A SYSTEM OF REMOTE CONTROL FOR AN ELECTRIC TESTING LABORATORY

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I. INTRODUCTION

The remote control of electrical apparatus and machinery has an extensive technical application, but the range and precision of adjustment required in a great deal of laboratory work are greater than are provided for in regular commercial equipment. The apparatus here described is in use in the laboratory of the Bureau of Standards for testing electrical measuring instruments, instrument transformers, and similar testing and investigational work. Much of it would also be applicable to other purposes.

1. *Scope.*—The range and scope of a remote control system required for such work is well illustrated in testing wattmeters or watthour meters on low power factor, using separate sources for current and voltage. For the best conditions the observer should have both a coarse and a fine control of frequency, current, voltage, and power factor. If a test of the standard instrument on direct current is included, two other controls are necessary for the direct current and voltage. To accomplish this without the use of some system of remote control would require the observer to have access to at least 10 rheostats, 5 for fine and 5 for coarse adjustment, as well as to some phase shifting device. As will be shown in detail later, the system described provides the same flexibility of control by the use of a single multiple-lever controller, each lever giving a two-direction, two-speed control of voltage, frequency, power factor, and current, respectively. The purpose of the two speeds is to provide coarse and fine adjustment. The controllers may be used in connection with any one of five motor-generator sets, each of which has three or more machines on the same shaft. Provision has been made to extend the system so as to include additional machines. The machines are all small, the largest having a capacity of but 25 kilowatts.

II. CHOICE OF SYSTEM

There are various arrangements which might be used for such a system of remote control, and it may be well to mention a few of the considerations which led to the adoption of the system described.

Most of the disadvantages which are mentioned below as applying to the various possible arrangements could be overcome by sufficient complication in design, but such detailed considerations can not be entered into here. Only a general outline of the simpler of the possible arrangements will be attempted

1. *Advantages of Using a Single Rheostat.*—Where both a wide range and fine steps are required it is customary to use two rheostats, one for fine and one for coarse adjustment. While this gives a wide range and accuracy of adjustment with relatively small rheostats, the wiring is considerably more complicated than in the case of a single rheostat, and two operating motors are required. Moreover, a single rheostat is more convenient to operate if it can be arranged to give the necessary range and accuracy of adjustment with a single control handle, as the annoyance of having to

continually change from one handle to another is obviated. In using two rheostats one frequently finds that he has reached the limit of the fine adjustment, and so has to change to the coarse adjustment and back again. From these and other considerations it was decided to attempt the use of a single rheostat with a single control handle, rather than one rheostat for coarse and one for fine adjustment.

2. *Methods Available.*—For the accuracy of adjustment and range of resistance required in the present case any ordinary slide-wire device, such as straight bifilar wires, or wires on the edge of a disk, was entirely out of the question. However, four different methods suggest themselves for securing the necessary range of resistance in a single rheostat suitable for motor operation. In each, coarse and fine adjustment may readily be secured by operating the motor at widely different speeds.

(*a*) Winding resistance wire (or tape) on a long, insulated tube, contact being made by a brush moved lengthwise on the tube, similar to well-known types of commercial rheostats. For short rheostats the brush may be driven by a worm, but for long ones it is practically necessary to operate it by a cord passing over a pulley driven by the motor. This is the method finally adopted. (For cross section of rheostat, see Fig. 1.)

(*b*) Tape or wire wound helically on the surface of a cylinder, the arrangement being such that the brush can make contact with any portion of the entire length of the wire or tape. Either the brush or the cylinder may be rotated, the other being stationary.

(*c*) Tape or wire wound from one reel to another. Contact may be made by special brushes, or the resistance may be short-circuited as it is wound on the metal reel, as is done in the Kelvin type of rheostat.

(*d*) A tape or wire arranged in the form of a flat spiral, the contact brush being moved along the conductor by a rotating arm. Provision would have to be made for motion of the brush radially in and out on the arm.

3. *Reasons for Choice.*—The first method was chosen because it is less complicated both in design and construction and generally better adapted to the ranges of current and resistance required for this particular installation than either of the other methods (resistance range, 0 to 1060 ohms; current range, 0.1 to 17 amperes). Self-cooling is more effective and artificial cooling more easily carried out than in either of the other methods. The con-

tact is distributed over several turns of conductor instead of being made on one conductor only. In cases in which a tapered rheostat is required the change from one size of wire to another, or from wire of one kind of alloy to that of another, is much more easily carried out in this method, without danger of trouble with the moving contact at the point of junction.

For compactness, tape would naturally be used in the third method, but in this case some mechanical complication would be necessary, as the two reels could not be directly geared together on account of the changing diameter of the reels as the tape is wound on and off. There would also be a danger of the conductor's breaking, either in regular use or in becoming accidentally fouled.

The fourth method was out of the question in the present case, since to keep the size within bounds the conductor would have to be too thin to withstand the mechanical strains. A minor objection is the changing curvature of the surface on which contact is made. A greater length of conductor is also necessary than in the other methods. This arises from the fact that the accuracy of setting depends upon the angular backlash, and since the outer turns are longer than inner ones, the length of conductor involved in taking up a given angular backlash is not a constant, but is proportional to the radius. Hence, for any predetermined law of accuracy of setting, a greater length of conductor is required than would be necessary if all the turns were of the same radius.

For larger currents, or lower voltage circuits, the second method would probably be preferable, as the first method does not lend itself as readily to the use of larger conductors, especially when accuracy of setting is of importance.

The method chosen (*a*) is, of course, not without its difficulties. The great length required for fine setting (up to 12 m in the present case) makes it inconvenient and somewhat unwieldy. Yet, where a group of rheostats is to be installed, the total space required is at most no greater than for the other methods. If a cord is used to move the brush, the stretching of the cord introduces lost motion, while if a steel tape is used there is danger of the windings being destroyed by short circuits in case of an accidental breaking of the tape. Theoretically, the method is at a disadvantage, since the adjustment is step by step, being limited to a turn of wire (or at best to a part of a turn), while in the other methods the adjustment is continuous. Practically, however, this disadvantage is largely only apparent, since the fineness of adjustment in the other methods is limited by lost motion, etc.

While the great length required in the rheostat makes the method seem a somewhat brutal solution of the problem, it forms a very simple, straightforward arrangement. Over two years' experience with it has been so satisfactory that it has confirmed the opinion that the method is the most satisfactory one for the work in hand, the nature of which has already been indicated.

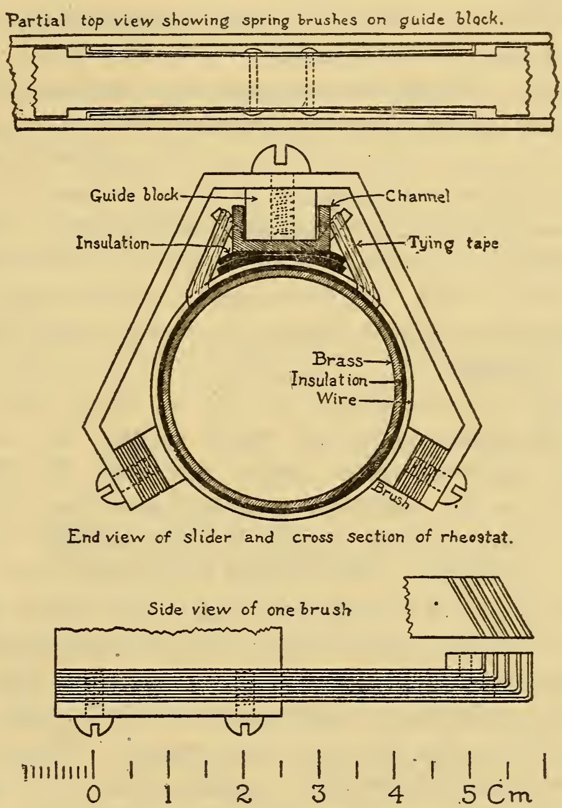

FIG. 1.—*Details of construction of tubular rheostat*

III. FIELD RHEOSTATS

A full-size cross section of a field rheostat is shown in Fig. 1. The arrangement for leading the current in and out is also shown. Two lengths were used, 5.5 m for the motor field rheostats and 12 m over all for the generator field rheostats.

Brass tubes were used, and the lengths were soldered end to end so as to make a perfectly smooth winding surface, a short sleeve being placed inside to make a good mechanical joint.

1. *Insulation.*—A coat of insulating varnish was applied to the tubes and allowed to dry. A 5 cm strip of varnished cambric was then wound on, after which another coat of the liquid insulator was applied and allowed to dry. This was followed by another coat each of varnished cambric and the insulating compound giving a smooth, hard surface on which to wind the wire. The resulting insulation was excellent, the completed rheostats showing 100 megohms or more, and each was tested at 1200 volts a. c. before being put into service.

2. *Winding.*—Enameled resistance wire was used, the enamel serving for the insulation between turns, which were wound snugly together so that the rheostat has a smooth, rigid surface. Splices were made by silver soldering the wires in butt joints. The winding was done on an extemporized lathe arrangement. After winding, the enamel was removed from the surface of the wire where the contact was to be made. In fact, a small amount of the metal was removed in order to slightly flatten the surface of the wires, and so improve the contact.

3. *Brushes, etc.*—As shown in Fig. 1, the contact brushes, which are laminated phosphor bronze springs, are carried on a sheet brass support which nearly surrounds the tube. Two brushes bear on the resistance winding, near the bottom, while a third, and longer brush, runs in a brass channel which serves as a return conductor. The channel is insulated from the winding by two layers of impregnated tape. The most satisfactory method of attaching the channel to the tube was found to be by pieces of thin silk tape placed at intervals along the tube, and each inserted under two or three turns of wire. This, of course, had to be done as the tube was being wound. These are tied to ears on the channel formed by sawing slots in the edge of the channel and bending out the strip between the slots.

4. *Mounting of Tubes.*—As shown in Fig. 2, the rheostats are mounted horizontally in a single tier, the operating motors being placed on a shelf at one end. They are placed near the ceiling of a long hallway into which the dynamo room opens, and so do not take up space useful for other purposes.

The motor end of each tube is clamped in position, but otherwise the tubes are supported on rollers to allow for expansion. Those rheostats which require water cooling have their ends connected by flexible copper tubes to provide for the water circulation.

5. *Cooling System.*—As already stated, artificial cooling is provided, wherever necessary, by circulating water through the brass tubes on which the resistances are wound. When first installed the city water supply was used, the small amount of water necessary for cooling being allowed to run to waste. Occasionally, however, under extreme atmospheric conditions, moisture condensed on the winding, and it was feared that the insulation might become injured. Accordingly, a closed circulation of the cooling water was substituted, a low-speed motor being directly connected to a gear pump. The motor is automatically started whenever a motor generator is operated whose field rheostat requires water cooling.

A vertical mounting of the tubes would be preferable in a building whose arrangement permitted it; as, for example, in a shaft large enough to allow of easy access. A simple thermal circulation

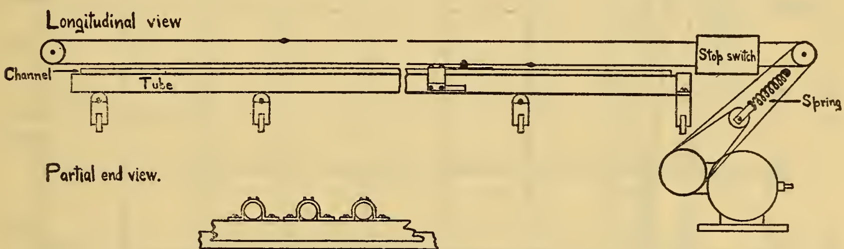

FIG. 2.—*Method of mounting tubular rheostats*

of a cooling liquid would then be sufficient, the tubes being connected in parallel with one common return tube.

6. *Design of Windings.*—Preliminary experiments had shown that under working conditions settings could be made on a motor-operated slide-wire rheostat of the type described to about 1 mm, about the average diameter of the wire which it was found convenient to use in winding the rheostats. It was arbitrarily decided to make the sensitivity of setting on the generator rheostats approximately 0.01 volt per millimeter, or 10 volts per meter of length of rheostat.

In Figs. 3 and 4 are shown the design curves for a typical generator rheostat. The magnetization curve of the generator was experimentally determined in the usual way (curve 1). From this, the resistance of the field winding and the normal voltage of the source, curve 2 was calculated, showing the resistance in the rheostat as a function of the generated voltage. By scaling off tangents to curve 2, the ratio of a small change in resistance to

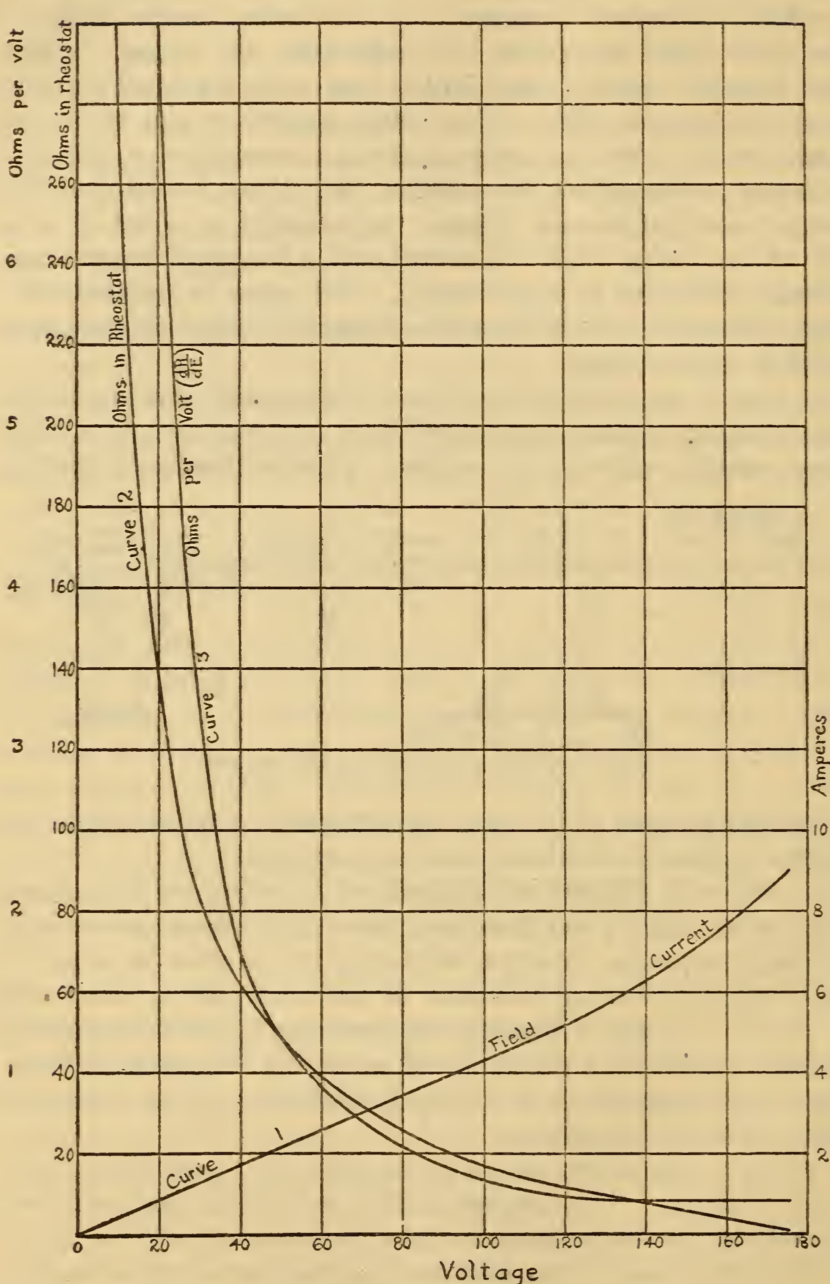

FIG. 3.—*Design curves for typical rheostat*

the resulting change in voltage can be determined. This is shown as ohms per volt in curve 3; but since each millimeter of the length of the rheostat represents a change of 0.01 volt in the generator voltage, curve 3 may be plotted in the form shown in curve 4 (Fig. 4) by merely a change of scale, giving the resistance of the rheostat per millimeter throughout its length.

From a consideration of the conditions to be met in all the field rheostats required in the system, the sizes of wire shown in the following table were chosen, somewhat arbitrarily:

TABLE 1

Wire Used for Winding Rheostats

Material	No. (A. W. G.)	Diameter	Resistance per turn
		Millimeters	
Copper	17	1.15	0.0021
Do	20	.81	.0043
Brass	17	1.15	.0075
Do	20	.81	.015
Do	22	.64	.023
18 per cent German silver	17	1.15	.034
Advance	18	1.02	.063
Do	21	.72	.13
Do	24	.51	.26

With the exception of the No. 22 brass, which was used only in two special rheostats, the wires are so chosen that the resistance per turn increases by a factor of about 2 from step to step, while the total change in diameter of wire is only slightly over 2 to 1.

The final data for the winding is shown by the broken line (No. 5) of Fig. 4, in which the horizontal steps indicate the lengths wound with the various sizes of wire. It will be noticed that the ideal curve does not cut the steps of the actual curve quite symmetrically. This is caused by slight arbitrary changes in design to adapt to materials, and also by the fact that the former is based on resistance per millimeter, the latter on resistance per turn. The final result is that settings can be made on the rheostat to an accuracy of about 0.02 per cent or better, since the mechanism allows the adjustment to be made, when necessary, to a single turn of wire.

The design of the motor field rheostats was much simpler, an untapered winding being found to be sufficient to secure a change of but 0.01 per cent in speed for a single turn of the wire on the rheostat. The motors are not of the interpole type, and rheostats 5.5 m long suffice to cover the safe range of speed, with the sensitivity just given.

IV. RHEOSTATS FOR THE CONTROL OF DIRECT CURRENT AND VOLTAGE

1. *Voltage Rheostats.*—These are identical in general construction with field rheostats already described. They are 7.5 m long and are wound with about 11 500 turns of No. 22 brass wire, giving a resistance of 254 ohms. Definite voltages from storage batteries (in multiples of 80, up to 320) are connected across the

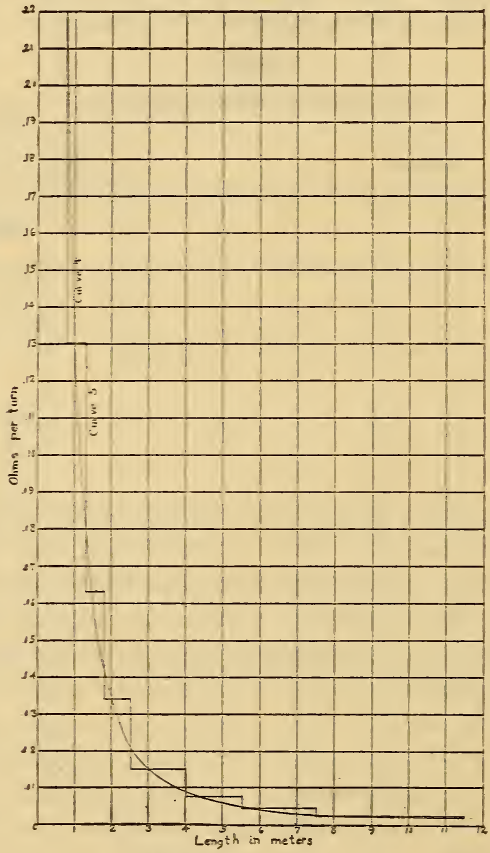

FIG. 4.—*Design curves for typical rheostat*

whole resistance and a variable voltage is tapped off by means of the sliding contact for use in testing. The current capacity of the rheostat is sufficient to allow enough current to be drawn from it for all ordinary work in instrument testing.

2. *Current Rheostats.*—Satisfactory current rheostats operating on a low voltage source and arranged to fit in with the same system of remote control have so far been worked out only for the larger ranges of current, from 300 up to 10 000 or 12 000 amperes.

This rheostat, which was originally designed for hydraulic operation,[1] was rearranged so as to be operated by four 0.1 kw motors. The resistance elements are flattened tubes through which water flows for cooling. Contact is made directly on the tubes by heavy laminated copper brushes, of circuit-breaker construction. The tubes are arranged in four sets of four each. The four brushes of a set are rigidly connected together, and are propelled by a single screw on the shaft of a motor, as shown in Fig. 5.

The four tubes of three of the sets are connected in series parallel. Tubes *A* and *B* are in series, as are also *C* and *D*, while the two pairs of tubes are in parallel. All four sets of tubes are connected in parallel, but as at the end of their travel the brushes

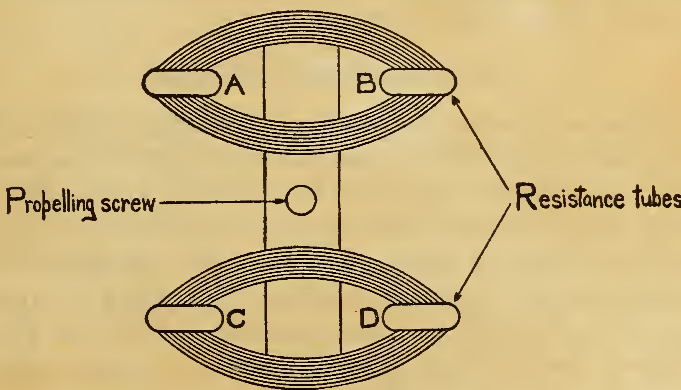

FIG. 5.—*Arrangement of brushes and resistance tubes of heavy-current rheostat*

ride onto insulating strips, the circuit through any set may be broken.

In order to extend the range of the rheostat downward the tubes of the fourth set are all connected in series, making the resistance of this set four times that of each of the other three. For still smaller currents, the brushes of all four sets are run out to the open points and a hand-operated rheostat is connected in parallel.

The operation of the motors is precisely the same as for the other parts of the control system, two speeds giving coarse and fine adjustment, etc. In fact, the control wiring is entirely symmetrical with that for the field rheostats. A general view of the complete rheostat is shown in Fig. 6.

[1] The main portions of the rheostat were designed several years ago by E. B. Rosa, H. B. Brooks, and F. S. Durston, and built in the instrument shop of the Bureau of Standards by Joseph Ludewig.

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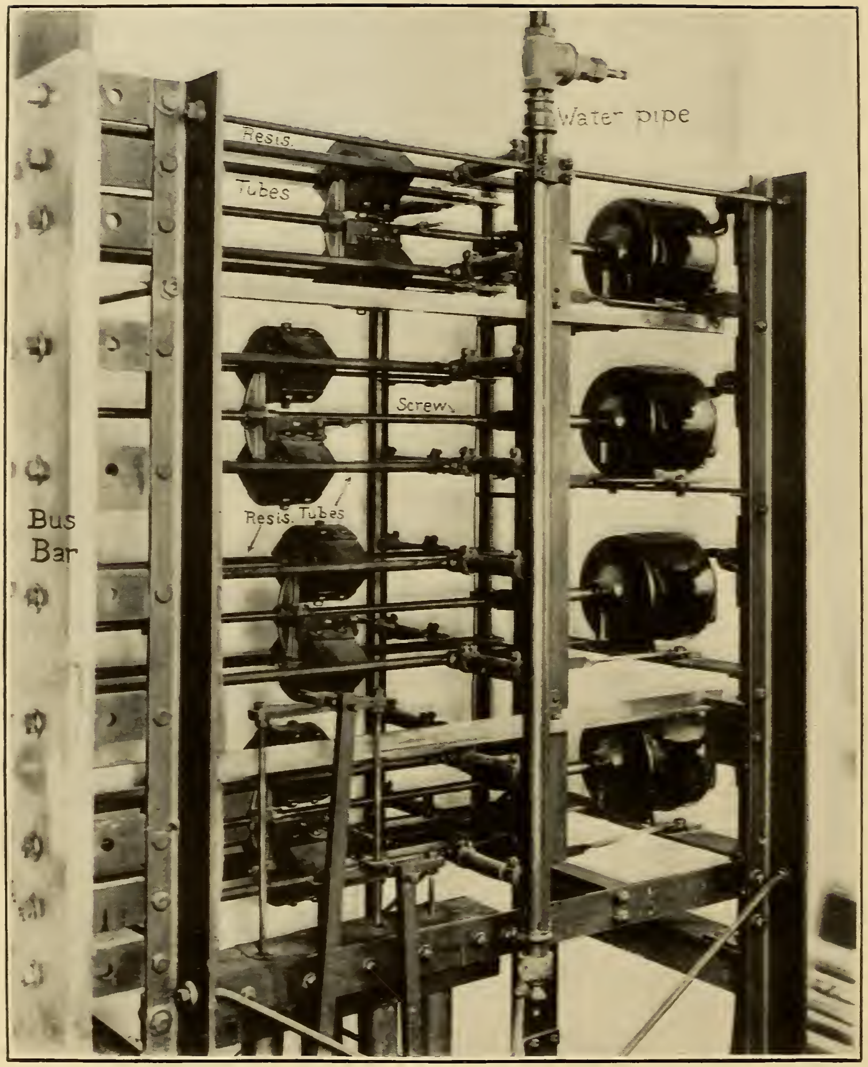

FIG. 6.—*General view of heavy current rheostat*

V. PHASE CONTROL

Use is made of two well known methods of phase control. The more satisfactory one is by the use of two similar alternators on the same shaft, one being used as a source of current and the other as a source of voltage, the phase adjustment being made by shifting the angular position of the stator armature of one alternator. In the other method the adjustment is accomplished by slowly moving the rotor of a phase-shifting transformer. In either case the motion is accomplished by a small motor actuating a compound worm drive.

This arrangement also fits in very nicely with the other parts of the motor-generator control, the two speeds giving coarse and fine adjustment of the phase relation.

VI. OPERATING DETAILS

1. *Motors.*—In order to operate satisfactorily at widely different speeds, a fairly high-speed motor has been found to be most satisfactory. The motors used are of the Eck worm-geared type, one-sixth hp 2500 rpm, worm geared in the ratio of 46 to 1, and arranged to rotate in either direction. For full speed 120 volts are applied to the armature, and for slow speed 10 volts. On account of the resistance of the armature, the ratio of the speeds is, however, greater than the ratio of the voltages, being about 18 or 20 to 1, instead of 12 to 1.

2. *Power for operation.*—The low speed can not be obtained merely by inserting resistance in the armature circuit, since the starting torque is then entirely too small for satisfactory operation. A small 20-volt, 3-wire storage battery is used to provide the low speed. The neutral of this battery is connected to the neutral of the regular 240-volt, 3-wire d. c. supply, thus forming a modified 5-wire system.

The arrangement is shown in Fig. 7, from which it is easily seen that a 2-speed, 2-direction control is obtained from the 4 contact positions of the controller.

3. *Controllers.*—As shown in Fig. 8, the controller for operating a motor-generator set has five levers, one each for frequency, phase, the fields of two generators, and an auxiliary d. c. voltage. The two inner contacts are for low speed and the two outer ones for high speed, and the normal position of the spring levers is at the center with the circuit open. In all cases the connections are such that motion to the right raises voltage or frequency, while

motion to the left causes a corresponding lowering. Accordingly, a small displacement to the right causes a very slow increase in voltage or frequency, and a further motion to the right against the stop gives a rapid increase. Similarly, slow and rapid decreases are obtained by motion to the left.

The springs controlling the levers are small helical springs, wound so as to be under an initial tension. The handles are removable, so that the danger of accidentally closing circuits not in use may be avoided.

Excepting where used at fixed "set-ups," the controllers are portable and are provided with flexible leads so that they may

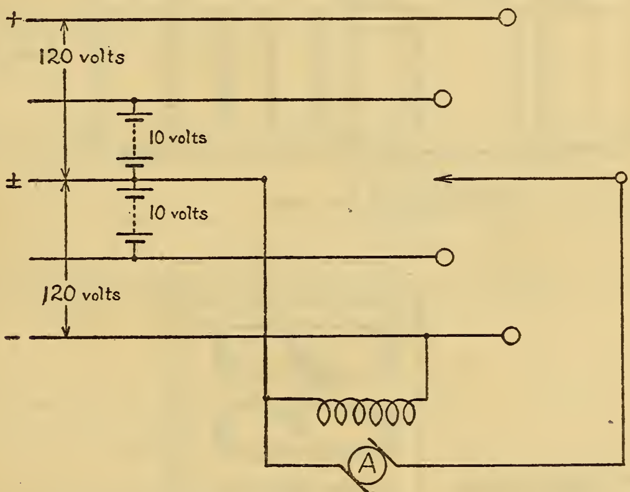

Fig. 7.—*Method of obtaining 2-direction, 2-speed control from 5-wire system*

be placed wherever the convenience of the work demands, and they are all interchangeable.

4. *Jacks*.—To provide a controller at each outlet for each motor-generator set would be too complicated and inconvenient. Hence, only one controller is used at an outlet, and it is arranged so as to control the output of any motor generator desired by merely plugging in two jacks, one connecting to the source of power and one connecting to the control motor armatures. This arrangement is indicated in Fig. 8. A commercial telephone jack is used, somewhat modified to adapt it to the required conditions.

The fixed parts of the jacks are mounted directly on the special conduit containing the wiring.[2]

[2] For a brief description of the electrical distribution and general laboratory arrangements for the building, see P. G. Agnew, Elec. Rev. and West. Electrician, 64, pp. 811, 820; 1914.

5. *Automatic Stop Switch.*—It is necessary to have some automatic device to limit the travel of the brush at the ends of the rheostat, as otherwise the motor would stall and fuses blow or injury to the apparatus result. Merely an automatic switch to open the armature circuit is not feasible, as this would make the

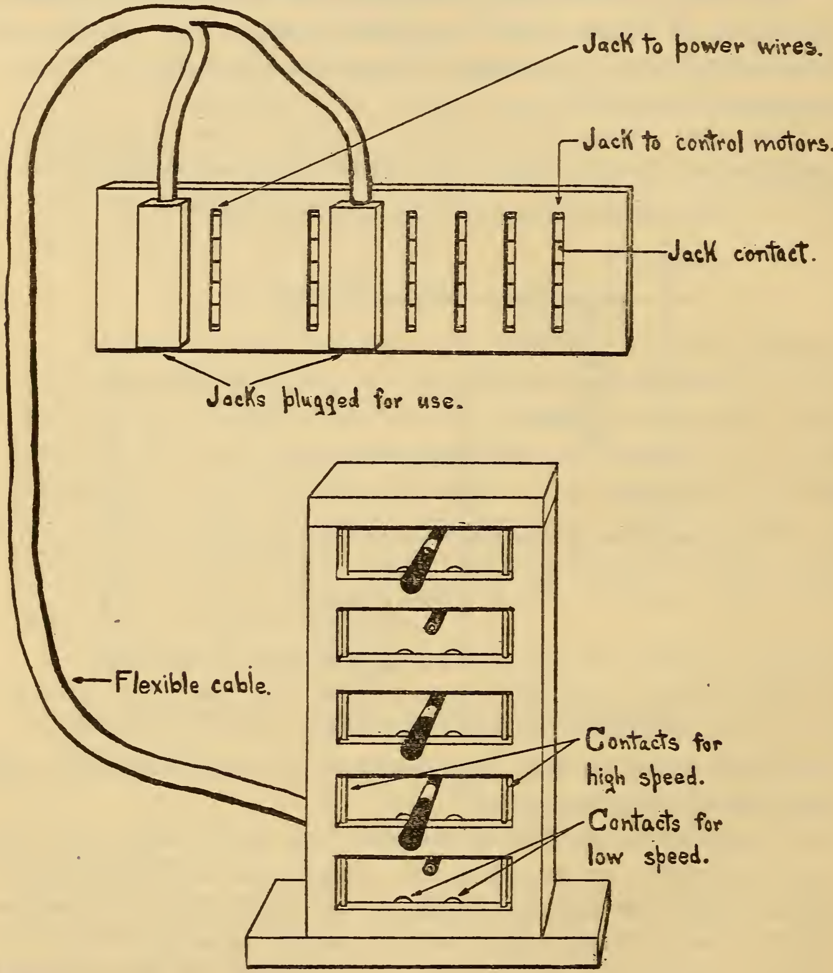

FIG. 8.—*Controller and jacks*

whole device inoperable whenever a brush accidentally reached the end of the rheostat adjustment. At first a simple friction drive was tried, so that the pulley or cord would slip when the brush reached the end, but this arrangement did not prove to be satisfactory. The switch indicated in Fig. 9 has, however, been entirely satisfactory.

As the rheostat brush reaches the end of its travel, a small brass bob, *B*, attached to the cord which operates the brush, enters the space between a fixed brass bar, *F*, and a spring, *S*, opening the circuit at *K*, thus stopping the motor. But *B* makes electric contact between *F* and *S*, completing the circuit through *R* to the positive side of the line, so that by throwing the controller lever to the negative side of the line the motor will rotate in the opposite direction, thus moving the brush toward the other end of the rheostat. When the brush reaches the other end of the rheostat, a second brass bob on the lower section of the cord enters the lower part of the switch, and the opera-

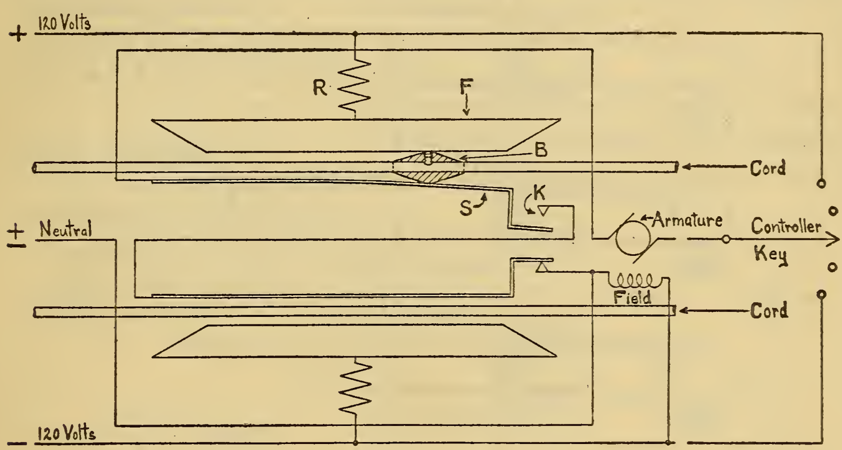

FIG. 9.—*Details of automatic stop switch*

tions are precisely like those just described for the upper part of the switch.

6. *Wiring.*—The wiring is surprisingly simple. In addition to the four power wires (the neutral is not necessary at the controller stations) only one wire for each control has to be carried around the laboratories—that is, one wire for each motor armature. In the original installation there were 17 controls, and therefore 17 motors, and but 21 wires were necessary. Only one additional wire is required when an additional control is added.

In the general wiring diagram, Fig. 10, the complete connections for one motor-generator set are shown with jacks at a controller station, together with one controller.

7. *Motor Fields.*—The four control motors required for the complete control of a motor-generator set have their fields connected in parallel, and the switch controlling their fields is placed on the panel from which the motor-generator set is started. The

closing of this switch thus becomes a part of the process of starting the set.

VII. EXPERIENCE WITH SYSTEM

In over two years' operation the system has given very little trouble—much less than was anticipated. The cords gradually

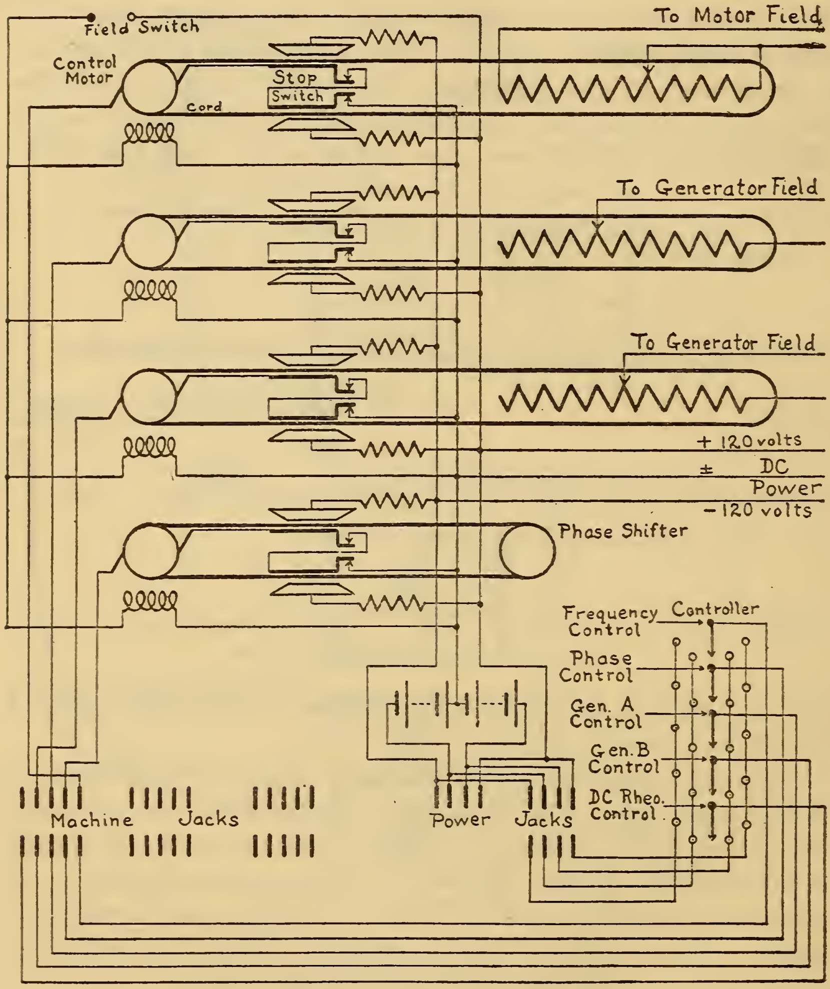

Fig. 10.—*General wiring diagram, showing details for complete control of one motor-generator set, with controller, and jacks for plugging so as to control other sets*

stretched slightly and had to be tightened once or twice, and a few very slight changes have been made in details of design or construction as experience has suggested them. Otherwise the whole system has required little more attention than would ordinarily be expected in the use of the same number of small motors in a laboratory.

There is a slight amount of backlash, due to the elasticity of the cord, but it is not at all serious, amounting to only about 0.1 or 0.15 per cent on the average.

One limitation that has sometimes proved inconvenient is that care has to be exercised in the use of an a. c. generator with so wide a range of field excitation not to draw too much current at low excitation, else the armature reaction may cause wave-form distortion. For this reason it is not permissible to draw full-load current at very low excitations if purity of wave form is important. The admittance of the connected load is a more logical basis for determining the permissible generator load than is the armature current.

The simplicity and convenience of the system, both in testing and in investigational work, has greatly increased the efficiency of the work of the laboratory, frequently saving the time of one observer.

WASHINGTON, May 26, 1916.