The Story of the Induction Motor

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This paper covers the history of the technical side of the development of the induction motor, principally as the author saw it. It indicates the various stages of development from the early Tesla motor, with polar field construction, to the distributed field construction, and from the early wound-rotor type to the later almost universal cage type. Reference is made to the development of the cage motor with high starting torque, and the reasons which led up to it. The early single-phase induction motor is also treated, indicating various stages in its development.

The latter part of the paper covers the growth of the motor as an industrial apparatus and its application to various unusual services, such as heavy mill work, locomotive operation, ship propulsion, etc. Speed control of such motors is also described.

The papers refers, principally, to American practise, although occasional reference is made to foreign work. The description covers, primarily, the development work of the company with which the writer is connected, and reference to the work of other companies is incidental, due, largely, to lack of sufficient inside data.

LOOKING back over the technical history of the induction motor, we see an apparatus which is of extreme theoretical interest, and, at the same time, is of inestimable practical value. It is impossible to define just what effect it has had upon the general development of the electrical industry. It is probably safe to say that without this motor the whole trend of the art would have been greatly modified; for unquestionably the induction motor has had a very great part in placing the polyphase alternating current system in its dominating position of today. Practically 95 per cent of the generated electric power of today is by alternating current. It is beyond belief that the a-c. system could have reached anything like this dominating position if there had been no induction motor for the utilization of alternating current for power purposes. The induction motor should, therefore, be considered as a fundamental element in the alternating current system as a whole.

Considering the importance of the induction motor, the writer has considered it to be of interest and value to record a history of its development as given in the following pages. It should be understood distinctly that this applies only to American development, and only insofar as has come within the writer's knowledge and experience. European countries, it should be understood, were not behind America in the development of the motor itself, and, in fact, in some ways Europe was a year or two ahead. The historical Lauffen-Frankfort experiment of 1891, where a relatively large induction motor was operated over a long transmission line, is a good example. The story of the European development would be a most interesting account in itself and, unless this is soon recorded, undoubtedly valuable parts of the early history of this work will be lost.

This story, as presented, covers principally those developments with which the writer has been in more or less personal contact through his connection with one of the large manufacturing organizations. If members of other organizations would record their part of the story, it would undoubtedly be of material benefit to future engineers. All manufacturers have had their troubles and their successes and their triumphs and discouragements, presumably pretty much as shown in this story. It is one of the greatest misfortunes of the engineering profession that so few of the great pioneers and the development engineers have recorded the steps which have led to success or failure. With such a record, a failure may be of just as much value as a success, for the art is built upon failures as well as successes.

The induction motor, in its early days known as the "Tesla motor", appeared in 1888. It is difficult to say just when it was invented. Tesla invented it without question. Professor Ferraris also invented it. Shallenberger was treading on its heels in his alternating-current motor-driven meter. Bradley was very close to it in his polyphase synchronous converter. Thomson was also close to it in his three-coil arc machine. All of these men were working independently of each other, so that it appears that the induction motor was bound to be invented sooner or later. However, to Tesla belongs the true credit of independent invention and of bringing the matter before the public in such a way as to lead eventually to practical results.

When the Tesla motor first came out, it was doubtful whether anyone had any real conception of its actions or its characteristics as we now see them. Tesla knew two things, namely that if a magnet was moved across a conducting surface or plate, it would tend to drag the plate with it, and that the action of such a moving magnet could be produced by out-of-phase alternating currents. These are very elementary conceptions, but, come to think of it, what more fundamental conception of the real operation of the induction motor can there be, than the above? The induction motor of today is simply the above action put in practical form. True, it is an immense jump from these early conceptions to the practical machine of today. The intermediate gap has required years and years of highest effort to span, and unquestionably some of the best analytical ability expended in the electrical field, has been on the induction motor problem The development of the induction motor being, in reality an analytical problem, it did not make much

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headway in the "cut and try" days of 1888 and '89, when the Westinghouse Company was undertaking to put it into commercial form. Our only frequencies in those days were 133 and 125 cycles and the only alternating current supply circuits were single phase. None of these were suitable for the new motor and, therefore, it was badly handicapped at the start. In

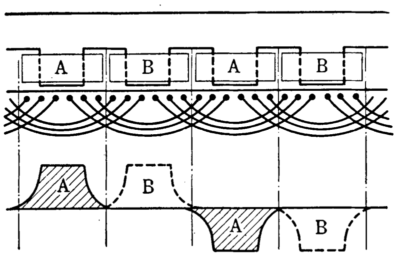

FIG. 1

fact, it was an almost hopeless proposition to bring it out commercially. However, the full extent of the handicap was not fully realized at the time and, therefore, a vast amount of development work was carried on with the idea of producing an operative device. Tesla worked on this development himself in 1888 and '89 assisted by Mr. C. F. Scott who later took charge of the development and made very important advances. Considering the lack of knowledge of magnetic problems and conditions of those days, it is really a source of surprise that Mr. Scott developed the motor as far as he did. He devloped the slotted secondary, with overlapping distributed winding, up to a quite effective point. Apparently he did not fully recognize the relations of secondary resistance to starting torque, nor did he know the inherent speed-torque characteristics of the machine, but neither did any one

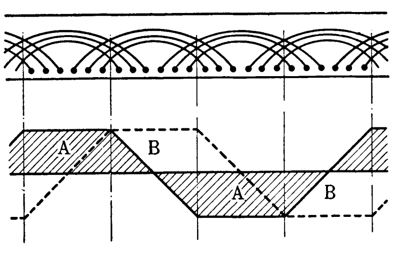

FIG. 2

else. In fact, a full working knowledge of the characteristics of the induction motor did not develop until some years later. However, Mr. Scott's work showed quite clearly that the motor required some materially lower frequency than any in existence at that time, but as such lower frequency and polyphase circuits were not yet in existence he was fighting a hopeless battle for the motor.

These early Tesla motors, as developed by Mr. Scott, showed quite good operating characteristics and might have proved commercial with suitable supply circuits. In fact, some small installations for operating mining machines were made near Pittsburgh, which were successful from the motor standpoint. Yet the motors were fundamentally handicapped in one feature, namely, the primary flux distribution. In those days, distributed field or primary windings were unknown and only the simple polar types of magnetic construction were recognized. In consequence, these early induction motors were made with distinct polar projections, each projection carrying a primary or field winding, with alternate coils belonging to one phase of a two-phase circuit. The flux, therefore, of the adjacent poles or phases did not overlap each other as in the modern induction motor and uniform progression of the magnetic field, as we now understand it, was not possible. This early arrangement might be illustrated by Fig. 1. Obviously with such an arrangement, the magnetic field of one pole covered a relatively small percentage of the pole pitch, and one of the greatest steps forward, in motor design, was the recognition of the advantages of distributed overlapping primary windings. The difference may be illustrated by Fig. 2. Here it may

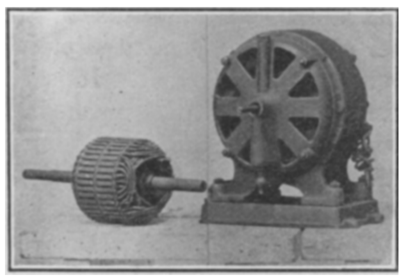

FIG. 3

be seen that the magnetic flux per pole covers practically the whole pole pitch as compared with one-third of the pitch in Fig. 1. Moreover the magnetic field can progress at a comparatively uniform rate and the resultant of two phases can give a magnetic field comparable with either one of the phases. Fundamentally, the more important feature in the distributed field winding is the large magnetic flux per pole compared with the former construction. This has a direct bearing upon the output characteristics of the machine. With the same expenditure in magnetizing current, an increase to two to three times the total flux means a revolutionary improvement in the characteristics of the machine in general.

When Mr. Scott dropped the work in 1890, primarily due to the handicap of unsuitable supply system, as mentioned before, but also due to financial stresses in the company's affairs, he had probably gotten out of the motor about all that was possible with the type and construction and knowledge at hand. As stated before, he had a distributed short circuited secondary winding adapted for averaging the torque conditions, although not of a type desirable for later machines; he had an odd or hunting tooth in the secondary to lessen magnetic locking; he also tried the skewed secondary construction; he had a relatively small air gap; and he had a well laminated primary structure. In general appearance, the motor was not unlike some of the induction motors of today, see Fig. 3. This was a prideworthy result, considering that it was developed largely by "cut and try" methods.

In 1890, this induction motor development as a whole, was dropped by the Westinghouse company and was not taken up again actively for about two years, although some slight experimental work was carried on meanwhile.

During 1890 and '91, slotted type armatures for railway motors and direct-current generators were developed by the Westinghouse company to supersede the older surface-wound types. In carrying out this work, the writer considered the use of similar types of windings for alternating-current machinery and even built a slotted type single-phase alternator armature, as early as 1891, this having a large number of slots per pole. These developments led to the consideration of the use of a direct-current type of slotted armature winding for generation of *polyphase* alternating current and it was recognized that the mere addition of polyphase collector rings to the armature winding of a direct current machine would allow it to be operated as a polyphase alternator. This was principally in connection with the possibilities of building synchronous converters. This work also led to the consideration of similar types of windings on induction motors. This led the writer to take up the induction motor problem, in his idle moments, and in working out the idea of a distributed polyphase winding of the above type, he realized that the magnetic conditions set up by such a winding would be far superior to those of the early Tesla motors. He explained this matter to Mr. C. F. Scott, who was very much interested, and it was then suggested that the writer take up this work, at the first opportunity, with a view to building such a motor. Mr. Albert Schmid, then superintendent of the company, was also so much interested that he soon authorized building such a motor experimentally This was undertaken about 1891. The induction motor situation looked more promising at that time, for in 1890, it had been decided, after careful consideration, that a new standard frequency, much lower than 133 cycles, should be adopted by the Westinghouse company. Mr. L. B. Stillwell, who was giving this matter active attention, finally, after considering all sides of the question, recommended in favor of 60 cycles, and, in 1891, this was making some progress. This, therefore, indicated that one handicap on the induction motor would soon be removed. It is true that polyphase circuits had not yet come, but we were hopeful in those days that this would be one of the next advances.

This first motor with distributed windings, was tested in 1892. This motor had both distributed primary and secondary windings, with a number of secondary slots prime to the field slots. The secondary winding was of a polyphase type, short-circuited on itself at the polyphase terminals. The stator was the primary and the rotor was the secondary. In fact, this motor resembled very much the modern induction motor.

On test, this motor gave very surprising results, compared with anything which had gone before. Its pull-out torque was very large and its starting torque was very much better than expected. In fact, we felt that we had here practically a commercial motor. The interesting feature was that the current capacity of this motor was materially larger than anticipated, probably due to the effect of the distributed winding in dissipating the heat. Taken all in all, this motor was most satisfactory in showing that very good induction motors could be built when the proper time came.

An interesting test in connection with this motor was in determining the effect of short-circuiting the secondary winding from coil to coil, instead of the usual polyphase terminals. In the final test, the insulation was scraped or burned off the end windings of the secondary, exposing the bare copper, and the ends were then thoroughly soldered together, thus making a continuous ring of metal at each end. In other words, this was practically a modern type of cage winding. On test, this showed even better results than before and proved conclusively that short-circuiting of all the end windings together was, if anything, much better than simply short circuiting the groups of windings on each other. In other words, this was an early proof that the cage type secondary was a most effective type where the starting conditions would permit. However, the cage type secondary had been tried in Europe at a still earlier date.

For a year or so, the induction motor development lagged due principally to the fact that there were yet no supply systems. In the latter part of 1892, however, the Westinghouse company prepared designs for a large induction motor to be used in connection with the World's Fair exhibit at Chicago in the following year. This motor was actually built and put on exhibition and a description may be of interest as it was apparently the first quite large induction motor put in operation in this country.

The World's Fair lighting system, as laid out and installed, was 60 cycles, single phase, 2200 volt. However, in the early stages of the development of the lighting machinery, Mr. Westinghouse suggested that this would be a good opportunity to illustrate the possibilities of the polyphase system, and, therefore, he proposed that the generating units, of 1000 h. p. each, be made with double fields and armatures, that is with two 500 h. p. machines side by side on the same shaft, but with the single-phase armature windings of the two units displaced 90 deg. from each other. His idea was that the general lighting of the exposition would be from single-phase circuits, as was the usual practise in those days, but by bringing two out-of-phase circuits to the same locality, polyphase current would be available for operating polyphase apparatus. This arrangement was adopted and, therefore, this Chicago exposition represented the first large installation of polyphase generating machinery in this country.

On account of the availability of polyphase current, a special polyphase exhibit was then devised for the Electricity Building at the Fair. In this exhibit was a 300-h. p., two-phase 220-volt induction motor, to be operated from the polyphase lighting circuits. This motor in turn was belted to a 500-h. p. a-c.-d-c., 30-*cycle*, generator for delivering 550 volts direct current and approximately 390 volts, two-phase, from its collector rings. The low-frequency current from the a-c. side of this a-c. - d-c. generator was then carried, through step-up and step-down transformers, to the collector rings of a machine of corresponding size, used as a synchronous converter, to deliver direct current at about 550 volts. This synchronous converter was started by means of an auto-transformer on the a-c. side, with five voltage steps. In addition, a synchronous converter of about 50 to 60 h. p., giving about 60 volts d-c., was also operated. It can thus be seen that this was a true polyphase exhibit and it was very much ahead of its time, as neither induction motors nor synchronous converters were yet on the market. Moreover, the 300-h. p. induction motor was apparently far ahead of anything yet built, in regard to capacity. This motor had a rotating primary with stationary secondary. It had twelve poles and the distributed primary winding was of cable threaded through partially closed slots, this construction being adopted in order to decrease the primary magnetizing current, thus indicating that even at that early day this feature was quite fully appreciated. The stationary secondary also had partially closed slots with one conductor per slot, these conductors being connected to give two secondary circuit 90 deg. apart. When the motor reached full speed the secondary circuits were short-circuited, but during starting they were closed through a series of long heavy carbon rods, placed in a basement beneath the exhibit, these rods being used for starting resistance. Not much was known about starting resistances in those days, and, as this carbon starting outfit would sometimes get red hot while the motor was being brought up to speed, it was not considered desirable to let the public see it. However, the arrangement was quite effective and, although crude, nobody knew anything better. This exhibit was started about the first of July, 1893, being late in delivery due to the many new features involved. When this exhibit was first started it created quite a commotion, as many of the neighboring exhibitors had concluded that the apparatus was never intended to run. It made enough noise to attract an undue share of attention and, therefore, was quite successful as an exhibit. The writer was present during the starting and the first few days of operation of this exhibit and noted many amusing incidents. For instance, one morning he observed a very intelligent looking man staring quite intently at the large induction motor. Upon being asked if he wanted to know something about it, the man said that he wanted to know what kind of a machine that was. Upon being told that it was an induction motor of 300 h. p. capacity, he blurted—"My Lord! I didn't know they made them that big." He then explained that he was a college professor from a southern university, and was quite interested in induction motors, but thought that they were built mainly on paper and didn't know that induction motors had been made which would run and carry loads. This is an instance of the kind of attention the apparatus attracted.

Something should be said here concerning other polyphase exhibits at the Chicago Fair. The A. E. G., of Berlin, had an exhibit right across an aisle from the Westinghouse. This exhibit while much smaller and less pretentious than the Westinghouse, was quite interesting as it contained a small polyphase generator, of about 100 kw. capacity, and an induction motor of about 75 h. p. This exhibit was in the charge of a young engineer who was apparently concerned simply with technical matters, while the daily operation was in the charge of an older man. A few minutes after the writer first called at the Westinghouse exhibit, he was informed of the A. E. G. exhibit across the aisle and immediately visited it. Upon examining the A. E. G. generator and noting its *distributed* armature winding, he asked the young engineer who was present, how the regulating characteristics of the distributed armature winding compared with those of the toothed type. The German engineer looked at him and replied—"Ah, you are from the Westinghouse company", and he volunteered nothing further. An interesting thing about this A. E. G. induction motor was the use of a water rheostat in the secondary, for starting purposes. One evening when the jury on electrical awards visited the A. E. G. exhibit for inspection and report, the motor was started and a fire resulted in the starting apparatus, which created excitement and brought the fire engines. It was found that the water rheostat had caught fire, which fact in itself was considered quite a joke among the Westinghouse engineers. This A. E. G. exhibit was interesting in showing that Europeans and Americans were independently developing polyphase apparatus along very similar lines.

In the Schuckert exhibit, also in the Electricity Building, there was a polyphase induction motor of small capacity with distributed windings. This, however, was not operated as there was no suitable supply circuit.

If the writer remembers rightly, the General Electric Company also had certain polyphase apparatus on exhibition. A synchronous converter of about 75

h. p. capacity was shown. However, no polyphase apparatus in operation was observed.

It was in 1893 that the induction motor business in this country really got into motion. It was about this time that the question was taken up, in a conference in the Westinghouse company, as to how to get this motor on the market. After various plans had been discussed, the suggestion was advanced by the writer

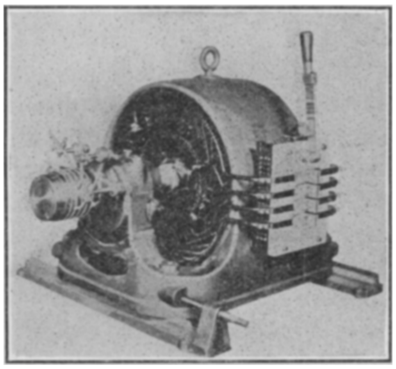

Fig. 4

that if we would make a "fad" of polyphase generators, so that everybody would buy them, the motor question would soon settle itself. This suggestion apparently was considered a good one, for instructions were given immediately to get out a standard line of polyphase generators and push them on any and every occasion. This was done and it was remarkable how quickly the public actually took to the polyphase generator. It became a real fad and soon developed into standard practise. The development of a standard line of induction motors

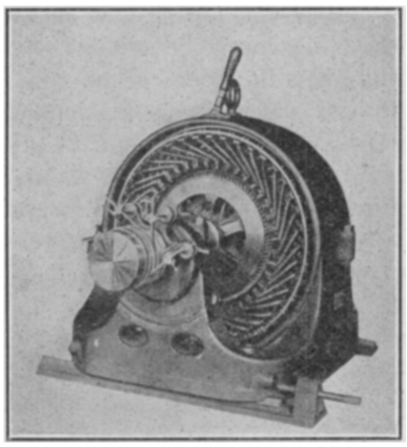

Fig. 5

was also authorized, and, to illustrate how quickly the commercial demand came, it may be said that customers' orders were taken for the motor quite a long time before any of them were ready for the market. In consequence, we had to rush the first line of motors on the market, even before we had much chance to do any development or experimental work. In fact, most of the experimental data had to be obtained from motors on customers' orders. However, this was common practise on most machinery in those days, and we got our data piecemeal, from several orders, rather than from complete tests on any one piece of apparatus. This first line of motors was for 60 cycles. Work was started on it sometime in 1893, and in 1894 motors were being completed for the market.

These first Westinghouse commercial motors, were of the rotating primary type with stationary secondaries. This construction was largely because the secondaries of these early motors were made with a number of comparatively large bar conductors with correspondingly low voltage and heavy current. As starting resistance was used, this meant that the problem of handling the current by collector rings and brushes was a quite serious one, and, therefore, by placing the secondary winding on the stationary element and the primary on the rotor, the collector ring and brush problems were much simplified. The primary winding was always of considerably higher voltage, with comparatively small currents which thus could be handled much more easily.

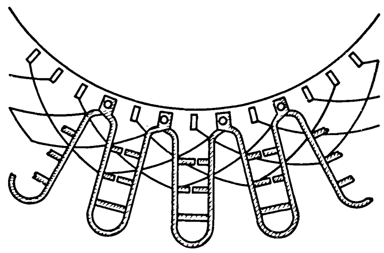

Fig. 6

On these first motors, "closed-coil" two-circuit types of secondary windings were used, with four leads carried out to a pair of switches on the frame of the machine. A cast iron resistance grid was connected permanently across each phase and the switches simply short circuited these grids after speed was attained. This was a relatively crude arrangement, but simplified the problem of putting these early motors on the market. We would make these iron grids with "bridges" in them and on test we would simply saw out bridges until we got the desired starting characteristics.

On one of these early motors the writer made some tests to determine whether two-phase short-circuiting of the secondary winding gave as effective results as three-phase. He brought out leads from the stationary winding to make a number of combinations and he made a very interesting discovery. It was found that when the closed coil winding was short-circuited at three points, representing three-phase, a certain pull-out torque was developed. Short circuiting at four points, representing the socalled two-phase, but in reality four-phase, a higher pull-out torque was developed. Short circuiting at six points, a still higher torque was developed and at eight points, etc., up to twelve, there was improvement. Beyond twelve points short-circuited there appeared to be but little gain. Furthermore, it was noted that the operating characteristics of the motor as a whole were considerably improved with more short circuits. This further verified earlier conclusions that from the running standpoint a complete cage winding was the most effective type. This then led to the development of an improved secondary winding which combined resistance starting with the effects of a cage winding at full speed. A closed-coil, two-circuit or "series" type of winding, of low voltage, was used in the secondary, with a large number of iron grids connected *between adjacent coils,* sufficient in number to span, all told, practically one pole pitch of the secondary winding, see Fig. 6. This gave very effective starting conditions. As full speed was attained, a short circuiting ring, surrounding the secondary winding, was shifted circumferentially to bring it into contact with the secondary bar end connectors at a large number of points, thus changing the winding virtually to a cage type,

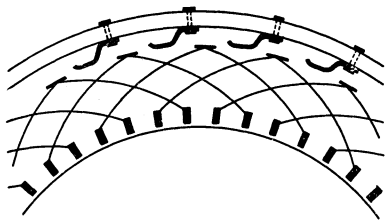

Fig. 7

Fig. 7. Thus the advantages of resistance starting and cage running were obtained. This was designated as the type *B* motor to distinguish it from the earlier motors gotten out by the Westinghouse company. The above construction was quite effective and motors of this type gotten out at this time and during the next year or so, are still in operation. This motor was so successful that a number of Westinghouse people said it was no use trying to beat it, as it was too near perfection. However, it was unduly expensive in construction and had certain inherent limitations which promised eventually to be troublesome. The rotating primary was all right for 200 and 400 volts, but for materially higher voltages, which showed promise of coming, it did not look so well. Also at this time, motors of one h. p. and smaller were being built with stationary primaries and with rotating cage type secondaries, and these indicated possibilities which were well worth following up.

It should be stated also that about the same time that the Westinghouse polyphase development opened up, a corresponding development took place in the General Electric Company and it began to put out polyphase motors with distributed primaries. Apparently this development was entirely independent of the Westinghouse company and arose primarily from analysis of the true conditions required for a successful induction motor. However, on account of the patent situation, the General Electric Company soon brought out what was called the "monocyclic system", with a view to avoiding the Tesla patents This was really a form of unbalanced polyphase system, in that it had one main phase and one auxiliary or "teaser" circuit for furnishing, principally, magnetizing current to the motor. The energy supplied to the motor was largely single-phase, but the magnetization was polyphase, at least to a considerable extent. This was supposed, by the inventors of the system, to avoid the Tesla patent, but when one looks at the problem from the present viewpoint, it is quite evident that this was simply a special case of the general polyphase problem. The General Electric Company developed excellent motors to operate with this monocyclic system. In fact, it was almost a case of necessity to use good motors with such a system, and, therefore, the monocyclic system may have been partly responsible for advancement in motor designs and construction. A motor which would work well on the monocyclic system would work extra well on a balanced system. One of the leading types of motors gotten out by the General Electric Company, either in this period, or at least quite early, was one of a rotating secondary type, with low resistance secondary windings, with iron or alloy grid resistance inside the rotor connected permanently to the windings, and with a mechanical means for short circuiting such resistance after the motor had accelerated to a certain point. In the Westinghouse type *B* motor, as already described, grid resistances were permanently connected to the low resistance secondary winding with provision for mechanically short-circuiting the windings at a number of points after the motor had accelerated. Obviously, these two arrangements were very similar in principle and general type, except that one had a rotating and the other had a stationary secondary. The General Electric arrangement presented one distinct advantage in having a stationary primary, which has proved to be the preferred form for induction motor work in general.

The Stanley-Kelly Company also put on the market an induction motor which, it was assumed, did not infringe the Tesla patents, because it did not produce a rotating magnetic field in the usual sense. The primary in this motor, really consisted of two polar type single-phase primaries side by side, but with the two sets of poles displaced 90 deg., and excited by currents 90 deg. out of phase with each other. These two single-phase fields acted upon a common secondary core and winding. The pole tips were slotted and contained a special distributed type of damper winding for lessening the armature reactance.

Due to the fact that the two magnetic fields set up were assumed to be simply alternating in space and not rotating, it was believed that this Stanley-Kelly motor, therefore, did not possess the rotating field of the Tesla motor, and thus avoided the patent. However, the chances are that any modern designer who would analyze this machine, would say at once that it was simply a special form of the Tesla motor and obeyed the general laws of such apparatus. These motors were put out in considerable quantities, during the 90's, and were built very largely for two-phase, as the structure was better adapted for this. If the writer remembers rightly, the Stanley-Kelly Company also put out some split phase motors, using condensers and reactances to get the desired phase relations. These attracted considerable attention at first, but eventually they dropped out of sight, as was the case with practically all induction motors using condensers for phase splitting. Apparently the inherent difficulties in the early condensers themselves were an undue handicap. Practically all companies which built induction motors tried, at some time, the condenser method of phase splitt ng. The General Electric Company tried this scheme on a relatively large scale. The Westinghouse Company tried the scheme experimentally to a considerable extent, but put out very few motors, principally because it did not have a sufficiently good condenser.

By 1895, the polyphase motor had become pretty firmly established as a commerical device and was making great progress. Except in very small sizes, resistance starting was used exclusively. The cage type secondary was well known, but was used only in connection with small motors or for small starting torque, as it was considered that this type of machine inherently had insufficient starting torque for heavy motor service. This notion was overthrown through a radical development which will be described later.

While the polyphase motor was being developed, the single-phase induction motor was also given much consideration. In fact, in the very early Tesla work, in 1888 and '89 when single-phase circuits of 133 cycles and 125 cycles were the only ones available, various attempts were made to construct single-phase motors, operated through phase-splitting devices. This was usually on a basis of two-phase circuits on the motors themselves with unequal reatcance in the two circuits. However, this did not prove successful even for fan motors.

It was discovered, quite early in the game, that the two-phase induction motor of the early Tesla type would operate quite well on single-phase by opening one phase after the motor was up to speed. It was also discovered that if the motor was at standstill it could be started up in either direction by giving it a little push at the pulley. Moreover, it was noted that with the secondary set in certain positions with respect to the primary, the motor would start itself, with current thrown on one primary phase only. It is thus evident that certain phenomena of the single-phase induction motor were recognized as early as 1888 and '89.

From 1890 to '94, the Westinghouse company built for commercial purposes, a number of single-phase synchronous motors which were used in connection with certain western mining power work. These single-phase synchronous motors were not capable of starting themselves and, therefore, the practise, was adopted of starting them by means of induction motors. The writer acquired considerable experience in this work and succeeded in making some fairly effective split-phase motors for starting the synchronous type machines. In one instance, he took an early experimental motor and placed a distributed primary winding on the stator element and used a high resistance bar winding on the rotor, this bar winding being tied together at the ends by *heavy high-resistance alloy rings*. In the first trials, the motor started and accelerated the load all right, thus proving that satisfactory torque conditions were obtainable, but as the secondary bars were soldered in slots in the end rings the solder all melted and came out. A metal wedge arrangement was then adopted, instead of solder, with a view to obtaining good joints by mechanical means. It was soon found, however, that unequal expansion of the secondary bars, in the early period of acceleration, was sufficient to cause relative movement between the bars and the end rings at the wedged joints. Eventually threaded holes were tapped into the bars and rings and set screws were used to maintain the joints. This appeared to be fairly effective and the motor was then operated a large number of times without apparent injury. The experience obtained with this cage type of secondary winding was of value in the later development of cage secondaries as will be described. This experimental starting motor was the writer's first real attempt at a commercial split-phase motor. Previous to this, old Tesla polar type experimental motors on hand had been adapted for this starting work, under Mr. Scott's direction. In this particular case, the writer incidentally made some suggestions to Mr. Scott about the possible advantages of a distributed type of primary winding, such as we were working upon experimentally, and he accepted the suggestion so gratefully, that he immediately turned over to the writer the job of producing a starting motor, with the hope that he would produce something materially better than the former t pe. An interesting comment on this development, is that the customer's operators reported later that this new starting motor was by far the best one that we had yet put out.

In this earlier period, single-phase operation of the induction motor was thus fairly well understood, but it was only in infrequent and special cases that such method of operation was practised commercially. There had been a few cases where small exciters had been operated by single-phase induction motors, and such motors had been used for starting synchronous motors as described. However, it was not generally believed that the single-phase induction motor offered great promise commercially.

Later, however, there were occasional calls for special single-phase or split-phase induction motors, for various purposes. Some of these were so special that manufacturers did not think it worth while to undertake them. In other cases these special machines were built simply because they carried with them other business of a very desirable nature but which was not special. Apparently this was the experience of all manufacturers. In one particular case, which the writer calls to mind, a 25-h. p. high-frequency single-phase motor was wanted for some foreign installation. As the contract included a great deal of other apparatus it was agreed to build this motor.

The writer undertook to build this machine, using a standard polyphase frame and winding, with a special wound-secondary with collector rings, so that resistance could be used during starting. Phase displacement in the primary was obtained by means of reactance in series with one of the primary windings. On preliminary test this motor was most discouraging, as it barely pulled its rated load. Little improvements were then made here and there which helped it out somewhat. However, its overload capacity was relatively small and the machine seemed to be very sensitive at high torques. Its power factor was considered unduly low. However, after several months of effort, it was agreed to send the machine to the customer to meet his immediate needs, with the intent of taking more time and building a better machine for him. The motor accordingly was shipped, and work was begun on the designs for a new more powerful motor. However, before this got into manufacture, word was received from the customer that the motor sent him was very satisfactory in every way. He stated that he had many single-phase motors in regular service, but that this motor was by far the best of all. This, of course, did not mean to us that our motor was in itself an extra good one, but it meant that the other motors which he had must have been pretty poor, from our viewpoint. Possibly we had set our standard too high.

Even before the induction motor was invented, commutator-type single-phase alternating motors had been built and experimented with. The principles of both the series and the so-called "Repulsion Motor" were known back in the latter '80s, and it was also known that they could develop relatively high torques at standstill. Such motors, however, did not have the constant-speed characteristics of the induction motor.

As has already been mentioned, it was discovered in the early years of the polyphase induction motor that it would operate in either direction on single-phase, provided it was once started and brought up to speed, or even brought up part way. In other words its accelerating torque was zero at standstill and increased rapidly with increase in speed. On the other hand, it was known also that the series motor, in its various forms, had just the opposite characteristics, namely, it could develop an accelerating torque which was high at start, but decreased rapidly with speed. It was recognized quite clearly that a combination of these two characteristics would be very desirable for single-phase induction motor work. Prof. E. E. Arnold, of Karlsruhe, combined these properties in his type of motor, this type later being taken up by the Wagner company in this country. In this Arnold motor, the secondary or rotor was in the form of a direct-current armature with commutator and brushes, the brushes being short-circuited on themselves and set in such position with respect to the primary or field as to give the usual repulsion motor characteristics. When sufficient speed was attained, the armature would automatically short-circuit itself at a number of points, thus becoming the usual induction type of secondary. This type, the writer believes, was first put out in this country by the Wagner company, but since the expiration of the fundamental patents it has been built in various forms by many other companies.

In 1892, the writer accomplished experimentally very much the same results in connection with tests on an early synchronous converter. This converter was constructed from a direct-current railway generator, by adding a set of polyphase collector rings over the commutator, leaving part of the commutator exposed, so that direct current brushes could be used when the machine was operated as a converter. Among the various tests made on this machine, was one of self starting by connecting the armature and the series field of the machine in series and bringing it up to speed on alternating current, as a single-phase series motor. When full speed was attained the supply circuit was switched over to the collector rings and the machine operated synchronously with the line. This is simply an early illustration of starting by single-phase alternating current, by means of a commutator and shows that this general principle was well recognized even as early as 1892.

Eventually, various forms of commutator type induction motors were gotten out by different companies. A special type was built by the Westinghouse company but was not marketed, although a number of machines were developed. This consisted of a four-pole-eight-pole primary winding and an eight-pole parallel-wound direct-current type armature winding, with equalizer connections connecting points of equal potential on the armature. The machine was started on the eight-pole combination, with the armature and field in series and when it came up to speed, the field was switched, by means of a centrifugal device, from eight poles to four poles, and the armature automatically became a short circuited four-pole secondary, by means of the eight-pole equalizing connections. This type of motor operated quite satisfactorily on test, and the writer believed it could be made a commerical success. Certain objections were raised against it, such as relatively high first cost (which proved to be unfounded), and the fact that *the brushes were not lifted from the commutator during normal operations*. This lifting of the brushes was claimed to be an absolute necessity, on alternating-current motors, regardless of the fact that on direct current machines the brushes remained on the commutator at all times. An interesting comment on the above is that recent practise on alternating commutator type induction motors has tended toward allowing the brushes to remain on the commutator. An inherent objection to the machine as constructed, was that it was of the *series* type during starting, and, therefore, was limited to voltages not exceeding 220. However, this type of machine could have been designed and used as a repulsion type, and thus would have been as adaptable for various voltages as any other commutator type induction motor. One advantage of this type was that no mechanical short circuiting device was needed on the armature.

Another type of single phase induction motor with commutator, which was brought out at a later period by the General Electric Company, is known as the repulsion-induction motor. This has a polyphase brush system, instead of single-phase on the secondary. This type of induction motor has been used to a very considerable extent in small sizes. It has no automatic short-circuiting device in its secondary, the circuits being closed through the commutator and the stationary brushes. In this motor the secondary current is commutated at all times unlike the preceding types, which have been described. Practically all these motors, except the Arnold type, belong to a much later period.

The induction motor had received very much study both in Europe and America, and many of the phenomena which are now the usual accepted knowledge, were first described in those early days. For instance, M. Leblanc in France had described and patented the use of resistance in the secondary for increasing the starting torque. Both European and American engineers had also discovered that an induction motor operated on polyphase primary, but with single-phase secondary would run at half speed. Also it was discovered, both in Europe and America, that cascade operation of two induction motors would give the equivalent of an increased number of poles, that is, a lower speed. The writer, with a view to making a polyphase railway equipment, designed and built a pair of two-pole, 25-cycle motors, in 1895, in order to obtain both cascade and multiple operation, for obtaining both half and full speeds. These motors were put on test and operated quite satisfactorily in cascade, and many interesting results were obtained. However, the work was carried no further on account of apparent limitations of polyphase trolley systems.

In the period between 1894 and '98, many odd "stunts" were tried with induction motors. In the literature of that time suggestions appeared, from time to time, regarding various possibilities or experiments and we were always inclined to check them up at the first opportunity. For instance, the half-speed operation obtained by operating the secondary on single phase was tried out, based upon a note which appeared in one of the European papers. The results, however, were not satisfactory due to the relatively poor power factor. Also, as early as 1894, attempts were made to obtain double speed by feeding the supply frequency to both the primary and secondary circuits of the motor. Double speed was actually obtained in this manner at no-load, but difficulty was encountered in attempting to carry any load and finally the test was abandoned.

In these early days it was also recognized that an induction motor, mechanically driven, could act as a frequency changer. The General Electric Company made some very early applications of this scheme.

Also in this early period, it was found that the induction motor would operate as a generator above synchronism. The first real experience of the writer. in this, was in 1894, when he was operating a 75-h. p. induction motor, driving a generator as a load. The motor was operated from a standard polyphase synchronous type generator which was motor driven. During these tests the driving power was purposely cut off the polyphase generator and it was observed that with the induction motor acting as a generator, and held at constant speed, the polyphase synchronous generator continued to operate, but as a synchronous motor, and at a somewhat lower speed than before. Measurements were then taken of the speed conditions and it was noted that when the synchronous generator was delivering full power to the motor, the motor had a speed of from two to three per cent lower than that of the generator; whereas, when the synchronous generator was disconnected from its power source and operated as a loaded motor, it ran at two or three per cent lower speed than the induction motor acting as a generator. This showed, therefore, that the induction motor was operative as a generator *above synchronism with its source of magnetizing current*, namely, the synchronous machine. It was known by the writer at even a considerably earlier date than this, that a synchronous motor could furnish "leading" or exciting current to its generator, and, therefore, it was obvious in this test that the synchronous generator, acting as a synchronous motor, was furnishing the necessary exciting current for the induction motor when the latter was operating as a generator. Quite elaborate tests were then made on this outfit primarily for the purpose of determining the general characteristics of a motor operated in this manner. This ability of the induction motor to act as a generator, was utilized experimentally shortly afterward, in connection with some electric hoisting apparatus which was being developed. The induction motor in these tests was used as a brake, when dropping the load, by operating it above synchronism.

The above illustrations are simply mentioned to bring out the fact that many of the now well known actions of the induction motor were fairly well comprehended as early as 1894 and '95. In this earlier work there were two polyphase schools, so to speak, namely, the two-phase and the three-phase. The Westinghouse Company was known as the advocate of the two-phase polyphase systems, although it built both; whereas the General Electric Company was considered as favoring three-phase, although it also built both. The fundamental reason for the Westinghouse two-phase was principally in connection with lighting systems. When polyphase generators were first advocated strongly, for general purposes, practically all the service was lighting. With two phases it was considered that there was materially less complication in the smaller number, of feeders, than was the case with three phases, and this was true. It was recognized that the three-phase motor in itself was slightly better than the two phase, but it was felt that the disadvantage of the more complicated supply system considerably overbalanced the advantages in the three-phase motor and in the transmission. However, after a few years, conditions changed materially so that the needs of the polyphase transmission began to overbalance the advantages of two-phase distribution, so that there was a growing call for the three-phase system. It was about this time that the well known Scott two-phase-three-phase transformer system was devised, so that the advantages of the two phase and three phase systems could be combined. However, with the coming of true transmission systems and the further growth of the polyphase work, the three-phase system eventually dominated the market and the induction motor business became primarily three phase. This does not mean that the two phase system was a mistake, for it is probable, that, without this simpler system at the start, the polyphase system might have had more difficulty in making headway. It is simply one of the many illustrations in the electrical engineering field, where a simpler system, initially, has been driven out by a somewhat more complex system which contained greater possibilities in the end.

Nothing has been said yet regarding the 25-cycle frequency. This was inaugurated in 1893 in connection with the first Niagara Falls power installation and was quickly adopted, especially for synchronous converter work. The use of 25 cycles, however, did not have any controlling effect on the induction motor development in the earlier years, although it did have a bearing on certain of the later work, such as industrial plants and steel mill electrifications, as will be explained later.

By 1896, apparently the induction motor had settled down to fairly standard practise. As stated before, this practise covered the use of secondary resistance for starting except in the case of very small motors. The standard General Electric motor of this time was of the stationary primary type, while the standard Westinghouse had a rotating primary. Both motors were quite satisfactory machines, and, as mentioned before, there were people in the Westinghouse company who fully believed that the Westinghouse motor was 100 per cent perfect and could not be improved. However, the writer had his doubts. From time to time, as opportunity occurred, he had done considerable experimenting on cage type secondaries and was somewhat predisposed toward such a construction, provided the starting limitations could be overcome. This was one of the matters upon which he spent his spare time in analyzing and investigating, and finally as a result of his analysis of the characteristics of the motor, he saw a way to obtain the desired result. In those early days induction motors could be designed from calculations in a fairly satisfactory manner, and the effects of reactance, resistance, etc., upon the starting and pull-out torque were fairly well understood. Also crude methods were in existence for calculating the reactance. It was about 1895, while testing an experimental motor for hoisting purposes that the writer noted that, in this particular motor, very large starting torques were attained, although the motor had a pure cage winding in the secondary. Here was something worth following further, to find the fundamental reasons for this extremely good result. About this time the writer was working over the vector relations of the induction motor with a view to obtaining better methods of analysis and calculation. He found that by taking given motors and showing the various relations graphically, he could produce various points on the actual speed torque, current-torque and various other curves of the motor. This was a slow and laborious process, for a complete diagram had to be constructed for each point. After checking a number of machines and reproducing their characteristics, he then began to study special cases and among other things, he varied the reactance, *on paper*, over a wide range and found that if this could be reduced in a given machine, below a certain value, then not only good pull-out torques, but correspondingly good starting torques could be obtained *with permissible slips for constant speed work*. This was most interesting and several cases were checked up where unexpectedly high torques with cage windings had been found, especially in the case of some of the experimental motors already mentioned. The results showed that these were motors of small reactance, and they indicated, furthermore, that *sufficiently small reactance was actually obtainable in motors of commercial proportions with cage type windings*. This was most interesting as showing the possibilities for the development of a cage type motor for general power purposes. The writer then went into the analysis of reactance conditions most fully, and spent months partly in daytime, but mostly in the evenings, analyzing magnetic conditions, with a view to predetermining all the "leakages" or "stray fields", etc., and checking with existing machines. It developed, in time, that he could reproduce, by calculation, the reactance conditions of practically all the existing machines. Also he took up the question of reducing the reactance fluxes to a point which would give relatively large starting torques with cage wound machines. In the early stages of this work he gave up the graphic method of solution, by transforming his diagram from graphics to a set of mathematical equations, derived directly from the geometry of the vector diagrams. With this set of equations he was able to produce quite quickly a complete set of characteristic curves of any motor. Also to obtain any desired starting and pull-out conditions, he could very quickly determine the limiting value of the reactance necessary. This work showed very definitely that it was entirely possible to produce a commercial line of polyphase induction motors with *pure cage type secondary windings with starting torques up to two or three times the rated torques* of the machines.

With these data available, it was decided to undertake to build commercial induction motors with cage secondaries. Motors of 20, 30 and 50 h. p. were first undertaken. All were brought through *from calculation* and all developed the expected starting torque conditions, namely, about two and one-half times the rated full-load torque and from three to three and one-half times pull-out torque. This was considered a most remarkable result at the time, as it had been generally held that cage motors could not develop, very high starting torques. In conjunction with this work, there was another fundamental departure from older practise, namely, in the use of voltage reducing transformers in connection with these motors. While these cage type motors could develop starting torques of from two to three times rated load, they also required starting or "line" currents of six to nine times full load current which was considered a prohibitive condition. Naturally the suggestion arose to reduce the starting current, and the starting torque proportionately, by the introduction of a small transformer at start, so that the motors would take not more than three times full-load current from the line when starting full-load torque, while at full speed they would be switched to the line voltage and would have the corresponding full-power characteristics. This was the origin of the auto-transformer or "compensator" method of starting.

Naturally the use of cage windings pointed directly to an inversion of type in the Westinghouse machines; that is, with the cage construction, the secondary or cage winding should naturally be placed on the rotor, in order to do away with all collector rings or other rotor connections, the stator winding being placed on the primary. These new motors were built in this manner and a few of them were put in service in 1896, in order to obtain some practical experience. Steps were taken immediately to carry the development below 20 h. p., in order to have a reasonably complete line. This line was gotten out in fairly complete shape in 1897 and was pushed actively during that year. At first this type of motor was received with a good deal of doubt, especially by technical people. Operators, however, especially in industrial plants, took to this type of motor on account of its substantial simplicity, and, in spite of many criticisms, they bought more and more of such motors until, in a short time, evidence began to show that this type was liable to take possession of the field. In fact many users of this motor would consider no other type. This line of cage-type motors was known as the Westinghouse type *C*. When first put out, it was criticised as containing a most palpable absurdity in the fact that no cage type motor could develop high starting torques, and yet here was a cage type motor with a reducing transformer for lessening the torque at start. What could be more absurd? A not uncommon statement at that time, in referring to the inadequacy of any kind of electrical apparatus, was—"It is as bad as the Westinghouse type *C* motor."

However, in time certain people awakened to the fact that this motor was able to develop the necessary starting torque, for the customers were thoroughly well pleased with it, and here and there it was used in places where the starting conditions were known to be very severe and yet it met these conditions quite satisfactorily.

However, while the real development in the cage-wound motor came as above indicated, yet there are numerous evidences of earlier work having the cage type of construction in mind. For instance, among the writer's specifications is one dated May 16, 1893, calling for an induction motor with a solid cast iron rotor core with 48 slots, and with the winding of "poured-in" copper, forming a complete copper cage.

Also as described before, in connection with a single phase motor for starting a synchronous motor, various types of secondary construction had been attempted. In building the high-torque type *C* motor described above, the secondary was first made with a simple bolted construction for attaching the secondary bars to the end rings. However, in the first 50 h. p. motor brought through, very severe starting tests were made, the motor being repeatedly started from rest under heavy torque, during many hours. At the end of this test it was noted that the per cent slip for large torques had increased considerably. The bolted secondary construction was then examined, and it was found to be defective in that expansion of the copper bars and end rings, due to changes in temperature, had actually stretched many of the bolts until the contacts were loose, and in some cases the bolts were broken. This looked like a most serious defect. However, one of the testing engineers, Mr. R. S. Masson, then made the suggestion that this trouble might be overcome by using heavy spring washers under the bolts, simply to take care of expansion and thus maintain good contact of the bars with the rings, regardless of temperature. This was immediately tried, and the former test repeated, which resulted in no loose or broken bolts. This construction was then adopted as standard practise and was used for many years. However, it was difficult to get the manufacturing departments to understand the function of these spring washers, being prone to believe that they were purely to keep the nuts from turning loose.

Other companies also found it necessary to adopt this spring washer construction for maintaining good contact. This construction eventually went out of use in favor of cheaper types and not through operating defects in the bolted construction itself.

This cage type construction soon led to some very interesting developments and it was found necessary to obtain quite definite resistances in the secondary winding for giving the required torque, current and speed conditions. In consequence, as the secondary bars themselves were usually of copper, it was found necessary to vary the resistance of the end rings by using various alloys. Iron was tried, both cast and wrought, but usually with harmful results. Various bronzes, brasses, etc., were also tried, and in time quite a choice of materials became available for end rings. Moreover, it became usual practise to vary the resistance of the end rings of individual motors by slotting one or both of the rings radially to a certain depth, thus virtually lengthening the current path. This apparently did no harm and was quite effective in increasing the resistance of the rings, a range of possibly 100 per cent or more in resistance being obtainable in this manner.

This type C motor was not quite as efficient as later types, but it was of such sturdy construction and has such a high thermal capacity, compared with former constructions, that it obtained an almost undesirably good reputation in some ways. For instance in service, it could be pulled to standstill momentarily by a heavy overload and upon removal of the load, would immediately recover to full speed with no apparent injury, except in extreme cases. This was because the motor at standstill, on full voltage, had a starting and accelerating torque of two or three times the rated load. On account of these interesting, and, at that time, unusual properties, many people obtained an exaggerated notion of the motor's capabilities. For example, some of the Westinghouse people wanted to advertise that the type C motor could not be burned out, based upon certain experiences of the above nature. The writer, however, warned repeatedly that this was not a fact, but that the motor could be burned out just as surely as any other type of machine *if overloaded for a sufficient length of time*. He insisted that this motor, while a very good one, could not accomplish the impossible and that any claims that the motor could be overloaded to any extent without injury were dangerous and liable to react upon the manuacturer sooner or later.

These type C motors, in some cases, had pull-out torques of four times their rated capacity, and starting torques of three times their normal running torques. In consequence, due to the general shape of the speed torque curve, a sudden application of very heavy load would not easily jerk them out of step, so to speak, as was the case with the earlier types. In many of the motors of that time, a drop in speed of ten to fifteen per cent, due to sudden heavy overload, would bring the motor down to a decreasing torque so that it would very quickly pull down to rest. This condition is illustrated by Fig. 8.

Partly on account of the shape of the speed torque curve and partly due to the great thermal capacity of the type C motor, it acquired a reputation for sturdiness, reliability and capacity, held by no other motor before or since. This was a very good thing in those early times, when this type of motor was establishing itself, but in later years it has been recognized that some of these characteristics can be partly sacrificed to advantage, in order to favor other characteristics, such as efficiency, power factor, reduced dimensions, etc. In consequence, while the general characteristics of the type C motor have been retained to a greater or less extent in all general purpose cage motors of later times, yet a compromise has been made between the various characteristics, in order to give the most satisfactory all around results, with our later more accurate applications of motors to their service.

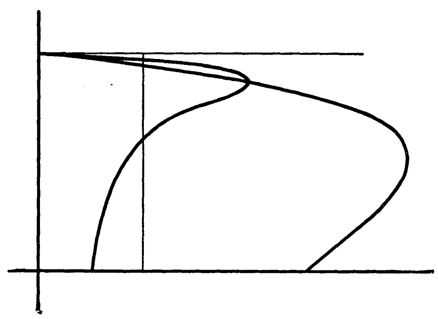

Fig. 8

It was not long after the cage-wound motor was put on the market until rare instances were noted where the motor, when used where speed reversal was necessary, would not reverse, but would continue to run in the same direction as before, (but at a much lower speed) when the primary terminals were reversed. The reason for this was not understood at the time, but investigation showed that, in each case of this sort, both in numerous shop tests and in outside instances, the relative resistance of the secondary end rings, compared with the secondary bars, was low. As a direct result of this, the end rings of such motors were slotted to increase their resistance compared with the bars; and in every case where this was done the motor would then reverse in a satisfactory manner.

This effect was noted as early as 1897 and '98 and is now recognized as due to the well known "cusps" in the speed torque curves of such motors, as shown in Fig. 9, but, at that time, the whole matter was more or less of a mystery. The writer recalls that in 1900 a prominent European engineer mentioned to him that the A. E. G., of Berlin, had claimed to have encountered cases where induction motors failed to reverse, but he said that he believed it to be theoretically and practically impossible. He was then informed that we had encountered similar difficulty in a number of cases and that there was no question about it,—it could happen. It was also explained to him that all cases of this sort, which we had investigated, were of the cage type and the relative resistance of the end rings in such cases was considerably less than that of the bars, the trouble being corrected by increasing the end ring resistance. He then remarked that as we said so he believed it, but he did not understand how it could be.

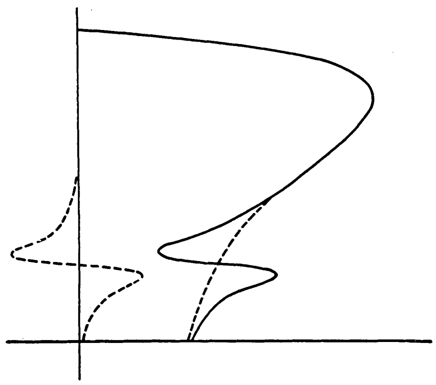

Fig. 9

In the analysis of the magnetic conditions, leading up to the development of the cage type of motor, as already described, the writer did much work in, plotting and analyzing the flux distributions and obtaining the magnetic "field forms" in the induction motor, during the cyclic changes. He investigated the effect of "chorded" or fractional-pitch windings and found their influence upon the magnetic distributions, reactances, etc. and incorporated expressions in his formulas for covering such windings. He determined that more uniform magnetic fields could be obtained by the use of such windings and that the most uniform effect was obtained when the span of the coils was shortened by an amount corresponding to half the width of one phase belt. Also the advantage of chorded winding, in giving the equivalent of a fractional number of wires per coil or slot, was worked out at that time and this feature has been used since to a very great extent.

The use of a fractional-pitch winding had been proposed and patented by the writer, in connection with commutation of direct-current machines, but in this the function of the chording was to reduce the reactance of the coils undergoing commutation. In the induction motor a somewhat similar reduction in reactance was accomplished, but this was not considered as the primary object in chording. The saving in the length of the coils, better flux distribution of the main field and the ability to obtain the equivalent of a fractional number of turns were all considered of more importance. This improvement in induction motor windings was also patented about this period.

It was along in the period from 1894 to 1898, that the writer actually constructed multispeed motors, by changing the number of poles in a given frame, as distinguished from cascade-parallel operation. This had been talked about a great deal, at different times, but there had been no occasion to build such motors. However, in some preliminary considerations for electrifying a certain large railway, the possibilities of polyphase current were taken up. Mr. Westinghouse suggested that a pair of induction motors be built with a view to determining whether satisfactory characteristics were obtainable for railway work. In order to simplify the outfit, motors with cage secondaries were considered and two large motors were built for four poles and 25 cycles. These motors were made with very high starting torques,—about six or seven times full load, the reactance being made purposely very small, so that the motors could have relatively small slip at full load and yet develop very high starting torque. It was the intention to control the speed during starting by varying the voltage supplied to the motor, an induction regulator being used for this purpose. Two motors and a regulator were built, but the system was found to be quite unsuitable for the purpose, partly due to the fact that only one speed was available. To overcome this, the writer then devised an arrangement for recoupling the primary winding to give eight poles as well as four. This was then tried out and it was found that both the four and eight pole speeds were quite effective. As far as the writer remembers, this was about the earliest large work in pole changing.

Among other objections raised against this proposed a-c. railway system, was the use of two trolley wires. The suggestion was made that such a system should really be single-phase. With this in view, as an experiment, the writer then operated one of the two special railway motors across *one phase of the supply circuit* and from it, as a phase converter, fed polyphase current to the four-pole-eight-pole motor. The tests showed that this latter machine, operating as a polyphase motor, acted quite satisfactorily on both the four-pole and eight-pole combinations. This, therefore, was an anticipation, experimentally of the split-phase traction system, which came out many years later. This feature of transforming from single-phase to polyphase by means of an induction motor, however, was not new or unknown at this time; for it had been brought out very clearly by the General Electric engineers, in connection with the monocyclic system already mentioned, that if the monocyclic supply system could once get a large induction motor in the system up to speed, this motor would be of direct assistance in the starting of other motors, due to its phase converting qualities. It had even been claimed that with one induction motor up to speed, the "teaser" circuit of the monocyclic generator could be cut out, and the induction motors themselves would maintain the polyphase characteristics, provided all the phases were tied to the circuits. Thus it was known very early that the induction motor possessed these "phase-splitting" characteristics. The above tests for phase splitting with a polyphase railway motor are interesting merely as an attempt to obtain railway operation in this manner and also as early anticipation of much later practise.

The introduction of the cage type secondary, had a considerable bearing on the development of multi-speed motors, for a properly proportioned cage secondary could operate fairly well with various combinations of poles; whereas with the "polar" type of secondary, one winding was suitable for only one speed, without considerable reconnection, which was not convenient in practise with the relatively small motors in common use in those days.

Shortly after the above experiments with the two sets of poles on a railway motor, the writer designed various two-speed and three-speed induction motors for special purposes, some of which are in operation at the present time, after more than twenty years. An interesting and curious incident occurred in connection with one of these early commercial motors. A two-phase two-speed motor for four and eight poles was designed and built, using a single primary winding which was recoupled for change in poles. On this motor some mistake was made in the primary connections and it was discovered that, under certain conditions of switching, an effective twelve pole speed was obtained. This was not on the program, and was considered quite interesting and an attempt was made toward investigating the reasons for it. It was realized that this result was due to some mistake in the internal grouping of the coils and the writer set about determining the cause. However, before a proper examination of the winding itself was made, the winding department men got hold of the machine, and, knowing that there was a mistake somewhere, they disconnected the winding completely and reconnected it. Thereafter the machine would not show the twelve-pole speed, and neither could the shop men give any explanation as to what changes were made. Thus we were unable to make any complete tests or any investigation in the actual machine to find the reasons for this curious speed combination, and, furthermore, we were never able to work out a possible combination which gave the three speeds, as shown in the preliminary tests. Here, therefore, was a lost characteristic or combination, which might have proved useful, but which, on the other hand, on more complete tests, might have proved unsatisfactory. The writer took up the study of this problem at odd times during the next year or two, but eventually gave it up. It, therefore, stands on his records as one of the mysteries or unsolved problems in his engineering work.

The period from 1894 to 1900, might be called the "Golden Age" of induction motor development. Nearly all the things that have been developed since, originated or were first put into practical use during this brief period. During this time the induction motor business was practically revolutionized by the introduction of the cage winding with high starting torques. In this period the polyphase motor became so thoroughly established as a commercial device that it was already taking the offensive against its d-c. rival. During this time the theory of the induction motor was worked out and applied in practical forms of calculation, and the methods of calculation, developed in that time, hold with slight modification until today. The method of analysis and calculation derived by the writer in connection with the development of the cage tyye motor, as already described was used throughout the following years by the Westinghouse engineers and is the basis of their present methods. In the General Electric Company the methods devised by Dr. C. P. Steinmetz, during this period, are also used very generally throughout that company. These methods are naturally closely related to each other, although expressed in somewhat different form. The writer's paper "The Polyphase Motor," presented in 1897 at the convention of the N. E. L. A. at Niagara Falls, which is a non-mathematical exposition of the subject, was a direct outcome of his work on the cage type motor and his methods of calculation, and many of the curves shown in that paper were derived directly from his formulas.

Among the early analysts was Mr. B. A. Behrend, leading technical expert of the Bullock Company and later of the Allis-Chalmers Company. His early book on the induction motor was an exposition of fundamental principles and practises well worthy of study now, after twenty years, even with the great advances and developments in the art.

Indeed, this period might be called the "Age of Induction Motor Analysis," as well as development, for practically all the modern analysis is based upon fundamentals developed during this time. All the analytical work was not published, but the methods of those times were carried into the practical fields, with marvelous results, and it may be said that the methods of today are largely refinements of those of twenty years ago. These refinements in methods have led to refinements in the machines, but not to any new principles which have allowed any radical departures in types.

By 1900, the induction motor had become pretty thoroughly established, with the cage type of construction far in the lead of all others. In fact, the enthusiasm for this type was so great that in some applications it was used where the wound-secondary type would have been superior. It took time, however, to determine its true limitations and its handicaps.

The period beginning about 1900, was one of application rather than of new developments of the induction motor. In Europe, the Ganz Company was applying the induction motor to locomotive work, in Italy. Eventually Mr. Westinghouse bought the American rights of the Ganz patents, but never used them. However, in this country one early attempt was made at electric traction by polyphase current, namely, on the Miami & Erie Canal near Cincinnati, by substitution of small locomotives for mules for towing the canal boats. A track was laid along the banks of the canal and two overhead trolley wires were installed. The locomotives were of comparatively small capacity and each was equipped with two three-phase motors adapted for cascade-parallel operation. The overhead voltage was 2000 and step-down transformers were placed on the locomotives.

In operation these polyphase electric locomotives did all that they were expected to do, and yet the installation was a failure, due to reasons outside of electric operation. In the first place it was intended that each locomotive should pull a series or "train" of canal boats, but in practise this was not feasible, at least on this particular canal. As the engineer on the job reported, the first boat of the train "piled up" the water ahead of it, thus lowering the level behind, the second boat did the same, and the fifth or sixth boat, in consequence, was dragging in the mud. In other words, the train of canal boats acted somewhat like the old fashioned chain pump.

A second trouble reported, which, however, was not necessarily a fatal one, is amusing in showing how the effects of little things sometimes are unforeseen. In the days of mule towing, the mules kept the grass down, along the tow path. However, with electric towage the grass grew so high that the locomotive pushed it over on the rails where it acted like a good lubricant so that, in some instances, the traction diminished to almost nothing. This trouble, however, could have been overcome, in case that the boat-towage had been more successful. After operating this system for a short time it was abandoned as impracticable.

Some years later, the General Electric Company installed polyphase locomotives in the Cascade Tunnel of the Great Northern Railway. These were three-phase, 25-cycle, 1200 to 1500 h.p. equipments and were used primarily for hauling trains through the tunnel. A single speed, with rheostatic control, was used on this electrification. An interesting feature was the use of 6000 volts on the two overhead wires.

At a still later period, three phase locomotives were installed by the General Electric Company along the Panama Canal, for towing purposes. This latter is the largest application of polyphase current to traction in America.

Beginning about 1896 and '97, steps were taken to apply induction motors to crane and hoist work. Among the earliest crane applications, were cage-wound induction motors with high-resistance secondaries and with means for supplying variable voltage to the primary windings for obtaining speed control. Quite a large number of crane equipments of this type were installed and the writer believes that some of them are still in operation. However, in general the polyphase motor for crane work has never been considered as fully competitive with direct current, due to the greater complexity required in polyphase crane trolley systems.

In the same way early attempts were made to apply induction motors to hoisting work. Both cage type motors and wound-secondary types were tried out and in some cases both were successful, in other cases both were failures, due, however, to misapplication in some instances. In later years more success attended such application due to a better understanding of the problem.

Induction motors quite early were applied to elevator service, especially for freight elevators. In the early days a high-resistance cage secondary was the preferred type and, in many cases, for low-speed service, such motors were thrown on and off directly without any control apparatus. Gradually, however, the opinion grew that the cage type motor did not fit such application as generally as the wound type. Quite recently there is a return to the squirrel-cage type, but with pole changing for two speeds.

About 1900, the induction motors began to extend to quite large sizes. The self-starting synchronous motor had not come yet, to any extent, and, therefore, practically all large power applications were through induction motors. These began to appear in 500, 1000 and 2000-h.p. sizes, sometimes of the cage secondary type, but quite frequently with wound secondaries; for the starting problem was recognized as of more or less controlling importance in these large motors. It must be remembered that in this period the present huge power plants were not even dreamed of, and generators of 2000 or 3000-kv-a. capacity were considered quite large. In consequence, the starting of a 2000-h. p. motor, especially if it was necessary to develop considerable torque, was a matter of much importance, for the reactive effects on the generator were liable to be serious, if not disastrous.

Power Factors

Almost from the first, it was recognized that the induction motor, in its normal form, would always have a power factor considerably less than 100 per cent, due to the fact that its magnetization was represented by a reactive current drawn directly from the supply system, and, therefore, at full voltage and full frequency. It was also known quite early that the so-called magnetic leakages or stray fluxes gave reactive e. m. fs. which affected the power factor. However almost as soon as the designers began to calculate the induction motor characteristics, it was noted that the smaller the number of poles, the lower would be the magnetizing current. In fact, this was obvious from their knowledge of direct-current design. Consequently it was soon recognized that 25-cycle motors with their smaller number of poles, would require less magnetizing current than 60-cycle motors, and, therefore, such machines would naturally show higher power factors, due both to the smaller magnetizing current and the low reactance voltages. Consequently, in the earlier days the 25-cycle motor was looked upon quite favorably, due largely to its better performance This was particularly true where low speeds were desired, requiring motors with a relatively large number of poles. In the early days, in many of the larger applications, direct connection was considered as most desirable and, in consequence, relatively low speeds were required. In consequence, the frequency of 25 cycles was favored for industrial plants, due to the more suitable characteristics of the induction motors. In fact, this had a predominating influence in fixing the steel mill standard of 25 cycles, which was adopted nearly twenty years ago, after careful consideration by the steel mill engineers. In those days, many of the heavier steel mill operations called for speeds of less than 100 rev. per min. on the motors and this was considered prohibitive for anything but 25 cycles. Largely on this account, but also for other reasons, this frequency was adopted as the standard. However, at the time, this seemed to be very much in line with other practise, for central stations, transmission systems, railway systems fed from synchronous converters, etc. were all tending toward 25 cycles.

In steel mill work, in those days, heavy gears were looked at askance. However, in time, cases came up where gearing was desirable and with the need came the development of good reliable gears, so that in later years there has not been the same necessity for the low-speed induction motor as was formerly the case. In consequence, the tendency has been toward higher speeds with proportionately smaller number of poles, and, therefore, toward conditions which could be well met by 60 cycles. Furthermore, due to various causes, particularly the development of the 60 cycle synchronous converter, the general trend of the power systems throughout the country has been toward 60 cycles for both generation and transmission. In consequence there is some question today whether the old steel mill standard is not becoming obsolete. The interesting point, however, that it is intended to bring out, is that this choice of standard for mill work was fixed very largely by the induction motor design itself.

While the power factors on the early induction motors were quite good, yet when the type *C* motor came out, the quite remarkable results in power factor obtained with 25 cycles, was a subject for doubt and criticism at first. For instance, in a paper on the polyphase motor, delivered in 1897, before the N. E. L. A. Convention at Niagara Falls, the writer showed power factors as high as 95 per cent on certain 25 cycle polyphase motors. After the meeting, certain designing engineers, privately discussing the matter with him, said that this high power factor looked well on paper, but could not be obtained on actual test. The writer replied that the published results were obtained from actual test, and that they checked with the calculations. The critics then stated that if such was the case, they would accept the results as actual facts, but they considered them most marvelous.

In those days, power factors were not usually looked upon as simply representative of certain reactive components, and naturally it was not recognized by most people that a 95 per cent power factor represented a 31 per cent reactive component, whereas a 90 per cent power factor represented only 43½ per cent or only about 40 per cent more. A jump from a 90 per cent power factor, which up to that time had been considered quite good, to 95 per cent did really seem a marvelous and almost unbelievable result and yet, in fact, did not actually represent a very great reduction in the total reactive component. Even today many people think too much in terms of power factor rather than reactive component and are misled accordingly in many matters of importance.

Naturally, engineers quite early turned to the question of eliminating the reactive component in the induction motor. The possibility of reducing the magnetizing current quickly forced manufacturers to very small air gaps. In the very early motors a total gap of ⅛ in. ($^1/_{16}$ in. on each side) seemed extremely small and the manufacturing departments grudgingly accepted such narrow limits. However, before very long, and with more manufacturing experience, the air, gaps began to diminish until $^1/_{32}$ in. clearance on each side was considered quite satisfactory even in moderately large motors.

One of the first engineers to attempt to reduce the reactive component supplied from the line, was M. Leblanc, the well known French engineer. He proposed to supply the magnetizing current to the secondary of the motor instead of the primary, by generating in an auxiliary machine in the secondary circuit, suitable out-of-phase e. m. fs. which would circulate exciting currents in the secondary winding of the motor. Heyland, in Belgium, accomplished similar results by means of a commutator on the secondary circuit of the motor itself, by which the primary frequency could be converted to the secondary frequency at very low voltage, compared with the primary. Neither of these schemes, however, persisted for any length of time in Europe and neither of them were adopted in America, at least not until many years later. Both of them involved the commutation of alternating current and, in the early days, this was considered a more serious problem than the reactive component of the motor input. In later years, many attempts have been made, and many schemes devised, in connection with correction of power factor of induction motors, but none of these have as yet come into general use, for they all involve the commutation of alternating current. This means complexity in the design of the induction motor, which apparently has not yet been accepted by the public in general. Gisbert Kapp, and Miles Walker, in England, have developed practical types of "phase advancers." Kapp's device has been tried out experimentally in this country by the Westinghouse company, while Walker's was built by the British Westinghouse company. The General Electric Company has tried out a form of the Leblanc phase-correcting device.

Developments from 1900 to 1910

The decade following 1900 was very largely one of growth as distinguished from development. In other words, the induction motor came in so rapidly and business was relatively so large that the manufacturing companies were busy extending standard lines rather than producing new types. This was a period of growth in size as well as in quantity. Also, due to greater refinements in application, etc., manufacturing companies were getting ready with new lines of apparatus, having improved characteristics, less weight, etc.

During the period from 1895 to 1905, the Westinghouse company, as well as other companies, had built many alternators with partially closed slots. In consequence, this construction was also carried into induction motor primaries and secondaries, so that the merits of partially closed slots were well known in the way of decreased losses, improved power factors, etc. However, practically all the moderate size and smaller induction motor primaries had been made with open primary slots, the "closed-in" slot construction appearing only on the larger machines. In attempting to obtain the merits of the partially closed slot machines for moderate and small size machines, the Westinghouse company developed a new line of motors called the type *CC*. This type had form-wound coils, without insulation except on individual wires, which were fed in through openings at the top of the slot. The insulation in the slot was a special cell. The end windings were then taped after being placed on the core.

This line of machines was about ready for the market when it became apparent that a somewhat lighter and smaller machine was desirable. In consequence, almost at once this new type was reconstructed, both mechanically and electrically, to form the type *C C L* line, which was then put on the market. This was the first radical departure from the type *C* line. It had many of the characteristics of the type *C* motors, but its efficiency and power factor were materially better. This line was on the market for a number of years, but it was found that many customers did not like the dropped-in type of winding, with partially closed slots, as repairs were more difficult than with the former open slot construction such as the type *C*. Moreover, when exposed to severe conditions of moisture, dirt and other foreign materials, the insulation on the end windings was assumed to be less satisfactory than the type *C* with its competely insulated coils. This condition, however, later was improved materially by dipping the end winding into insulating gums and varnishes. However, after a few years, with this type of winding, it developed that the operating public in general would be willing to sacrifice certain characteristics, to a slight extent, in favor of easier types of construction requiring less expert skill in repairs. In consequence, the open type of primary slot then came into general use in later constructions. This is not true, however, of the small sizes, for here the gains, due to partially closed slots, have been so great that they have apparently much more than offset the problems of repair, so that the trade in general has accepted the partially closed slot for the smaller motors.

In attempting to combine the advantages of the partially closed slot with those of the open slot construction, many manufacturers of induction motors, including the Westinghouse and General Electric companies have sought to develop and use some form of magnetic retaining wedge, which would serve to hold the primary coils in place and, at the same time partially close the slot magnetically. During the past ten years, many forms of wedges have been devised and many motors have been built with such wedges, and, within their limitations, several forms of these have given quite satisfactory results. In fact, this is still one of the active development problems in several of the manufacturing companies.

Speed Control of the Induction Motor

In applying the induction motor to steel mill work, many new problems have come up, and many new and unusual developments have occurred. Among the problems involved was that of obtaining speed adjustments, or variations, in an economical manner. Inherently the induction motor is a constant speed machine and has been recognized as such almost since the first. This being the case the motor has been applied with this limitation in mind, and, in consequence, there have been certain classes of service where the induction motor inherently does not fit well. Adjustments in speed in such cases must be obtained either by the use of some other kind of motor or by some mechanical means. However, in steel mill work, where large powers are involved, these indirect means have not been applicable, in many cases. Direct-current motors in large sizes are not desirable on account of voltage limitations, and mechanical speed-changing devices on a large scale do not appear to be applicable or feasible. In consequence, pressure has been brought, by the needs of the situation, to develop means for obtaining the necessary speed adjustments or variations with induction motors.

Adjustable speeds, of course, are obtainable with induction motors by varying the supply frequency, but this is not a general solution as it involves means for obtaining variable or adjustable frequency, which usually contain the same difficulties as speed adjustment in the induction motor itself. Speed control is also obtainable by varying the number of poles in the motor, but obviously this is limited to a relatively small number of combinations, and fine graduations in speed are not obtainable. Speed control is also possible by means of a resistance in the secondary circuit, but speed changes obtained in this manner are uneconomical and the speed varies with changes in torque. However, if instead of expending energy in resistance in the secondary circuit, such energy is expended in some useful way such as in a motor, or other devices which can either utilize it or return it to the system, then economic speed control becomes possible. However, with each change in speed in the secondary circuit of the motor there is a new frequency and a new voltage and, consequently, any means for absorbing the secondary energy must be of a kind which is adapted for adjustable frequency and voltage. Obviously, therefore, we have simply transferred the variable frequency problem from the primary to the secondary, with this difference, however, that the secondary frequency is proportionate to the slip, and, therefore, for moderate slips on either side of synchronous speed the frequency involved will be relatively low. This is of direct importance, because a number of the practical means for furnishing low frequency are dependent upon alternating-current commutation, which, in general, holds certain relations to the frequency.

In some of the earlier mill work, where only two speeds were called for, either cascade operation of two motors or pole changing in one motor was resorted to. In 1906, the Westinghouse company installed a relatively large cascade set in the Illinois Steel Company, at Chicago. This set had twelve poles in one frame and twenty-four poles in the other, and was adapted for operation at speeds corresponding to 24 and 36 poles. This set is still in operation after fourteen years.

However, the cascade arrangement proved to be expensive compared with the use of two combinations of poles on one frame and in later work, requiring two speeds, single frame motors were installed as a rule, with their windings adapted for giving two sets of poles. Some very large motors of this type were installed in steel mills by both the General Electric and Westinghouse companies.

However, it gradually developed, both in Europe and in this country, that finer gradations in speed were necessary and, therefore, various methods were developed for obtaining close speed adjustment. Most of these methods were tried commercially in Europe before they were undertaken in this country, but, in recent years, practically all the available methods have been tried out commercially in one form or another in this country. The methods of speed control by utilizing the loss in the secondary may be considered as primarily three in number; (1) by converting the secondary frequency and power to direct current; (2) to mechanical power; and (3) by converting the variable secondary frequency to some definite constant frequency, such as the primary, by means of a frequency changer.

The first of these methods, utilizes a synchronous converter in the secondary circuit, converting to direct current, but at a variable voltage. This power can then be utilized by an adjustable-voltage d-c. motor. This method usually known as the Kraemer, had been much used by both the Westinghouse and General Electric companies.

The second method involves the use of a variable frequency motor, which of necessity is a commutating type a-c. machine. The variable-frequency secondary power is thus converted directly to mechanical power, in which form it can be utilized in various ways. This arrangement, known as the Scherbius, has been used quite extensively by the General Electric Company.

The third method involves the use of a frequency changer, which is also a commutating type machine. This method is practically the equivalent of the first method above, except that it transforms from one frequency to another instead of to zero frequency (direct current). This third method has been used recently by the Westinghouse company.

It may be noted that all these methods involve the use of extraneous devices for regulating the speed and, therefore, it may be said that this development should not be classed with the induction motor problems, but is really a control problem. In consequence, it may be said that this need for adjustable speed has not really affected the induction motor development itself, but has simply extended its field of operation, and has given to it some of the flexible characteristics of the direct-current machine, but at the expense of considerable complication.

Heavy Power Applications

Steel mill work is a good illustration of what happens in extending electric power application into heavy work. Originally the steel mill applications were largely direct-current, which presented the greatest flexibility in the motors themselves. However, before long, it was seen that the power requirements in general would overtax the direct-current type unless abnormal voltages were used, and, in consequence, the trend was soon toward the alternating current, simply because of its capabilities in large powers and its flexibility as regards voltage. This had been the trend in many other lines, such as power station work, railway work, etc. Long ago the direct-current power station for railway work became obsolete and alternating current generation, with synchronous converters in distributed substations, took the place of the former direct-current power generating stations. In central station work, in general, the alternating-current system had driven out the direct-current type so long ago that the present generation knows practically nothing else. In direct-current generator work, machines of from 3000 to 5000 kw. have been considered as monsters, but in the alternating current work, single generators of 30,000 kw. are not uncommon. Therefore, the direct current system with its greater flexibility in speed control, etc. has not been able to hold its own against the alternating system with its greater flexibility in voltage transformation. This trend followed naturally into the steel mill business, for here motors up to 6000, 8000 and 10,000 kw. came into use many years ago and the need for such huge capacities has forced the situation to the alternating-current system throughout. When these huge horse-powers are referred to, it must be borne in mind that, in some cases, these also represented very low speeds, such as seventy-five revolutions. An 8000-h.p., 75-rev. per min. mill motor, represents almost the acme of design in induction motor work. Here the mechanical problems of construction may dominate the electrical. Such machines not infrequently have been made with purely engine type frames, similar to engine type alternators, which construction necessitates relatively large air gaps compared with other kinds of induction motor work. A total gap of ¼ in. could seem prohibitive in induction motors, yet such gaps and even larger have been used in some of these huge steel mill motors, as constructed by the larger manufacturing companies. Such machines are especially interesting when constructed for two speeds, usually involving two sets of windings in both the primary and the secondary elements.

Induction Motors in Railway Work

As already mentioned, the General Electric Company applied the induction motors to railway work in connection with the Cascade Tunnel on the Northern Pacific Railway. A much more recent application of such motors to railway work is the Norfolk & Western application at Bluefield, West Virginia. Here the induction motor appears in two radically different functions; one as a generator of power, in the main locomotive motors themselves, and the other as "phase generators" in the so-called "phase converters" which serve to transform from the single-phase trolley system to the three phase circuits for the motors.

As mentioned before, even back in the days of the monocyclic system, induction motors were used for "balancing" polyphase circuits. It was found in the very early days of the induction motor, (the writer does not know who first made the discovery) that when an induction motor was operated at full speed, on one primary phase from the supply system, polyphase circuits could be taken from the machine by simply tapping in on all the primary phases of the motor. In other words, if one phase or terminal of the motor should be disconnected from the line, that phase or terminal would still be active as far as voltage and phase generation was concerned. This principle has been applied many times, and in various ways, within the past twenty or twenty-five years. As mentioned before, the writer tried this method experimentally for operating a polyphase railway motor from a single-phase circuit, in the later 90's. Alexanderson also proposed this general scheme for railway work about twelve years ago, and the General Electric Company made elaborate tests on an experimental equipment. The scheme used on the Norfolk & Western locomotives

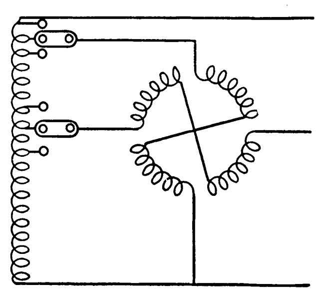

Fig. 10

is based on the same principle. In these locomotives, the phase converters are simply high-capacity induction motors connected to the circuit in such a manner as to transform from a single-phase supply system to a practically balanced three-phase motor system. The phase converter has a two-phase primary winding with a cage secondary. One of the two-phase windings connects across the secondary circuit of the step-down transformer, while the other phase has one terminal tapped to a mid-point of the transformer, thus forming the equivalent of the Scott transformer system. The two terminals of the transformer and the remaining terminal of the phase converter thus form a three-phase system, the proportions of the two windings on the converter being such as to give practically balanced three-phase relations. To compensate for unbalanced conditions with change in load, the tap at the middle of the transformer can be shifted back and forth a certain amount.

Induction Motors in Ship Propulsion

Another huge application of the induction motor, of quite recent date, is in the propulsion of battleships. This started only a relatively few years ago with the electric propulsion of the collier *Jupiter,* by the General Electric Company, under the supervision of Mr. Emmet. This it might be said was an experimental equipment in the sense that its purpose was to find whether electric motors were suitable for the propulsion of large vessels. Based upon these results the Navy went into electric ship propulsion on a large scale so that at the present time there are nineteen large battleships and battle cruisers under contract for propulsion by electric motors, ten of these being built by the General Electric Company and nine by the Westinghouse. Only one of these has been in extended service as yet, namely, the *New Mexico* with General Electric equipment, this being the first battleship contracted for. A second battle ship, the *Tennessee*, with Westinghouse equipment, has only recently gone into service. The equipment of these battleships in general, may be of interest as showing special features of speed control.

In this battleship drives the main propulsion motors form the only load for the generators. In consequence, the frequency can be fixed by design conditions, such as the desired speed for the generators and propelling motors and this frequency can be varied up and down over a wide range by simply varying the speeds of the driving turbines. Thus speed control is primarily by means of primary frequency, this being one of the few instances where this is practicable.

As the desired steam economies can not be obtained at the lowest required speed with this arrangement, a change in speed by means of pole changing, or its equivalent, in the motors themselves is obtained. For example: The motors on the *New Mexico* and the *Tennessee*, and a number of other battleships, are designed for twenty-four and thirty-six poles. In the battle cruisers, however, a different combination is used as will be mentioned later.

In ship propulsion by electric motors such as the above, there are several conditions which are very favorable to the electrical equipment, and which make the whole operation relatively simple and easy compared with other kinds of motor operation. In the first place, the motor is not tied rigidly to its load, as is the case, for instance, in locomotive work. In other words, the motor can start and come up to speed long before the ship has reached its full speed. On this account the secondary losses, rheostatic or otherwise, can be made very low, for the motors come up to speed in a very short time, while the boat may take many minutes to obtain full speed. If it were not for this feature, the rheostatic loss in starting and accelerating would be enormous, unless all such starting was done by means of speed adjustment of the turbine. As it now stands the propeller acts as a slipping clutch which gradually pulls the motor up to full speed without undue load on the motors themselves and with principal expenditures of power at the propellers themselves, which produces no harmful heating.

In the second place, the switching of the motors can be done without power. In other words, the excitation can be cut off from the generator when it is desired to switch the circuits, such as for pole changing or for reversing, for it is not necessary to maintain the driving torque at all times, as is the requirement in locomotive work. When drawing a locomotive up a grade, for instance, the tractive effort must be maintained during the operation of switching and this is one of the features which makes the problem difficult. In ship propulsion, on the other hand, this condition is absent or is of minor importance.

A third favorable condition in the ship propulsion problem is that there is no need for parallel operation of the generators.

In the *New Mexico* and the *Tennessee*, there are two generating units and four motors. For the higher speeds two motors are operated from each generator and, for lower speeds, four motors are operated from one generator. In the larger units, such as the battle cruisers, there are four generators and four pairs of propeller motors. At the highest speed there is one pair of motors on each generator. At intermediate speeds there are two pairs of motors on each of two generators, while at the low speeds there are four pairs of motors on one generator, but at no time is there any occasion for paralleling any of the generators. This simplifies the whole proposition materially.

On account of the huge capacities of the propelling equipments, not only is alternating current required but relatively high voltages. On the *New Mexico*, the *Tennessee*, and vessels of the same class, there are four main motors of about 7000 h. p. each, operated from two generators of suitable capacity. The size of these equipments necessitates a maximum operating voltage of about 3500. This voltage, of course, decreases with reduction of frequency in speed control.

In the battle cruisers, however, where there are four pairs of motors, each pair consisting of two 23,000 h. p. motors on one propeller shaft, the power of the motor is such that a maximum operating voltage of about 5500 is needed. Considering the possibilities of salt spray, etc. some very difficult problems are involved in the use of such voltages on sea-going vessels. On the battle cruisers a two-to-one combination of poles is desired instead of three-to-two on the smaller vessels. In consequence, here either pole changing or simple cascade arrangement of the motors is permissible.

On the speed control of the motors themselves, during starting, two radically different arrangements have been put out by the General Electric and Westinghouse companies. In the *New Mexico*, equipped by the General Electric Company, the two-phase motors are of the double cage secondary type, that is, the secondaries of the motors are equipped with two cage windings, the outer one, that is the one next the air gap, being of relatively high resistance for starting and accelerating and the inner one being of relatively low resistance. Between these two windings is a sort of magnetic bridge for introducing a certain amount of reactance for the bottom winding. During starting and acceleration, the high-resistance winding furnishes a considerable part of the torque, whereas at full speed the low-resistance winding becomes effective. These two windings are proportioned to give the required torque results with both the 24 and 36 poles. Many problems of expansion, etc. came up in the development of this cage winding and, in fact, the end rings of the secondary contain what might be called "expansion joints."

In the contract for the *Tennessee,* which came later than the *New Mexico,* the Westinghouse company designed their motors for three-phase current, using two primary windings, one for 24 poles and the other for 36. The secondary winding is of the wound type and is connected to the collector rings in order that a starting resistance can be inserted. Certain cross connections on this 24-pole winding automatically act as short circuits when the primary is thrown to 36 poles, so that the secondary automatically becomes short-circuited under this condition. The rheostat is, therefore, inserted only for control on the 24-pole combination, the 36-pole being simply a running speed.

In later equipments of the *Tennessee* and *New Mexico* types of ships, the General Electric Company arrangement is somewhat different from the above, according to the information which the writer has received. Here there are apparently two windings on the secondary, one being a high-resistance winding equivalent to the cage type, while there is a 24-pole winding of the distributed type, which is inoperative on 36 poles, but which is short-circuited on 24 poles. The high-resistance cage winding is in circuit on both 36 and 24 poles.

While this arrangement, on the face of it, does not look as simple as the double cage of the *New Mexico,* yet it is intended to give better speed-torque and power factor characteristics.

On the battle cruisers the writer does not know what motor combinations are used by the General Electric Company, but in the Westinghouse, a special cascade arrangement is used to give half speed and lower. As the motors were laid out with wound secondaries, this cascade arrangement involved little or no additional complication for cascade operation.

In the super-dreadnoughts, which were contracted for after the battleships and battle cruisers, four motors of about 15,000 h. p. each are required with two generators of necessary capacity. The general arrangement is, therefore, quite similar to the battleships, except that the power requirements are practically double. In the Westinghouse equipment, the motors are for 24 and 36 poles, each motor containing two primary and two secondary windings, each secondary winding being suitable for starting on resistance.

It may thus be seen that this electric propulsion of large ships is not a radical undertaking. The motors are huge in capacity, but their speeds are such that from the mechanical standpoint they are not nearly as large as some of the steel mill motors which have been in operation for many years. One of the principal problems has been in the ventilation, for the equipment has to be installed in confined spaces and, therefore, artificial cooling has been resorted to in all cases. In fact, this has been possibly the most difficult problem in the whole design of these huge equipments.

This brings the induction motor up to the present. Its history has been a most interesting one to those who are at all familiar with it. To a certain extent this type of apparatus stands apart, in that its development has been due, almost entirely, to the analytical engineer. It is almost impossible to conceive that the induction motor could have been developed to its present high stage by ordinary "cut and try," methods. Some good motors might have been obtained in that way; but they would have been accidents of design, instead of the positive results of analysis, as the art now stands.

New applications are continually leading to new developments which are worked out by the analytical designer with an assurance of success not exceeded in any other branch of the electrical art. And the result of all the elaborate theory and complicated analysis and calculation is a practical machine of almost unbelievable simplicity and reliability;— a standing refutation of the too common idea that complexity in theory leads to complexity in results.

AUSTRALIAN STEAM-ELECTRIC PLANT TO USE 50-CENT COAL

Construction is to be started April 1 on a 125,000,000 kw. steam-electric plant, 112 mi. from Melbourne, Australia, according to announcement from Australian government offices. This is a governmental undertaking, to be carried out by the Victoria Electricity Commission, which proposes to develop extensive coal deposits at the plant sites, use the coal for generating electrical energy and transmit the power electrically to Melbourne and other industrial centers. Included in the project for which immediate construction is planned are a total of 1800 mi. of high-tension transmission line and three terminal substations. The trunk line voltage will be 132,000.

The coal deposits are said to be very extensive, . . . The coal can be delivered to the power house for about 50 cents per ton the report states. Condensing water is supplied by a river alongside the power house. . . . . . —*Engineering News-Record.*