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Carrier in Cable *

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In order to meet future demands for high-grade and economical circuits in cables, considerable carrier development work has been done which has included an extensive experimental installation on a 25-mile loop of underground cable. Sufficient pairs were provided in the cable and repeaters were installed to set up nine carrier telephone circuits 850 miles long. Tests on these circuits showed the quality of transmission to be satisfactory, while the methods and devices adopted to prevent interference between them were found to be adequate. The trial has, therefore, demonstrated that the obtaining of large numbers of carrier telephone circuits from cable is a practicable proposition.

This paper is largely devoted to a description of the trial installation and an account of the experimental work which has been done in this connection. Due to present business conditions, it is expected that this method will not have immediate commercial application.

This work is part of a general investigation of transmission systems which are characterized by the fact that each electrical path transmits a broad band of frequencies. Such systems offer important possibilities of economy particularly for routes carrying heavy traffic. The conducting circuit is non-loaded so that the velocity of transmission is much higher than present voice-frequency loaded cable circuits. This is particularly important for very long circuits where transmission delays tend to introduce serious difficulties.

A TRIAL installation was recently made in which, for the first time, carrier methods were applied to wires contained wholly in overland cable for the purpose of deriving a number of telephone circuits from each pair of wires. The trial centered at Morristown, New Jersey. A 25-mile length of underground cable was installed in the regular ducts on the New York-Chicago route in such a manner that both ends terminated in the Long Lines repeater station at Morristown. The cable contained 68 No. 16 A.W.G. (1.3 millimeter diameter) non-loaded pairs on which the carrier was applied. Sufficient repeaters and auxiliary equipment were provided at Morristown so that these 68 pairs could be connected together with repeaters at 25-mile intervals to form the equivalent of an 850-mile four-wire circuit.

From this 850-mile four-wire circuit nine carrier telephone circuits were derived, using frequencies between 4 and 40 kilocycles. The diagram of Fig. 1 shows the system simulated by the experimental setup.

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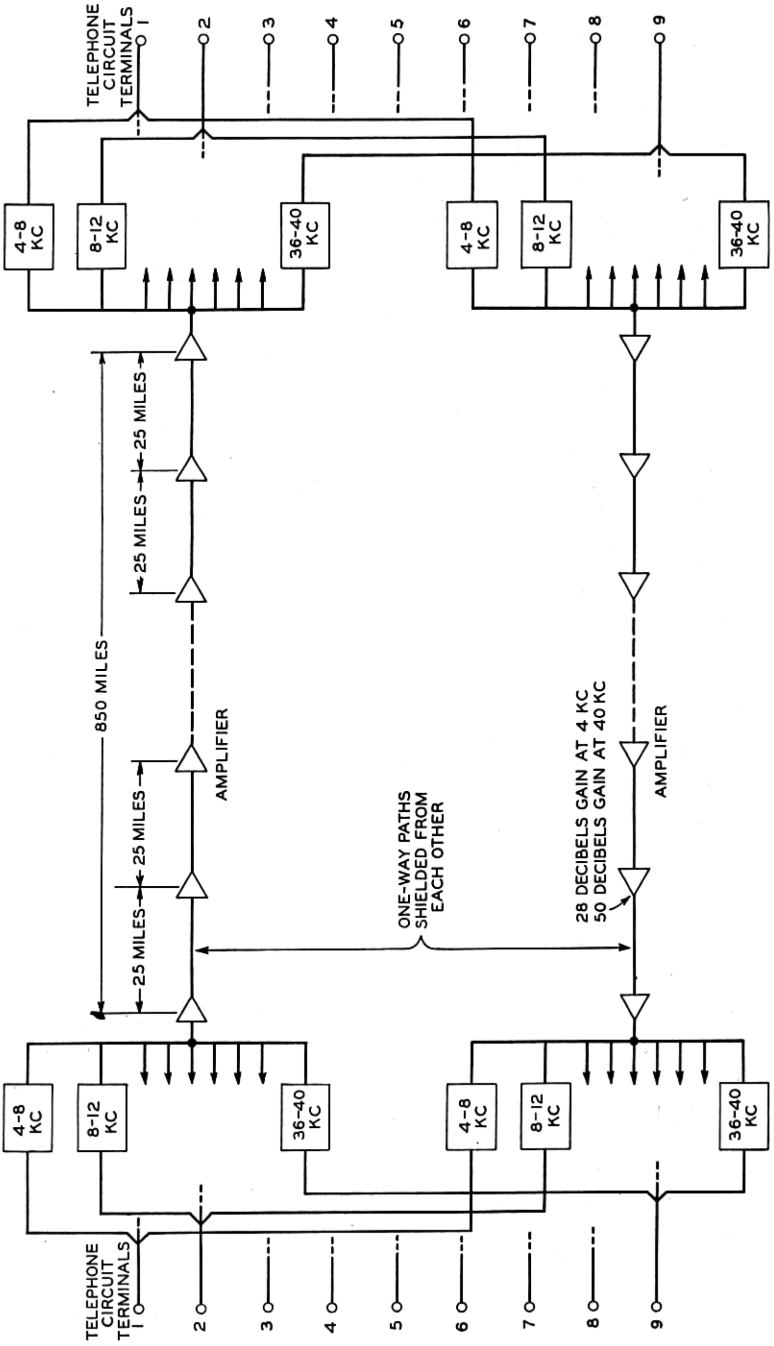

Fig. 1—Schematic of cable carrier system.

Note: In a practical installation the one-way paths would be shielded from each other either by placing them in separate cables or by placing them in a single cable divided into two electrical compartments by means of a specially arranged shield. In the setup at Morristown the circuit was necessarily arranged somewhat differently since only one cable was available. Transmission over all loops in this cable went in the same direction, half the loops then being connected in tandem to simulate one direction of transmission through a long circuit and the other half in tandem to simulate the other direction of transmission.

It will be noted that in this cable system the practical equivalent of two electrical paths was provided, one for transmission in each direction, the same range of frequencies being used in each direction. This differed from common open-wire practice in which the frequency range is split in two and used, one half for transmission in one direction, the other half for transmission in the other. Fig. 2 compares the frequency allocation of the Morristown cable carrier system with existing open-wire systems in this country. Except for this matter of difference in frequency allocation, the fundamental carrier methods used in this cable system did not differ in principle from those already used on open wires. As will be noted in Fig. 2 all of these carrier telephone systems use the single sideband method of transmission with the carrier suppressed.

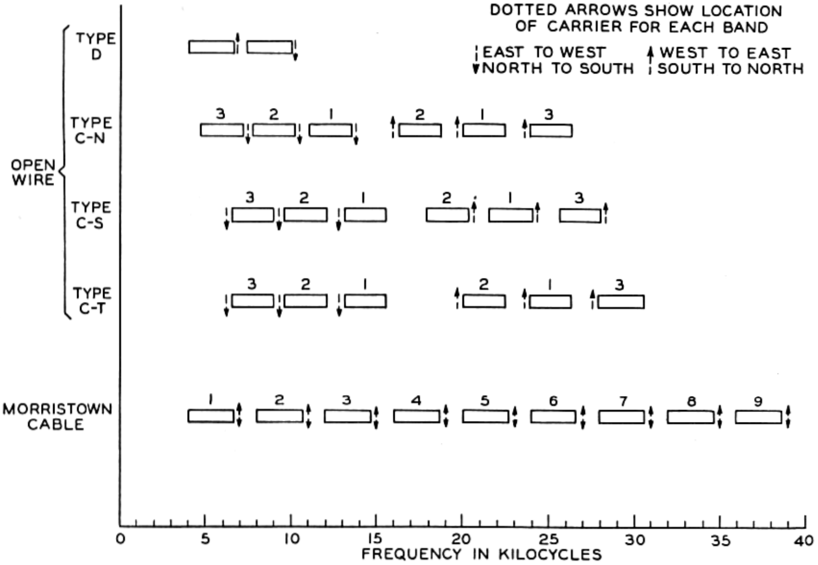

Fig. 2—Frequency allocations of carrier telephone systems.

Fig. 3 is a schematic diagram of the terminal apparatus used in deriving one of the telephone circuits. Its general resemblance to

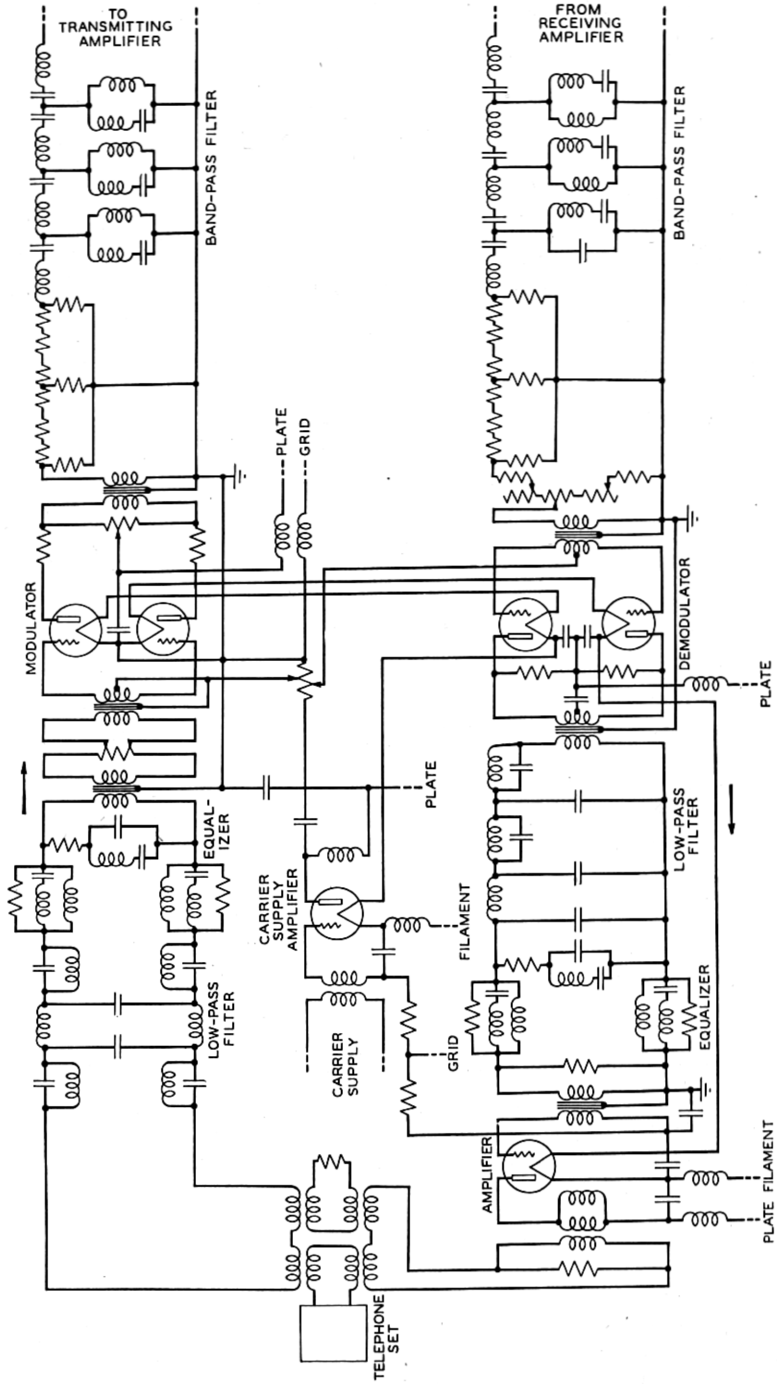

Fig. 3—Terminal of one telephone circuit.

the terminal apparatus used in present open-wire systems is evident so no further discussion of this seems required. Fig. 4 shows five relay rack bays carrying terminal equipment (exclusive of line amplifiers) for one system terminal yielding nine telephone circuits.

Important problems in cable carrier transmission are:

1. Keeping circuits electrically separated from each other, i.e., preventing troublesome crosstalk.
2. Maintaining stability of transmission.

CROSSTALK

With respect to crosstalk, the first and most important requirement is to secure a very high degree of electrical separation between paths transmitting in opposite directions. Careful crosstalk tests demonstrated that by placing east-going circuits in one cable and west-going circuits in another, the necessary degree of separation could be obtained even though the two cables were carried in adjacent ducts. Tests on short cable lengths indicate that adequate separation can probably be secured by means of a properly designed shield; one practical form of such a shield consists of alternate layers of copper and iron tapes. With such a shield a cable may be divided into two compartments and thus carry both directions of transmission.

Having thus separated opposite bound transmissions there is left the problem of keeping the crosstalk between same direction transmissions within proper bounds. In the cable used for the Morristown trial the 16 A.W.G. pairs used for the carrier were separated from each other by sandwiching them in between No. 19 A.W.G. (.9 millimeter diameter) quads of the usual construction. These quads served as partial shields between the carrier circuits and would in a commercial installation have been suitable for regular voice-frequency use. Thus a considerable reduction in the crosstalk between the carrier pairs was effected.

When the problem of keeping crosstalk between circuits transmitting in the same direction within proper bounds is examined it becomes evident that no matter how high the line amplifier gains may be, these gains do not augment this crosstalk since if all of the circuits are alike transmission remains at the same level on all circuits. Not so evident perhaps is another fact that crosstalk currents due to unbalances at different points tend to arrive at the distant end of the disturbed circuit at the same time. This makes it possible to neutralize a good part of the crosstalk over a wide range of frequency by introducing compensating unbalances at only a comparatively few points.

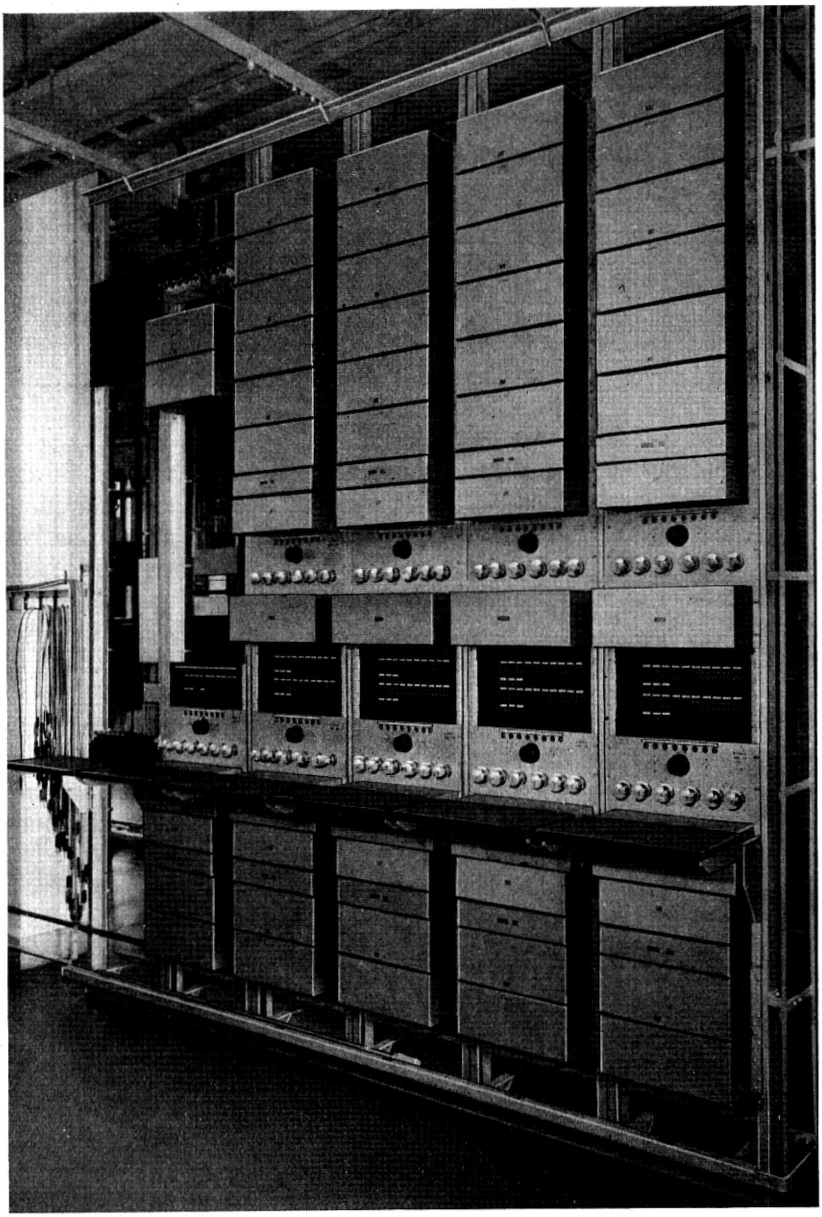

Fig. 4—Terminal equipment for 9 telephone circuits.

In practice, balancing at only one point in a repeater section (which may be an intermediate point or either extremity) serves to make possible considerable reduction of the crosstalk. In the Morristown setup balancing arrangements were applied at an intermediate point in the cable and found to be entirely adequate for the frequency range involved; in fact, transmission of considerably higher frequencies would have been possible without undue crosstalk. Other tests have indicated that, thanks to these balancing means, the 19-gauge quads used in the Morristown cable for separating the 16-gauge pairs from each other can probably be dispensed with, even for frequencies considerably above those used in the trial.

The photograph of Fig. 5 shows the experimental panel on which the circuits were brought together for balancing. This panel was installed in a weather-proof hut near the center of the 25-mile repeater section. By this means all pair to pair combinations in the group to be balanced were brought into proximity so that the leads to the balancing devices could be kept short. The actual balancing was

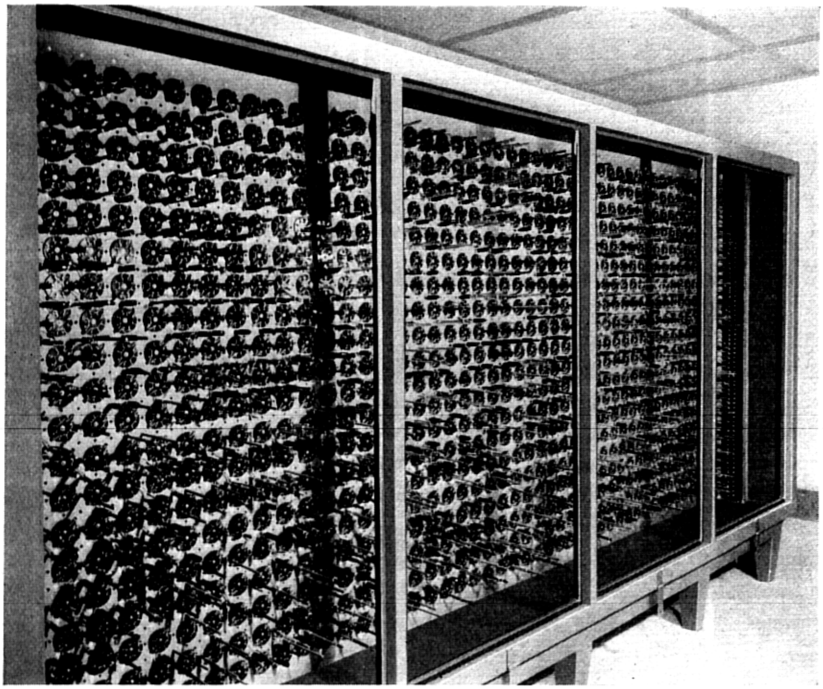

Fig. 5—Special crosstalk balancing panel.

accomplished by connecting small condensers made up of twisted pairs, between wires of different cable circuits and/or by coupling wires of different circuits together through small air-core transformers. Each unit was individually adjusted after measurement of the cross-talk between the various combinations.

MAINTAINING STABILITY OF TRANSMISSION

Referring to the problem of stability, the importance of this will be appreciated from the fact that the average attenuation at the carrier frequencies employed in the 850-mile circuit as set up at Morristown was about 1300 db. A circuit was actually set up and tested consisting of nine of the carrier links in tandem, giving 7650 miles of two-way telephone circuit whose total attenuation without amplifiers was about 12,000 db. This attenuation, on an energy basis, amounts to 10^{1200}. This ratio, representing the amplification necessary, quite transcends ratios such as the size of the total universe to the size of the smallest known particle of matter.

Balancing this huge amplification against the correspondingly huge loss, to the required precision, one or two db, is a difficult problem. Fortunately, a new form of amplifier employing the principle of negative feedback has been invented by Mr. H. S. Black of the Bell Telephone Laboratories and may be described later in an Institute paper. By making use of this negative feedback principle, amplifiers were produced for this job giving an amplification of 50–60 db and this amplification did not change more than .01 db with normal battery and tube variations. This is ample stability even when it is considered that, with amplifiers spaced 25 miles apart, there would be 160 of these in tandem on a circuit 4000 miles long.

As is well known, the losses introduced by cable circuits do not remain constant even though the circuits are kept dry by means of the airtight lead cable sheaths. Variation in temperature is principally responsible for the variation in efficiency of the circuits. The change in temperature, of course, alters the resistance of the wires and to a lesser extent changes the other primary constants, particularly the dielectric conductance. Fig. 6 shows the transmission loss plotted against frequency of a 25-mile length of 16-gauge cable pair at average temperature (taken as 55° F.) and also the effect of changing this temperature ± 18° F. which is about the variation experienced in underground cable in this section of the country. For a circuit 1000 miles long the yearly variation amounts to about 100 db.

The transmission loss at any frequency is a simple function of the d-c. resistance. Consequently, measurement of the d-c. resistance of a pilot wire circuit exposed to the same temperature variations can be used to control gains and equalizer adjustments to overcome the effect of this temperature variation. Fig. 7 shows a schematic diagram of the pilot wire transmission regulation system used in the Morristown experiments, while the photograph of Fig. 8 indicates the appearance of the apparatus. This pilot wire regulation system takes care of a 25-mile length of cable. The arrangement of the regulating networks is such that variation of a single resistance causes the transmission loss to be varied a different amount at different frequencies as required by the variation in the line loss shown in Fig. 6 above. In Fig. 7 the relay system is omitted for the sake of simplicity. The function of the relay system is, of course, to control the rotation of the shaft carrying the variable resistances so that it follows the rotation of the shaft associated with the master mechanism. The centering cam is provided to avoid "hunting."

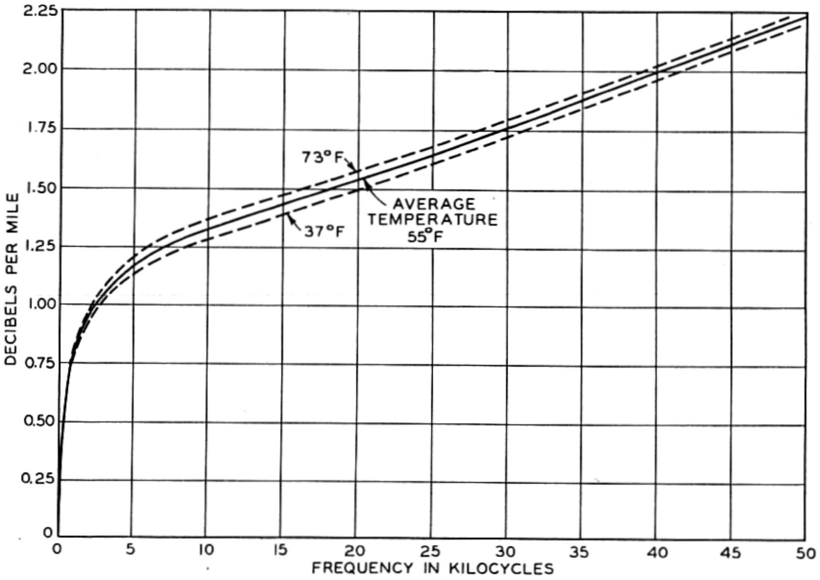

Fig. 6—Transmission loss of 16-gauge cable pair.

The Morristown experiments have shown that this form of regulation is adequate when underground cables are employed. Similar regulation of aerial cables in which the transmission variation with time is three times as large and several hundred times as rapid presents greater but not insuperable difficulties.

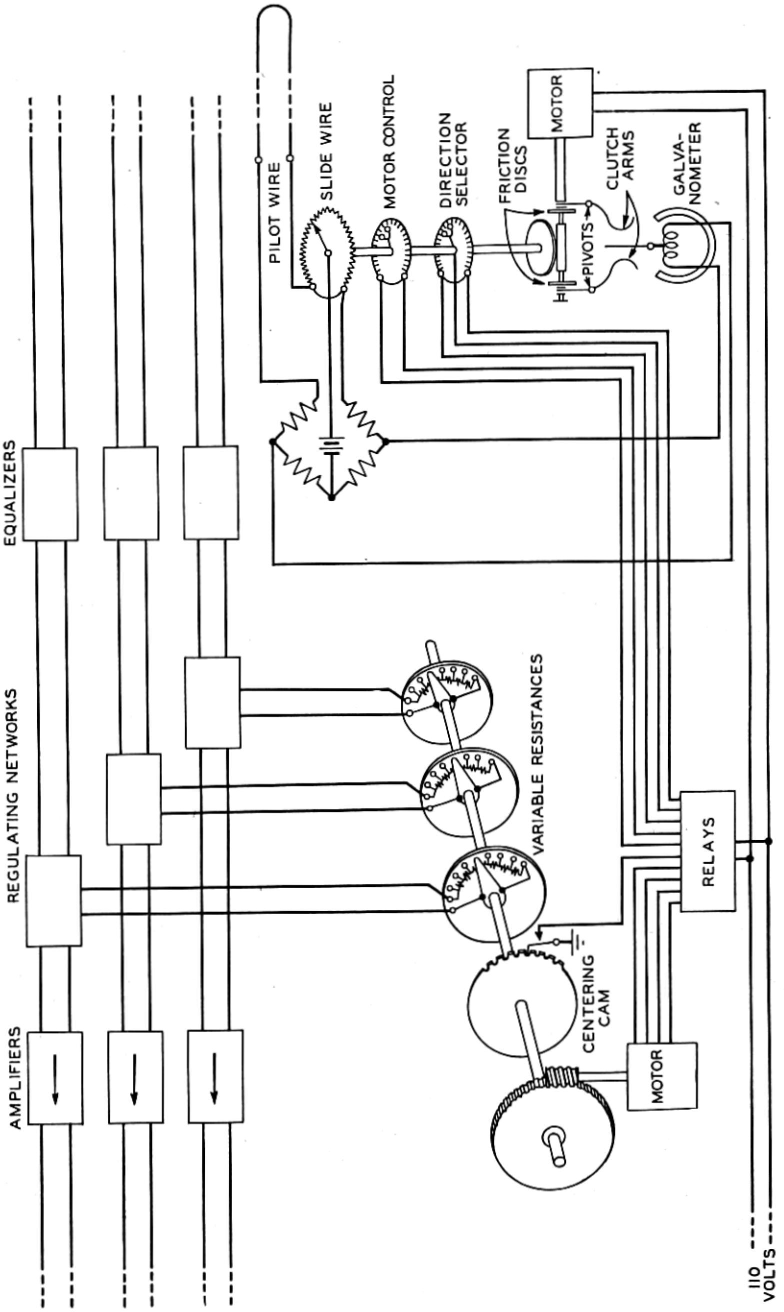

Fig. 7—Automatic transmission regulating system.

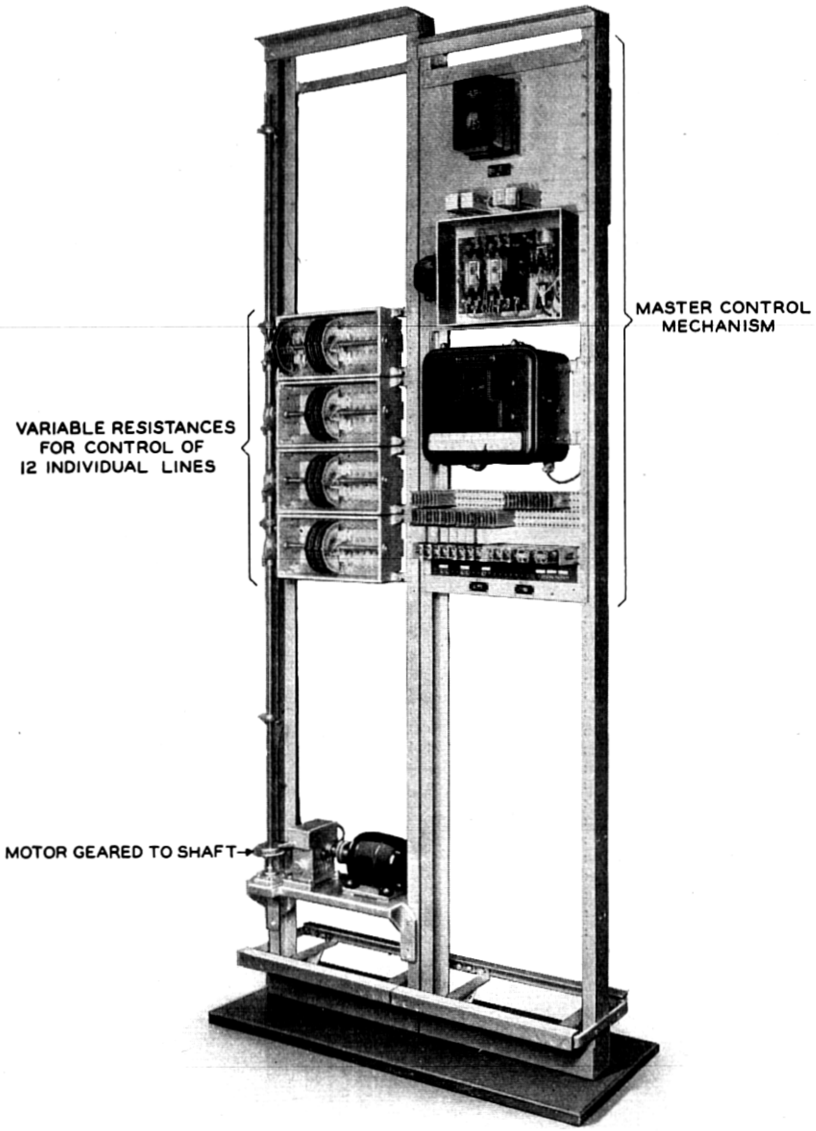

Fig. 8—Automatic transmission regulating equipment—covers removed.

Obtaining High Amplifications

The attenuation of cable pairs being inherently high at carrier frequencies, high amplifier gains are called for, otherwise the cost of the carrier circuits goes up very materially. Since as the power carrying capacity of the repeaters is increased a point is soon reached where it becomes very expensive to go further, high amplifications must be secured by letting the transmitted currents become very weak before amplifying them. A natural limit to this is found in the so-called thermal or resistance noise[1] generated by all conductors. Similar natural and largely insuperable noises are introduced by the vacuum tubes in the amplifiers. Other sources of noise are:

1. Telegraph and signaling circuits worked on other pairs in the same cable with the carrier circuits.
2. Radio stations.
3. Noise from power systems, particularly electric railways.

The latter two disturbances originate outside the cable so that they are subject to the shielding effect of the lead sheath which increases rapidly with increasing frequency. Generally speaking, in a new cable both of these and also the noises from other circuits in the same cable may be relegated by location and design to comparatively minor importance. On existing cables, however, they may require special treatment. In all cases, however, the lower levels at the upper frequencies, which largely determine the repeater spacings, are established primarily by the thermal noise in the conductors and by the corresponding noises in the vacuum tubes. In the Morristown installation the amplifications were kept small enough and the levels high enough so that noise was not an important factor.

Experimental Results

A large number and wide variety of tests have been made using the setup at Morristown. These were generally of too technical a character to be of interest in a general paper such as this one. It will be of chief interest to note that no serious difficulty was experienced in setting up the 850-mile four-wire 4 to 40-kc. circuit with the necessary constancy of transmission loss at different frequencies, although the equalizer arrangements which made this possible presented intricate and difficult problems of design. Nine separate carrier telephone con-

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[1] "Thermal Agitation of Electricity in Conductors," by J. B. Johnson, *Phys. Rev.*, Vol. 32, p. 97, 1928, and "Thermal Agitation of Electric Charge in Conductors," by H. Nyquist, *Phys. Rev.*, Vol. 32, p. 110, 1928.

versations were transmitted over this broad band circuit without difficulty due to cross-modulation.

Each carrier telephone circuit was designed to yield a frequency band at least 2500 cycles wide, extending from about 250 cycles to somewhat above 2750 cycles when five such carrier links are connected in tandem. This liberal frequency band and the very satisfactory linearity of transmission over the entire system, gave a very excellent quality of transmission. In order to exaggerate any quality impairment which might have been present the nine carrier circuits were, as noted previously, connected for test in tandem giving a total length of about 7650 miles of two-way telephone circuit. The quality of transmission over this circuit was also found very satisfactory. In fact, the quality was not greatly impaired even when twice this length of one-way circuit was established by connecting all the lengths in tandem, giving a 15,300-mile circuit whose overall loss without amplifiers was about 24,000 db.

As noted previously, the fact that the cable pairs are left non-loaded gives the cable carrier circuits the advantage of very high transmission velocity. Including the effect of the apparatus this velocity is approximately 100,000 miles per second—five or six times as great as the highest velocity loaded voice-frequency toll cable circuits now employed in the U.S.A. This velocity is ample for telephoning satisfactorily over any distances possible on this earth.

Conclusion

Under the present economic conditions there is no immediate demand for the installation of systems of this type. Consequently development work is being pursued further before preparing a system for commercial use. The final embodiment or embodiments of the cable carrier system will probably differ widely, therefore, from the system described in this paper. Since the transmission performance of the experimental system was so completely satisfactory, emphasis is now being directed toward producing more economical systems which will be applicable to shorter circuits. Preliminary indications from this work are that some form of cable carrier system will ultimately find important application on circuits measured in tens rather than hundreds of miles.