DISCUSSION ON "COMMERCIAL LOADING OF TELEPHONE CIRCUITS IN THE BELL SYSTEM." CHICAGO, JUNE 28, 1911

E. H. Bangs: One of the most valuable features of Mr. Gherardi's paper is its frank admissions in regard to the practical limitations of circuit loading. In the past there have been some extravagant claims made for the possibilities of this practice, and this paper, in its description of the actual results obtained in the best practice is most welcome.

Mr. Gherardi answers, in a way, a question that has been put to me on several occasions by engineers experienced in power transmission as to why it was that the telephone engineers did not long ago take advantage of the common knowledge of the power transmission engineers, on the subject of added inductance. In asking this question the power engineers say, in effect, "We gave you the idea. All that you had to do was to work out the details." This statement contains its own answer, an answer which is illustrated by Mr. Gherardi's paper. As a matter of fact, it has taken from 10 to 15 years of very earnest effort on the part of a number of people to simply "work out the details." Telephone transmission is only power transmission in its most minute form, and of course the same laws apply to both methods of conveying energy. The difficulties encountered have not been found so much in applying known laws, as in perfecting practical details, and the ingenuity displayed in simply that portion of the problem relating to the loading of phantom circuits and the phantoming of loaded circuits is of a high order. I think that the development of this whole problem has proceeded with dispatch, along logical lines, and abreast of, or well in advance of the economical demand for its solution.

F. B. Jewett: While there is not much that I can add to what Mr. Gherardi has said on the subject of commercial loading of telephone circuits in the plant of the Bell system, there are one or two points which I think may be of interest to those who are not familiar with loading. One of these is with regard to the mathematical development which forms the foundation upon which our present loading practice has been built. All of our experience has tended to confirm this mathematical theory and so far as I am aware it is entirely rigorous. Although the first results on actual loaded circuits seemed not to agree with theoretical expectation, we soon learned that discrepancies which existed resulted from a lack of reliable data as to line constants at high frequencies and not to any imperfection in the mathematical theory of loading. With increasing knowledge as to the high frequency constants of different classes of circuits, the discrepancies between the computed results and the results of actual transmission tests are each day becoming less, and the theoretical forecasts more amply verified.

Mr. Gherardi shows that the general equation for the attenuation constant, which involves the four factors, series resistance,

series inductance, shunt capacity and shunt conductance or leakage can be greatly simplified by the elimination of the last of these constants. In the early stages of our work it was assumed that on both cable circuits and open wire lines having high insulation, this could be done. Later work showed us, however, that the direct current insulation was not necessarily a criterion for the high frequency shunt conductance even in the case of open wire circuits where dissipation of energy in the dielectric would, at first sight, seem to be almost negligible.

High frequency measurements during the last few years on both open wires and cable circuits have given us values of the shunt conductance which, when substituted in the general formula, tend to bring the computed and measured attenuation constants into close agreement. I have every reason to believe, therefore, that when we are able to determine the four line constants at high frequencies with the accuracy with which we can now determine direct current resistance, capacity and insulation, we will find that the formulæ used in our computation work are rigorously in accord with the results of actual observations on loaded lines.

The other point which I wish to mention briefly has to do with the enormous change which the introduction of loaded circuits has brought about in the terminal apparatus and outside plant, both in the original installation and in the matter of maintenance. The deleterious effect of low line insulation is so much more pronounced on loaded circuits than on non-loaded circuits that the introduction of loading on a large scale has necessitated a very much higher grade of line maintenance than was ever found necessary in the case of non-loaded circuits even of large gauge. Also in the case of any extensive loading, especially on cable circuits, the necessity of placing a large number of loading coils in the plant has made it absolutely essential that the loading applied to the various circuits be such as to give a resultant plant of maximum simplicity. It was early seen that any general attempt to engineer the loading for each particular line so as to give maximum efficiency to this line would result in a plant that was unmaintainable on account of its complexity. The result has been that for both open wires and cables a system of standard loadings has been developed and the loading of any particular circuit is that standard which most nearly conforms to the theoretical best loading.

In the case of cable loading, especially on congested runs where a great number of circuits are to be loaded, it is very desirable that the loading coils for all circuits having a given type of loading be placed at the same points. This factor has reacted on the art of cable manufacture to the extent that all cable for loading is now manufactured to meet a standard capacity requirement irrespective of gauge or the number of conductors in the sheath—the standard capacity being that which will result in the lowest annual charge on the loaded circuits of given efficiency.

Also the fact that the sending end impedance of loaded lines is very much larger than for non-loaded lines and varies greatly with the type of loading, with resultant high and variable reflection losses, has meant that we cannot connect loaded lines together and to non-loaded lines in the indiscriminate fashion permissible with non-loaded circuits. We have, therefore, been forced to design our loading so that the circuits of various character, whether loaded or non-loaded, may be connected together or to the terminal apparatus with the minimum amount of reflection loss. Further the necessity for having maximum circuit flexibility in a large and growing plant has made it imperative that all loading be planned with the view to future growth and the necessity for avoiding special operating practices as much as possible.

Although a great step in advance has been made since the first introduction of loading on commercial circuits, there is still a large amount of development work to be done before we have succeeded in deriving all of the benefits possible from the use of inductance coils on telephone circuits.

E. H. Colpitts: I wish to call attention to one or two features connected with loading; that is, the necessary engineering studies and scientific investigation in connection with the application of loading are making telephony, from the standpoint of line transmission, an exact art.

Ten years ago when the rule for loading was first given us by Professor Pupin, the only method of determining whether a certain piece of apparatus introduced into the telephone line would cause a transmission loss or a transmission gain, was to actually make a transmission talking test over the circuit. When the art of loading was introduced it was recognized that much more refined methods of measuring the electrical constants of telephone apparatus and telephone lines under the electrical and magnetic conditions of telephone service must be developed. It was seen that actual telephone currents could not be employed, but that it would be necessary to employ alternating currents of telephonic frequencies and amplitudes. At that time no high frequency generators had been designed which would satisfactorily deliver the necessary high frequency currents. Therefore, one of the first problems the telephone engineer had to undertake was to design high frequency generators capable of delivering alternating currents at frequencies of from 200 to 3,000 periods per second. In order to employ this current in the methods which seemed most practical and desirable it was necessary that the open circuit electromotive force of these generators should be as nearly as possible free from harmonics. Such generators were designed.

Among the problems of a physical nature which confronted the telephone engineer it was necessary to devise methods of measuring accurately the losses in iron and its various alloys when subjected to magnetizing forces as small as 0.005 c.g.s.

units and when fluctuating corresponding to alternating currents at frequencies of from 200 to 3,000 periods per second. The telephone engineer today is able to measure such losses with a high degree of accuracy. The engineer had to devise methods of measuring losses in dielectrics at the telephonic frequencies which I have mentioned and at the low potentials which are involved in actual telephone transmission.

In addition to this, methods of measuring very accurately the inductance and effective resistance of loading coils were developed. The measurement of inductance accurately in terms of inductance standards is not at all difficult, but the measurement of effective resistance with a small current and at a high frequency requires most carefully designed apparatus and a complete knowledge of all the factors involved, many of which factors it would seem at first sight to the ordinary engineer could be neglected.

In connection with loaded lines themselves, as Dr. Jewett has already indicated, we soon found that we had to take account of facts which had hitherto been neglected. As an instance, it became evident that we had to measure accurately and consider the effect of bridged impedances on the efficiency of loaded circuits; whereas, in case of unloaded circuits the effects of such bridges could very generally be neglected. Also, in the design of cables which are to be loaded it is very important that electrical symmetry or balance be preserved, and the engineer is interested in capacities and differences of capacities as small as one-millionth of a microfarad in lengths of 400 or 500 ft. of cable. He can today measure and take account of these small differences in capacities between the wires of one pair and the adjacent pairs.

So far I have referred merely to measurements upon the elements used in loading. A large amount of work has been done in connection with the development of methods of making measurements upon telephone circuits, in order to determine the various terms involved in their transmission efficiency. I mention these merely as illustrations of the general nature of the development work necessary to the present condition of the loading art.

E. B. Craft: It may be of interest to note some features in the construction and design of the loading coils themselves. The art of constructing inductance coils is an old one. The use of inductance coils in loading, where we must deal with currents of very high frequency, however, involves a consideration of details and methods of reducing losses to a point which I doubt is reached in ordinary practice.

As an example we may consider a coil such as is being used in loading the new New York-Washington underground cable circuits. The core of this coil consists of a toroid built up of approximately 90,000 turns of No. 38 gauge iron wire. To reduce losses each of these turns must be insulated from the

other. This in itself was a problem of considerable magnitude and it eventually led to the development and use of an insulating enamel coating having a thickness of less than 0.0005 in.

In working out the design of the coil windings we also had to consider means for reducing losses, that led to departures from ordinarily used methods. In order that the copper losses might be reduced to a permissible figure, the conductor was subdivided, using a number of strands of enamel insulated wire, which, in turn, were insulated in the usual manner to provide a stranded copper conductor. The winding itself was then subdivided into sections to properly control capacity balances between adjacent sections of the windings.

In the construction of the coil such as we are using in the New York-Washington cable there is required a total length of $2\frac{1}{2}$ miles of copper wire wound around a core composed of 30 miles of iron wire. The mechanical problems involved in the application of these windings were quite difficult. Toroidal coils have been used in the past and were usually wound up by hand, involving a great deal of time and labor. In order that coils of this type might be turned out in large quantities on a commercial basis, it was necessary to develop special machinery by which these windings could be applied automatically. This has resulted in a considerable reduction in cost and increase in efficiency.

After the cores are prepared and the windings applied, it is necessary also to give consideration to the proper control of the losses in the dielectrics. This has led to the application of refined methods of manufacture in the way of vacuum drying and impregnation.

Consideration of the amount of material used in their construction will indicate that, when completed, these loading coils are of no mean proportions. As they are applied to the line or cable they are usually grouped in pots or cases similar to transformer cases, and the larger cases containing 21 coils weigh in the neighborhood of 2,000 lb. and because of size and weight are usually located in the manhole of the subway.

Various speakers have dwelt upon the necessity for adhering to accurate mathematical methods in calculating the electrical constants of the completed circuits, and the development of the design of the coils themselves has reached the stage where we can, by the application of proper methods of calculation, predict with certainty the various electrical characteristics of the completed coil. When we consider that these electrical characteristics involve not only the ohmic resistance and inductance of the coil, but such factors as capacity unbalance and alternating current conductance as well, it can be seen that it has been necessary to employ methods that have not heretofore been commonly used in the design and construction of inductance coils for various commercial uses.

Allard Smith: It might be of interest to get a brief idea of how we have applied loading in conjunction with the A. T. & T.

Co. engineers to a large telephone system like that in Chicago. We have developed a comprehensive loading plan for the entire city, and have advanced the work under that plan as rapidly as conditions would permit. Briefly, only 16 and 19 gauge cables in Chicago are loaded, although there is one cable which carries 14 gauge loaded conductors between Chicago and Milwaukee.

Radiating out from the Chicago Telephone Co's. toll building, in the center of Chicago, there are six loading paths, and these paths bring into the center of Chicago the trunk and toll lines from the outside and outlying exchanges. All of the work is underground. We have no aerial loading because the lines going out into the country are not long enough.

There are distributed around Chicago about 10,000 loading coils, which load about 19,000 pair miles of wire. These coils are incased in sealed iron pots and are placed in manholes, spaced one mile and three-quarters apart, except the coils on the Chicago Milwaukee cable, which are placed one mile and a quarter apart. These cables run out north as far as Waukegan, with 16 gauge conductors, and with 19 gauge conductors to Evanston—about 12 miles. Waukegan is about 25 miles.

Another cable runs south to Hammond, about 25 miles, with 16 gauge conductors and 19-gauge conductors as far as South Chicago, about 16 miles. Also one directly west, going to Maywood, with 16 gauge conductors; another southwest, along the C. B. & Q. R.R. to La Grange; another directly south to West Pullman. All of these cables bring the 19 gauge pairs from the outlying Chicago exchanges within a belt line, say, four to five miles out from the city, into the toll board. The 16 gauge conductors bring in the exchanges still further out called the "neighborhood exchanges" and the immediate suburban exchanges. Now we are just starting another loading path, which will be a belt line, continuing in a radius between exchanges about five miles from the center of the city.

J. G. Wray: I would supplement what Mr. Smith has said by stating that in Chicago if our trunk lines were not equipped with loading coils, it would be impossible to carry on commercial conversations between offices on opposite sides of the city. If loading coils were not available and there were no satisfactory substitute, it would be necessary to provide over-head open wire construction for trunk lines between such offices. Such construction would involve high pole lines with many cross arms, would congest the streets and alleys and make them unsightly and would add greatly to the cost of construction and maintenance and would provide a less satisfactory service than is provided at present. As a matter of fact, it would be physically practically impossible to provide pole lines enough to carry the open wire construction which would be necessary.

The problem of local telephone transmission in a big city like Chicago or New York would be exceedingly difficult if it were not for the loading coil. I believe that this fact is not generally

realized by engineers who have considered the advantages of the loading coil usually from the standpoint of long line transmission such as the New York-Denver circuit which Mr. Gherardi has just described.

The problem of telephone transmission in a big city, I think, however, has hardly received the attention that it deserves.

Frank F. Fowle: One of the very earliest practical tests of Dr. Pupin's system of inductance loading was made on a 670-mile circuit of No. 12 N. B. S. G. (173-lb.) open wire (hard drawn copper), in 1900. The coils then employed had an ohmic resistance of 9 ohms, an inductance of 0.225 henry and a shunt capacity of 0.0042 microfarad. These coils had no iron and were enclosed in wooden boxes, filled or impregnated with an insulating compound. They were spaced $2\frac{1}{2}$ miles apart. Comparative transmission tests conducted during clear dry weather showed that this loaded circuit was substantially equal to a non-loaded circuit of No. 8 B. W. G. (435 lb.) open copper wire.

The successful result of this trial gave immediate impetus to the development of better loading coils, with the result that the original type was abandoned in favor of the coil described by Mr. Gherardi. In coils of the type now used extreme precautions are necessary to keep the effective resistance at a minimum and not in excess of the resistance stated in the paper.

It is interesting to note that the toroidal coil finally developed is identical in its form with Faraday's original experimental transformer, which consisted of a simple iron ring with two windings, one on either half of the ring.

Quite extensive loading was soon undertaken on commercial circuits, but two prominent difficulties arose. The first was the effect of lightning, which necessitated the development of suitable protection. The second arose from low insulation. It was quite generally assumed at first that the leakage conductance, S , could be neglected, as Mr. Gherardi points out. But it developed that this was not the case. This fact was not clearly demonstrated until several thousand miles of line had been loaded and the commercial operation had shown clearly that during extremes of wet weather the insulation of open lines was inadequate. The reasons for this are clear both mathematically and physically.

This trouble affected the No. 8 circuits most, because they had lower resistance and impedance, non-loaded, than No. 12 circuits and were therefore more efficient initially. Being the more efficient circuit to start with, the gain due to loading was relatively less and the injurious effect of leakage was felt sooner.

Substantial improvements in line insulators did not follow for several years and then glass was abandoned in favor of glazed porcelain.

Experiments were also carried on in relation to the effect of different spacings, varying from two miles to eight miles. It was found that there was little or no gain by short spacing and heavy

loading, because the gain secured by increased inductance was practically nullified by the increased apparent resistance of the coils. This will be seen by comparing the apparent resistance of the coils with the resistance per mile of No. 8 conductors.

It was first pointed out by the writer that the proper location of coils with respect to cross-talk disturbances was every eight miles, at the junction of 8-mile transposition sections, or every S pole in Barrett's 1898 standard transposition system. This fact, taken in conjunction with the advantages of light loading in respect both to the effects of leakage, and the cost of installation, led to the adoption of the 8-mile spacing.

The increase in cross-talk as a result of loading is the direct consequence, in a large measure, of the increased transmission efficiency, which increases the volume of cross-talk as well as direct talk. At the same time the relative proportions of electrostatic and electromagnetic induction are disturbed and the former is increased. This necessitates increased attention to the electrical balance of loaded metallic circuits, both in open wires and cables. Barrett's earlier system of transposition, known as the A B C system, has certain untransposed exposures and in some cases will permit considerable cross-talk between non-loaded circuits, so that its use is not to be recommended. The standard system of 1898 contains no untransposed exposures, and in general is much superior to the early system.

The use of loaded circuits undoubtedly calls for a high standard of maintenance, and increases the maintenance expense in comparison with non-loaded circuits. While this slightly diminishes the net commercial gain secured by loading, it presents no particular difficulties and its consequences need not be feared.

There is a lower limit of line length which it pays to load, just as in the case of cables. Therefore loaded circuits cannot economically be cut up into short-haul lines, for use part of the time. Equally true, loaded circuits should not be connected to intermediate or way stations, both for the reason just given and further because bridged impedances are of harmful effect on loaded circuits in general.

Some difficulty was experienced with the coil shown in Fig. 1, of the paper, from magnetization caused apparently by telegraph currents when a loaded circuit was composited. Morse currents in either side of the coil magnetized it at once, of course, and in some cases set up a permanent flux which impaired the properties of the coil telephonically. The dividing current of the simplex system was much less harmful, tending only to pole the core at opposite ends of the diameter dividing the windings. The coil shown in Fig. 7 prevents any magnetization by the simplex, through its balanced arrangement of windings. There is probably some advantage in using a polar duplex on either side of the composite, because of the very frequent reversals in the direction of current.

Bancroft Gherardi: Professor Shepardson has asked a question concerning the connecting of loaded cable circuits with

open wire circuits. As I understand the question it refers to what special arrangements, if any, are needed when loaded cable circuits are to be connected to open wire lines. Is that the question, Professor Shepardson?

G. D. Shepardson: The question in my mind is whether you use the transformer or use the tapered loading to minimize the reflection.

Bancroft Gherardi: In general we do not do either. There are practical difficulties in the placing of terminal transformers at the outer end of underground cable circuits; there are also a large number of practical difficulties brought in by undertaking to taper off the loading of a circuit. One of the greatest of these difficulties in connection with tapering off the loading would be the extensive changes and re-arrangements which would become necessary from time to time as it became advisable to increase the length of the loaded cable involved, or otherwise change the layout of circuits. Suppose you had a cable that ran out five miles and later was going to be extended two miles more. In case the loading on this cable was tapered there would be a variation in the inductance of the loading, the spacing, or both. When, however, the cable was to be extended, substantial changes would have to be made in the loading coils and their arrangement. In general, we aim as far as possible, to load open wire circuits and cables so that the sending end impedance on the different classes of circuits will be the same, and so that the spacing of the loading coils on the two types of circuits are relatively the same electrically, that is to say, the relative spacings bear a definite relation to the relative electrical characteristics of the two circuits. If these conditions are attained there are no reflection losses where loaded underground cable circuits are connected with loaded open wire circuits. In practice these conditions are so nearly attained that the reflection losses in the case mentioned above are negligibly small.

The discussion of this paper has taken so much the form of a statement of additional facts in regard to loading and so little question has been raised in regard to any of the points brought out in the paper that I do not see that I can add anything in closing except to thank those who have participated in the discussion for bringing out many points of interest in connection with the subject which for the sake of keeping the paper down to a reasonable length were either omitted from the paper or only touched upon briefly.