion of the materials, causing loss of mechanical balance, or loss of accuracy on the wearing surface. The limit of the allowable sparking on a commutator or collector-rings is the resulting temperature rise, the damage to the surface of the commutator or collector-rings, and the disintegration of the brushes. All these effects must be considered in relation to the duration of the specified load; and as in such cases it is difficult for the purchaser to decide, without an actual test, the amount of damage that will result from a certain condition of operation, he must, to a great extent, depend upon the guarantees of the manufacturer; which guarantees, however, will be subsequently checked by the actual operation of the machine in service.

Testing and Specifications.—Testing to determine in what degree a unit meets the specified detailed performance guarantees is always a very difficult question. It is almost impossible to get an accurate direct test of the voltage regulation of any alternator, as the result is measured only as the difference of two high readings, and a variation in any one of the conditions of test affects the result. Unless made in a laboratory, away from masses of iron which would affect the accuracy of the instruments, an input-output efficiency test of a motor-generator can not be made with a greater accuracy than 2 or 3 per cent on account of the impossibility of obtaining accurate instrument readings under practical conditions. In both of these cases, the direct method of test has to be abandoned in favor of an indirect method, which enables more accurate results to be obtained. Temperature tests are very difficult to carry out accurately, and unless careful precautions are taken by experienced observers, it is often impossible to be sure of results to 5 degrees. Generally speaking, the customer will more profitably spend his time in investigating the conditions of operation, and in specifying a machine suitable to operate under these conditions, than in making tests to determine regulation, temperature rise, and other similar characteristics which will be of only doubtful accuracy and value when made. If a generator or motor is specified suitable for the work, then the most satisfactory and convincing test for the machine is the manner in which it performs its work; and by means of suitable performance specification this should be made something definite, and something to which the customer can hold the manufacturer. If this were done, we should have fewer disputes on the question of whether or not a machine satisfies its contract guarantees, we should have fewer unsuitable units installed, and I think we should have better operating conditions on most power systems.

[*Presented before the National Electric Light Association, June* 3, 1909.]

INPUT-OUTPUT EFFICIENCY TESTS ON ROTARY CONVERTERS AND MOTOR-GENERATORS

The objection to the input-output method of testing the efficiency of rotary converters or motor-generator sets is in its inaccuracy. This is due to the fact that an error of one per cent in any reading results in a one per cent error in the efficiency; and when it is considered that it is very difficult to duplicate instrument readings with a greater accuracy than from one or two per cent, the importance of this objection can be realized. In such a test we have two readings to take, one of the input and one of the output; and an error of one per cent in each of these readings may result in an error of two per cent in the efficiency. The reason for the popularity of the input-output method of measuring efficiency is the extreme simplicity of the test: as it only requires simultaneous readings to be taken of the current, voltage, and watts on both the alternating and direct current sides of the machine. The fact that it is a simple test which is easily made, and that it gives direct readings without any calculation, has led engineers to often overlook the fact that its accuracy under the usual conditions of test is very doubtful.

Measuring instruments, even when carefully calibrated, cannot be relied upon to give readings to a greater accuracy than one per cent under practical operating conditions, and the error is often nearer two or three per cent. The reason for this is that the presence of large masses of iron or stray magnetic fields affects their accuracy very considerably, and these local conditions are continually changing and rarely the same for any two tests. In addition to the inaccuracies of the instruments, errors in observation also affect the results, and it requires extremely careful work on the part of accurate and experienced observers to repeat readings consistently to one per cent. As a result of this, it is very doubtful whether the readings taken under practical operating conditions, in the factory or in the sub-station, can be obtained with a greater average accuracy than two per cent. And, when it is considered that this inaccuracy of two per cent may occur in both the input and output readings, resulting in a possible error of four per cent in the combined efficiency, we can see that such a test is valueless to check guarantees.

An additional source of inaccuracy in a commercial input-output sub-station efficiency test is that due to the power-factor of any synchronous alternating current machine tested, being other than 100 per cent, and that due to the increased loss caused by inaccurate setting and poor condition of the brushes in a direct current machine. There are a number of such conditions which affect the efficiency as tested by this method, which are apt to be overlooked, or which are controlled with difficulty under practical conditions.

When we contrast the above objections with those which can be raised against the separate loss method, we realize that the extra complication of this method is justified by the more accurate results obtained. In the separate loss method each individual loss is measured separately, and a possible error of two or three per cent in the measurement of the losses, will usually not make an error of more than 0.25 per cent in the combined efficiency. Each loss can be measured under favorable conditions, or under the particular conditions which are being considered, and when the test is completed there can be no suspicion that the accuracy of the results has been influenced by unknown factors. Separate measurement of the individual losses also shows at once how the losses are distributed, and allows the operating characteristics of the machine under various conditions of load to be defined more accurately.

The input-output method of testing rotary converters and motor generators has long been considered convenient and sufficient by operating engineers, on account of the ease with which readings can be obtained. But, from what has been said above, it will be realized that the additional time and expense of measuring the efficiency by the separate loss method is well justified by the more accurate results, and by the additional information obtained in regard to the characteristics and operation of the machine. The input-output method can be used as a rough check in cases where accuracy is not of importance, but in all cases where an accurate efficiency test is required there seems to be little doubt that the separate loss test is the only one which can be relied upon.

[*Presented before the National Electric Light Association, May* 26, 1910.]

DIRECT CURRENT TURBO GENERATORS

Direct Current Supply.—Large lighting and railway central stations supplying power to direct current systems are gradually abandoning the use of direct current generating apparatus, and are instead generating alternating current, which is transformed to direct current after distribution to sub-stations. But the number of small power stations and isolated plants generating direct current is increasing yearly, while the use of direct current for excitation of alternators, or for train lighting, also creates a large demand for small and medium size direct current generators. It has long been recognized that this demand is most satisfactorily met by some form of direct current steam turbine driven set. The difficulty in building such a unit is to design a direct current generator which will operate satisfactorily at the high speed required for the economical operation of the steam turbine.

The advantages of the steam turbine set are smaller floor space and lower maintenance, due to absence of reciprocating parts. And as these advantages are often relatively important, several methods have been employed for obtaining direct current from a steam turbine driven generator. The most important of these are:

1. A direct current generator direct connected to the steam turbine, and designed to operate satisfactorily at the high speed required.
2. A unipolar generator.

3. An alternating current synchronous or induction generator direct connected to the steam turbine, and supplying current to a rotary converter which transforms the alternating to direct current.

The rotary converter method has, up to the present time, proved to be the most conservative arrangement, and probably will continue so for large units. The unipolar generator has been used in a few special cases, but both it and the combined rotary and alternating current generator, are at the present time being gradually displaced by the direct-driven direct current turbo generator for all small capacity units.

Historical.—Direct current turbo generators have been built in Europe for the past fifteen years, but their design and operation has not until recently been sufficiently satisfactory for them to be considered under American conditions. The early direct current turbo generators were built with smooth core armature and copper brushes, so that the operation was poor. Recently, however, several European manufacturers have built direct current turbo generators in sizes up to 1,250 K.W. and 4,000 amperes which have proved much more satisfactory. All the machines above referred to operated with metallic brushes, and naturally suffered from the handicap of excessive maintenance cost. But about two years ago, when the direct current turbo generator was extensively adopted, the question of maintenance became so serious, that operating engineers took matters into their own hands and insisted on replacing the metallic brushes by high-grade carbon or graphite brushes. In a number of instances these European direct current turbo generators, which were originally built and shipped from the factory to operate with metallic brushes, have, because of the difficulty of keeping this brush gear in running condition, been modified after installation, so as to operate with carbon brushes. The result of this has been that European manufacturers are now adapting their machines where possible to operate with carbon brushes. American manufacturers realized early that the direct current turbo generator would never be a satisfactory commercial machine until it could be built with carbon brushes. But it is only within the last five years, that the skill of designers and manufacturers has been equal to constructing direct current generators to operate satisfactorily with carbon brushes at speeds materially higher than those of the standard belt-driven generator. By careful design with auxiliary commutating poles and by accurate shop-work it has been possible to build motor-generators for double the speed which was formerly considered possible, while the development of direct current generators for coupling to steam turbines has proceeded under the same conditions. It can now be considered that the direct current turbo generator has been developed, suitable for satisfactory operation with carbon brushes under American conditions. They are being built in sizes from 10 to 300 kilowatts at 125 volts, and from 50 to 500 kilowatts at 250 volts, while designers are working on still larger units. Although 600 volt generators do not seem to be in a great demand for this type of unit, a number

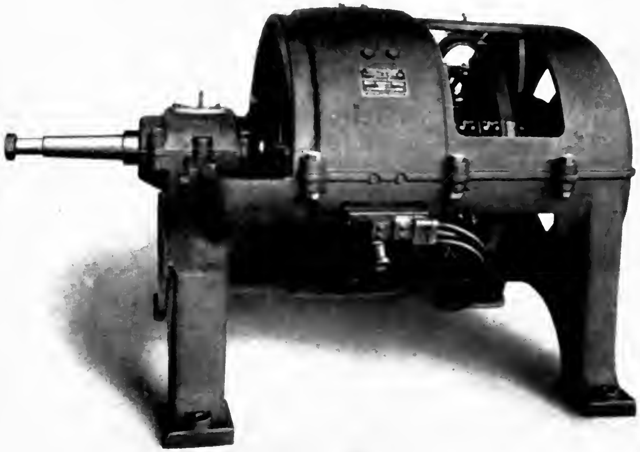


FIG. 28.—50 K.W., 125 Volt, 3,000 R.P.M., D.C. Turbo Generator.

have been in satisfactory operation for some time, notably a 1,000 K.W. unit (consisting of two 500 K.W. generators coupled to one steam turbine), operating at 1,500 R.P.M., which was installed by the North Shore Railway Company, California, in 1907.

Designs.—The following is a list of approximately standard speeds which have been found most suitable for these generators:

K.W.	R.P.M.	Volts.
10	6000	125
25	4500	125
50	3000	125 and 250
75	2800	" " "
100	2400	" " "
150	2200	" " "
200	2000	" " "
300	1800	" " "
500	1500	250

All of which machines can be satisfactorily built to operate with commutating poles when carefully designed. At one time engineers considered that a commutating pole of almost any design was a universal remedy for all commutating troubles, but experience with direct current turbo generators and other high speed machines, has shown that this is very far from being true. The commutating pole must be proportioned as carefully as the other parts of a machine; and it was the neglect of this fact which caused the failure and abandonment of this device when first used many years ago.

The two factors which limit the design of direct current turbo generators are the commutation, and the collection of large currents at high speeds. The commutating difficulties can be satisfactorily overcome in the generators given in the above list, if a properly designed interpole construction is used, though for generators of more special or more extreme ratings a complete system of distributed compensating winding in the pole-faces is usually necessary. The limiting speed for which it is possible to build large direct current turbo generators is decided by the maximum commutator peripheral speed, which can be conservatively operated with the particular grade of brushes adopted. The following equation limits the design of the commutator:

Commutator peripheral speed = Circumferential distance between brushes on the commutator × the number of poles × R.P.M.

The minimum distance between brush-arms on the commutator, which can be conservatively allowed for any given voltage, is definitely fixed by the mechanical clearance necessary for accessibility and to prevent flashing, and by the space required for the necessary number of commutator segments per pole. The number of poles is decided by the current the machine is to commutate. The maximum commutator peripheral speed is decided by the standard of workmanship and by the type or quality of carbon brushes adopted; while the revolutions per minute should be fixed by the question of maximum economy for the steam turbine. Thus we have the above equation stating a relation between a number of factors, each one of which is subject to restriction.

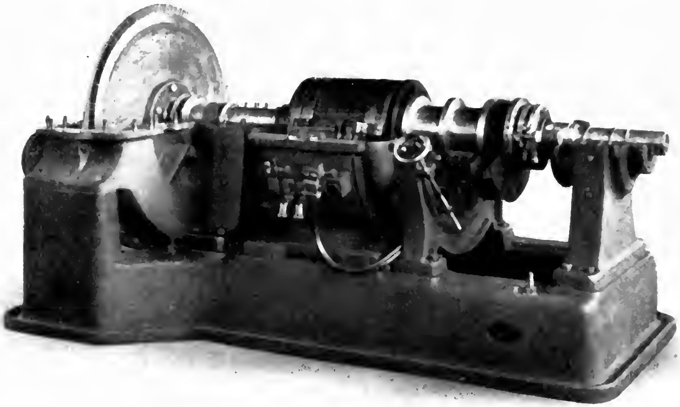


Fig. 29.—100 K.W., 125 Volt, 2,400 R.P.M., D.C. Turbo Generator.

As an example of this we can consider a 500 K.W., 250 volt direct current turbo generator, to operate with a commutator peripheral speed of 5,500 feet per minute. We have 2,000 amperes to commutate, which will require at least four, and preferably six poles. The minimum allowable distance between brushes on the commutator for a machine of this size and type is about 7 or 8 inches, while preferably it should be 10 or 12 inches. The more conservative figure would result in a 14-inch diameter commutator at 1,500 R.P.M. for a four-pole machine, or a 21-inch commutator at 1,000 R.P.M. for a six-pole machine, though adopting $7\frac{1}{2}$ inches distance between brushes we could operate the six-pole machine at 1,500 R.P.M., using a 14-inch diameter commutator. But adopting the more conservative figure, and a four-pole machine at 1,500 R.P.M., we must commutate 1,000 amperes per pole, which will require approximately twenty-six $1\frac{1}{4}''$ x $\frac{3}{4}''$ brushes. Thus we will require a commutator 14 inches in diameter and approximately 56 inches long, or two commutators each 14 inches in diameter and 28 inches long. This example shows the difficulties in operating large direct current turbo generators at high speeds when a conservative design is followed; and explains also why generators of extreme rating, in regard to voltage or current, become so difficult to build.

Commutator and Brush-Gear.—On account of the careful design and accurate shopwork required, the question of collecting large currents at high speed with carbon brushes is the most difficult problem in connection with the design and manufacture of direct current turbo generators. Flexible metallic brushes will operate whether the commutator runs true or not; while having low contact resistance, they are suitable for collection of large currents; and this explains why they were adopted universally on the early European machines. The difficulty in operating with this type of brush is due to the fact that it is almost impossible to entirely eliminate sparking, unless carbon trailing tips are used; while it is necessary to keep the brushes carefully trimmed if the operation is to be at all reliable. If the brushes are not trimmed frequently, the trailing edge of a copper gauze or wire brush becomes ragged, and when the brush is in such condition a short-circuit or sudden violent change in load is liable to make the machine flash over. A new type of copper-leaf-graphite brush has been used recently in Europe with better results, but the operation cannot be considered satisfactory, and the cost is high. Carbon trailing-tips have been used with metallic brushes, but this results in a complicated and sensitive brush-gear, which is almost as difficult to manufacture and keep in operative condition as a brush-gear using entirely carbon brushes. The only reason for the adoption of a carbon trailing-tip and copper brush combination is that it makes possible the use of a smaller commutator than would be necessary with all carbon brush-gear. In addition to the excessive attention required, the life of metallic brush-gear of all types is so very short that the cost of maintenance usually becomes prohibitive; and this is the main reason why engineers consider that the only satisfactory solution of the commutator problem on a direct current turbo generator is the use of carbon or graphite brushes. The better the quality of these brushes, the more satisfactory the operation, but the greater the difficulty of obtaining spare brushes for renewals. It is an open question whether it is better commercially to design these machines to operate with ordinary good quality graphitic carbon brushes, or with some special high grade imported brush. There is no question, however, but that the direct current turbo generator should have only carbon or graphite brushes if it is to give satisfactory commercial service under American conditions.

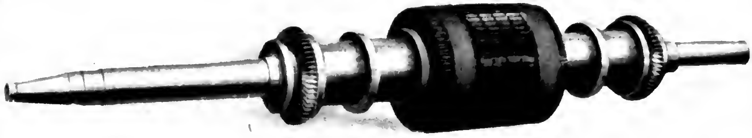


FIG. 30.—Armature for 200 K.W., 125 Volt, 1,800 R.P.M., D.C. Turbo Generator.

The question of good operation with carbon brushes is a mechanical one, and requires a commutator which runs absolutely true under all conditions and at all times. Commutators to carry a large current at high speed are always relatively small in diameter and long. The diameter is fixed by the revolutions per minute, and the maximum peripheral speed which can be satisfactorily operated with the particular grade of carbon used, and with the degree of accuracy obtainable in the commutator manufacture. The peripheral speed usually adopted at the present time in America is from 4,500 to 6,000 feet per minute, although peripheral speeds 40 per cent higher than this have been used by European manufacturers with a special grade of brush. With the diameter fixed, the length of the commutator is decided by the questions of temperature rise and correct spacing of the requisite number of brushes. When the length of the commutator is greater than about 30 inches it becomes usually advisable to build two commutators of half the length instead of one of full length. These two commutators can be arranged either one at each end of the armature, or both in tandem at one end of the armature; in the latter the bars of the two commutators being connected by suitable lugs. A difficulty which is experienced with any long commutator, or with two commutators in tandem, is the lack of uniformity in the distribution of current between the different brushes on each brush-arm. With two commutators, one at either end of the armature, we have difficulty in distributing the current equally between the two commutators; this difficulty being especially marked if a single armature winding instead of two independent windings is used. The difficulty in obtaining uniform distribution of current is about the same with each of these three types of commutators, and it can be avoided only by selection of a suitable type of brush-holder, with good quality brushes of uniform quality, and a suitable arrangement of generator leads.

The standard construction adopted for direct current turbo generators is a cylindrical commutator of the shrink-ring type. Radial commutators have been used to a certain extent in

Europe with good results, but the inaccessibility of the brushes has prevented their extensive adoption. The only advantage claimed for them is a reduction in over-all length, and less trouble due to vibration of the armature caused by lack of balance. This latter advantage is due to the fact that the operating surface of the commutator is at right angles to the shaft, and consequently in the same plane as any vibration, instead of being at right angles to such a plane, as is the case with a cylindrical commutator. The standard cylindrical shrink-ring type of commutator is in small sizes built directly on the shaft, while in large sizes it is built on a bushing. The success or failure of a commutator depends upon extremely accurate shop work, and on the adoption of a design such that the deflections and stresses due to centrifugal action and temperature variation are moderate. Accurate and experienced shop work is the foundation of all good operation in direct current turbo generators, and it is this education and development of the shop as much as anything else which has rendered this type of generator possible.

The manufacture of high-speed commutators differs from that of the corresponding low speed in that much greater accuracy is required. The micanite or mica used in the construction, instead of being a heterogeneous combination of mica and shellac, must be built up of carefully gauged and selected mica segments of uniform thickness regularly arranged and cemented together with the minimum amount of shellac. This micanite has to be suitably treated so that it takes its final dimensions before being placed in the commutator. Every element in the commutator, that is, the copper, micanite, bushing and shrink-rings, must be accurately gauged, and after the commutator is assembled it must also be carefully seasoned, so that there remains no possibility of distortion or of change in the relative position of segments after the machine is placed in operation. Variation in temperature and mechanical stresses are the primary causes of commutator mechanical trouble, and the more perfect the commutator the better will it stand these. The V-ring type of commutator is unsuitable for long high-speed commutators of small diameter, as with this construction it is difficult to keep the mechanical stresses within reasonable limits, and the advantage of the shrink-ring construction is that the stresses can be directly calculated and arrangements made to take care of them. The shrink-rings should be of high grade steel of sufficiently heavy section, so that the stresses due to centrifugal action become moderate. They must also be stiff enough to retain their circular form and to prevent any local distortion of the commutator.

Practice varies in regard to undercutting the mica segments. When soft graphite brushes are used, undercutting the mica segments is essential for good running, but with hard brushes it is not. Probably the best results are obtained on these high-speed commutators when graphite brushes and undercut mica are used. The undercut grooves should, however, be cleaned out occasionally to prevent the accumulation of carbon dust and dirt.

Mechanical Construction.—The mechanical construction of the armature is of great importance, since it is essential that the balance of the armature should not change after the machine is put in operation. This necessitates that the punchings do not become loose nor move on the shaft, and that the armature winding does not move under the action of centrifugal forces. The punchings are usually either pressed on the shaft one at a time, or built up on a mandril bored out, and shrunk on the shaft, no intermediate spider being used on account of the small diameter. Opinion varies as to whether the armature coils are better held in position by wedges or by wire bands, but the most satisfactory arrangement seems to be the use of bands on the small, and wedges on large armatures. The end connections on the armature are probably better held in position by steel wire bands. Bronze rings have been used for this purpose, but there is danger that they may become loose and change the balance of the armature, as it is very difficult to fix them securely. The question of insulation of the armature winding is extremely important, as the armature winding is exposed to carbon and copper dust from the commutator, and the collection of dirt on such a high speed armature is very much greater than on the corresponding low speed. On account of this it is necessary to be extremely careful in insulating all bare metal on the armature, so that there will be no danger of flashing over dirty surfaces to ground; while the insulation on the armature coils must be carefully baked and pressed, so that there will be no shrinkage and consequent movement of the coils. The whole question of satisfactory armature and commutator construction lies in working out the numerous details in design and manufacture, so as to obtain an armature and commutator, satisfactory both mechanically and electrically at the time it is built, and so thoroughly seasoned before put in operation that it will not change appreciably with time.

The question of vibration is one of the most serious difficulties to be considered in these machines. It is difficult to predetermine the critical speed of a direct current turbo generator armature; but it is very important that this critical speed of the generator, when coupled to the steam turbine, shall not be close to the normal running speed. This usually requires that the armature must be designed with the maximum possible diameter of shaft, and it is generally necessary to sacrifice the advantage of low commutator peripheral speed to enable a sufficiently stiff shaft to be used. The question of permanency of balance is equally important, and this requires that there be no relative movement of the component parts of the armature with time, and also that the shaft neither spring nor deflect under the influence of the temperature variations obtained. Direct current turbo generators as built a few years ago would operate perfectly on test, when first built, but after running six months mechanical vibration and deterioration of commutator were frequently so great that they could no longer be considered commercial.

One of the most satisfactory constructions for small units is a two bearing set, the turbine wheel being overhung and the two bearings self-aligning; as this construction obviates any trouble due to lack of alignment. With larger units, however, it is no longer suitable on account of the axial space required by the turbine, and a three or four bearing set with a coupling, preferably a rigid one, beomes necessary. Such sets again require careful alignment and careful fitting of the coupling and bearings; otherwise there will be trouble with vibration. Oil-ring lubrication is effective in the smaller sizes, but forced flow lubrication is usually required in capacities above 50 K.W., if the temperature of the bearing is to be kept within reasonable limits and operation to be reliable.

Foreign practice is usually to completely enclose the armature, except the commutator, and to supply cooling air from a special duct. This is hardly considered good American practice on account of the difficulty of access, and usually on small machines a semi-enclosed construction with natural cooling is adopted. On large machines, however, as the noise is appreciably more than in corresponding low-speed units, it may ultimately be found advisable to adopt a more enclosed construction.

Present Situation.—At the present time the direct current turbo generator can hardly be considered as commercially suitable for the American market above 500 K.W. at 250 volt; and the probability is that in larger sizes it will be necessory, for the present, to use an alternating current turbo generator and rotary converter as a substitute, though this substitute may be only temporary in the 750 K.W. and possibly the 1,000 K.W. sizes. Considerably larger sizes are at present in use in Europe, but it should be remembered that operating conditions there, are by no means as severe as they are here. A typical example of European direct current turbo generator installation which was recently inspected by the writer on a large steamship, exemplifies this latter point. It consisted of four units operating with metallic brushes; the normal load being sufficient only to fully load two machines, and the load being changed around from one unit to another. The generators after operating six days in this way were subject to three or four days' overhauling while the boat was in port, which overhauling consisted in replacing the brushes with a newly trimmed set, and in carefully sand-papering the commutator and adjusting the brushes. With this attention the units gave very good satisfaction, but it is obvious that such results, and they are to be expected from the use of metallic brushes, make these machines unsuitable for the American market. It is the necessity of developing direct current turbo generators capable of operating with carbon brushes and a minimum amount of attention, that has caused American manufacturers to delay in placing this type of machine on the market. At the present time such units can be considered commercial in the smaller sizes, while there is the possibility of larger units being developed in the future.