

THE SINGLE PHASE ALTERNATING CURRENT SERIES MOTOR.

*(A paper read before the Sydney University Engineering Society,
on October 9th. 1907.*

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THE SINGLE PHASE SERIES MOTOR.

Although written under the general head of the **Single Phase Series Motor**, this paper will be confined rather to the starting and sparking troubles and the possible means of overcoming them.

The simple uncompensated motor is so much of a bygone that it is not worthy of consideration, and so we shall treat only of the compensated types. The compensation of this motor may be accomplished in practice by one of two methods, viz.: Conductively or Inductively.

The conductively compensated motor is shown diagrammatically in Figure 1. The compensating winding is connected in series with the main field and armature. It consists of a winding of the Ryan or Deri type, distributed in slots over the pole face. It is obvious that by this method we can vary the compensation at will by means of a shunt, and can so arrange to have a little over-compensation, thus assisting commutation. This arrangement is, of course, applicable to both D.C. and A.C. motors, although in the former case Interpoles seem to be more efficient chiefly on the basis of first cost. Figure 2 shows the Inductively compensated motor in which the compensating winding as before is wound in the pole face, but is not in electrical connection to the main circuit. It is short-circuited on itself, and thus acts as the short-circuited secondary of a static transformer, the primary being the motor armature. Here the compensation is practically complete at all loads since the secondary ampere turns will exactly counterbalance those of the primary except for leakage reactance, which is extremely small and negligible.

The conductive method of compensation, or, as it is sometimes called, forced compensation, is in almost universal use—G. E. Co., Westinghouse Co. and on the Continent, Messrs. Siemens Schuckert.

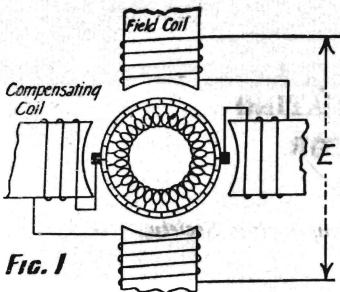


Fig. 1

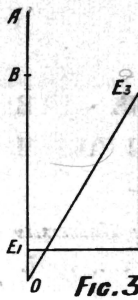


Fig. 3

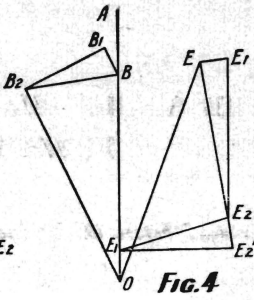


Fig. 4

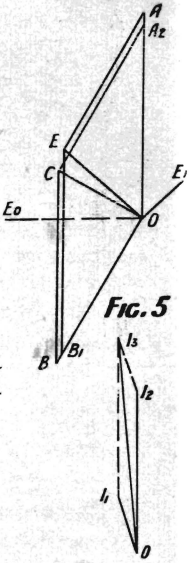


Fig. 5

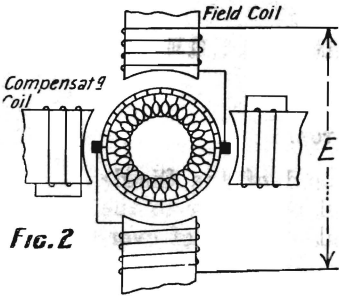


Fig. 2

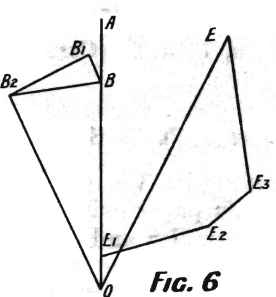


Fig. 6

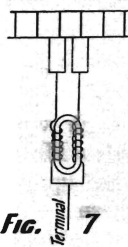


Fig. 7



Fig. 8

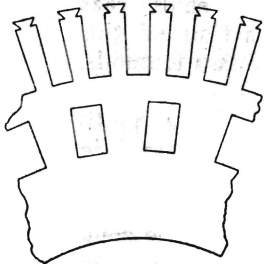


Fig. 9

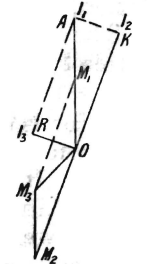


Fig. 10

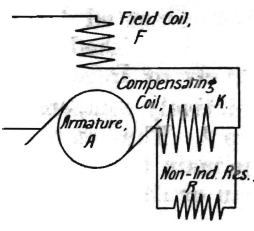


Fig. 11

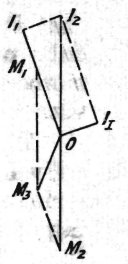


Fig. 12

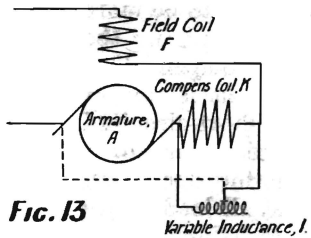


Fig. 13

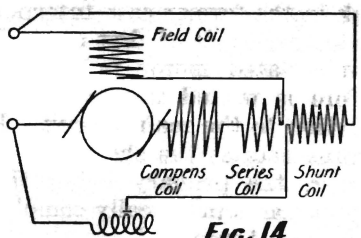


Fig. 14

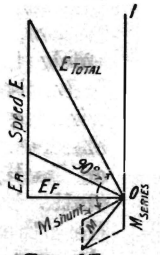


Fig. 15

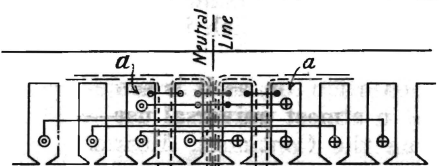


Fig. 16 ARRANGEMENT OF WINDINGS IN STATOR SLOTS

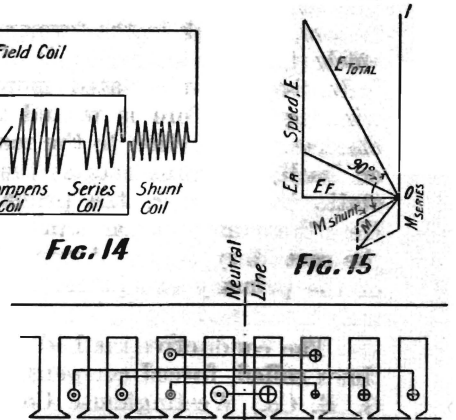


Fig. 17 SIMPLIFICATION OF ARRANGEMENT IN FIG. 16

Neglecting for the moment the effect of the short-circuited armature coils, let us construct the vector diagram of the motor for a constant current, assuming negligible leakage, and no iron loss, i.e., for an Ideal Motor. Referring to Figure 3, let OA represent the direction of the current, and hence also, that of the field and armature magnetomotive forces. The armature flux will be zero on account of the compensation, and that of the field will be in phase with OA, and proportional to the current—if we neglect the effect of saturation, which can, however, be taken into account in any special case. Let this exciting flux be represented by OB. The potential due to the motor resistance is represented by E_1O , in phase opposition to the current. The e.m.f. of self-induction of the field winding is represented by E_2E , in quadrature with the current. E_3E_2 represents the c.e.m.f. of rotation at a certain speed U. The resultant e.m.f. of the motor is E_3O , and calls for an applied voltage of OE_3 .

To take into account the effect of the short-circuited armature coils, let us consider the electromotive forces present in any such coil at the instant of commutation.

We have here four component voltages as follows:—

E_1 . The re-actance voltage of the coil which acts in direct opposition to any change in current, and is directly proportional to the current.

E_2 . The resistance e.m.f. due to the ohmic resistance of the coils, leads, and brush contact.

E_3 . The speed e.m.f. due to the rotation of the conductors in the magnetic field.

The above three voltages appear in all commutator motors, whether they be of the direct or alternating current type.

In the A.C. we have in addition a transformer e.m.f. E_4 , due to the fact that the field flux threading the coil is alternating. To appreciate the effect of this, it should be borne in mind that the whole field flux threads the coil.

Hence, the sparking voltage of the motor is the vector sum of—

$$E_1 + E_2 + E_3 + E_4$$

With the brushes on the neutral point, as in all motors for railway work which have to run in both directions, the value of E_3 is obviously zero. Again, since the reactance of the coils is very small in comparison with their resistance, including the leads and brushes, we may safely neglect E_1 , as compared with E_2 , and write the sparking voltage as—

$$= E_2 + E_4$$

Hence it is seen that the current in the short-circuited coil is

in phase with the transformer, e.m.f., so that, as the transformer, e.m.f. is in lagging quadrature with the flux producing it, the current in the short-circuited coils, and hence the flux, due to this current is in lagging quadrature with the resultant flux.

The e.m.f. due to the self-induction of the coil is in quadrature with the current, and if of sufficient size to make the previous assumption incorrect it may be represented by a flux in phase with the resultant flux. We have above called this the reactance e.m.f.

Figure 4 is constructed to take into account the effect of the short-circuited coil on the diagram, for the same current as figure 3.

OA is as before the current, and OB the exciting flux.

BB_1 is the flux corresponding to the e.m.f. of self-induction of the coil.

B_1B_2 is flux due to the transformer e.m.f. in the coil.

E_1O is the voltage due to resistance as above.

E_2E_1 is the voltage induced in the field winding by the resultant flux, and is composed of the e.m.f. of self-induction of the field coil E'_2E_1 , corresponding to E_2E_1 in figure 3, and the e.m.f. due to the flux produced by the short-circuited coil (BB_2), viz. : $E_2E'_2$.

$E'E_2$ is the speed e.m.f. due to the field flux OB, and is the same as E_3E_2 in figure 3.

EE' is the speed e.m.f. due to the coil flux BB_2 |

The subdivision of the voltages EE_2 and E_2E_1 is purely arbitrary, and is only introduced to show the derivation.

From a comparison of figures 3 and 4, we can draw the following conclusions:—The reaction of the short-circuited coil produces:—

1. A displacement of the resultant flux from the current with an increase or decrease in the absolute value of the flux—probably increase—depending to a great extent on the value of the self-induction of the short-circuited coil, the greater the self-induction, the greater the flux. This is not of practical value since the self-induction is kept as low as possible for commutation purposes. The actual effect of the phase displacement of the current and flux is a decrease in torque for the same flux. This is obvious from the fundamental relation:—

Torque = Flux \times Component of current in phase with flux \times Const.

2. An increase in power factor.

This is wholly harmful, and is due to the ohmic losses in the short-circuited coil.

3. An increase in voltage for the same speed or a reduction in speed at a constant applied voltage.

We have assumed complete compensation in the armature which is never realised in the inductively compensated motor, although it may even be exceeded in the conductively compensated motor. In any case the effect is very small, but for the sake of completeness it is well to consider its effect. Referring to figure 5. OA represents the armature ampere turns, and OB those of the compensating winding. It is noticed that the compensating ampere turns are not in direct phase opposition to the armature ampere turns. This is due to the obvious fact that we cannot have any inductance without appreciable resistance. Now the voltage induced in the compensating winding—on open circuit—due to the m.m.f. of the armature is in lagging quadrature with that m.m.f., and further were the power factor of that compensating winding zero, the current which would flow on the circuit being closed would lag another quarter period resulting in direct phase opposition. Due to the resistance the second angle is less than 90 degrees.

Again the windings have some mutual leakage reactance, so that the most convenient method of introducing the armature self-induction due to incomplete compensation, is by considering that only a part of the armature m.m.f. affects the stator and vice versa. AO_1 is that part of the armature m.m.f. which affects the stator, and OB_1 is that same for the stator m.m.f.

The vector sum of OA and OB is OC, and induces in the compensating winding a voltage sufficient to overcome the resistance of that winding.

Similarly OE is the vector sum of OA and OB_1 , and represents the ampere turns which give rise to the self-induction of the armature. OE produces in the armature winding an e.m.f. E_1O , such as requires an applied e.m.f. to counter-balance it = OE_1 .

In figure 6 is given the complete diagram of e.m.f.s. and fluxes. The only additional vector to figure 4 is the E_2E_3 which represents the e.m.f. required to overcome the armature self-induction.

The transformer voltage in the short-circuited coil can be neutralised when running by a rotation voltage, but when starting this is impossible, so that other means must be found to suppress as far as possible the trouble from this cause.

Many methods have been suggested for improving conditions, among which may be mentioned the following:—

1. Reducing the Ampere Turns of the Short-circuited Coils.—With a given armature and flux density we may reduce the transformer e.m.f. by increasing the number of poles keeping the number of armature turns per pole the same, and also the number of turns per commutator segment the same. This applies only to lap wound armatures for obvious reasons.

In this way the flux cutting the coil is less than before, and hence also the induced voltage is less. This method, however, increases the number of commutator segments, and also increases the total m.m.f. required since it must be the same per pole as before. This necessitates an increase in copper, or reduction in efficiency, with accompanying greater rise in temperature.

Again, if we have more than one turn per commutator segment, we can increase the number of commutator segments with obvious advantage.

We may also reduce the length of armature, thus calling for more turns for the same flux density, voltage, and speed. This permits of an increase in the number of commutator segments.

In all cases we have a practical mechanical limit to these alterations since the number of poles and diameter of armature are generally fixed by other considerations, and further, any narrowing down of the armature means a reduction in cooling surface, and also an increased ohmic resistance since the proportion of end connection to active conductor becomes greater. Also, we cannot continue to increase our commutator indefinitely, because even if space permitted the mechanical difficulties increase immensely in the construction so that it becomes a question of cost.

Another method, and one now worked to the limit in all machines, is to make the armature very strong with regard to the field when we reach a limit due to distortion.

2. The Use of Hard Brushes.—This is a very effective method as it increases the contact resistance, but we must allow only a reduced current density in these brushes, thus requiring a larger commutator with a greater friction loss.

3. The Use of Thin Brushes.—We may reduce the thickness of the brush until it covers only one, or even less than one commutator segment, thus greatly reducing the period of short-circuit, but although there is an immense gain, especially at starting, the brushes are very brittle and liable to break in service, thus requiring a lot of attention. Furthermore, they require a longer commutator, and its attendant evils. A method of avoiding the lengthening of the commutator is to use a double winding, each half complete in itself, and connecting to alternate commutator bars.

The two windings thus work in parallel, and the brush is made thin enough so that no short circuit can occur between adjacent segments of the same winding. Two brushes are used separated a short distance on the periphery of the commutator and connected together through a large inductance which is so wound that it is non-inductive to the main current, and highly inductive to the short-circuit current. The obvious

effect is to reduce the short circuit current without expenditure of energy. To prevent sparking on breaking this highly inductive circuit a resistance is shunted across the inductance. Figure 7 shows the arrangement of brushes on the commutator.

4. Increasing the Reluctance of the Magnetic Path.—This will cause an increase in the exciting m.m.f., and the comparative effect of the short-circuit m.m.f. will be less. This is open to the objection that it involves an increase in the self-induction of the field winding and a consequent reduction in power factor.

5. Putting a choke coil in multiple with the field winding. ing.—This is of little use, especially if the leakage between the short-circuited coil and the field is large. Further, it seems almost impossible to get an economically lower power factor than that of the field winding. Assuming such a possibility, the current in the choke coil OI_1 will lag behind that in the field coil OI_2 (figure 8), and the armature current OI_3 being the resultant of these two will lag behind OI_2 , thus coming more nearly into phase with the resultant flux. This does not help the sparking, but increases the output of the machine.

6. Connecting Resistances Between the Armature Winding and the Commutator.—This is almost universal. The effect of these resistances is obvious if we consider their effect on the commutation voltage.

The increase in resistance causes a reduction in the effective short-circuit current. Thus we reduce not only the sparking tendency, but also the reactive effect on the field. It is not easy, however, to arrange these resistances without unduly increasing the length of the motor. The most practicable solution of the difficulty is in placing the resistances in the armature slots as introduced on the Continent of Europe some years ago by Messrs. Ganz and Co., and used with variations in U.S.A.

In this way it is possible to arrange large enough resistances between the windings and the commutator to ensure satisfactory starting.

But here we, of course, sacrifice efficiency. Further, the windings take up slot space and increase the armature losses, and hence temperature rise in the armature, giving only the one advantage of increased resistance of short-circuit. Again, for the same amount of active armature copper the insertion of the resistances means an increase in depth of slot, and unless placed themselves at the bottom of the slot increase, the reactance of the main winding and thus in some measure counteract their own beneficial effect. As regards their own reactance, they are, when employed, straight and wound doubled back on themselves, thus having no reactance. The method

employed by the Westinghouse Co. is to place the resistance connections in separate slots below the main armature slots as indicated in punching shown in figure 9. In small sizes of machines in which the current carrying capacity of the resistances has not to be very large, the firm of Siemens-Schuckert, employ strip resistances. Owing to the limited length of strip we must run the current densities very high, and a perforated strip is used to increase the radiating surface without increasing the effective conductor cross-section.

In large sizes it is impossible to get sufficient carrying capacity and resistance in these strips, and the above company reverts to the practice of placing the resistances in the slots.

They have just brought out a new arrangement, a description of which appeared in the "Elektrotechnische Zeitschrift," about August, 1906, and although the claims of a 15 per cent. increase in output, and 3 per cent. increase in efficiency, may be realised over the plain resistance in the main armature slots, it is hard to see where the method can compare with the Lamme method used by the Westinghouse Company.

RUNNING CONDITIONS.

It was mentioned above that the conditions could be more easily improved while running than at rest, due to the possibility of neutralising the transformer voltage. Could the transformer voltage be neutralised by an opposing voltage, then one would obtain not only favourable conditions for sparkless running, but also one could build an armature for a smaller effective current—due to absence of short-circuit—and thus reduce the size of commutator. It is obvious at a glance that it is impossible to neutralise the transformer voltage with an induced voltage in the opposite direction, since when the resultant e.m.f. falls to zero, so also must the turning moment. The only course open is to neutralise the transformer e.m.f. by an e.m.f., induced by rotation of the armature in a cross field. The mechanical position of the field will be in the centre between the main field poles, and so any flux there will not affect the main filled flux in value.

The required e.m.f. must be produced by a flux whose time phase is one quarter period ahead of the main field flux—as is the case in repulsion motors.

As any methods applicable to conductively compensated motors are also applicable to Conductively compensated motors, a discussion of the latter will include the former.

In the conductively compensated motor, the armature and field and compensating winding all carry the same current, I . The m.m.f. M_1 of the armature and that M_2 of the compensating winding act in opposition to one another, so that the

resultant m.m.f. M_s is 180 degrees out of phase with the current I . We, of course, assume that the compensation will be enough, or more than enough, in which case only we have the resultant M_s . In order, however, to neutralise the transformer e.m.f. by an e.m.f. due to rotation, it is necessary to produce a flux which is 90 degrees ahead of the phase of the excitation current. In order to neutralise the reactance voltage, we need a voltage such as would be produced by M_s . Hence, in order to neutralise both of these two voltages, the flux in the neutral zone must be at an angle between 90 degrees and 180 degrees, according to which is the greater, with the excitation current.

A resultant m.m.f. of this nature is obtained if one allow either the current I_2 to lag behind the current I_1 as in figures 10 and 11 or the phase of the armature current I_1 to be in advance of the motor current I_2 , as in figures 12 and 13.

The first case will occur when an inductionless resistance is connected in parallel with the compensation winding figure 11. The current in the compensated winding will then lag 90 degrees behind that in the resistance, and their resultant flows through the armature and the field winding.

The magnitude and phase position of the resultant m.m.f. can, by suitably proportioning the parallel resistance, and the number of windings of the compensating coils, be so arranged that the resultant m.m.f. of the armature coils becomes zero.

The second case will occur when a choking coil is connected in parallel with the armature figure 13. Neglecting the armature reactance, the armature current when running will be in phase with the armature voltage, but the current of the choke coil will lag 90 degrees behind. Their sum will flow through the field and compensating winding. Here also we can adjust the phase position and magnitude of M_s to suit.

If one wishes to avoid regulation of the choking coil, the connections shown in Figure 11 have the advantage that the resultant m.m.f. is directly proportional to the armature current—but only when the field is unsaturated is the transformer voltage proportional to the armature current.

Against this arrangement we must count a reduced efficiency.

Against that of figure 13 we must count a lower power factor and a higher speed due to the phase difference in flux and current. Neither of the above arrangements are very satisfactory on account of the complicated regulation required.

The latest method of Messrs. Siemens-Schuckert is to neutralise the reactance voltage by an interpole winding, as commonly done on direct current machinery, and to neutralise

the transformer voltage by a speed voltage induced by a flux which is supplied by a winding arranged in shunt either with the armature or the whole machine.

The diagrammatic arrangement of windings and vector diagram for the same are shown in figures 14 and 15, while figures 16 and 17 show the method of arranging them in the stator slots.

In the vector diagram—

- OI represents the direction of motor current
- E_t is the voltage drop due to field inductance.
- E_r is the voltage drop due to motor resistance.
- E is the e.m.f. induced in the armature by its

rotation at a speed U .

This gives a total voltage at motor terminals of E_t .

The m.m.f. of the shunt winding is shown by M-shunt, in quadrature, with the voltage E_t , the winding being so arranged that the m.m.f. leads the terminal voltage.

The m.m.f. of the interpole winding is shown by M-series, its change in direction being obtained by reversal of the winding.

The resultant of these two is shown by M, which is the flux due to the composite excitation of the auxiliary pole.

In figure 16 that part of the compensation winding whose m.m.f. is completely neutralised by that of the armature is shown by the large circles, and that part which is used for compensating the reactance voltage of the short-circuited coil—shown in the diagram figure 14, as the series coil—is indicated by the small circles. The direction of currents is shown by the familiar convention of dots and crosses.

It will be noticed that in the slots, a. a. the m.m.f. of the series coil opposes that of the compensation winding, and in the others assists. It would obviously be better to omit the opposing coils and reduce the turns of the compensation winding correspondingly, in a similar manner the other coils could be included in the compensation winding.

In the slots where we omit the opposing coils we also have the shunt winding—which is shown by the finer lines and circles—so that we may use the space thus made available for the shunt winding.

In figure 16 the dotted lines indicate the direction of the series, and shunt fluxes, and from a study of the same it is obvious that the arrangement there shown obviates any mutual inductive effects.

As the strength of the shunt excitation required depends on the current taken by the motor, it is obvious that to obtain

complete compensation at all loads we must regulate the shunt field. This is done with a variable inductance in series with it.

Since the current in the shunt coil should—for the best effect—be in quadrature with the current in the armature, it is generally found advisable to connect the shunt field across the armature instead of the motor as shown in figure 14. This is due to the fact that the armature voltage and current are nearly in phase due to compensation.



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