

DISCUSSION ON "SELF-STARTING SYNCHRONOUS MOTORS"
(FECHHEIMER). PITTSBURGH, PA., APRIL 25, 1912.

R. B. Williamson: Mr. Fechheimer's paper presents a large amount of interesting and valuable experimental data regarding a type of motor that is rapidly coming into use, and about which comparatively little has been published.

The self-starting synchronous motor, when started with the exciting field open-circuited, is essentially a squirrel-cage induction motor for the time being, although it is a more or less imperfect one. In general, all the tests given by the author point to the conclusion that the same rules laid down for the design of induction motors to secure the maximum starting torque with minimum line current, must also be observed in the design of a self-starting synchronous motor. For example, the reactances of both stator and rotor windings must be kept down as much as possible, and this in turn affects the number and proportions of stator and rotor slots. The squirrel-cage winding must be designed with sufficient resistance to give the required starting torque, and the rotor bars must be spaced to avoid dead points as far as possible. This last point is very important. It is of little use to make elaborate calculations and go into refinements of design to obtain a squirrel cage which will produce a given *average* torque if the arrangement of bars is such that the *minimum* torque is insufficient to start the machine. The author has very properly called attention to this point. It is true that some of the requirements for a good induction motor cannot well be met in the synchronous motor, but the nearer the induction motor design can be approached, the better, at least so far as starting is concerned. The large air gap and discontinuous rotor surface are desirable for the synchronous motor. So far as starting torque is concerned, the large air gap is not a great disadvantage; an induction motor may have a relatively large gap and yet be quite satisfactory so far as starting characteristics are concerned. It is true that the larger the gap, the larger will be the component of line current required for setting up the flux across the gap, and to this extent the total line current will be increased.

A point to be noted regarding the squirrel-cage winding of a self-starting synchronous motor is that it is in use only during the starting period, except possibly for momentary or periodic currents that may flow in it if hunting takes place. The squirrel cage can therefore be designed with reference to the starting conditions rather than operating conditions. On the other hand, in a regular induction motor, working currents flow in the squirrel cage and the loss at starting must necessarily be limited in order to secure a satisfactory efficiency while the motor is running under regular load.

In designing the squirrel cage for a synchronous motor, the

service for which the motor is to be used should be kept in mind. For starting air compressors (unloaded), motor-generators or similar service, the torque required to overcome static friction is relatively high, but drops off rapidly as soon as the machine starts. At or near synchronism, the driving torque required is relatively small. For such service, a high-resistance squirrel cage is desirable, as it will develop a high torque at starting, and will allow the motor to come nearly up to synchronism on a half-voltage tap, on account of the light running load. There will not, therefore, be an excessive rush in current when the motor is thrown over to full line voltage. On the other hand, a motor used for starting, say, a centrifugal pump or fan, where the torque required to overcome static friction is not large, while the running torque near synchronism may be very high, requires a low-resistance squirrel cage in order to approach closely to synchronism before full line voltage is thrown on. It has been found that in case a motor is brought into synchronism on the low-voltage tap by the application of direct current in the fields, it sometimes happens that when the motor is thrown over to full voltage, an excessive rush of current that may trip the circuit-breakers takes place. This can be avoided by increasing the field excitation to quite a large amount just before the switch is thrown over, thus increasing the counter e.m.f. of the motor. In case this is done, sufficient time must be allowed for the field current to increase to the required amount before throwing over to line voltage.

Mr. Fechheimer has called our attention to the falling off in torque near synchronism, and mentioned that the application of a small direct-current excitation will help the motor to pull in. The writer noted this effect some time ago, but the present paper is the first place where he has seen it pointed out that there is in each case a critical value for this excitation giving the best results. The curves shown in Fig. 11 are particularly interesting in this connection.

In applying direct-current excitation, care must be taken that it is not done when the machine is much below synchronism. Cases have occurred where this resulted in an insulation breakdown of the exciter armature, on account of the high induced voltage in the field of the synchronous motor when running with a large slip.

It is a well-known fact that synchronous motors, when started with the field circuit closed, frequently tend to stick at half speed. This, however, can hardly be attributed to higher harmonics in the wave form of the motor. For such to be the case, the harmonics would be of an even order, whereas even harmonics do not exist in a symmetrical wave. It seems that the phenomenon of running at half speed might be explained as follows: If an alternator of frequency n cycles per second is excited with direct current, it must be driven at synchronous speed to generate this frequency. If, on the other hand, it is excited with alternating

current at frequency n instead of direct current, and at the same time driven at synchronous speed, it will generate an e.m.f. having double frequency $2n$. Or, if it is driven at one-half synchronous speed and excited with alternating current of frequency $\frac{1}{2}n$, it will generate normal frequency n . Now, if the latter case is reversed, and the generator operated as a synchronous motor at line frequency n , and if at the same time its fields are excited with alternating current at frequency $\frac{1}{2}n$, the motor will run at one-half synchronous speed. When a synchronous motor is started with its fields closed and attains one-half speed, the frequency of the current in the closed rotor circuit is $\frac{1}{2}n$, and the effect is the same as if the motor were excited from an external source at one-half frequency. The motor, therefore, tends to lock into step and will so continue running unless the conditions are such that the torque due to the squirrel cage exceeds the pull-out torque of the synchronous motor when operating in this manner. When the field circuit is opened, the half-frequency exciting current disappears and the squirrel-cage torque brings the motor nearly to synchronism.

Regarding the high e.m.f. induced in the fields at starting, particularly those wound for 250-volt excitation, this can usually be taken care of by extra insulation on the coils and collector rings. It should be remembered, however, that the same precautions regarding insulation should also be taken in connection with the wiring for supplying the exciting current. Mention has been made of the effect of solid poles in reducing the voltage generated in the field. Laminated poles without dampers or squirrel-cage winding undoubtedly permit a high induced voltage, but this is very greatly reduced in machines provided with a squirrel cage, so that the solid pole has little advantage in this respect. In one case with which the writer is familiar, the addition of dampers reduced the induced voltage to approximately 25 per cent of its former voltage.

The analytical discussion is of value in that it shows the relative importance of the various quantities entering into the determination of a given torque and the corresponding line current, power factor, etc., during the starting period. However, the whole subject is complex, and so many assumptions have to be made on which to base calculations, that the engineer must place reliance on tests more than anything else.

F. D. Newbury: The Institute is to be congratulated on having a paper of this quality on a design subject. We do not often get them. This is a very complicated subject. The synchronous motor is such a rapid-change artist during starting, starting as an induction motor, sometimes changing to a synchronous motor at half speed, and sometimes not changing until it gets pretty near the full speed, that the conditions are quite complex. I will not attempt any general discussion of Mr. Fechter's paper, but I do want to call attention to one or two points.

The "non-uniformity of torque at the instant of starting," and the "unbalance in phases," I have noticed are very much larger without amortisseur windings or without continuous end rings, when there are damper windings upon the individual poles. I do not believe Mr. Fechheimer mentions whether the motors he tested had continuous end rings or not.

In connection with the field circuit at starting, with an open field circuit, as Mr. Fechheimer points out, there is a large voltage induced in the field windings, particularly with the higher exciting voltages. He also points out that there is considerable decrease in starting torque with the field short-circuited, but the curves also show that with some resistance in the field circuit this decrease in torque is practically nil. I think it is, therefore, preferable to start the motors with the field circuit closed, and through as much resistance as is ordinarily placed in the field rheostat. This reduces, in fact, eliminates, the danger of any insulation strains in the field circuit, and does not cause any great decrease in starting torque.

Mr. Fechheimer devotes one section to the subject of "driving of fans and pumps." I am familiar with a motor of about 200 kv-a. at 500 rev. per min. on 25 cycles, which is arranged to drive a fan in which the starting conditions are very severe. The motor must be placed on the line with about 80 per cent of full load torque, at the instant of falling into step, with not more than 2.5 normal kv-a. from the line. I think that is about as good as a corresponding induction motor could do, which also bears out well the contention which has been made, that there is not a great deal of difference between a properly designed synchronous motor and a corresponding induction motor.

I agree with Mr. Fechheimer, that in obtaining good starting conditions, the distribution of slots in the rotor and in the stator is important and that it is not good engineering to decrease the air gap in order to get a little better starting conditions. The decrease of air gap of course results in much smaller pull-out as a synchronous motor, and the pull-out as a synchronous motor is undoubtedly much more important than the slightly smaller starting current.

Mr. Fechheimer has devoted most of his paper to the conditions of actual starting. There is an equally interesting field for discussion—the conditions after the motor is connected to the low voltage, and the starting operation is completed by connecting to the line voltage and exciting the field.

As Mr. Williamson pointed out, the complete starting conditions are improved with an increased field current. The armature current on low voltage may be considerably higher than it would be with lower field current, but in throwing over to line voltage there is not an excessive rush of current which will open the current breakers.

H. M. Gassman: The mention of induced voltage in the fields of synchronous motors recalls some comparative tests I made on

synchronous motors with 250-volt windings. The motors were of 250 kv-a. capacity and the voltage was measured at the field switch on the switchboard. In both cases approximately one-half normal voltage was applied for starting the motors.

The solid-pole motor gave as a maximum 1500 volts induced in the field at starting. The motor with laminated poles and copper end rings showed an induced voltage of 4000. Such induced voltage deserves consideration on account of the danger to which the operator is exposed when starting synchronous motors, and the chance of such induced voltage breaking down the ordinary insulation used on the complete field circuit and even breaking down the rotor insulation after it has deteriorated from use or exposure. The rotors in this case were designed to withstand 5000 volts when new, which leaves a very small factor of safety for deterioration when the induced voltage is so high.

When the ammeter of the synchronous motor is not short-circuited in starting, it is an advantage to insert the resistance in the field, as suggested by Mr. Fechheimer, for the purpose of reducing the chances of damaging the ammeter needle. Damage to the needle might be avoided by selecting an instrument with larger capacity and also by an increase in the size of the current transformer. This, however, is not desirable, on account of the performance of wattmeters and the indicating meters on light loads.

A. M. Dudley: One point in Mr. Fechheimer's abstract of his paper must be taken with certain modifications and also brings out the need for correction in one of our existing Standardization Rules. I understand that such correction is contemplated in connection with the revision now under way. I refer to Mr. Fechheimer's statement that the real watts input into the rotor is a fair measure of the starting torque. This statement is reasonably correct, but he said, in addition, that if the real watts input into the primary at standstill were measured, and the loss in primary copper were subtracted therefrom, the remainder would reasonably represent the input into the rotor which reappears directly as starting torque. It is well known at the present time that there are certain losses at standstill due to eddy currents in different parts of the machine, which do not appear as starting torque and which are not present as losses when the machine is running at normal full load speed. For this reason the starting torque, as figured in this manner from the locked kilowatts input, is usually higher than the machine actually develops, and the secondary copper loss as so figured is too high, showing an efficiency at full load speed which is less than is actually the case. This discrepancy is not always so small as to be negligible and in extreme cases a starting torque of 1.7 times full load torque may be indicated from the locked kilowatts and the machine may actually test out only 1.2 times.

Referring to the Standardization Rules on this point, under Section 167, they definitely state that the locked watts when the

full load primary energy current is flowing in the windings are directly chargeable against the motors either as copper losses in the primary and secondary or as so-called load losses. This, I believe, we all recognize as incorrect and the rules could be modified so as to correct this inaccuracy.

W. J. Foster: I would like to say a word with reference to the solid pole versus the laminated pole. I agree that it is not permissible to have such high induced potential as mentioned in a particular case by a previous speaker. Of course, in the designing of the synchronous motor we must strike a compromise. There are a good many conflicting factors, and we must combine them so as to obtain a motor that is practicable.

Now in the case mentioned of the motor with solid poles, undoubtedly the reduction of the induced voltage, due to the solid pole, is a good thing, when you consider the danger of the induced potential. We ought not to allow a synchronous motor to be built that is absolutely open-circuited and with laminated poles and nothing to keep down the induced potential. In the particular motor that the speaker had in mind as subject to criticism, probably the squirrel-cage winding, there is very high resistance. There has been that danger in the past. Many motors have been built with altogether too high a resistance. Such a motor shows up well in the initial start, since it keeps down the amount of current taken from the line, and if the question is asked as to the current required to start, the answer is made so as to apply at the instant of starting. Hence there is the temptation to make that very low, say, full load current or less than full load current. This proportioning of squirrel-cage windings does not, it seems to me, result in a machine which is a practicable one—either the windings should have much lower resistance, or, what is simpler, short-circuiting collars should be put on the poles, as they will cut down the induced potential. I recall some experiences in the matter of short-circuiting collars. There is danger of getting too low resistance, so that there will be trouble at the half-speed point in starting up. There is danger, if alloys are called for, on account of the uncertain character of what one gets from the foundry. You sometimes get material with 50 per cent higher resistance than at other times.

In general, it is better to design the squirrel-cage windings with lower resistance, or with that which it needs as it approaches synchronism.

I agree with the emphasis laid by the author on the desirability of providing definite paths for the current in the starting winding. It seems to me more scientific and approaches more nearly the induction motor design. The synchronous motor is at a disadvantage when compared with the induction motor, since no serious attempt has been made to develop synchronous motors as a class of machines by themselves. Most commercial synchronous motors are generators adapted to the use as motors.

The author brought out a number of points with which I agree.

As to the matter of air gap—when you consider all the characteristics of a good motor, I think the gap of a synchronous motor should be approximately the same as of a generator.

I would like to ask Mr. Fechheimer, in closing, if he is ready to make a statement with reference to the ratio of slots, the region within which he considers good practise to lie? Mr. Fechheimer has warned us in both directions, against the multiple and against the prime relation; this helps a good deal, but I should like him to make a positive statement. I think we are all greatly indebted to Mr. Fechheimer for the paper, which is an excellent treatise on the subject.

B. G. Lamme: Considering the synchronous motor problem as a whole, it has been known for many years that, in starting and accelerating such a machine, it is an induction motor until it comes up to synchronism, and that, while acting as an induction motor, it followed the laws of the induction motor; or rather that it followed these laws as closely as the crudeness of the construction would permit, for the synchronous motor is naturally an imperfect form of induction motor. It has been known for a long time that the starting torque of the synchronous motor varies as the square of the impressed voltage, which is a well-known law of the induction motor. The same is true of many other relationships which Mr. Fechheimer has brought out, and the great value of his paper lies in the fact that he has shown how very closely the synchronous motor follows the same laws as the induction motor, when its imperfect construction as an induction motor is taken into account.

One of the first things which we teach designers of induction motors is that, to obtain full load torque at the start, there must be an expenditure of at least full load energy in the secondary circuit. Mr. Fechheimer shows that in the synchronous motor we get practically the same result in spite of the fact that the field structure of the synchronous motor, which becomes the secondary of the machine as an induction motor, is, magnetically, badly proportioned, compared with the usual secondary construction of the normal induction motor. At half speed the synchronous motor tends to hesitate, one might say, or to drop into a sub-synchronous speed. In this feature it also follows the principles of the induction motor, which, with a wound secondary, will tend to run at half speed when its secondary has only one circuit or phase closed on itself, and will even pull a considerable load. The synchronous motor at half speed represents a similar condition to a certain extent. The secondary conditions, represented by the polar arrangement of the magnetic circuit and the field coils of the synchronous motor, tend to give, to a certain extent, a single-phase condition in the secondary. In particular, the field winding, closed on itself, tends to give the effect of a single secondary circuit, and therefore tends to lock the machine at half speed. This action is neutralized, to a certain extent, by any polyphase actions in the secondary

circuit, and the greater the polyphase tendency compared with the single-phase, the less difficulty there is in carrying the machine past the half-speed point. If the single-phase action of the secondary preponderates, the motor may have a strong tendency to lock at half speed.

When the motor speeds up, it approaches as near synchronism as the resistance of the secondary winding will allow. With a very low-resistance secondary winding, a very close approach to synchronism is attained, as in the induction motor, and it is easier to pull the machine into step. The higher the resistance of the secondary, and therefore the better the starting conditions, the greater will be the "slip" at full speed, and therefore the harder will it be to pull the motor into synchronism. It is difficult to "see" just what is going on in the motor at the instant it pulls into synchronism, but the conditions can be approximated by considering the synchronous motor at standstill with its terminals connected to an alternating-current generator which is started from rest, the fields of both the generator and motor being excited by direct current. At the first instant of movement of the generator, there can be no current between the machines, because there is no electromotive force generated until the generator gets into motion. A certain low speed is required to generate enough e.m.f. to overcome the resistance of the armature windings of the two machines. At one per cent of normal speed there may be sufficient current flowing between the machines to exert a considerable torque, but the motor is at standstill while the generator is rotating at one per cent of normal speed. Observing the rotor of the synchronous machine under this condition, it will be seen to quiver or oscillate back and forth a few times, and then jerk or swing itself into step. Sometimes there is simply a small quiver and then a sudden jerk into synchronism with the generator. At other times, there may be a very pronounced oscillation or swing of the synchronous motor, and finally it swings itself to such an angle that it naturally falls into step. It is obvious that the nearer the generator can be to zero speed when this action occurs, the easier it will be to pull the synchronous motor into step. Watching a motor start under these conditions gives a very good impression of what happens under ordinary conditions of synchronizing when the generator is running at normal speed.

In one important feature the synchronous motor is quite different from the induction motor. In the synchronous motor, in order to get a good pull-out torque, usually the direct-current field magnetomotive force must be high compared with the armature magnetomotive force. Ordinarily, the field ampere-turns in the synchronous motor will be about one and one-half times as great as the effective armature ampere-turns at full load, in order that the motor may be able to develop a maximum of about two times full load torque. This high field strength is

necessary in order to give the proper overload torque. On the other hand, in the induction motor the magnetizing ampere-turns are possibly only 30 per cent of the full load ampere-turns; that is, in the induction motor, the exciting ampere-turns are only about 20 per cent as great as in the synchronous motor. Herein is one prominent difference between the two types, and in this lies the difficulty in making a machine which will be both a good synchronous motor and a good induction motor. If the induction motor requires only 30 per cent of full load ampere-turns to excite its field, then as a synchronous motor it would still require only an excitation corresponding to 30 per cent of the armature ampere-turns, whereas, in fact, it should have about one and one-half times the armature ampere-turns for excitation, as stated before. With 30 per cent excitation, it would have a pull-out torque of possibly 40 per cent of full load torque, as a synchronous machine, which is an impracticable condition. In order to get two times full load torque it would require an excitation of one and one-half times the ampere-turns of the armature, as stated before, and when acting as an induction motor the same excitation would be required. This would therefore lead to an induction motor having a magnetizing current of one and one-half times the value of the work current, which would mean a power factor of less than 50 per cent. This, therefore, indicates the impracticability of making a good synchronous motor which is able to drop out of step and operate as a good induction motor. The two conditions are conflicting, when running conditions are taken into account. A good synchronous motor therefore will not make a good induction motor, when carrying load.

Francis B. Crocker: I do not think there is time, when we have such an important and difficult paper to discuss, to defend the Standardization Rules, but there is opportunity, I believe, at the present time, to say that the Institute's Standards Committee is in existence, and that this committee is considering the revision of the rules, and any points of that kind which need consideration or revision should be presented to the committee.

I think also that the Standardization Rules should be revised from time to time. What may now be the actual wording of them may require modification as greater knowledge and change of practise takes place. In fact, I think it would be very extraordinary, and perhaps very undesirable, if they should remain unchanged, and not be revised from time to time. They have already been completely revised twice since their inception, and several other important changes and additions have been made when they were needed.

I think the point that Mr. Lamme has just spoken of is a thing we should bear in mind. Two machines, the synchronous motor and the induction motor, are shown to be more alike than we have previously considered, having been regarded, in fact, as quite different. After all, they are quite alike, and, of

course, the same laws necessarily apply to both, but, unfortunately, it does not seem to be possible to make a compromise machine which would have the advantages of the induction motor in starting up, and the advantages of the synchronous motor in being able to have leading current and improve the power factor of the other apparatus. If such a result could be obtained, there would be a great field for a motor which would have the advantages of both.

C. P. Steinmetz: Mr. Fechheimer's very valuable paper is especially interesting to me, as I always had a very strong predilection for the synchronous motor, especially its larger sizes, since I consider this type of alternating-current motor as decidedly superior in its electrical characteristics, in its reaction on the electrical system, and more particularly with regard to power factor and voltage regulation. The synchronous motor does not spoil the power factor, but can operate at unity power factor, or can be used to improve the power factor spoiled by other apparatus.

The synchronous motor gives a fixed voltage point determined by its direct-current excitation, and thereby is able to, and does, hold up the voltage or pull down the voltage, depending on the conditions of the system, and thereby can be used to, and does, control the voltage of the system, especially in long-distance power transmission, where voltage regulation is more difficult. This is a very important characteristic, as the experience on the Pacific slope since the early days seems to have shown.

The synchronous motor has no starting torque, as such. It starts as an induction motor. It has not always been realized, especially with the squirrel-cage synchronous motor, that is, a synchronous motor provided with the amortisseur winding, how large a starting torque you can get from it, and it is not completely realized today. When we first considered the introduction of the squirrel-cage pole face winding in the synchronous motor, to give it powerful starting characteristics, we made a number of investigations which were rather startling. With a standard alternating-current generator of moderate size, provided with squirrel-cage windings, we determined the torque characteristics from standstill to synchronism, and found that the maximum torque of the machine as an induction machine was materially higher than the maximum torque of the same machine as a synchronous motor at unity power factor, with the same terminal voltage applied.

That means you can provide any desired starting torque in the synchronous motor. In giving the powerful starting torque to the synchronous motor by means of the squirrel-cage winding or amortisseur winding we naturally meet with the same difficulty we meet with in the induction motor, that the requirements at standstill and requirements at speed are opposed to each other. High torque at standstill requires fairly high secondary resistance. To bring high torque up

close to synchronism requires very low squirrel-cage resistance. Now, in the synchronous motor, it is not merely sufficient to start from rest and run up to some speed, but we must run up so close to synchronism that the motor can pull into synchronism, into step; that is, we must go to a fairly low slip. The ability of the machine to pull into synchronism depends on the slip, and therefore the resistance, of the squirrel cage, and on the momentum of the moving masses, and also it depends very essentially on the mechanical configuration of the stator and rotor, as you can easily see by considering a machine with uniform reluctance all around, like a standard induction motor. Such a machine, without direct-current field excitation, could never pull into synchronism, and with the direct-current field excitation it is less able to pull into step than a machine with definite polar projection, and in the latter, also, we naturally find very wide differences, depending on the configuration of the polar structure of the machine.

In the early days of the synchronous motor, twenty years ago, when we built the first of these machines, we were very much afraid of the machines not being able to start off, and we provided three-phase bar windings in the field poles, brought out to a switch, to be able to insert resistances in starting, and afterwards to short-circuit them. Fortunately, experience showed that such complication was not necessary, and it was very soon abandoned. However, it would be extremely desirable if we could design the squirrel-cage windings of the synchronous motor, and probably also of the induction motor, so that their resistance would automatically vary to suit the conditions, from high resistance at standstill to very low resistance at speed.

Mr. Fechheimer mentioned the question of the short air gap. In the induction motor start of the synchronous motor, a short air gap is advantageous within certain limits, just as within other limits a short air gap is advantageous with the synchronous motor, but when you consider a still further decrease of the air gap, you reach a point where a further reduction of the air gap becomes objectionable in the starting of the synchronous machine as an induction motor, where we lose again by further reduction of the air gap. Decreasing the air gap, with the same size and relative position of stator and rotor slots, etc., at the same volt-ampere input, the average starting torque increases, but finally it increases very little. At the same time the irregularity of the starting torque increases, that is, the uniformity of the torque in different positions decreases.

What counts in the starting of the machine is not the average starting torque, but the minimum starting torque, the starting torque in the minimum torque position, and this depends on the relative proportions of air gap and width of slot, and also on the relative number of stator and rotor slots.

To get a reasonably uniform torque with a small air gap means very many narrow slots, which is uneconomical in general

in the synchronous motor, and impracticable in a high-voltage machine, but with such a reasonable number of stator and rotor slots as is economical, and even as is permissible, in the synchronous motor, there is a limit in the air gap below which you cannot go without impairing the starting of the machine as an induction motor, by decreasing the torque in the minimum torque position.

We usually think of a large air gap as producing a high exciting current, and so it does in the induction motor, but the high exciting current counts in proportion to the total current. An induction machine would be inoperative if the magnetizing current were 200 per cent of full load current. In the induction motor starting of the synchronous motor such a magnetizing current of 200 per cent is unappreciable, if you consider the synchronous machine starting by auto-transformer at half terminal voltage, twice full load current, which means taking from the line only full load volt-amperes: 200 per cent magnetizing current, referred to half voltage and double current, is only 50 per cent, and would thereby increase the total current only very little.

If, instead of allowing a nominal 200 per cent exciting current, you would go down to as low an exciting current as is the limit in the poor induction motor, or 50 per cent, the increase of irregularity of the starting torque would be very much greater than the percentage decrease in the total of current, and therefore, to get a minimum starting torque equal to that which you get with the bigger air gap, you would have to increase greatly the volt-ampere consumption. Thus it would be an engineering mistake to reduce the air gap still further.

You see that the conditions in the starting of the synchronous motor are different, with regard to magnetizing current, from what they are in the running of the induction motor, and economical proportioning requires a larger air gap in the synchronous motor starting than in the induction motor operation, although there is naturally a limit in the size of the air gap, beyond which it is uneconomical to go.

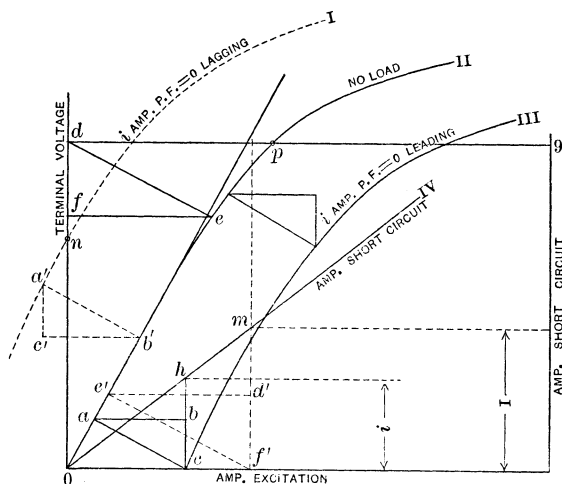
The last point which I desire to make has reference to Standardization Rules. I would like to say here to you what I have said before: There is no use in kicking against the Standardization Rules or objecting to them. Instead of saying that such and such a rule is unsatisfactory and should be changed, say how it should be changed, and give the evidence proving your contention, formulate a better rule and you will find that Mr. Lamme and myself, who have the very questionable pleasure of providing for the changes, will be delighted to act upon your suggestion. But a mere statement that the rules are not satisfactory, means nothing, and we cannot act on such a statement until something better is offered.

We know that things had to be put in the rules, as representing the best that could be obtained with the limited experience and

knowledge had of certain subjects. Now, what we want is to be provided with the data by which we can correct any existing rules that are not satisfactory, and we shall be delighted to do so, but, as I say, a mere objection to the rules means nothing. We know ourselves that many things should be changed, and the only question is how to change them and prove how the change should be made.

Bradley T. McCormick (by letter): During the period of starting, the self-starting synchronous motor acts as an induction motor of special type, but when synchronous speed is attained, the machine operates as a synchronous motor under the special condition of no excitation, until the field circuit is closed.

While the starting characteristics of the self-starting synchronous motor, before it has reached synchronous speed, can only be determined by methods which are more or less empirical,



the current input to the motor after it has reached synchronous speed, but before the fields are excited, can be accurately determined. Although this current is less than the starting current at rest, it is still of some interest, as it represents one of the points on the current-speed curve which can be determined easily and with accuracy.

In the figure presented herewith, curve II shows the no-load saturation curve of a synchronous motor, while curve III shows the saturation curve at a leading power factor of zero, with the full load current of i amperes per phase. Curve III is the path traced by the point c , as the triangle abc moves upwards in such a manner that point a follows curve II. The line ab is the armature reaction expressed in terms of amperes excitation, and bc is the reactance drop of the stator in volts.

Curve I is the full load saturation curve for zero power factor lagging, and is obtained by turning the triangle abc into the position $a'b'c'$, and moving along curve II as before.

The point n , where curve I crosses the axis of ordinates, locates the terminal voltage at which the motor will draw full load current when running at synchronous speed without excitation. In order to find the current drawn on full voltage od , draw de parallel to ac and construct the triangle efd similar to abc . The required current can either be found from the relation

$$I = i \frac{f e}{a b}$$

or by transposing the triangle into the position $e'f'd'$ and taking the current from the short-circuit curve at the point m directly above. Were it not for the saturation of the iron, which causes the no-load saturation curve to deviate from a straight line, the perpendicular line through $f'd'$ would cut the no-load saturation curve at the point p .

The above treatment can therefore be simplified into the following simple rule:

Neglecting the saturation of the magnetic circuit, a synchronous motor running on any voltage at synchronous speed without excitation, will take from the line a current equal to the short-circuit when run as a generator with the fields excited to a value corresponding to the above-mentioned open-circuit voltage.

The copper loss of a squirrel-cage winding of a self-starting synchronous motor can be calculated by the same method as that employed for induction motors. The following formula I have used with good success for induction motors, and although it does not go into the refinements to the extent of Mr. Fechheimer's formula, it gives results whose accuracy falls within the variation of the resistance of the composition metal in the end rings.

Squirrel-cage copper loss in watts

$$= \left[\left(\frac{s}{\pi} \right)^2 2 R_r + R_b s p \right] I_b^2$$

I_b = the current per rotor bar.

R_b = the resistance of one rotor bar.

s = the number of rotor bars per pole.

p = the number of poles.

R_r = the resistance of one end ring measured clear around its circumference.

C. J. Fechheimer: It is indeed gratifying to me to have heard from so many prominent engineers that most of the conclusions at which I arrived in my paper are in accordance with their own

views. I was to some extent expecting opposition to a number of my conclusions, especially in reference to the size of air gap and the good results which it is possible to obtain with the synchronous motor at starting as compared with the squirrel-cage induction motor.

Mr. Williamson speaks of the prevention of the current rush accompanying the throwing over to full voltage when the fields are excited with direct current. The method which I favor consists in keeping the stator circuit closed and at the same time having sufficient current in the fields of the motor to enable the power factor to come approximately to unity when throwing on the higher voltage. In this way the current is reduced rather than increased.

The explanation offered by Messrs. Williamson and Lamme of the tendency to refuse to accelerate beyond half speed when the field circuit is closed upon itself, I believe accounts for the phenomenon better than the theory I advanced. After more mature consideration, I am quite willing to agree with these gentlemen that this tendency is due not to higher harmonics, but rather to the single-phase reaction of the rotor upon the polyphase stator.

In regard to Mr. Newbury's question in reference to the rotor construction of the motors which were tested, I would inform him that the solid pole rotors were not provided with any kind of squirrel-cage winding; only those curves shown in Figs. 7 and 8 pertain to motors with amortisseur windings, the construction consisting of bars in the poles which were connected at the ends with continuous rings. Figs. 7, 8 and 9 refer to the same motor; the amortisseur windings had been removed in tests plotted in Fig. 9.

In general, I do not think it advisable to connect the field rheostat in series with the rotor at starting. It is possible that the motor Mr. Newbury has in mind is different from those I am familiar with. It is seldom that the field rheostat has a resistance more than four times that of the field. In order to obtain more favorable starting conditions the resistance in the field circuit should be approximately equal to the reactance thereof. Usually the reactance is more than one hundred times the resistance. Hence, with the rheostat in series, the resistance in the field circuit would be approximately equivalent to one-twentieth of the reactance. Therefore, this resistance is entirely too small to secure small line current for a given torque. The unfavorable results obtained by short-circuiting the fields or by having a comparatively small resistance in series with them, is, as one would suppose, less marked when the amortisseur winding is present than when it is removed. This can be seen by a study of Figs. 3, 4, 7, 8 and 9.

It would seem that Mr. Newbury has achieved remarkably good results in the 200-kv-a. synchronous motors, and this would tend to bear out more fully the statements that have been made

by others contributing to this discussion, that the synchronous motor, when properly and carefully proportioned for starting conditions, can be made comparable to the squirrel-cage induction motor.

In regard to Mr. Dudley's statement to the effect that all of the losses in the rotor are not necessarily productive of torque at the instant of breaking loose from rest, I would refer him to item 7 in the paper under "Determination of Starting Characteristics with Laminated Poles and Amortisseur Winding" as follows: "Losses due to a pulsating component of flux not productive of torque." This I believe covers the condition which Mr. Dudley pointed out. In this connection, however, I would call attention to the inaccuracy of commercial starting tests. When an error from tests is as great as Mr. Dudley describes, it is usually due to the pronounced effect of bearing friction, to overcome which a considerable portion of the developed torque is required.

There is no doubt that the high potential induced in the rotor circuit is undesirable. From comparisons which I have made between solid and laminated pole machines, I am inclined to believe that solid pole machines give rise to lower induced potential than those with laminated poles. As Mr. Foster says, however, much depends upon the resistance of the amortisseur winding. For a given flux entering the pole heads the induced potential in the rotor coils is decreased as the resistance of the amortisseur winding is lowered. There is, however, this disadvantage—the line current drawn for a given starting torque is materially increased, and the starting torque for a given impressed electromotive force on the stator terminals reduced, by the low-resistance squirrel-cage winding. On the other hand, if a carefully proportioned high-resistance amortisseur winding is used, less flux and less stator potential is required for a given starting torque, and with this lower flux I do not believe a prohibitively large potential is induced in the rotor coils. Comparisons I have made lead me to believe that the induced potential for a *given starting torque* with a high-resistance squirrel-cage winding is not very different from that with a low-resistance winding. On the other hand, however, with solid poles, the induced potential in the rotor coils is much lower than with a high-resistance or even low-resistance squirrel-cage winding when the poles are laminated, due, of course, to the skin effect; at the same time the currents are crowded into such a thin shell that the torque is increased rather than decreased.

As Mr. Foster reminds me, the statement which I made in my paper in respect to the number of slots in the rotor as being dependent upon the judgment of the designer, is somewhat vague. If the motor is to be directly coupled to an unloaded, reciprocating air compressor, the starting torque should be greater than the torque during acceleration. In such cases, therefore, a high-resistance winding is desirable. The variation of starting

torque for different positions of the rotor when the number of rotor slots is an exact multiple of those in the stator is very much less with a high-resistance squirrel-cage winding than with one of low resistance. Hence, when starting air compressors with the high-resistance winding, it should be satisfactory to pitch the rotor slots a multiple of the stator slot pitch. On the other hand if the motor is to be directly coupled to a centrifugal pump which is usually high-speed, the pole pitch will be large and the air gap long. We can, in general, apply the same rules to the losses in the squirrel-cage winding when operating at synchronous speed if the rotor slot pitch is not a multiple of the stator slot pitch, as apply to solid poles and open slots. By making the slot pitches in the stator and rotor small enough we can effectively eliminate eddy current loss when the large air gap is taken into consideration. When driving centrifugal pumps the high torque is needed just below synchronism, hence a low-resistance winding should be used to make the slip as small as possible. This, then, implies that the pitch of rotor slots should be other than a multiple of the stator slot pitch. In a similar way each case can be decided upon its own merits, in the same manner in which the designing engineer is called upon to use his judgment in proportioning other parts of the apparatus.

As Mr. Lamme says, it is a little difficult to understand why the synchronous motor pulls into synchronism instead of "slipping" as is the case with induction motors. Also, as Dr. Steinmetz states, the motor would not pull into synchronism without direct current in the field coils were it not for the peculiar configuration of the rotor. I have usually compared this phenomenon with the tendency of the shuttle-wound armature used in magnetos to fall into line with the permanent poles. This, of course, follows the fundamental laws and conceptions of the magnetic field. With the distributed winding type without definite poles, there would be no tendency to lock into synchronism unless direct current were applied to the field coil. With definite poles, as is illustrated by the tests given in the paper, when the rotor is near synchronism the "pull-in" effect is more pronounced, due to the poles being more clearly defined. In the definite pole machine at synchronous speed without direct current in the field coils, the excitation is produced by currents in the stator which set up a field revolving at synchronous speed. Neglecting power factor, qualitatively but not quantitatively, the same effect is produced as with direct current in the field coils.

Mr. Lamme has compared the excitation of the induction motor to that of the synchronous motor. The question naturally arises: why do we have to supply so many more ampere-turns in the synchronous motor than we do in the induction motor? The answer of course is that we must take up these ampere-turns in various parts of the magnetic circuit to prevent the motor from falling out of step when the load is placed upon it. In

other words, approximately five times as much magnetomotive force is required to hold the rotor in synchronism as would be the case with a certain "slippage."

This brings up another interesting question: why cannot a phase-wound rotor, star-connected, be used to advantage in a synchronous motor if all of the rotor winding is employed in the ordinary way for starting and two legs of the star be excited with direct current for synchronous operation? We could, of course, use a large air gap, for, as has been pointed out, the large air gap is not a bad feature as regards starting. With the rotor construction ordinarily used in synchronous motors—motors with definite poles and edge-wound single layer fields—we have the ideal conditions for cool operation. On the other hand, with a phase-wound rotor construction we are extremely limited in space and unless the motor be made very large, it would be difficult to get sufficient ampere-turns in the rotor for leading power factor, or in many cases for unity power factor, to provide a liberal pull-out torque, unless prohibitively high temperatures are obtained. In other words, a good induction motor will not make a good synchronous motor.

Dr. Steinmetz calls attention to the valuable characteristics of the synchronous motor in that it can be used to great advantage for voltage regulation, and at the same time can pull a mechanical load. It is for this reason that the tendency is toward using the synchronous motor in preference to the induction motor. This is also true where slow-speed motors are required, such as are used for driving reciprocating air compressors. The speed is then so low that the induction motor has extremely poor power factor, whereas the synchronous motor can be used to advantage to improve the power factor of the system. Were we compelled to resort to the use of an auxiliary device for starting such apparatus, it would not come into use to nearly so great an extent as with self-starting motors.

The method which Mr. McCormick has proposed for predicting the amount of current which would flow when the motor is in synchronism and without direct-current excitation, depends upon a number of approximations. As this current usually flows for a short interval, it is seldom important that it be predicted with great accuracy, and hence approximations which appear in Mr. McCormick's method should give sufficiently accurate results for commercial purposes. This brings up another interesting point in connection with the size of air gap, previously referred to. When operating at synchronous speed without direct-current excitation, the current drawn from the line depends almost wholly upon the magnetomotive force required to force the flux across the air gap. This current can be greatly reduced by exciting with direct current while operating on fractional voltage, as has been stated.

The formula which Mr. McCormick has given for calculating losses in the conducting circuit of squirrel-cage induction motors is similar to that which I have used. It depends upon a sinusoidal space distribution of flux. I do not think that we could apply this formula to the case of a synchronous motor in which the distribution of flux is so far from being sinusoidal due to the peculiar rotor configuration.
