THE SINGLE PHASE RAILWAY.

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It was not until recent years that the single phase alternating current motor assumed much importance and only very recently that it was found to possess a certain adaptability to traction; on account of the simplicity of the design and the great amount of speed regulation that one can obtain. With the rapid development of the applications of electricity, alternating current motors were required for railway and similar work which had a high-starting torque efficiency and a high efficiency which extended over a great range of speed, that is, one which had a speed torque characteristic similar to that of the direct current series motor. The characteristic of an alternating current induction motor is that of a constant speed motor but by the introduction of a commutator almost any speed torque characteristic can be produced. It is evident, then, that we refer only to the commutator type; as the induction motor without commutator has not as yet been found suitable for traction work.

In its general form the alternating current motor consists of one or more stationary electrical circuits magnetically related to one or more rotating electric circuits. These circuits may be excited by alternating current or some by alternating current and some by direct. Before taking up in general the theory of the of the single phase induction motor, it might be well to give the classes and types into which alternating current motors may be subdivided. They are of two classes - those in which the electric and magnetic relations between stationary and moving members do not vary with their relative positions, and those in which they vary with the relative positions of stator and rotor. In the latter class there is a tendency for the motor to lock at a certain speed, maintaining a definite ratio between the frequency of rotation and the frequency of the impressed electro motive force. Such motors therefore, are synchronous motors. The main types of synchronous motors are as follows: -

1. One member supplied with alternating and the other with direct current - polyphase or single phase synchronous motors.

2. One member excited by alternating current, the other containing a single current closed upon itseld - induction motors.

3. One member excited by alternating current, the other by different magnetic reluctance in different directions - reaction motors.

4. One member excited by alternating current, the other by alternating current of different frequency or different direction of rotation - general alternating current transformer or frequency converter.

It is commonly known that if the current is reversed both in the the field and armature of a direct current motor, that the direction of rotation of the armature will not be affected. If the direct current is reversed rapidly it has the same effect as the alternating current and it is therefore natural to suppose that alternating current supplied to a direct current motor would produce continuous rotation of the armature. The operation of the single phase motor is dependent upon this principle. Generally speaking, the series motor will operate as well with alternating current as with direct current, but there are certain peculiarities of the alternating current that makes it more difficult than it would at first appear. One of these phenomena is the loss which occurs in any solid core when the magnetism is rapidly reversed or changed in strength. When alternating current is used, the iron core must be laminated as the magnetism of course varies with the strength and direction of the current. When the core is laminated the loss above mentioned is greatly reduced. Another and probably more serious difficulty encountered when using alternating current is the transformer action which occurs between the field and armature.

The alternating current motor in appearance resembles very closely the direct current motor. The frame of the alternating current like that of the direct current is of cast steel but the entire magnetic part of the poles and yoke is laminated, differing from the direct current wherein the poles alone are laminated. When noting the general performance of the direct current and alternating current motors, we might say that the alternating current motor may be started on full voltage without danger while the direct current must always be started on a reduced voltage.

Other peculiarities of the alternating current type are,

1. An electro motive force is generated in the armature

winding by the alternating current magnetic field.

2. The iron loss extends over the entire magnetic circuit.

3. There is an active electro motive force existing between the turns of the field.

The single phase induction motor will not start of its own accord but when once started in either direction a torque will be exerted and the motor will then run up to near synchronism. The means invariably employed for starting consists in using some form of "phase-splitting" device - that is, the stator is wound with two sets of windings, a "working" winding and a "starting" winding, the two being displaced from one another by 90°. At starting, one winding is put on the mains directly, while the other is connected through a choke coil or capacity. The result is that the current on the two windings have a phase displacement with one another and a torque is set up.

If this phase splitting device is used on very large motors, a very imperfectly rotating field is produced, and before the motor will start a non-inductive resistance has to be temporarily placed in the rotor winding. For this purpose the motor must be of the wound type and be provided with slip rings whereby these resistances may be connected in. The resistance should be so arranged that it can be cut out as the motor speeds up. The effect of inserting a resistance in the rotor winding is to increase the initial torque but not the maximum torque. It causes the maximum torque to occur at a lower speed , or in other words, it increases the slip.

The starting point of the theory of the single phase induction motor, usually is the general alternating current transformer; and from the equation of the alternating current transformer the motor equations can be developed.

An alternating current I, flowing through an electric circuit produces a magnetic flux ϕ, interlinked with this circuit. On considering equivalent sine waves of I and ϕ; ϕ lags behind the current I by an angle . This magnetic flux ϕ induces an electro motive force E equal to $2\pi Nn\phi$, where N = frequency, n = number of turns of electric circuit. This induced electro motive force, E, in turn lags 90° behind the magnetic flux ϕ, and hence consumes an electro motive force 90 degrees ahead of ϕ, or 90 - degrees ahead of I. This may be resolved into a wattless:

$$E' = 2\pi Nn\phi \cos \quad = 2\pi NLI = xI,$$

the electro motive force consumed by self induction, and an energy component:

$$E'' = 2\pi Nn\phi \text{ sine } \quad - 2\pi NHI = r''I$$ = electro motive force consumed by hysteresis and eddy currents aand is therefore in vector represented denoted by $E' = -j\,x\,I$ and $E'' = r''I$ where $x = 2\pi NL$ = reactance L = inductance, r'' = effective hysteretic resistance.

The ohmic resistance of the circuit r' consumes an electro motive force $r'I$ in phase with the current and the total or effective resistance of the circuit is therefore $r = r' + r''$ and the total electro motive force consumed by the circuit or the impressed electromotive force is

$E = (r - jx)I = ZI$, where $Z = r - jx$ = the impedance in vector notation.

$Z = \quad r^2 + x^2$ = impedance in absolute terms.

In considering electric circuits, if one is in an inductive relation to another electric circuit it is best to separate the inductance L of the circuit into two parts - the self inductance, S, which refers to that part of the magnetic flux produced by the current in one circuit, which is interlinked only with this circuit but not with the other circuit; and the mutual inductance, which refers to that part of the magnetic flux which is interlinked with the second circuit. The self induction induces a wattless electro motive force and thereby causes a lag of the current; while the mutual inductance carries power into the secondary circuit and therefore generally does the useful work of the apparatus. This calls forth this distinction between the self inductive impedance $Z_0 = r_0 - jx_0$ and the mutual inductive impedance $Z = r - jx$ where r_0 = coefficient of power consumption by ohmic resistance, hysteresis, and eddy currents - effective resistance. X_0 is the coefficient of electro motive force consumed by the self-inductive flux - self inductive reactance, r, is the coefficient of power consumption by eddy currents and hysteresis due to mutual magnetic flux and therefore contains no ohmic resistance component. X is the coefficient of electro motive force consumed by the mutual magnetic flux. Therefore the electro motive force consumed by the circuit is $E = Z_0I + ZI$.

Furthermore if one of the circuits rotates relative to the other, then besides the electro motive force of self-inductive impedance: Z_0I; and the electro motive force of mutual inductive impedance or electro motive force of alternation: ZI; an electro motive force is consumed by rotation. This electro motive force

This electro motive force is in phase with the flux through which the coil rotates - while the electro motive force of alternation is 90^0 ahead of the flux alternating through the coil. If therefore we let Z' be the impedance corresponding to the former flux, the electro motive force of rotation is $jaZ'I$ where a is the ratio of frequency of rotation to frequency of alternation or the speed expressed as a fraction of synchronous speed. Therefore we see that the total electro motive force consumed in the circuit is:

$$E = Z_0I + ZI + jaZI$$

In the single phase induction motor one primary circuit acts upon a system of closed secondary circuits which are displaced from each other in position on the secondary member. For convenience let the secondary be assumed as two phase, that, is, containing or reduced to two circuits closed upon themselves at right angles to each other. It then offers a resultant closed secondary circuit to the primary circuit in any position, the electrical disposition of the secondary is not symmetridal but the directions parallel with the primary circuit and at right angles thereto are to be distinguished. The former may be called the secondary energy circuit, the latter the secondary magnetizing circuit since in the first, power is transferred from the primary to the secondary while in the second place the secondary circuit can act magnetizing only.

Let $E_0I_0Z_0$ = the impressed electro motive force, current and self inductive impedance, respectively, of the primary circuit. I_1Z_1

I_1Z_1 = current and self inductive impedance, respectively of the secondary circuit.

I_2Z_2 = current and self inductive impedance of the secondary magnetizing circuit.

Z = mutual inductive impedance

a = speed

and let

$S_o = 1 - a^2$ (where S_o is not the slip.)

In the primary circuit then:

$$E_0 = Z_0 I_0 + Z(I_0 - I)$$

The secondary energy circuit:

$$0 = Z_1 I_1 + Z(I_1 - I_0) + jaZI_2$$

Secondary magnetizing circuit:

$$0 = Z_1 Z_2 + ZI_2 + jaZ(I_0 - I_1)$$

Therefore

$$I_1 = I_0 \frac{Z(Zs_0 + Z_1)}{Z^2 S_0 + 2ZZ_1 + Z_1^2}$$

$$I_2 = -jaI_0 \frac{ZZ_1}{Z^2 S_0 + 2ZZ_1 + Z_1^2}$$

and substituting

Primary current:

$$I_o = E_0 \frac{Z^2 S_0 + 2ZZ_1 + Z_1^2}{D}$$

Secondary Energy Current:

$$I_1 = E_0 Z \frac{Zs_0 + Z_1}{D}$$

Secondary magnetizing current:

$$I_2 = -jaE_0 \frac{ZZ_1}{D}$$

The electro motive force of rotation of secondary energy circuit

$$E'_1 = jaZI_2 = a^2 E_0 \frac{Z^2 Z_1}{D}$$

Electro motive force of rotation of secondary magnetizing circuit:

$$E_2 = jaZ(I_0 - I_1) = jaE_0 \frac{ZZ_1(Z + Z_1)}{D}$$

where $D = Z_0(Z^2 s_0 + 2ZZ_1 + Z_1^2) + ZZ_1(Z + Z_1)$

It is at synchronism $a = 1$, $s_0 = 0$

$$I_0 = E_0 \frac{2Z + Z_1}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$I_1 = E_0 \frac{Z}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$I_2 = -jE_0 \frac{Z}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$E_1' = E_0 \frac{Z^2}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

$$E'_2 = jE_0 \frac{Z(Z + Z_1)}{Z_0(2Z + Z_1) + Z(Z + Z_1)}$$

Hence, at synchronism the secondary current of the single phase induction motor does not become zero as in the polyphase motor but both components of secondary current become equal.

At standstill, $a = 0$, $s_0 = 1$, it is:

$$I_0 = E_0 \frac{Z + Z_1}{ZZ_0 + ZZ_1 + Z_0Z_1}$$

$$I_1 = E_0 \frac{Z}{ZZ_0 + ZZ_1 + Z_0Z_1}$$

$$I_2 = o;\ E'_1 = o;\ E'_2 = o.$$

That is, the primary and secondary have the same corresponding values in the polyphase induction motor. Introducing the counter electromotive force of mutual induction and substituting for I_o

$$E_o = E\,\frac{z_o(Z^2 s_o + 2ZZ_1 + Z_1^2) + ZZ_1(Z + Z_1)}{ZZ_1(Z + Z_1)}$$

$$I_o = E\,\frac{Z^2 s_o + 2ZZ_1 + Z_1^2}{ZZ_1(Z + Z_1)}$$

$$I_1 = E\,\frac{ZS_o + Z_1}{Z_1(Z + Z_1)} = \frac{s_o E}{Z_1} + \frac{a^2 E}{2 + z_1}$$

$$E'_1 = a^2 E\,\frac{Z}{Z+Z_1}$$

$$I_2 = -j\frac{aE}{Z+Z_1}$$

$$E'_2 = jaE$$

and

$$I_o - I_1 = \frac{E}{Z}$$

These differ from those of polyphase types by containing the term $s_o = (1-a^2)$ instead of $s(1-a)$ and by the appearance of the terms $\frac{aE}{Z + Z_1}$ and $\frac{a^2E}{Z + Z_1}$, of frequency $(1 + a)$ in the secondary.

The power output of the motor is

$$P = E'_1 I_1 + E'_2 I_2$$

$$P = \frac{a^2e_o{}^2z^2}{(D)^2} \quad (ZZ_1Zs_o+Z_1) - Z_1(Z+Z_1)Z_1$$

$$= \frac{a^2e_o{}^2z^2r_1(s_oz^2-z_1{}^2)}{(D)^2}$$

and the torque in synchronous watts

$$T = \frac{P}{a} = \frac{ae_oz^2r_1(s_oz^2-z_1{}^2)}{(D)}$$

at synchronism torque and power become zero for

$$s_oz^2 - z_1{}^2 = 0$$

$$a = 1 - \frac{z_1}{Z}^{2}$$

In the single phase motor the torque contains the speed a as factor and thus becomes zero.

Neglecting quantities of second order

$$I_o = E_o \frac{Zs_o + 2Z_1}{Z(Z_oS_o + Z_1) + 2Z_oZ_1}$$

$$I_1 = E_o \frac{ZS_o + Z_1}{Z(Z_oS_o + Z_1) + 2\ Z_oZ_1}$$

$$I_2 = -\ jaE_o \frac{Z_1}{Z(Z_os_o + Z_1) + 2Z_oZ_1}$$

$$E'_1 = a^2E_o \frac{ZZ_1}{Z(Z_oS_o + Z_1) + 2Z_oZ_1}$$

$$E'_2 = jaE_o \frac{ZZ_1}{Z(Z_os_o + Z_1) + 2Z_oZ_1}$$

$$P + \frac{a^2 e_0{}^2 z^2 r_1 s_0}{Z(Z_0 s_0 + Z_1) + 2Z_0 Z_1)^2}$$

$$T = \frac{a\ e_0{}^2 z^2 r_1 s_0}{Z(Z_0 s_0 + Z_1) + 2Z_0 Z_1)^2}$$

This formula represents the phenomena at different speeds which are only approximated in the transformer theory of the induction motor.

INDIANAPOLIS AND CINCINNATI RAILWAY.

The first electric railway in America to put a single phase traction system into regular commercial use was that of the Indianapolis and Cincinnati Traction Company. This company has adopted the Westinghouse single phase rail road system and the first car equipped was put in service December 30, 1904 and on January 21st, a regular service was opened between Rushville and Morristown, two places sixteen miles apart.

The company was organized to build a double track through from Indianapolis to Cincinnati, and up to the present time, March, 1905, the line is constructed between Rushville and Indianapolis, a distance of forty one miles.

Transformer stations are about ten or twelve miles apart, and the single phase current is transmitted from the power house to each of these stations by No, 4 wires at 33000 volts, 25 cycles, and is reduced and fed into the trolley at a potential of 3300 volts. As the wires make a complete·circuit and permit therefore the placing of the circuit breaker and switches at the control power house, attendants at the transformer stations are dispensed with. The high tension lines being carried on poles which are set near the edge of the right of way.

The system is provided with two telephone lines; one for the sole use of the train dispatchers; while the other is for general use; each car being provided with a telephone. The form telephone lines are carried by porcelain insulators on cross arms near the near the top of the trolley poles and they are thus far removed from the high tension lines. They are then transposed every 500 feet. Within the city of Indianapolis for a distance of three miles the cars are run over the existing lines using the continuous current at 550 volts.

In each of the transformer stations there are two 300 K.W. oil insulated step down transformers, 33000 to 3300 volts; while on the second floor of each station are located the lightning arresters and disconnecting switches, no switches of the automatic type being used in these stations.

In the power house there are two 300 K.W. transformers wound for 3300 volts primary and 550 volts secondary.

The boiler room is equipped with three 300 HP boilers, natural gas being used for fuel. In the engine room, side of the building are the two generator units which consist of a 500 K.W. Westinghouse revolving field alternator 25 cycles, direct-connected to a 700 HP Corliss type condensing engine. Each being designed for a 50% overload capacity. There are two exciters; one being driven by an induction motor while the other is coupled to a Westinghouse steam engine.

There are ten passenger cars each measuring fifty five feet; and are arranged to carry thirty eight passengers besides the room left for baggage and the like. Each track has two 75 HP single phase motors and the cars are operated on the multiple control system.

The motor circuit begins with an auto-transformer of special design connected between the trolley wire and the ground. This transformer is fixed underneath the car and is so arranged that the current of air created by the car, circulates through it and thereby keeps it cool. At a point approximately 230 volts from the ground a circuit is led from this auto-transformer through the secondary of the inductive regulator and another tap at 650 volts from the ground is led through the primary of the regulator. The voltage applied to the motors andconsequently the speed of the car is governed by the induction regulator. This is in effect a transformer with its primary core and winding movable with respect to the secondary. It is operated by means of a small pneumatic motor, controlled by means of electro magnetic valves and may be turned so that its voltage either opposes or aids that of the auto-transformer by an amount within the capacity of the regulator.

The field coils of the single phase motors are wound with copper strip bent on edge and insulated. The field coils are connected permanently in series. The armature is in all essentials similar to that of the direct current motor, having the same dimensions and fitted with the same commutator. The armature and field coils are connected in series exactly as in the direct current motor but there is an auxiliary field in addition which is also placed in series with the main field and armature.

In conclusion it might be well to set forth a number of the chief features of the direct current and alternating current systems. There are two main reasons why the direct current system has proven satisfactory, first because the direct current series motor is especially adapted to railway work on account of its speed torque characteristics and second because a single trolley only is necessary. The main and above all a very serious disadvantage is that a low trolley voltage is necessary and consequently a great loss is incurred. This alone has hampered to a great extent the development of such roads.

In the case of alternating current work the voltage can be easily transformed and by the use of alternating current motors, a high trolley voltage could be used and at the same time a low voltage at the motor as a transformer could be placed on each car. Formerly the alternating current motor that was used did not possess the proper torque characteristics and besides it was of the polyphase type and required at least two trolley wires; but recently a motor has been designed which does away with these two disadvantages and possesses all the advantages of the direct current type.

Besides possessing these two advantages the use of an alternating current does away with many of the limitations of the direct current and these can be most readily shown by drawing a comparison between the two.

In the case of direct current it is generally necessary to use power at the voltage at which it is transmitted as it can be changed only by the use of rotating machinery. It is readily seen why a high voltage is wanted for transmission as this decreases the loss.

In the case of alternating current the use of transformers on the cars makes it possible to obtain the greatest economy in transmission and gives minimum motor trouble.

Up to about five miles power can be transmitted rather cheaply by direct current at 500 volts but when this distance in exceeded the cost becomes excessive.

To do away with this expense the power is transmitted as alternating current at a high a high voltage, but this necessitates the placing of stations along at various intervals and the use of rotary converters. The cost of installing these stations is very great and besides this a skilled attendant is required at each which again adds to the expense.

When using alternating current long distance roads can be supplied by transformer stations. The cost of installing these will be very small as compared with the direct current stations as they will require no synchronous or moving machinery and the salary of an attendant will also be done away with. Where there are few moving machines on a line the service is less liable to interruptions and where a short circuit or break down occurs it takes much less time to again put the circuit into operation as where there are a number of rotary converters all these have to be synchronized before current can be taken from the line.

With direct current variable speeds are obtained by connecting the motors in series and parallel and an additional range is obtained by use of a rheostat in connection with the two methods above mentioned. The rheostats are so constructed that they can be left in the circuit for only a short time so that we might say that there are only two methods of varying the speed with a given torque that of parallel and series running of the motor.

When using alternating current the voltage is very easily transformed to any desired voltage, so that the motors may be run at any desired speed.

When starting a direct current car, almost the entire voltage is taken by the rheostat and this of course necessitates a great loss.

Since there are no rheostats used in the alternating current system this loss is not met with.

It is found that direct current grounded circuits are always attended by electrolysis while this will practically disappear when alternating current is made use of.

The advantages arising out of the use of the alternating current system are due to the alternating current and it is great enough praise for the alternating current railway motor to say that it weighs about the same as the direct current motor, has as good characteristics for traction work and has about the same efficiency but in the end we must give the motor all the praise as it has made possible the use of single phase alternating current in railway systems.