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THE INDUCTION MOTOR AND THE ROTARY CONVERTER AND THEIR RELATION TO THE TRANSMISSION SYSTEM.

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Two important functions of an alternating current transmission system are the production of mechanical power and the furnishing of direct current.

The induction motor and the rotary converter have become the usual means of transforming energy into these forms. The wide extent to which they are now used is a notable feature of recent electrical progress. An examination of their behavior in service, especially in connection with other apparatus which might be used for the same purposes, will indicate the particular characteristics which have made them so successful. Occasion will be taken also to note some of the important inter-relations between the various kinds of receiving apparatus and the transmission circuit and the generators by which they are supplied with current.

I.—The Induction Motor.

Power may be produced by the synchronous motor or by the induction motor. A comparison between the two motors may be made by placing in parallel columns their respective characteristics in services, *i.e.*, those which concern the operation rather than the design. An induction motor with a secondary of the "squirrel cage" type, started by applying a low E. M. F. to the primary, is taken for comparison—the description will require modification in some particulars if the secondary circuit is provided with adjustable resistance. These are of minor importance and do not affect the general comparison.

Synchronous Motor.	Induction Motor.
AUXILIARY APPARATUS.	
1. A starting motor; or, if self-starting, some form of resistance or transformer for reducing the voltage.	1. A two-way main switch with auto transformers giving a low E. M. F. for starting. This may be located at any distance from the motor.
2. An exciter, driven by the motor or otherwise, with circuits to switchboard and motor.	2. No exciter is required.
3. Rheostats for exciter and motor.	3. No field rheostats are required.
4. Instruments for indicating when field current is properly adjusted.	4. No instruments are required.
5. Main switch and exciter switches.	5. No exciter switches are required.
6. A friction clutch is required in many cases.	6. No friction clutch is required, as the motor starts its load.
CONSTRUCTION.	
1. Armature winding.	1. Primary winding.
2. Field winding with many turns. Liable to accident from "field discharge" if exciting current is suddenly broken; or from high E. M. F. by induction from the armature if the field circuit is open.	2. Secondary, short-circuited.
3. Collector rings and brushes.	3. No moving contacts on "squirrel cage" secondary.
STARTING—NORMAL.	
1. Motor is brought up to speed without load; if starting motor is used, the main motor must be brought to proper speed and "synchronized"; if self-starting, the starting devices must be cut out of circuit at proper time.	1. Throw switch to starting and then to running position.
2. Exciter is made ready for delivering proper current and the motor field must be excited, adjustments being made by rheostats until instruments give proper indication.	2. There is no exciter. (The motor is magnetized by lagging current from the generator.)
3. Load is thrown on by friction clutch or other means.	3. The motor starts its own load.

STARTING—ABNORMAL.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
1. If the several operations in starting be performed improperly or in wrong order injury may result. If a starting motor is used the synchronizing may be attempted at an improper speed or phase; if the motor is self-starting and it is connected to the circuit without the starting devices a large current will flow which may induce a high E. M. F. in the field circuit; if the field circuit be open a high E. M. F. may be induced in it at other times also.	1. The only possible error is in starting with the switch in the running or full voltage position, which simply causes the motor to exert a greater torque and consume a greater current than is necessary.
2. If a load having inertia be applied by closing the friction clutch too quickly the motor may be overloaded and stopped.	2. The motor starts its own load and requires no friction clutch.
3. If motor stops owing to failure of current supply, it is not self-starting when the current returns. An attendant is always required for starting.	3. The motor will stop if the current is cut off at the power house and then start again when the current is supplied to the circuit.

STARTING AND MAXIMUM RUNNING TORQUE.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
1. The starting torque of the self-starting motor is very small and an excessive current is required for developing it. The motor starts as an induction motor, but inefficiently, as the design which is best for synchronous running, is not good for starting.	1. The starting torque is adjustable and may be several times full load torque.
2. The maximum torque is several times the full load torque, and occurs at synchronous speed; below this speed the torque is very small; any condition which momentarily lowers the speed causes the motor to stop.	2. The maximum torque is usually greater than that of the synchronous motor, but it occurs at a reduced speed and there is a large torque at lower speeds.

Synchronous Motor.	Induction Motor.
SPEED.	
1. The motor has a single definite speed; at other speeds its torque is very small and the current is very large.	1. The motor may be designed for a practically constant speed, with large torque at lower speeds; or for several definite speeds by changing the number of poles; or for variable speed work, such as is required for cranes, elevators, hoists and the like.
CURRENT.	
1. If there is useful starting torque the current required for producing it is very great.	1. The starting current may be made proportional to the torque, and is 1½ to 2½ times that required for the same torque at high speed.
2. The running current depends upon the wave form. If the wave form of the motor and of the circuit differs, a corrective current will follow, which cannot be eliminated by adjustment of field excitation.	2. The running current is practically independent of the difference in wave form, as it has no wave form of its own.
3. The running current depends upon uniformity of alternations of the current, *i. e.*, upon the uniformity of the speed of the generator and other synchronous motors. The motors attempt to follow the generator speed exactly. If the latter pulsates, the motors pulsate also; they vibrate about a mean position, "hunting" or "pumping." One motor pumping incites others. The current is increased even though the conditions may still be operative.	3. The current is practically independent of fluctuations in generator speed, as there is a slip between the synchronous and the actual speed of the motor.
4. The running current depends upon the relation between the field current (which is adjusted by the attendant) and the E. M. F. of the circuit. The main current may be made leading or lagging or theoretically it may be neither. The E. M. F. of the circuit is an element which is under the partial control of the attendants at every motor as well as at the generator station.	4. The current is not subject to any adjustments which the motor attendant can make, nor is the E. M. F. of the circuit in any way under his control.

Synchronous Motor.	Induction Motor.
POWER FACTOR.	
1. As the power factor is the relation between actual current and energy-current, it is dependent upon wave form, hunting and field current. Under favorable conditions the motor may have a high power factor; under many actual conditions it may not; under some conditions the highest attainable power factor is less than that of the induction motor.	1. The power factor varies with load, but is definite and is practically independent of wave form and hunting.
2. The current may be lagging or leading, depending upon the motor field strength.	2. The current to the motor is always a lagging current.
REACTION UPON GENERATOR AND CIRCUIT.	
1. The motor impresses its own wave form on the circuit.	1. The motor has no wave form to impress upon the circuit; its tendency is to smooth out irregularities in a wave which is not a sine wave.
2. A motor may augment the fluctuations in generator speed by the oscillation of its own armature. One motor may increase the disturbance in the circuit so as to interfere with other motors which would not have been seriously affected.	2. The motor has a damping action upon fluctuations in frequency; in some cases a synchronous motor which hunts may run smoothly when an induction motor is connected to the same circuit.
3. As the current may be either lagging or leading, the drop in E. M. F. in the generator and between generator and motor may be either more or less than that which could be caused by a non-inductive load or by an induction motor.	3. The drop in the E. M. F. is always greater than would be caused by non-inductive load.
4. If a short-circuit occurs in the transmission system the motor acts as a generator, which thereby greatly increases the current and the intensity of the short-circuit.	4. The motor does not generate current when there is a short circuit.

Synchronous Motor.	Induction Motor.

REACTION UPON GENERATOR AND CIRCUIT.—Continued.

Synchronous Motor.	Induction Motor.
5. If the circuit is opened, either by a switch, a circuit breaker, a fuse or the breaking of the line, the motor speed falls, its E. M. F. is no longer in phase with that of the circuit; the two are thereby added, thus doubling the normal E. M. F. and bringing increased strains on the insulation and the opening devices.	5. The motor does not generate E. M. F. when it is disconnected from the circuit.

CAUSES WHICH MAY ACCIDENTALLY STOP A MOTOR.

Synchronous Motor.	Induction Motor.
1. Momentary lowering of E. M. F. caused by short-circuit on the line, or by accident at another motor, or by error in synchronizing a generator, or by the "switching over" of the motor from one circuit to another, is apt to cause the motor, particularly if carrying load, to fall from synchronism and come to rest.	2. Momentary lowering of E. M. F. causes momentary decrease in speed.
2. A heavy load, even momentary, may exceed the limiting torque and cause the motor to drop from synchronism, even though the load be removed immediately. The connection between generator and motor is rigid.	2. An excessive load receives the stored energy of the motor and of the load itself as the motor falls; when the excess load is removed the motor speed increases again. The connection between generator and motor is elastic.
3. If the generator speed suddenly increases, a motor carrying a load having inertia may be unable to increase its speed quickly without exceeding the limiting torque, which will cause the motor to stop.	3. The motor readily follows changes in generator speed.

SUMMARY.

Synchronous Motor.	Induction Motor.
1. The motor is an *active* element in the system; it acts as a generator in impressing its own wave form, its E. M. F. and its fluctuations upon the circuit. These fluctuations may be caused by an intermittent load.	1. The motor is a *passive* element in the system. Each motor attends to its own work and does not try to run the system.

SUMMARY.—Continued.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
2. The motor is a sensitive element in the system. Its successful operation is dependent upon a proper relation between the design of the motor itself and of other machines connected with the system. Its successful operation also depends upon the proper adjustment and freedom from speed fluctuation in generators and other motors. It is liable to momentary variations from normal conditions, such as a sudden overload and sudden increase of generator speed or a momentary fall in E. M. F.	2 The motor is not sensitive to differences in the design of other apparatus operating on the same system.
3. The motor requires skill and care on the part of the attendant for starting, for readjusting and for keeping the various brushes and auxiliary apparatus in proper condition.	3. No experience and electrical skill are required of the attendant and there is little or nothing to get out of order either through carelessness or design.
4. The power factor is under the control of the operator and the current may be made leading or lagging. Instruments are necessary in order that proper adjustments may be made by the attendant.	4. The motor has a definite power factor, depending upon the load; the out-of-phase current does not vary greatly at different loads. The changing load, therefore, has comparatively little effect upon the drop in voltage, and in regular service there is little liability that the motor will disturb the E. M. F. of the circuit.
5. The motor and its operation are complex and involve many possibilities of accident.	5. The motor and its operation are simple and reliable.

The synchronous motor is obviously not suitable for general distribution of power, owing particularly to its lack of starting torque, the skill required in attendance and the liability of the motor to stop if the conditions become abnormal. These objectionable features, however, are of much less importance when motors are installed in sub-stations or are of sufficiently large size to justify an attendant.

The characteristic of the synchronous motor which may be particularly advantageous is the fact that the power factor of the current can be varied and that the current may be made leading. In this way the current required and the drop in the generator and transmission circuit may be reduced. If the motor is used on a circuit supplying induction motors the synchronous motor may be given a leading current, thus neutralizing the lagging current to other motors. The extra current taken by the synchronous motor for this compensation necessitates a larger size than would otherwise be required.

The characteristic of the induction motor which is usually regarded as most unfavorable in comparison with the synchronous motor, is the fact that its current is always a lagging current. In a comparison with synchronous motors only large sizes should be included, as synchronous motors of small size are not to be seriously considered in practical work. The induction motors of large size have relatively high power factors, *i. e.*, the out-of-phase current is small. Moreover, this current is definite in kind and nearly constant for different loads, so that it is a definite and constant element which may be provided for. It may therefore create less disturbance on the system than the out-of-phase current of the synchronous motor, which is either lagging or leading, large or small, depending upon the intelligence and care of the attendant and upon other conditions. In one case the voltage of the system is under the control of the attendant in the power-house and the lagging current to induction motors which are running with either constant or varying load is practically constant. On the other hand, when synchronous motors are used, the voltage of the system is dependent upon all the motors, and uncertain or disastrous results are liable to be caused by adjustments by the various motor attendants. In many cases it is far better to provide the generators and circuits suitable for supplying the lagging current required by induction motors, rather than to attempt to gain the theoretical advantages attending the use of synchronous motors, as the securing of these advantages requires that so many conditions be favorable. At best the synchronous motor is less satisfactory to operate and is far more sensitive to abnormal or emergency conditions than the induction motor.

The foregoing considerations will indicate why it is that the induction motor has taken such a leading place, while the synchronous motor has been less favored and is now rarely considered seriously as a competitor of the induction motor except in large sizes.

II.—The Rotary Converter.

The rotary converter is in its relation to the transmission system essentially a synchronous motor. The foregoing characteristics of the synchronous motor, except those which involve a load upon the motor, apply also to the rotary converter. The starting, however, is somewhat simpler, as there is no load to accelerate except the armature. No separate exciter is necessary as the converter can furnish its own direct current for exciting. A converter may be compound-wound so that as it is loaded the increased excitation changes the out-of-phase current in such a way as to compound the voltage, thus overcoming the drop which would otherwise occur in generator and transmission circuits; whereas, the synchronous motor would cause a falling off in voltage. The rotary converter is generally used in units of considerable size placed in sub-stations having skilled attendants. For these reasons the operation of rotary converters does not involve so many difficulties as that of synchronous motors.

Direct current is obtained from alternating circuits, either by the rotary converter or a motor-generator, in which either a synchronous or an induction motor is employed.

The rotary converter has the advantage over the motor-generator in point of cost, there being but one machine instead of two; in point of efficiency, there being the loss in one machine instead of two; and in its effect upon the voltage of the transmission system, as it may be compounded to overcome the drop which would otherwise occur in generator and transmission circuit. On the other hand, the E. M. F. of the direct current delivered by the converter depends upon the E. M. F. received; whereas, the E. M. F. of a motor-driven generator is independent of the E. M. F. of the supply circuit and may be adjusted or compounded as may be desired. It is found in practice, however, that the voltage delivered by a rotary converter can be satisfactorily adjusted and controlled by regulating devices or by compounding so that usually the close relation between the E. M. F.'s at the two ends of the converter is not disadvantageous, provided the E. M. F. of the supply circuit is reasonably constant.

This statement applies to those cases in which a practically constant voltage is desired. There are, of course, special cases in which the voltage is to be adjusted over a very wide range or where for other reasons the motor-generator is to be preferred.

In many cases the motor may be used either with or without transformers, whereas they would be required with a rotary converter.

A motor generator employing a synchronous motor does not seem to possess any essential advantage over the converter except that sometimes the motor may receive the line voltage without transformers, and in some cases the independent control of the direct current voltage is desired. The use of the synchronous motor does not remove the objections to the rotary converter, which are based on the fact that it is a synchronous machine.

A motor-generator employing an induction motor has the advantage of employing induction instead of synchronous apparatus; thereby securing many of the advantages set forth in the comparison between synchronous and induction motors. Circuits which are supplied by generators in which the speed has a rapid and periodic fluctuation, or in which for any other reason the use of a synchronous machine is impracticable or undesirable, may nevertheless operate an induction motor driving a generator with full satisfaction. The various characteristics of the induction motor under emergency conditions, such as sudden overload, momentary interruption or lowering of the voltage of the supply circuit, may cause little or no inconvenience if the induction motor is used, whereas, it might cause serious interruption to a rotary converter or a synchronously driven generator. The induction motor driving a generator is also to be preferred where units are quite small and the attendance is unskilled. The rotary converter, like the synchronous motor, is unsuited for general distribution in small units.

The foregoing statements and comparisons involving the rotary converter doubtless comprise the principal reasons why this apparatus is being so widely adapted and is in such general use. To indicate the wide use of this apparatus it may be stated that the Westinghouse Electric and Manufacturing Company, with which the writer is connected, has sold over 400 rotary converters. Of this number 30 per cent. are for a frequency of 60 cycles or more. The aggregate output is over 165,000 K. W.

Most of this apparatus is now installed and is in successful operation. In fact, the difficulties in connection with the installation and operation of rotary converters on circuits which are suited for them are trivial and do not materially differ in amount from those which may be expected to occur in connection with other kinds of apparatus.

The very wide use of the induction motor and the rotary converter is an established fact, and it is believed that many of the reasons for their selection in preference to other kinds of apparatus have been set forth in the foregoing notes.

III.—The Alternator.

Many of the specific relations between the induction motor and the rotary converter and the supply system have been indicated. There is obviously a close relation between the alternator and the apparatus which it supplies. The conditions are radically different from those involved in incandescent lighting. An alternator which may be quite satisfactory for lighting purposes may be highly inadequate for successfully supplying current for either induction motors or rotary converters.

For supplying current to induction motors an alternator should have good inherent regulation. The lagging current taken by induction motors requires a greater increase in field current for maintaining a given voltage than is required when the load is non-inductive. In order that the field current may not be excessive, the generator should be properly proportioned to have close regulation. The adjustment of the field current by external devices is not a wholly satisfactory substitute for close inherent regulation. Suddenly changing loads or the throwing on or off of motors causes fluctuations in voltage, as the external devices cannot act quickly enough to prevent the disturbance. The necessity of good inherent regulation is all the more necessary where the motors are large in proportion to the size of the generator and where loads are fluctuating.

For the operation of rotary converters the generator speed should be uniform. Engines which are sufficiently uniform in angular velocity to enable generators to run successfully in multiple may nevertheless be unsuited for operating rotary converters or synchronous motors. It is preferable also that generators for operating rotary converters should have good inherent regulation, not only in order that the E. M. F. may be maintained at heavy loads, but also for the purpose of holding the converter rigidly in synchronism. If the alternating field is comparatively weak, as is usual in machines of poor regulation, there may be a shifting of the magnetic field back and forth with different armature currents, quite similar to the shifting of lead in direct current machines. It is obvious that if the effective position of the field poles may shift back and forth, this shifting is comparable with fluctuations in generator speed, and becomes a source of unsteadiness in the system which may contribute to the "hunting" of rotary converters. This shifting may occur also in a machine having a strong field if a large proportion of the magnetizing force is absorbed in the iron of the field magnet, *i. e.*, a machine with a saturated field. Such a machine may have good E. M. F. regulation, and still be of an inferior type for the driving of synchronous machinery.

It follows, therefore, that a generator which is to supply induction motors or rotary converters should be selected with reference to the service which it is to supply. In some cases unsatisfactory results have been obtained in the use of motors or converters, duplicates of those which have given full satisfaction elsewhere. The trouble has been located in fluctuating speed or in the characteristics of the alternator supplying the current.

A transmission system must be considered as a unit and the inter-relation between the alternator and the apparatus to which it supplies power must be fully considered.

The theoretical arguments which are occasionally urged against the alternating system, the induction motor and the rotary converter, find their most effective answer in the plants which are now in operation and in their record of service.

The induction motor and the rotary converter to-day represent the survival of the fittest, and confirm the judgment of those engineers who have consistently and persistently advocated their use.