Synchronization of Television [1]

By H. M. STOLLER and E. R. MORTON

SYNOPSIS: Synchronization of Television is the problem of holding two scanning disks so that their phase displacement is always less than four and one third minutes of arc. A 240-pole synchronous motor of the variable reluctance type is used as a basis. Coupled to it a direct current motor carries the steady component of the load. Hunting is eliminated by a condenser in series with the two synchronous motors whose capacitance is slightly less than that required to tune the circuit.

As the motor might lock into step in any of 120 possible angular positions, only one of which would give the proper phase relations, a two-pole motor, with only one locking position, was provided by tapping the armature of the direct current motor at two points and bringing out the leads to slip rings. This was used for synchronizing while the 240-pole motor, connected subsequently, held the close synchronism required. The disks rotate at 1062.5 r.p.m. which gives 17.7 cycles on the two-pole and 2125 cycles on the 240-pole motor.

For transmission the synchronizing current is attenuated to a level of .6 milliwatt and amplified at the receiving end. The 17.7-cycle current is an undesirably low frequency for transmission over telephone cables and so is used to modulate a 760-cycle current through a polarized relay. This is demodulated at the receiving end, where a polarized relay by interrupting a local battery current gives a rectangular wave which acts through vacuum tubes on the field of the direct-current motor.

THE problem of synchronization involved in television transmitting and receiving equipment is similar in principle to any synchronous motor problem but the requirements are of such a special nature that it is necessary to employ unusual features of motor design and control circuits to secure the required results.

General Requirements

At the transmitting end a scanning disk is employed containing 50 holes spirally spaced around the periphery of the disk rotating at a speed of 1060 r.p.m.[2] It is desired to rotate a similar scanning disk at the receiving end so that the hole through which the observer is looking at a neon lamp will be in a position corresponding to the hole which is transmitting light at the same instant at the transmitting end. Since there are 50 holes in each disk, the holes will be spaced apart 7.2 degrees, thus 7.2 degrees of arc correspond at the receiving end to the width of the picture. Since the horizontal resolving power is approximately the same as the vertical (0.02 of the picture dimension), the arc occupied by a picture element is 0.02×7.2 or 0.144 degree. In order not to appreciably impair the quality of the picture,

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

[2] This speed was determined by transmission considerations and is discussed in the companion paper by Messrs. Gannett and Green.

it is necessary to hold the synchronization within approximately ½ of the width of one element. This gives 0.144 degree divided by 2 or 0.07 degree as the requirement within which synchronization should be held. By way of comparison it might be mentioned that the angular twist in a length of 6 ft. of 1-in. steel shafting operated at rated load is of about the same order of magnitude.

An ordinary four-pole synchronous motor when operating at full load, unity power factor, has an angular phase displacement of about 20 electrical degrees between the impressed and back e.m.f. This corresponds to 10 mechanical degrees since the motor has two pairs of poles. If this motor is operated at constant load and the line voltage is varied, the phase angle will decrease with increasing voltage, or when the voltage is held constant and the load is varied the phase angle will increase with increasing load. It is at once apparent therefore that the ordinary type of synchronous motor will not even approach the degree of precision required for the reason that any minute change in line voltage or load will cause variations in its phase angle of lag with respect to the impressed frequency of a far greater amount than 0.07 degree. Consider, however, a motor having 120 pairs of poles. Allowing 20 electrical degrees as the normal full load phase displacement, this would be equivalent to 20 divided by 120 or 1/6 degree mechanical phase displacement. Even this amount is over twice the required permissible displacement of 0.07 degree. Since the variation of the phase displacement is the important factor and not the absolute amount of displacement, it is evident that if the line voltage and load are held reasonably constant a synchronous motor with 120 pairs of poles should be sufficiently precise.

Another requirement in addition to close phase synchronization is regulation of the acceleration or deceleration of the generator at the transmitting end. Such regulation is required due to the fact that an appreciable time is taken for the transmission of the synchronizing current a distance of 220 miles (circuit length) between New York and Washington. The velocity of propagation over the cable was approximately 19,000 miles per second while that of the picture on the open wire of 285 miles circuit length was about 175,000 miles per second, the corresponding times of transmission being .0116 second and .0016 second, leaving a difference of .01 second approximately. Since the total permissible error in synchronization is .07 degree, it is reasonable to allow .02 degree as error due to acceleration regulation. Let a be the acceleration in degrees per second per second. Substituting in the formula $s = \frac{1}{2}at^2$ gives $.02 = \frac{1}{2}a(.01)^2$ or $a = 400$ degrees per second per second or a little over one revolution per second per second. For comparison consider a ¼-h.p. unregulated shunt motor. If the line voltage increases 10 per cent, it will cause an increase in speed from 4 per cent to 8 per cent depending on the magnetic saturation in its field circuit. This increase in speed will take place in a half second or more depending upon the moment of inertia of the load. Thus the acceleration in the case of a 1060-r.p.m. speed would be much greater than one revolution per second per second.

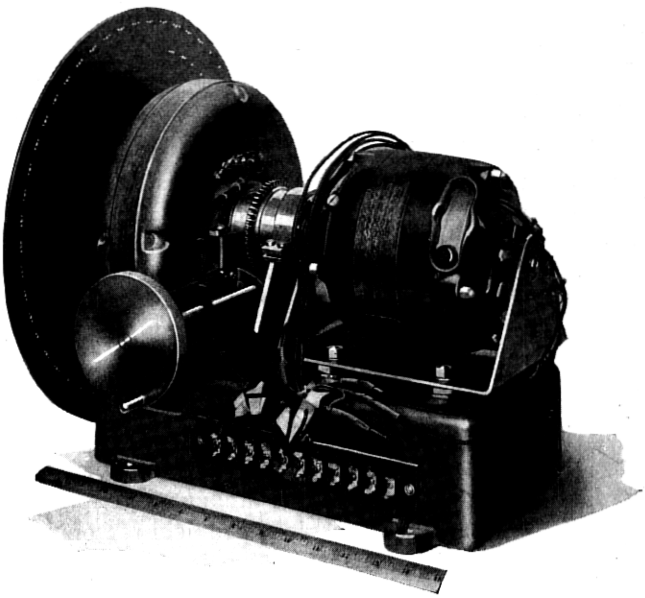

Fig. 1—Assembled motor

Since this problem of speed regulation is a separate one from that of the synchronization, the description of the regulating circuit is taken up later on.

Motor Design

In accordance with the phase displacement requirement as explained previously it was decided to build the synchronous motors with 120 pairs of poles, thus giving a frequency of 2125 cycles at 1062.5 r.p.m. which was the exact speed finally employed. For the sake of mechanical simplicity these machines were made of the variable reluctance type which gives one cycle per rotor tooth, thus requiring 120 teeth. The variable reluctance construction also simplifies the coil arrangement, the machine having only eight armature coils instead of a separate coil for each tooth. Fig. 1 shows a photograph of the assembled motor and Fig. 2 an inside view of the stator and rotor.

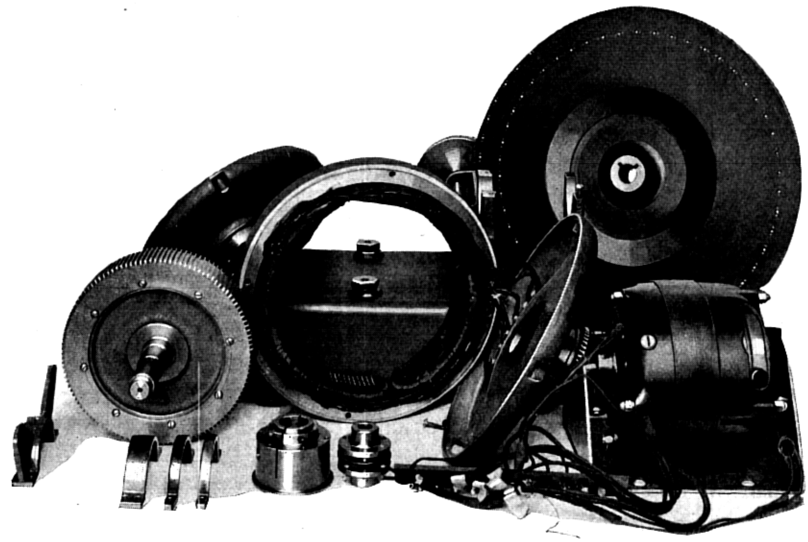

Fig. 2—Motor disassembled

In the preliminary experimental work two of these machines were directly connected (Fig. 3), permitting either machine to act as a

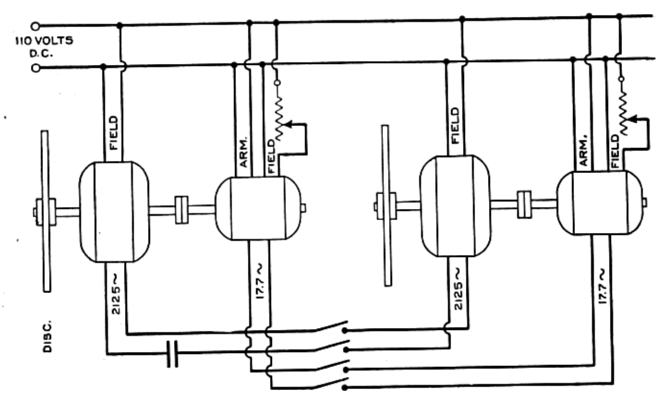

Fig. 3—Synchronization system over short wire line

synchronous motor loading down the other machine. Each machine was driven by a shunt d-c. motor having inherently poor regulation, the d-c. motors furnishing the power and the a-c. machines transferring the variations from one d-c. machine to the other to hold synchronism in a completely two-way system. As was to be expected, it was found that the motors hunted badly at a frequency of about four cycles per second. In other words, instead of holding within a fixed electrical phase angle of 20 degrees the receiving motor oscillated throughout a phase angle of about $\pm$ 20 electrical degrees. This, of course, made the picture wabble back and forth across the aperture and was therefore unsatisfactory.

The ordinary method of preventing hunting by means of copper bars embedded in the pole faces was not practical on account of the large number of poles and limited space. The hunting trouble was cured by employing a series condenser between the motors using a value of capacity somewhat less than that required to tune the circuit. A rigid analytical treatment of this anti-hunting circuit is beyond the scope of this paper but its operation depends in general upon the curvature of the tuning curve due to the variation of the inductance of the machine with phase displacement. Since the condenser operates on the total inductance of the circuit, it is desirable to make the natural periods of oscillation of the two motors different. Otherwise a decrease in the inductance of one machine may be accompanied by a simultaneous and equal increase in the inductance of the other, thus leaving the total inductance unchanged and preventing the condenser from functioning. This was done by making one disk substantially heavier than the other.

The series condenser also neutralizes the greater part of the internal reactance of the motors, thereby increasing the steady state torque.

Framing of Picture

There was still one unsatisfactory feature in this system in that the motor at the receiving end could interlock in any one of 120 different angular positions whereas in order to get proper framing of the picture it must be synchronized at a particular angular position. For example, if the disk at the receiving end is exactly 180 degrees out with respect to the disk at the transmitting end, the observer will see the lower half of the picture on top; a dark space representing the dividing line between pictures and the upper half of the picture at the bottom. Similarly, if the disk is 90 degrees out at the receiving end, the lower quarter of the picture will appear on the top and the upper three quarters of the picture on the bottom. The disk at the receiving end may be brought into correct angular position by providing means for turning the entire motor through the necessary angle. It was found, however, that the rate at which the motor can be turned was limited by the fact that if it were rapidly turned it would throw the motor out of step.

As an aid to framing, therefore, a second two-pole low frequency interlock was added to the system by providing the d-c. motors on each end with a pair of slip rings tapped to two opposite commutator bars. The d-c. shunt motors thus acted as converters furnishing 17.7 cycles at 1062.5 r.p.m. With this added feature on both the transmitting and receiving motors the process of synchronization was

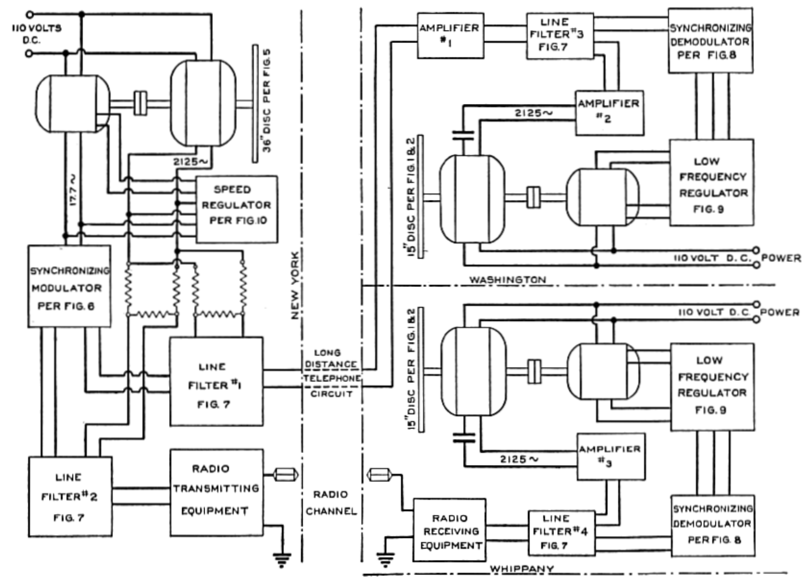

Fig. 4—Complete circuit of synchronizing system

first to close the 17.7-cycle circuit and adjust the field rheostat of the receiving motor until it came into step. Since this was a two-pole circuit there was only one angular position at which synchronization could occur. The high frequency synchronous machines were then connected together, thereby limiting the phase displacement to within .07 degree, as previously described. The high frequency motors in this system take the variation in load while the low frequency motor takes care of the steady constant component of load. Incidentally the addition of the low frequency synchronous motors greatly facilitated the synchronization of the high frequency motors inasmuch as it insured the proper initial speed. When the high frequency switch was closed there was merely a slight shift in phase angle to bring the receiving motor into step. The schematic circuit of the system thus far described is shown in Fig. 3.

Synchronization Over Long Lines

The above description explains the action of the synchronization system over lines of negligible impedance. In order, however, to secure similar results over a long distance telephone line or radio channel it is necessary to first attenuate the high and low frequencies to a power which can be safely applied to the transmitting end of the line and then amplify the power at the receiving end to restore it to the proper level. Fig. 4 shows the complete system employed.

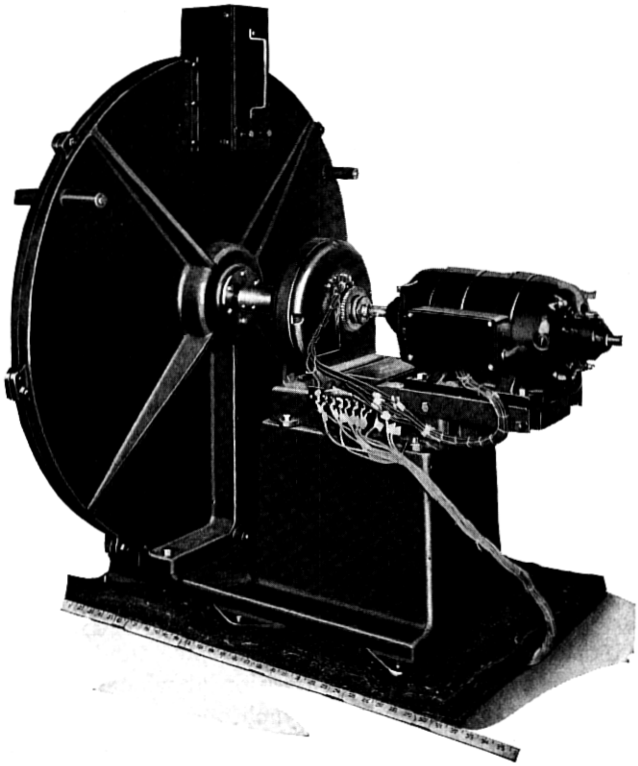

Fig. 5—Large scanning disc motor

While the high and low frequency machines on the transmitting end could have been designed so as to produce exactly the right power level, it was desirable, for the sake of interchangeability, to build the transmitting and receiving motor equipment of the same size. The output from the transmitting high frequency generator (shown in Fig. 2) when untuned was approximately 17 volts at 2125 cycles.

By means of a network this output was cut down to a level of 1 milliampere into 600 ohms impedance, the output impedance also being 600 ohms. This is a satisfactory level at which to transmit the high frequency, without inducing noise in adjacent wires in the telephone cables.

In the case of the low frequency interlock it was undesirable to attempt to transmit 17.7 cycles over a long distance line. The 17.7 cycles was therefore used to operate a polarized relay, the contacts of which modulated the output of a 760-cycle electro-mechanical oscillator[2] as shown in Fig. 6. In other words, the relay short-circuited

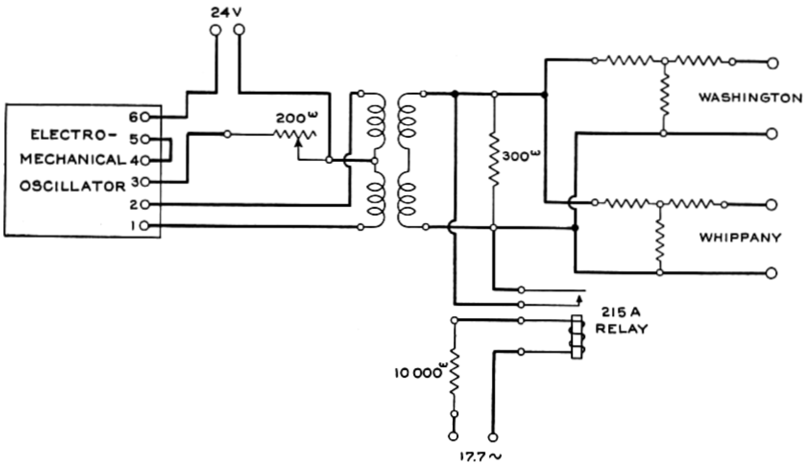

Fig. 6—Synchronizing modulator

the output of the oscillator alternate half cycles before application to the telephone line. Instead of using separate telephone pairs for the 2125-cycle and the modulated 760-cycle current, the two were combined by passing them through the line filter (shown in Fig. 7), thereby requiring only one pair for transmission of both frequencies. An identical network was employed for the radio channel. The problem of transmission of the synchronizing current is covered in the paper by Messrs. Gannett and Green and in the case of radio transmission in the paper by Mr. Nelson.

Receiving and Amplifying Circuits

Passing over this part of the problem, therefore, assume that the synchronizing currents have been obtained at the receiving end of the line. This power was delivered at a very low level, being about

[2] Described in the Bell Laboratories *Record*, March, 1927.

.3 of a milliampere into 600 ohms impedance, or 50 microwatts. It was then given a preliminary stage of amplification (amplifier No. 1, Fig. 4), passed through the line filter No. 3 (Fig. 7) and separated into 2125 cycles and 760 cycles modulated at 17.7 cycles. The 2125-cycle component was then amplified by two stages of amplification (amplifier No. 2) ending in push-pull 50-watt tubes and applied to

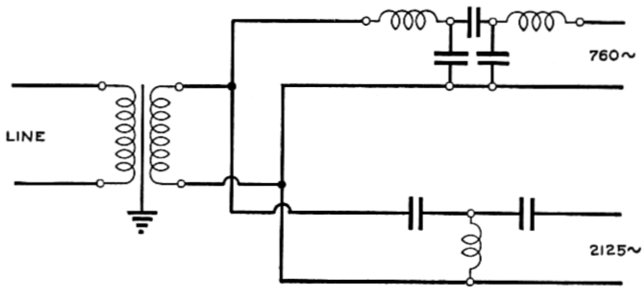

Fig. 7—Line filters for synchronizing frequencies

the high frequency motor. These amplifiers being of the standard type are not described. The terminal voltage on the output coil of the amplifier was made greater than that of the high frequency motor so that the power flow was normally from the amplifier to the motor.

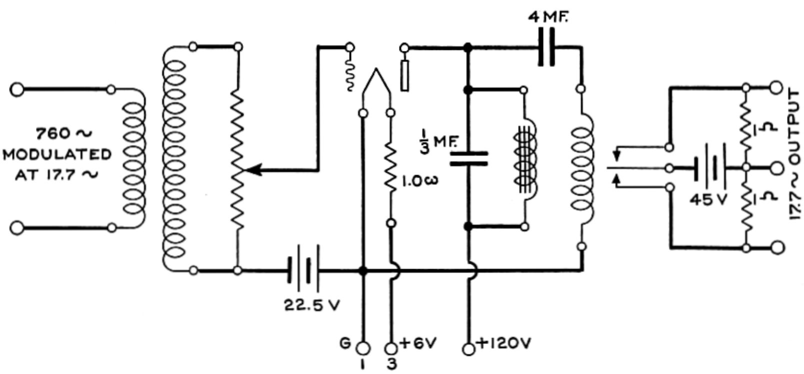

Fig. 8—Synchronizing demodulator

The anti-hunting condenser was retained between the amplifier and the motor.

In the case of the low frequency circuit the output from line filter No. 3 was received in the form of 760 cycles modulated at 17.7 cycles. This was passed through the demodulator (Fig. 8) which operated a polarized relay whose armature opened and closed its contacts at 17.7 cycles per second. The contacts of the relay provided square-wave low frequency current by interrupting power from a local battery source. On account of the limited power output which the vibrating contacts could safely handle without sparking, it became necessary to amplify this low frequency output. While this would have been possible by the use of ordinary amplifier circuits, it was found preferable from the standpoint of economy of apparatus to apply the low frequency regulation through a field circuit of the receiving motor. Referring to Fig. 9 it will be noted that the plate circuit of the reg-

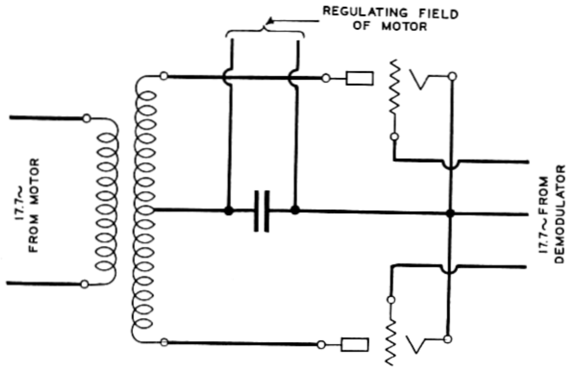

Fig. 9—Low frequency regulator

ulating tubes is supplied from the secondary of the transformer which is connected to the slip rings of the motor, while the grid circuit of these tubes is supplied with low frequency, low power 17.7 cycles from the contacts of the relay. As the motor is started up from rest the shunt field is weakened until the motor falls in step. At this point the frequency of the plate supply to the regulator tubes is identical with that supplied to the grids. If the phase relationship is such that the plates go positive at the same time that the grids are positive, then the space current of the tubes is increased and the regulating field (which is an aiding auxiliary field) is strengthened, thereby preventing a further rise in the speed of the motor. In other words, for each combination of load and line voltage there is an equilibrium phase position between the plate and grid voltages at which the corresponding regulating field current maintains the speed at the desired value.

Motor Operation

In actual operation the procedure was to first synchronize on the low frequency, and then on the high frequency circuit. The precise framing of the picture was then adjusted by rotating the motor by means of worm gearing through the necessary angle to center the image properly in the aperture. The high frequency current was of the order of 1.5 amperes at 2125 cycles with a terminal voltage of

100 volts at the high frequency motor. The power taken by the d-c. motor was approximately .8 ampere at 110 volts. The current through the regulating field controlled by the 17.7-cycle circuit was of the order of 20 to 40 milliamperes at 100 volts depending upon the phase position at which interlock occurred. It was found preferable to cut off the low frequency interlock feature after synchronization and framing had been obtained in order that irregularities in the time of contact closure of the relay might not produce changes in field strength of the d-c. motor which in turn would cause irregularities in power output. Such irregularities would give rise to phase shifts in the high frequency machine, thereby producing unsteadiness of the picture.

Operation on Radio Channel

In the case of transmission of the synchronizing current by radio instead of by wire the same apparatus is employed except that it was found necessary to use a much higher value of high frequency current in order to hold the high frequency motor in step, the current being approximately 4 amperes as compared to 1.5 amperes in the case of the other motors. This greater current was found to be necessary in order to hold the motor in step within the necessary phase angle of displacement, in spite of various types of interference picked up by the radio receiver, and associated circuits. This was mainly inductive interference from the picture and speech transmission sets arising from the fact that the synchronizing current was transmitted from New York to Whippany and picked up on a receiving set there, whereas the picture and voice current was transmitted from Whippany to New York. A certain amount of interference was also encountered from ship spark sets and static.

Speed Regulation of Transmitting Motor-Generator

As previously explained under "General Requirements" the essential requirement of the speed regulator at the transmitting end is to limit the acceleration to about one revolution per second per second, over intervals as small as .01 second. The ordinary type of centrifugally operated vibrating contact regulator keeps the motor continually accelerating and decelerating between an upper and lower speed limit and while such a system could theoretically be employed if the flywheel were made large enough, it was obviously preferable to employ a type of regulator in which the speed was inherently held constant without such acceleration and deceleration.

The regulating circuit employed is shown in Fig. 10. The complete theory of this regulating circuit is to be covered in another paper to be presented before the Institute. Briefly, the principle consists in employing a sharply tuned circuit as the primary speed-controlling element resonating at a frequency slightly less than the frequency at which the machine is operated. A voltage from the high frequency generator is applied to this tuned circuit and thence to a detector tube which in turn operates on the grids of a pair of push-pull regulator tubes; these tubes controlling an auxiliary regulating field winding on the motor. The circuit also contains anti-hunting means, the

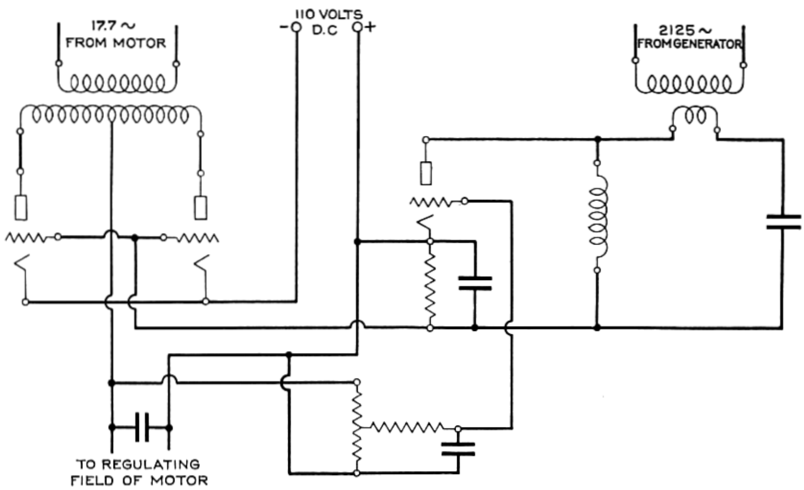

Fig. 10—Speed regulator

theory of which will be given in the later paper. Instead of applying this regulating circuit to the small 15-in. scanning disk motor shown in Fig. 3, it was decided on account of its greater flywheel effect to use the large 36-in. disk shown in Fig. 5 which was used for receiving the picture at New York. It therefore became the transmitter from the synchronizing standpoint for all of the other units although from the picture standpoint the big disk acted as a receiver.

Local Stations

In addition to the stations at Washington and Whippany there were three local stations in New York employing similar high and low frequency synchronous motors with 15-in. disks. These were controlled in the same manner except that first stage of amplification and the line filters were omitted. One station was employed for monitoring purposes, another operated a local transmitter, while the third operated the big grid receiver seen by the entire audience.