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INDUSTRIAL CONTROLLERS—WITH PARTICULAR REFERENCE TO THE CONTROL OF DIRECT-CURRENT SHUNT MOTORS

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ABSTRACT OF PAPER

Stating that present day development of motors and controllers is such that former limitations as to regulation of starting current from the viewpoint of motor, controller and supply system have been largely removed, the author presents a series of tests on 15 and 20-h.p., 230-volt, d-c. shunt motors, started from rest. The motors are of two types, constant and adjustable speed.

These tests were made to determine: first, the load driven by the motor; second, the power supply; third, the motor operation.

From these tests the author concludes, in part; that it is practical with automatic acceleration to use one switch to short-circuit the armature resistor used with motors as large as 15 h. p.; that the shunt field of small adjustable speed motors can be reduced in one step under normal load conditions (this practise can be safely followed up to motors of 50 h. p.); and that adjustable speed motors can use one step resistance for dynamic braking.

THE PRESENT practise in industrial control is the result of accumulated experience extending over the past twenty-five years. The theory consists in analyzing the characteristics of the motor to be controlled, and designing a controller which will furnish the characteristics not incorporated in the motor design. An analysis of the motor, from this standpoint, has brought out a number of features which were not generally appreciated.

The application of the controller requires an analysis of the load to be driven by the motor, as well as the characteristics of the motor. The controller must cause the motor to operate through a cycle which is best adapted to the motor load, or the machinery to which the motor is connected. The engineer must never lose sight of the fact that the purpose in using a motor and controller is to do certain work, and that he should select a type of motor and controller that will perform this work under existing conditions with the least apparatus, and require the minimum of attention.

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In the early days of the d-c. motor, great care had to be taken in starting, and in changing the motor speed, to prevent bad sparking or flashing. This led to the practise of using a considerable number of steps in the external armature resistor, to give a small change in amperes per step. The most common form of motor starter, even today, is a face plate, the design lending itself readily to the use of a large number of steps. Furthermore, the characteristics of this starter are such that considerable burning would result if there were a large change in current per step, so that a relatively large number of steps are necessary to protect the starter against excessive wear.

The steady improvement in the design of motors and controllers has removed many of the limitations formerly existing. At one time the permissible starting current was seriously limited by the danger of disturbance to the supply voltage. The increase in the capacity of systems supplying power now permits small and medium size motors to start with twice full-load current, or even more, without disturbing the supply voltage. Many motor applications are made in factories and mills where there is a continual change in the power demand, so that the starting of relatively small motors makes little difference in the total load.

However, there still exists a number of applications where starting current is an important feature, such as elevators and some other apparatus used in public buildings. Printing presses, paper machinery and applications of similar nature, require special controllers to give a slow start to properly manipulate the product.

Direct-current series and compound motors, as large as 20 h.p. are in successful operation, without the use of an external starting resistor. Mr. Hansen, in his paper published elsewhere in this issue, shows oscillograph records illustrating the starting of these motors. Shunt motors as large as 15 h.p. connected to drum controllers, short-circuiting the starting resistor in one step, have been in successful operation for over ten years.

In order to get a better understanding of the conditions when a d-c. shunt motor is started from rest, the writer arranged for a number of tests on standard motors for general purposes, equipped with automatic starters. These tests were made to determine the effect upon:

First, the load driven by the motor.

Second, the power supply.

Third, the motor operation.

No tests were made upon the controller itself, as commercial controllers are now available which are well able to meet all service requirements. A magnetic contactor controller, of modern design, should be able to take care of any starting conditions which can be met by the motor, without causing undue wear upon any part of the controller.

Most d-c. shunt motors, designed for general purposes, start with less than full load, so that the tests were made with different methods of loading.

The controller was adjusted to short-circuit the starting resistor, while the counter e.m.f. of the motor was quite low. The starting current was also kept small in order to exaggerate the starting conditions. The armature voltage at which the resistance was closed can readily be seen by the notch in the counter e.m.f. curve.

This investigation covered only small motors, as these are typical of most of the motors used, and cover a field where very little application engineering work can be done. It is very desirable to have a simple and strong controller for these motors, as they are often used where the operating conditions are bad and expert attention is not given them. The application of larger motors frequently requires the investigation of the load conditions by engineers, who can specify the correct motor and controller, and modify the controller to adapt it to any special requirements, if desirable. Furthermore, large motors usually receive better care.

Apparatus Used in Making Test.—An oscillograph was employed in all these tests. Figs. 2 to 14 for the 20-h.p. motors were taken on a cylinder, giving the total time of approximately two seconds. Figs. 15 to 21 for the 15-h.p. motor were taken on a long film attachment, and the time for these curves was four to six seconds.

In all cases, the motors used were standard 230-volt shunt-wound d-c. motors. The voltage at the supply circuit dropped a little below this value, and varied from 220 to 225 volts.

The load, in all but two cases, consisted of a d-c. generator, slightly larger in size than the motor, belted to the motor. The generator exerted no retarding force, other than that due to friction and inertia, except where noted. This will represent the majority of loads which a motor of this class will be called upon to start. In one case, the field of the generator was excited, and the armature short-circuited through sufficient resistance

to develop full motor torque at full speed. This condition more nearly represents the starting of a heavy fan, or centrifugal pump.

The tests on all 20-h.p. motors were made with an automatic controller having a wiring diagram shown in Fig. 1. The switches used on this controller were standard type C contactors, of 125-ampere capacity. The first resistance switch was of the series lock-out type, and the second switch of the counter e.m.f. type. Where the resistance was cut out in one step, the first switch was blocked in the open position.

For the adjustable speed motors, a series relay was used to short-circuit the field resistor during acceleration. This relay was open when the armature resistor was short-circuited, and

FIG. 1—DIAGRAM OF CONNECTIONS

allowed the field to decrease to its minimum value. When the motor was at rest, the shunt-field strength was either zero or equal to that for the maximum speed condition. The constant speed shunt motor had its field disconnected in the off position, in all of the tests. For the internal resistance of the motors and controller see the curves and diagrams.

Tests on 20-h. p., 750-rev. per min., 230-Volt, d-c., Shunt Motor. See Fig. 22. Fig. 2 shows the motor started with 1.35 ohms external armature resistance, which was reduced to 0.35 of an ohm when the counter e.m.f. equalled 120 volts. The second step of resistance was short-circuited when the counter e.m.f. reached 160 volts. This is a very good record of a two-step automatic starter.

Fig. 3 shows the same motor, with one ohm external armature resistance. The entire resistance in this case was short-circuited in one step. The resistance switch was not

FIG. 2—20-H. P. MOTOR—750 REV. PER MIN.—TWO-STEP STARTING
RESISTANCE 1.35 OHMS

closed until the counter e.m.f. of the motor equalled 190 volts. This represents an adjustment which is better than can usually be obtained in practise.

Fig. 4 shows the motor started with 1.35 ohms external re-

FIG. 3—20-H. P. MOTOR—750 REV PER MIN.—ONE-STEP STARTING
RESISTANCE 1.00 OHM

sistance, the resistance being short-circuited in one step, the switch closing when the counter e.m.f. of the motor was 150 volts. This adjustment gives equal current peaks, and represents a practical controller.

Fig. 5 shows a start under the same conditions as Fig. 4, except that the short-circuiting switch closed at 120 volts. This shows a peak at the time of short-circuiting the armature resistance, in excess of the starting current, and represents very

FIG. 4—20-H. P. MOTOR—750 REV. PER MIN.—ONE-STEP STARTING
RESISTANCE 1.35 OHMS

bad commercial practise. Figs. 3, 4 and 5 show very clearly the results obtained when the short-circuiting switch closes at different values of counter e.m.f.

Fig. 6 shows a one-step start, with one ohm external armature

FIG. 5—20-H. P. MOTOR—750 REV. PER MIN.—ONE-STEP STARTING
RESISTANCE 1.35 OHMS

resistance, the short-circuiting switch closing at about 125 volts, counter e.m.f. This curve has the same adjustment for short-circuiting the armature resistance as Fig. 5, and shows that the current peaks can be made approximately the same by increasing the initial current.

Fig. 7 shows a start with 0.765 of an ohm external armature resistance, with one short-circuiting switch. The load on the motor, in this case, was a prony brake, set to give full load torque. This represents a very difficult starting condition, as the

FIG. 6—20-H. P. MOTOR—750 REV. PER MIN.—ONE-STEP STARTING RESISTANCE 1.00 OHM

static friction of the brake is considerably in excess of full load torque. The start, however, was successfully made with one step of resistance.

In the curves referred to, armature volts, armature amperes

FIG. 7—20-H. P. MOTOR—700 REV. PER MIN. FULL LOAD—ONE-STEP STARTING RESISTANCE 0.725 OHM

and shunt field amperes were taken from the oscillograph records. The torque curve was plotted by assuming that the field flux was proportional to the shunt field amperes, except that the negative value of the shunt-field current, at starting,

was neglected, and the torque curve started at zero value. While these assumptions are not strictly correct, they serve to show the characteristic shape of the torque curve. Since the motor was connected to the line with zero field current, it can be assumed that the initial torque was approximately zero, and independent of the armature current. This torque shows a gradual increase, the armature current remaining constant for a brief period, until sufficient torque is developed to start rotation. Fig. 3 shows how this torque not only increased gradually, but decreased again, up to the point of short-circuiting the armature resistance. At this instant, the torque has a momentary increase, and again tapers off. Some of the curves show a slight change in the field current at this instant, due to the transformer action between the armature current and the field windings. This momentary change in field current was neglected in plotting the torque curve, as it was assumed that the field flux would show an opposite change.

I wish to lay special emphasis upon the characteristic shape of this torque curve, at the time of starting the motor from rest. This curve shows that the motor will start its load gradually, independent of the value of armature current. A heavy armature current, several times the value of full-load current, can be used with safety, providing there is no serious effect on the voltage of the supply circuit, which might be objectionable for other reasons. An easy start of the load is very desirable, as there usually is considerable lost motion in the gearing, or other mechanical connections, between the motor and its load. The sudden application of torque would cause a hammer blow, and might injure the machinery. The sudden increase in torque, at the time the section of the armature resistance is short-circuited, is not so dangerous, as long as a positive torque is maintained, and there is no lost motion in the machinery. Figs. 2 and 4 show that very little improvement can be made by using two switches to short-circuit the starting resistor.

Tests on a 20-h. p., Adjustable Speed, 230-Volt, D-C., Shunt Motor, Having Speed Adjustment of 500 to 1500 rev. per min. (See Figs. 23 and 24) These tests are duplicates of the previous ones, except that, in some cases, the shunt-field current has an initial value equal to the value when the motor is operating at 1500 rev. per min. Also, the field resistance, at the instant of starting the motor, is short-circuited, and again open-circuited at the instant of short-circuiting all of the external resistance.

Fig. 8 shows a typical start, short-circuiting the external armature resistance in two steps, the initial resistance being one ohm, and the resistance of the last step 0.25 of an ohm.

FIG. 8—20-H. P. MOTOR—500-1500 REV. PER MIN. FULL LOAD—TWO-STEP STARTING RESISTANCE 1.00 OHM

The first switch closed at approximately 125 volts and the second switch at 175 volts, counter e.m.f. It is evident, from this curve, that the second step of starting resistance was not necessary.

FIG. 9—20-H. P. MOTOR—500-1500 REV. PER MIN.—TWO-STEP STARTING RESISTANCE 1.50 OHMS

Fig. 9 shows a similar two-point starter, having an initial resistance of 1.5 ohms, the second step of resistance being 0.25 of an ohm.

Figs. 10 and 11 show similar starts, with 0.765 ohms external

resistance. In these two tests the armature resistance is short-circuited in one step.

Fig. 12 shows a single-step start, with the same amount of

FIG. 10—20-H. P. MOTOR—500-1500 REV. PER MIN.—ONE-STEP STARTING
RESISTANCE 0.765 OHMS

armature resistance 0.765 ohms), but with the generator loaded, so that it developed full-load torque, at full speed.

Fig. 13 shows a start under similar conditions, except that the motor was loaded with a prony brake, giving full-load torque.

FIG. 11—20-H. P. MOTOR—500-1500 REV. PER MIN.—ONE-STEP STARTING
—RESISTANCE 0.765 OHMS

Fig. 14 shows a single-step start, having an armature resistance of 1.5 ohms, the short-circuiting switch closing at about 140 volts, counter e.m.f., giving equal starting and short-circuiting current peaks.

These curves differ from the preceding set in characteristic shape, after the armature resistance has been short-circuited. This is due to a gradual decrease in the shunt field strength, with a corresponding increase in the armature current.

FIG. 12—20-H. P. MOTOR—500-1500 REV. PER MIN. FULL LOAD—ONE-STEP STARTING RESISTANCE 0.76 OHM

change in field strength and current is gradual, and it does not seem necessary to use automatic means for delaying this change in field strength.

Different methods of loading the motor do now show much

FIG. 13—20-H. P. MOTOR—500-1500 REV. PER MIN. FULL LOAD—ONE-STEP STARTING RESISTANCE 0.765 OHMS

change in the current peak when the resistance is short-circuited. This is largely dependent upon the value of the counter e.m.f. at the time of short-circuiting the starting resistance. In none of the tests was this peak excessive.

Tests on a 15-h.p., 230-Volt, 400 to 1600 rev. per min., D-C., Shunt Motor. (See Figs. 25 and 26). A number of tests were made on this motor, using a controller connected as shown in Fig. 27. In these tests the motor was belted to a generator a

FIG. 14—20-H. P. MOTOR—500-1500 REV. PER MIN.—ONE-STEP STARTING
RESISTANCE 1.5 OHMS

little larger than the motor. The only load to be overcome was that due to friction and inertia.

The controller differs from that shown in Fig. 1 in the connections to the shunt field relay. In this case a “fluttering” or

FIG. 15—15-H. P. MOTOR—400-1600 REV. PER MIN.

“vibrating” relay was substituted for the series switch. Provision is made for keeping these relay contacts closed during acceleration, by using more ampere turns on the relay during this period. (See Fig. 27.)

This fluttering relay is arranged to close its contacts when the current exceeds a fixed value, and to open the contacts when the current is reduced below this value. The difference between the closing and opening values of current is about 10 per cent.

FIG. 16—15-H. P. MOTOR—400-1600 REV. PER MIN.

The object of the relay is to control the weakening of the shunt field during the period of acceleration from 400 rev. per min. to a higher speed, depending upon the setting of the field rheostat. It operates in a similar manner to a voltage regulator. The

FIG. 17—15-H. P. MOTOR—400-1600 REV. PER MIN.

relay contacts short-circuit the field rheostat, the rapid cutting in and out of the field rheostat tending to retard the weakening of the shunt field.

Tests shown by Figs. 15, 16 and 17 indicate that the action of such a relay is not very smooth. When this principle is

applied to the exciter of a large d-c. generator, the pulsations are damped out to a considerably greater extent. Moreover, the parts of the voltage regulator are lighter and the regulator is much quicker in its operation and much more sensitive to a change in current.

FIG. 18—15-H. P. MOTOR—400-1600 REV. PER MIN.

By comparing these curves with the preceding curves, made on a three-to-one adjustable speed motor, it will be seen that the armature current and torque are considerably more disturbed when the relay is used, than in the cases where this relay

FIG. 19—15-H. P. MOTOR—400-1600 REV. PER MIN.

is omitted. It would, therefore, seem unwise to add this complication to the average small motor.

There is another objection to the use of this relay. If we consider the above motor operating at 1600 rev. per min., and quickly move the field rheostat to reduce the motor speed to

1200 rev. per min., the motor will regenerate and cause a heavy reverse current to flow. This excess current will lift the fluttering relay and short-circuit the field rheostat. This action still further increases the field strength of the motor and causes an

FIG. 20—15-H. P. MOTOR—400-1600 REV. PER MIN.

increase in the armature current. The action of the relay in this case is the reverse of its operation during acceleration, and has a very undesirable effect.

In order to correct this difficulty, a second relay known as a

FIG. 21—15-H. P. MOTOR—400-1600 REV. PER MIN.

“transfer” relay has been used. This relay has a compound winding so arranged that it reverses the connections to the fluttering relay when the motor regenerates. In order to properly protect the motor it is, therefore, necessary to use two relays instead of one. Controllers for paper calenders, printing presses

and other applications having motor-operated field rheostats, can use the fluttering relay without a transfer relay, as the movement of the field rheostat is slow.

Dynamic Braking. This same 15-h.p. four-to-one adjustable speed motor was arranged for dynamic braking. The connections were such that the field rheostat could be short-circuited during the period of braking. Figs. 18 and 19 show the braking characteristics with the field strength remaining constant and the motor operating at 1600 rev. per min. when the dynamic brake was applied. The drift in this case was considerable,

FIG. 22—CONSTANT-SPEED MOTOR—20-H. P.—230 VOLTS—750 REV. PER MIN.

as the motor was belted to a generator and there was very little friction to assist in bringing the load to rest.

Figs. 20 and 21 show dynamic braking with exactly the same conditions as the two previous curves, except the field rheostat was short-circuited during this braking period. The action of the shunt field in this case is very interesting. The increase in the field strength maintained the armature current at a fairly constant value over a considerable part of the retardation, the resultant torque curve showing very well sustained retarding effort. This indicates that the action on an adjustable speed motor gives very satisfactory results without the use of

additional steps in the dynamic brake resistance. Under normal operating conditions the friction load would be sufficient to bring the motor quickly to rest from the low speed. In the absence of considerable friction a mechanical brake should be used to obtain a quick stop, as very little dynamic braking can be obtained when the motor reaches low speeds.

SUMMARY OF TESTS

1. It seems unnecessary, with automatic acceleration, to use more than one switch to short-circuit the armature resistor used with small motors except where special requirements are to

FIG. 23—LOW-SPEED—20-H. P. MOTOR—230-VOLTS—500 1500 REV. PER MIN.

be met. I believe it is practicable to use one switch with motors as large as 15 h.p. for general purposes, and operate this switch by counter e.m.f., setting the switch to close at 75 per cent of normal voltage.

2. If the motor field is zero, or has a small value, when the line switch is closed, the starting torque is also zero or has only a small value and it will increase gradually so that the motor, or its load, will not be subjected to a heavy shock or jar when the lost motion in the drive is taken up.

3. The shunt field of small adjustable speed motors can be reduced in one step under normal load conditions without fear

of undue torque or current. I believe this practise can be safely followed with 50-h.p. motors and perhaps larger. This covers the usual range of sizes for this type of motor.

I believe that most machine tool motors are always started light. Under this condition the motor can be started successfully with minimum field strength and the field relay omitted. This will enable us to use the same controller for constant speed and adjustable speed motors supplying a separately mounted field rheostat for the latter.

4. Adjustable speed motors can use one step of resistance for dynamic braking as the change in field strength tends to

FIG. 24—HIGH-SPEED—20-H. P. MOTOR—230 VOLTS—500-1500 REV. PER MIN.

maintain the braking current constant over a considerable range of speed.

5. The use of a "vibrating" or "fluttering" relay is bad engineering for hand-operated field rheostats, unless a "transfer" relay is also used to reverse its action when the motor regenerates.

6. The time required to accelerate to 95 per cent of speed is very short. In these tests the time did not exceed three seconds.

NEW PROBLEMS

There are very few problems which present a more fertile field than the control of adjustable speed motors. The foregoing discussion covers only a few of the questions involved. The writer has observed cases where gearing has broken, due to

a momentary reverse torque of the motor. It is important to see that all interlocks or relays connected to the shunt field resistance are so arranged that they cannot cause a momentary reverse torque of the motor. After a positive torque has been applied to machinery, and all of the lost motion taken up, it is seldom that any part of the apparatus is injured, even if the driving torque varies over a considerable range, provided this torque is always positive. A slight negative torque allows lost motion to occur, and is apt to break some part of the apparatus, due to the hammering blow effect, when the positive torque is resumed.

FIG. 25—LOW-SPEED—15-H. P. MOTOR—230 VOLTS—400-1600 REV. PER MIN.

This reverse torque may also be caused by a drop in the line voltage below the counter e.m.f. of the motor, or it may occur due to a rapid movement of the field rheostat.

Trouble may also result from increasing the field strength of a motor when it is disconnected from the line. For example, a 400 to 1600-rev. per min. motor is operating at its maximum speed. If the controller disconnects the motor armature from the line, and at the same time increases the field strength to its maximum value, the voltage across the brushes of the motor will rise to something over three times normal voltage, unless the armature is slowed down very quickly. It can readily be

seen that a 500-volt motor, having over 1700 volts across its brushes, is apt to flash across at some part of its insulation and untimately be damaged. This rise of voltage has actually been

FIG. 26—HIGH-SPEED—15-H. P. MOTOR—230 VOLTS—400-1600 REV. PER MIN.

observed, and care must be taken not to manipulate the shunt field so as to cause it.

The use of dynamic braking introduces a good many interesting problems, both mechanical! and electrical. The additional

FIG. 27—DIAGRAM OF CONNECTIONS

heating effect on the motor is well known. The effect, however, upon the loading and lubrication of bearings, is not so well understood. The resultant change in the field flux of the motor, and the rate of change of current, are other problems.

The whole field of controller engineering presents many opportunities for the investigator. It has many problems that have not yet been solved, and I believe that engineers should not take the existing practise in controller engineering for granted, but study each application in a thorough manner, and design as simple a controller as possible for the work.

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