A technical history of phantom circuits

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Abstract

Phantom circuits, otherwise known as superimposed or derived circuits,were extra circuits obtained on a multipair telephone or telegraph cable, or open-wire pole route, by using both wires of one ordinary two-wire circuit, effectively in parallel, as one conductor of a phantom circuit. The use of suitable transformers and connections, together with special arrangements for balancing wire-to-wire and/or wire-to-earth impedances, enabled the phantom circuits to work with negligible interference to and from the ordinary (or 'side', or 'physical') circuits. The economic attractions were obvious. Invented in 1882, phantom working became practical around 1900 and was employed very extensively on open lines in the USA, and on cables in Britain, Europe and the USA, and probably elsewhere, in the subsequent few decades. The historical and technical development of the subject is outlined in this paper.

1 Introduction

The term 'phantom', or better 'phantom circuit', was introduced just before the end of the nineteenth century to describe a class of line circuit obtained by superposition on other circuits as shown in Fig. 1. In effect, the two wires of one 'physical' circuit (later called 'side' circuits) were used in parallel to provide one conductor for the phantom circuit, and the two wires of another physical circuit to provide the other conductor. If the system were correctly balanced, there would be no interference between the side and phantom circuits. The name 'phantom', although picturesque and of obvious attraction (hence its dominance), was much less accurate than the earlier terms, 'superposed', 'superimposed' and 'derived' circuit, all of which correctly described the arrangement. Another name, never widely adopted, was 'plus' circuit. 'Superphantoms', or 'plus-plus' circuits, could also be formed as shown, and so on, in principle *ad infinitum.* The general principle of phantom working on telephone systems was often called 'duplex telephony' in the early days.

No satisfactory history of phantom circuits appears to have been published. The brief account by Rhodes[1] contains a number of errors and is very biased towards the American Telephone and Telegraph Company, on whose behalf it was written. Furthermore, source material for writing such a history appears to be very scanty, at least, as far as sources available in Britain are concerned. Very little was ever published on the subject, and few unpublished notes appear to have survived. The present history must necessarily, therefore, be very imperfect, but an attempt has been made to give a comprehensive, accurate and fair account of the technical aspects of what was, in its day, a most important subject. Business aspects, including commercial rivalries and monopolies in relation to vital components, such as phantom loading, are not dealt with at all. Economic aspects are touched on briefly in the next paragraph.

The importance of phantom circuits was, of course, due to the economy they offered in the cost of providing telephone circuits. In principle, they increased the traffic capacity of a given route by at least 50% at negligible extra cost. In economic terms, therefore, they represented one of the most important developments in telegraphy and telephony in the first few decades of the twentieth century, almost in the same class as inductance loading of lines. In April 1909, J.J. Carty, then Chief Engineer of the A.T. & T. Company, wrote[2] that the achievement of phantom working on loaded open lines would save around \$500 000 a year in construction costs, and that the achievement of a satisfactory cable for phantom working would save around \$180 000 a year; and this was for just one company, albeit a very large one. As the underground cable system expanded in the 1920s, the saving due to phantom working must have run to many millions of pounds in Britain, with corresponding savings in other countries of Europe and Asia, and much larger savings in the USA.

There were four main stages in the history of phantom circuits:

(*a*) invention, in the early 1880s
(*b*) practical application with the development of suitable transformers, around 1900
(*c*) application to loaded open lines, around 1910
(*d*) application to loaded cables, around 1910 also.

The paper deals with these in order, then with some miscellaneous applications of phantom working, and finally with the theoretical background of transmission on phantom circuits.

2 Invention of the phantom principle

The first disclosure of an idea for using two line wires, in use for their own circuits, as a paralleled twin conductor for another circuit, appears to be the patent[3] of the Canadians Black and Rosebrugh in 1879. Here, the wires are considered as telegraph lines

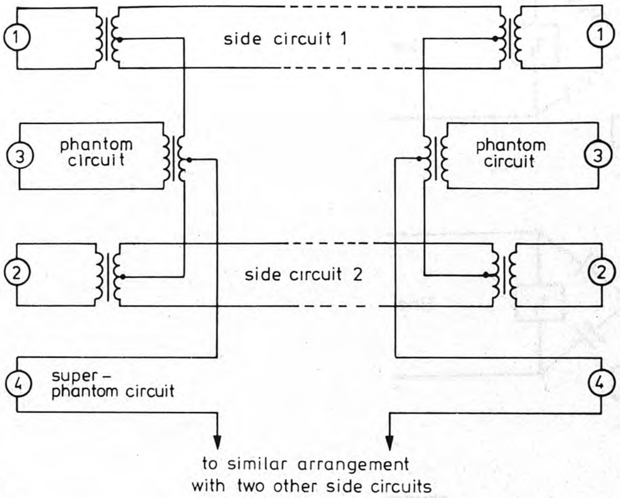

Fig. 1
Typical arrangement of phantom circuits

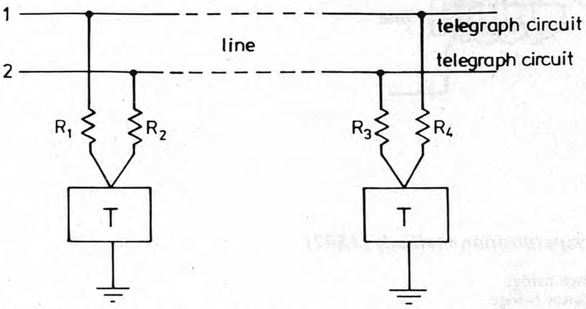

Fig. 2
One of Black and Rosebrugh's arrangements for earth-return telephone circuit (1879)

T = telephone set

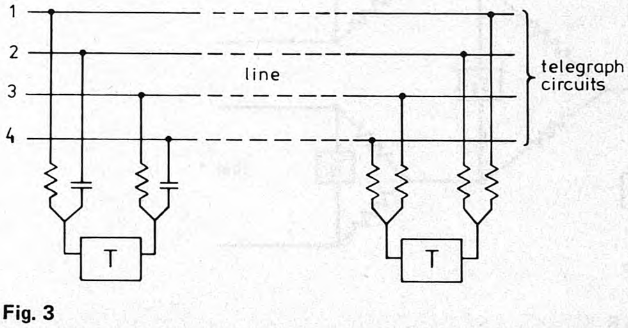

Fig. 3
One of Black and Rosebrugh's arrangements for metallic-loop telephone circuit

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which can be used simultaneously for telephony by means of the arrangements typified in Figs. 2 and 3. Because there is no concept of filtration, one must suppose that the use of two wires in parallel for the telephone circuit was itself supposed to reduce interference between the 'superposed' and 'side' circuits. The inventors, however, show no concept of the need for balancing in the superposition; it is never stated that R_1 and R_2 or R_3 and R_4 must be equal, and the peculiar use of resistance and capacitance in Fig. 3 seems to make it clear that balance was not even assumed. Moreover, the inventors distinguish the nature of the side circuits and superposed circuit as 'galvanic circuits' and 'induced-current circuit', respectively, perhaps indicating that they felt that signals were already of such different natures that mutual interference was not possible. Again, they did think that the arrangement would reduce extraneous induction into the telephone circuit: 'foreign induced currents . . . will flow in the same direction, and will meet and neutralize each other', which is incorrect. All in all, although we certainly have superposed circuits of a kind here, we do not seem to have much of the basic concept of what were to be known as phantom circuits.

The first presentation of the basic concept of a superposed circuit system, in which the signals all operated in the same frequency band, e.g. were all telephone signals, and in which mutual interference of side and superimposed signals was reduced to an acceptable level by balancing, was that by the Englishman, F. Jacob,[4] in 1882. He used a balanced-bridge arrangement as shown in Fig. 4 in which a pair of resistors, a pair of capacitors, or a two-winding inductor could be applied at each superposition. He showed how the system could be extended by superimposing on superposed circuits, and so on, in principle without limit, so that the result of as many metallic-loop circuits as wires is approached. One of his diagrams was effectively as Fig. 5, in which three loop and one earth-return circuit are obtained from four wires.

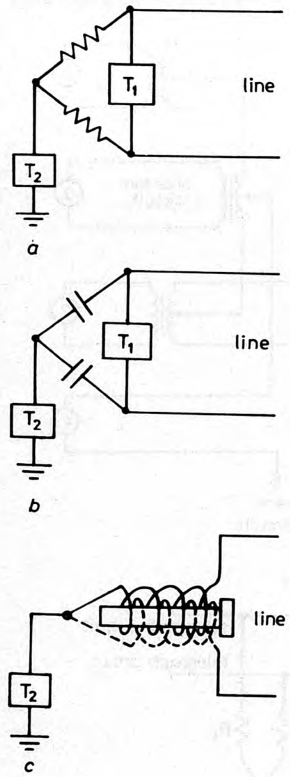

Fig. 4
Jacob's superposition methods (1882)

a Resistance bridge
b Capacitance bridge
c Twin-wound iron-cored telephone instrument (i.e. balanced inductor)

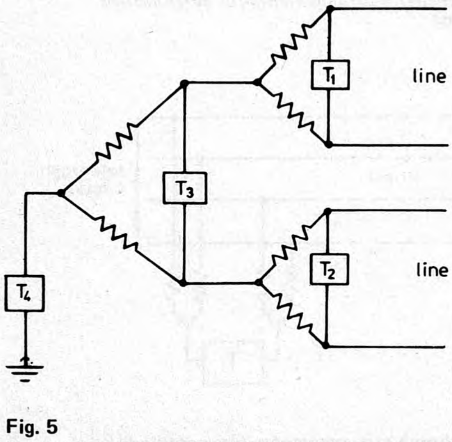

Fig. 5
Jacob's method of obtaining three metallic-loop circuits and one earth-return circuit on four wires

Although Jacob did not show the use of transformers as such, he was very close to the system which later became standard in using the balanced-inductance twin-wound instrument of Fig. 4*c*. He stated explicitly the need for balance, thus: "The two insulated wires of each circuit may be twisted together, and the twisted wires of one circuit may be twisted with those of another, to prevent induction," and "Resistances or condensers may be introduced to equalize the potentials on the two sides of each instrument, or the coils of the instruments may be differentially wound". It is interesting to note, in passing, that the first sentence quoted may well represent the first disclosure of the multiple-twin type of cable, so widely used 30–40 years later.

The Belgian, F. van Rysselberghe, included in a patent[5] of 1883 a system like Jacob's in which the purpose of the superposition was the separation of superposed telegraph signals from the side telephone signals; he too made explicit mention of balancing by adjustment.

The next important step was the disclosure in 1885 of a method of superposition using transformers, or differential coils;[6] the inventor was Rosebrugh of Toronto, already noted in connection with the 1879 patent. The method was effectively that which later became standard practice, using balanced transformers with a coupling winding, as shown in Fig. 6. This Figure uses modern symbols and ignores the fact that Rosebrugh used each transformer core also as the magnet of a telephone transmitter, the coupling coil being used for the receiver. The inventor envisaged some rather surprising uses for the system; e.g. to give a subscriber access to two different exchanges, but this does not detract from its priority as the first 'modern' phantom system, with the correct use of transformer windings.

A closely similar patent by the American Telegraph and Telephone Company's engineer, J.J. Carty, was filed[7] in February 1886; this was so similar indeed that there might well have been some justification in Rosebrugh's suggestion that his idea had been stolen by A.T. & T. when he submitted it to them for consideration[8].

A later patent by Rosebrugh[9] showed a similar (and correct) use of another kind of transformer in providing two telephone circuits, but was unfortunately marred by emphasis on an alternative arrangement that was equivalent to the circuit of Fig. 7, in which, in place of one transformer with balanced windings on the same core, two separate transformers are used. This arrangement is fundamentally unsound as will be discussed below, and cannot give satisfactory operation. It was, however, anticipated by nearly one month by J.A. Barrett,[10] a Bell

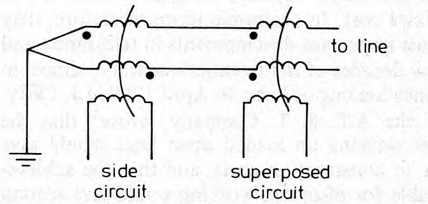

Fig. 6
Rosebrugh's system using transformers (1885)

The dot notation has been used to indicate direction of winding; if currents enter each winding at the dotted end, the fluxes are additive

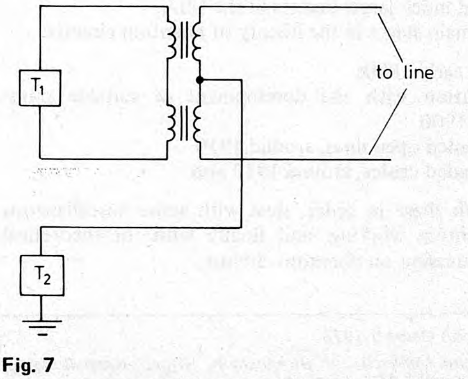

Fig. 7
Unsound system of Barrett and Rosebrugh (1886)

engineer in the USA. As Barrett's patent was claimed to have been applied successfully in practice, it is necessary to look at this arrangement closely. It is worth noting that Rhodes[1] attributed this circuit (without observing that it was unsound) also to Carty, but this was quite erroneous.

It seems to the author that it is obvious by inspection that the circuit arrangement of Fig. 7 presents the superposed circuit T_2 with an open circuit if the transformers are ideal, and with the reactance of the transformer windings in practical cases. For any current from T_2 would divide equally through the secondary windings of the two transformers, inducing equal but opposite voltages in the primaries. Across each primary there would thus exist a finite voltage, although the equal opposition would prevent current from flowing, and this condition represents an open circuit. Thus, this circuit arrangement is basically unsound. If, on the other hand, the coils in Fig. 7 were all on the same core, the situation would be basically sound. For, if the two secondary windings were tightly coupled, then the equal division of current through them from the centre-point would ensure that no flux was produced by T_2, and so, in practice, only the leakage reactance of the windings would be presented to the superposed circuit. It will be observed that Rosebrugh's 1885 arrangement did have the windings of the phantom-circuit transformer all on one core. It is, therefore, doubtless only just that he should have been awarded patent priority in the interference case which was considered by the US Patent Office[11], although the grounds of the award were almost certainly quite different.

There were, of course, immense practical difficulties in working phantom circuits. With the low quality and lack of screening in early transformers, and with the difficulty of maintaining any sort of balance on the lines, especially when extended locally to other lines, it is hardly surprising that the system was not brought seriously into use during the 19th century. Nevertheless, it was claimed that Barrett's system was used in 1886 on the New York–Philadelphia line.[12] If it worked at all, it must have been because of the imperfections of the transformers; for example, their low reactance and poor coupling. Yet the method was claimed to remove the loss caused by the resistances in Jacob's first system (Fig. 4*a*)!

3 Early years of the telephone transformer

Clearly, one of the factors determining the practicability of operating phantom, or superposed, circuits was the quality of the transformers which could be made. Discounting systems, such as Barrett's, which used transformers incorrectly, and could only function at all if the transformers were very poor, we see that phantom circuits could not reasonably be used unless

(*a*) the balance of the windings could be made good enough for the centre tap or superimposing point to be truly the centre of symmetry of the line impedances, and
(*b*) the transmission loss of the transformer could be made acceptably small.

If the first condition were not met, there would be crosstalk between side and phantom circuits. As for the second condition; clearly, any cost saving due to the saving in the number of conductors would be cancelled by the increased gauge of wire needed to compensate for the added loss, if the loss were large. This matter was examined, with some dramatic conclusions, by Hill in 1909.[13] Thus, although line balance was also of great importance, the really critical factor was the transformer. And, before about 1900, transformer designs were not good enough.

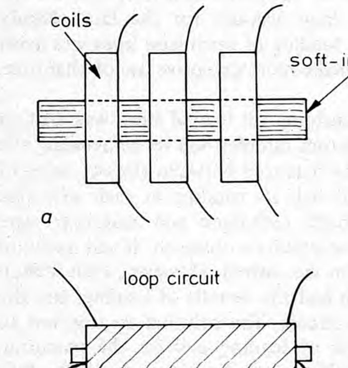

Fig. 8
Various transformers

a Rosebrugh's transformer arrangement (1885)
b Transformer as shown by Preece and Maier (1889)
c Transformer as described by Preece and Stubbs (1893) (cross-section)

During the period of the patent activity described in the preceding Section, power transformers were being developed and used for frequencies around 50 to 100 Hz, and no doubt something was learnt from these, but the problems of telephone transformers were different, involving a different and wide band of frequencies. Induction coils, which were transformers of high ratio, but not balanced, were used in telephone instruments to match the transmitter or microphone to the line. These were at first just simple solenoids with a bar core of soft iron. The same ideas were used in early line-to-line transformers, generally called translators or repeating coils.

Fig. 8 shows some progress in ideas of transformer design, from the side-by-side coils of Rosebrugh's patent of 1885, through the interlayered windings, still on a bar core, described by Preece and Maier in 1889,[14] to the closed wire-loop core described by Preece and Stubbs in 1893.[15] Preece and Maier stated that: 'The core . . . must be of the softest iron wire and . . . the coils must be wound as closely as possible and with the greatest exactitude. When the coils are well made, the strength of the speaking through a copper metallic loop working through two translators is not sensibly diminished.'

Four years later, and presumably with more adequate experience, Preece and Stubbs offer an improved design but a much less cheerful estimate of performance:

> The core must be of the softest iron wire and . . . the coils must be wound as closely as possible with the greatest regularity. The two sections are wound in alternate layers. The cores in the most approved form are rather more than double the length of the coils, and when the winding is complete the projecting ends of the soft-iron wire are spread out and folded back over the coil to overlap, so as to form a complete magnetic circuit.
> The introduction of a translator leads, as might be expected, to a somewhat serious loss of effect, so that it is most desirable to restrict the number to two as a maximum. The regulations of the National Telephone Company for the London district are made with a view to having not more than one translation.

It should be noted that ringing was possible through this transformer, and this might account for the loss being higher than otherwise. It is very clear, however, that there is nothing in this performance to give any encouragement to the use of phantom circuits as a means of effecting economy, even supposing that the balance could have been made good enough.

Other kinds of transformer were experimented with by the British Post Office; one design described in a report[16] in 1889 comprised two flat ring coils laid side by side and wrapped round and held together by iron wire.

As late as 1898, transformers (admittedly twin wound) using bar cores with open magnetic circuit were being used for deriving phantom circuits in Germany,[17] and no doubt elsewhere also.

Eventually, transformer design settled into the adoption of toroidal cores and carefully balanced windings, and, with improved iron wire for the core, a loss as low as 1·5 dB could be obtained by 1908 on a transformer intended for deriving phantom circuits and giving through ringing.[18] This, however, was still very high, and had to be reduced below 0·5 dB by sacrificing the through ringing. Losses were much improved when iron dust cores came into use.

4 Practical application of phantoms on open lines c.1900

According to Rhodes, Reference 1, p. 192 the use of phantoms on open lines was tried in the USA in 1899 without results good enough to warrant commercial use:

> The trunks between Gloversville and Johnstown [New York State – a distance of perhaps 10 km], in their present condition, cannot be commercially duplexed . . . because it would be impossible to ring on the duplexed trunks, because the phantom would be too noisy,

> and because there would be objectionable crosstalk on the phantoms and on certain trunks .... Before further duplex tests on aerial lines are made, systems of transpositions for duplexed lines should be worked out.

Rhodes is quoting from a contemporary report, and the use of the word 'phantom' at this date is to be noted.

Later the same year, some better coils (transformers) were made, and tested on a longer route of about 90 km between Lewiston, Maine and Berlin, New Hampshire. Satisfactory ringing was obtained, but 'the lines were too noisy for phantom use'. Rhodes then says that:

> In the closing years of the last century, sporadic installations of phantom circuits were made by adventurous persons ... where circuits of a high order of merit ... were not a matter of first importance ...

In the light of this lack of success in the USA, it is rather surprising to find an extensive use of phantoms (still called 'superimposed circuits') in Britain. The work was in hand in 1898,[19] and by 1899 phantom working was being used with success on the Leeds–Hull and London–Brighton routes, both about 100 km long.[20] By 1900, there were 77 phantom circuits in commercial use, the longest being London–Bristol, about 190 km.[21] The total number of British Post Office trunk lines at this time was about 1000. It is known that phantom circuits were also being used at this time on the continent of Europe; e.g. in Germany, where there were 19 phantom circuits, totalling 3552 km, in use as early as 1898.[22]

No explanation, other than a purely chauvinistic one, is apparent for such a marked success in Britain in a matter where there was no success in the USA. Admittedly, the British Post Office was very hard pressed for trunk lines at that time, but, throughout the world, the standard of acceptable transmission was merely that which permitted conversation to be just carried on, and it cannot seriously be believed that the British Post Office could accept a quality of speech which was not usable in the USA. According to Rhodes, it was 1903 before commercial use was made of phantoms in the USA, and then only because the toroidal transformer had been introduced and improved transposition arrangements made in the lines. No note has so far been found of the technical methods adopted by the British Post Office to achieve its success, but it does seem that considerable transformer loss was accepted even if the balance was good. In a footnote to the List of Trunks and Junctions of 1908,[23] it is stated that in calculating the equivalent 'miles of standard cable' (N.B. 1 m.s.c. was roughly equivalent to 1 dB) for each line, 6 m.s.c. should be added to allow for the transformers in the side circuits, indicating that the loss of each transformer was about 3 dB. It was in this same year that, as stated in the previous section, a loss of only 1·5 dB was attained in the USA for a transformer fulfilling what was almost certainly the same function.

By 1911, the British Post Office had 236 phantom circuits,[24] mostly on links of under 100 km in length. In that year, a phantom circuit was set up on the London–Liverpool route (about 300 km), and as that was successful, one was set up between London and Glasgow (about 600 km). That the performance of these phantom circuits was not quite all that could be desired is indicated by the Traffic Manager's desire that the provision of new lines should not be reduced on account of the provision of phantoms:[25]

> The recent formation of a very satisfactory superimposed, or 'phantom' circuit, between London and Liverpool marks the most important advance in engineering knowledge. The Engineer-in-Chief is, I understand, about to try superimposing between London and Glasgow and he evidently feels no doubt but that the phantom circuit will be satisfactory. The possibilities in respect of economy in trunk construction are most alluring, and it is necessary that some warning should be given ... It is far better to provide a service with a regular delay of 30 minutes in the busy hours of the day, than an erratic service with 10 minutes delay one day and an hour the next. It is in regard to stability that phantom circuits fail. No long superimposed circuit in this country has ever been satisfactory.

And as the possibilities of satisfactory long-distance telephony over cables became real, so did the satisfaction with phantoms on open lines wane rapidly, enabling Cohen and Hill to say in 1916:[26]

> Superposed circuits on long overhead lines are not found to be satisfactory in England owing to difficulties in maintaining an electric balance of the four wires making up the superposed group, especially in winter weather. Extraneous sources of disturbance on such circuits are also much more difficult to eliminate than on ordinary direct telephone loops.

The problems of balance which have been mentioned were mainly those of maintaining the capacitance of each conductor of a pair the same with respect to the centre tappings of the line windings of the transformers. With good transformers, this would be the same as maintaining equal capacitance to earth (see Section 10.2). Just as transpositions of the pairs on a pole route were systematically made to equalise or balance the coupling between the various pairs and so reduce pair-to-pair crosstalk, so regular transpositions of the wires in each pair (or in each pair of pairs) could be made to balance the line for phantom working. The idea of a system of transpositions in open lines appears to have originated in about 1884 as a replacement for the continuous rotation (or 'twist') of wires along a pole route, although the latter survived into the 1890s,[27] and possibly very much later. The idea of varying periodicity of transposition on different pairs was set out clearly by Bennett in 1887,[28] and the crossing of pairs seems to have been introduced by Carty in 1889.[29] The idea that capacitance coupling was the dominant interference mechanism seems also to be due to Carty.[30]

One potential advantage of the phantom circuit, which could be exploited when good enough transformers became available, was that the line loss of the phantom, if suitable line arrangements were used, could be less than that of the side circuit (see Section 10.1). On an unloaded open line of copper conductors of weight in the range around say 50–100 kg/km (200–400 lb/mile), the attenuation in dB of the phantom would be some 15% less than that of the side circuit.[31] An example where this was exploited was the New York–Denver line of 1910 (Reference 2, p. 364). This line, about 3400 km long, was at the limit of acceptable transmission between the two cities, so that the reductions of loss due to phantom working as well as loading were significant. Considering the British experience, the successful operation of this long line was a great achievement.

5 Phantom working with coil loading of the lines

The fact that the transmission characteristics of a line would be much improved by the addition of extra inductance was first pointed out by O. Heaviside in the 1880s, but no practical steps in applying this idea were taken until in 1899–1900 both M.I. Pupin and G.A. Campbell independently showed the basis on which discrete inductance coils could be connected in lines at regular intervals. Thereafter, the use of coil loading of both cables and open-wire lines developed fairly rapidly, the first application to commercial service being in July 1900 on the open-wire line between Bedford and Brushton, about 130 km, in the USA. This was equipped with air-cored coils of large dimensions, mounted in boxes between the cross arms on the poles (Reference 1, p. 142). The effect of loading was to more than double the length of line over which commercial speech was possible, and, not surprisingly, there was extensive application of loading to open lines in the USA. By 1911, there was in that country a total length of loaded open line of about 13000 km, all with coils inserted at intervals of about 13 km Reference 2, pp. 356 and 363. Because extensive use was also desired of phantom working, it was necessary to find a way of combining loading and phantom working. For some years, it had to be one or the other. This held back the use of phantoms in the USA, and may account for the fact, already pointed out, that Britain, where loading of open-wire lines was never seriously applied,[32] was able to make more extensive use of phantoms in the early years.

The problem in working phantoms on loaded lines was that, if crosstalk between side and phantom circuits was to be avoided, the loading coils had to be accurately balanced between the two wires of each side circuit. Each coil had half its winding in each wire (see Fig. 9) and improvements in both technique and materials were necessary before adequate balance could be obtained. It was not until about 1907–08 that this problem was solved. However, even then, it was only the side circuits which had the benefit of loading, and the phantom was still an unloaded circuit. The solution to this was to develop a slightly different type of loading coil for the phantom; namely, a four-winding coil, with one winding in each of the four wires making up the phantom group, as shown in Fig. 9. This idea was patented by Campbell and Shaw.[33] If the connections are correctly made, the side-circuit coils do not affect the phantom, and

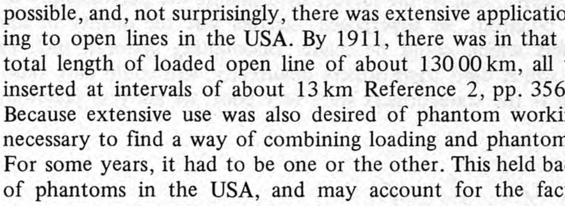

Fig.9
Arrangement of side- and phantom-circuit loading coils

Dot notation as explained in Fig. 6

the phantom-circuit coils do not affect the side circuits, assuming perfect coils. Satisfactory designs were achieved in 1910 Reference 2, p. 356. To give similar frequency characteristics to both side and phantom circuits, the inductance of the phantom coil had to be 163 mH compared with the 265 mH of the side coils, the cut-off frequency being then about 2400 Hz. The attenuation of the phantom circuit was about 20% less than that of the side circuit, a rather greater reduction than without loading. Because of this, phantom circuits were preferred for the longer routes. Note that, to obtain this result, the arrangement of wires must have been four wires side by side on the same pole arm (see Section 10).

Less extensive use was made of cables for long-distance transmission in the first decade of the twentieth century, but the application of loading to cables was made successfully from 1902 onwards in both the USA and Britain, as well as some other countries; and, where the use of phantoms on cable circuits was considered, similar problems to those described for open lines were encountered. The development of the cable system is considered in the following Section.

Air cores for loading coils gave a performance that was not adequate for use with cables, and, in consequence, the use of fine iron-wire cores developed from about 1904; within a few years, they displaced air cores on all cable circuits. The physical form of the coil was a toroid; great attention had to be paid to tight coupling as well as balance to keep the loss impedance low. The size of a coil was, typically, about 11 cm overall diameter; this was reduced as better cores made from iron dust were developed.

6 Phantom working on underground cable

Early telephone cables, in the 1880s, had been quite unsuitable for communication over distances of even tens of kilometres, and the trials made by the British Post Office of telephony over the London–Birmingham cable of 1899 were a failure.[34] It was only the application of coil loading that made the use of cables for long-distance telephony a practical proposition. Thus, the question of working phantom circuits on cables hardly arose until loading had become practicable. Early experiments had shown that it would be difficult to make cables with a sufficiently good balance of conductors to permit phantom working anyway. Thus, as the use of loading began to permit the extension of the cable network, attention was given to the requirements of cable for phantom working. It can easily be shown[35] that the main condition to be satisfied is that the capacitances from each wire of one side circuit to each wire of the other, i.e. four capacitances C_{13}, C_{14}, C_{23} and C_{24}, should all be equal. Here, C_{13} is the capacitance between wire 1 and wire 3, and so on. To prevent crosstalk between the side circuits, when phantoms are not involved, the condition is the less onerous one that $C_{13}/C_{14} = C_{23}/C_{24}$.

Now, it was found quite impracticable to control the manufacture of cables sufficiently to enable the cable to be made without capacitance unbalances. Thus, it was necessary to adopt a process of balancing after laying by selective connection of wires at jointing points. Some early ideas on selective jointing had been worked out by the British Post Office engineers in connection with the London–Birmingham cable of 1899, but the main development of the method, certainly as far as phantom working on loaded cables was concerned, was in connection with the short cable between Boston and Neponset in the USA. This 10 km cable was laid in 1909 as the termination of a loaded open-wire line which used phantoms, Reference 2, pp. 359–362. The wires in the cable were laid in groups of four, called 'quads'; two possible arrangements had been considered: one, the spiral four or star quad, in which in any cross-section the two wires of each pair lie at opposite corners of a square; and two, the multiple twin in which each pair is separately twisted up with the same lay and then the two pairs are twisted together with a different lay. The multiple twin was thought to be superior, although it was more bulky, because it gave a much lower phantom attenuation (see Section 10). When phantom working on loaded cable was introduced to Britain with the Leeds–Hull cable of 1913, about 80 km long, multiple-twin quadding was adopted, and it became standard for some decades.[36]

It is interesting that although the multiple-twin cable was patented in 1903,[37] both this and the star quad were really invented in the early 1880s, the latter by O. Heaviside in 1880,[38] and the multiple twin by F. Jacob, as already pointed out in Section 2.

The method of selective jointing depended on the measurement *in situ* of the unbalance capacitances in each length of cable. Then, as the first stage of balancing, the quads in one length were paired with quads in the next length on the basis of having similar patterns of unbalances, but of opposite sign, so that there was a basic potentiality for cancellation. Then, as the second stage, the individual wires of each pair of quads were selected for jointing in such a way that the residual unbalances were almost cancelled out. Pollock[35] gives an excellent account of the process. Because the wires of a pair have to remain twisted together, there are eight permissible jointing arrangements, as shown in Fig. 10.

From this period, there was rapid development of underground telephone-cable networks. The advent of the telephone repeater in its electronic form in the middle of the second decade of the twentieth century gave an enormous impetus to this growth. Phantoms continued to be used, it being necessary to fit phantom-deriving transformers at each side of each repeater, and to provide separate repeaters for the phantoms. In this way, the number of telephone circuits was three-quarters of the number of wires.

Phantoms on phantoms, or 'super phantoms' were, in principle, possible, of course, but in practice it was not possible to balance the cables well enough for this. To match up wires in groups of eight would have stretched the method beyond any reasonable limit.

The repeatered cable network remained the backbone of long-distance telephone communication for a couple of decades, but then, as carrier, or frequency-division-multiplex, systems came into use after the invention of the negative-feedback amplifier, the old loaded-cable network gave way to a network based on wider frequency bands of transmission, and in these phantom working had little part to play.

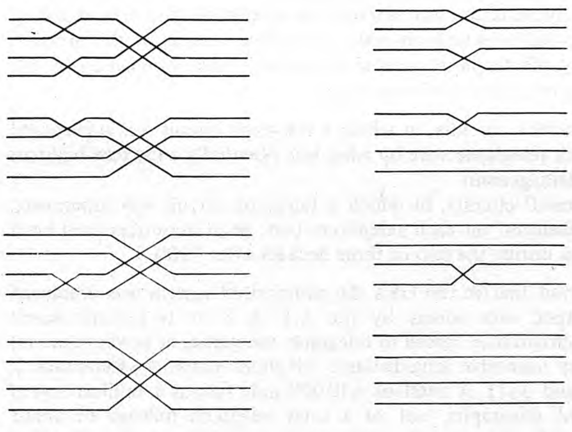

Fig. 10
The eight permissible ways of jointing the wires of a quad for balancing

7 Phantom working on submarine cables

Telephone working on submarine cables was limited to quite short distances in the days before loading was introduced, and the 4-core gutta-percha-insulated cable opened in 1891 between St. Margaret's Bay and Sangatte, across the English Channel, which enabled two telephone circuits to be provided between London and Paris, was a notable achievement for the British Post Office.[39] A similar cable was laid between Scotland and Ireland in 1893, and another across the English Channel in 1897. Traffic demand increased rapidly, and it is easy to appreciate the economic attractiveness of providing phantom working on such cables. It is not quite clear when this was first done, but in 1914 Hill stated that 'this is often done nowadays'.[40]

The British Post Office developed a method of working one phantom and one earth-return super-phantom circuit on a 4-core loaded cable in 1914.[41] However, experimental work on the design of a 2-core submarine cable, which would provide good side-circuit and phantom working between England and Holland, had been done as early as 1901 by F. Tremain,[42] although the complete cable was never made and laid.

The loading of submarine telephone cables by discrete coils was introduced in 1910 on a cross-Channel cable,[43] and led to a considerable improvement in transmission. Phantom working on such cables generally involved the use of separate coils in each leg of the phantom, instead of single coupled coils, so that the super phantom (with earth return) would also be loaded.[40]

The preferred method of loading for submarine cables was, however, the continuous-loading system in which iron wire was wound round each core of the cable. This was better for laying and maintenance. However, it led to greater complication in balancing for phantom working, since the continuous loading led to significant unbalances in inductance and resistance.

The balancing of submarine cables for phantom working was, in any case, more difficult than for underground cables, since it was not normal for submarine cables to be made in short lengths intended to be jointed *in situ*, and, therefore, balancing by selective jointing could not be done on quite the same basis as for underground cables. Because of this, balancing was often done at the ends of the cable by the connection between conductors of special impedance networks, which might be very complicated circuits of resistance, inductance and capacitance.[44] On the other hand, selective jointing at the factory, in lengths of 0·625 nautical mile (about 1·2 km), could give very good results, although unbalances in R, L, G and C had all to be cancelled out as far as possible; a side/phantom crosstalk ratio of around 60 dB could be achieved.[45]

8 Telegraph phantoms

There were many ideas in the 1880s for the working of telegraphs and telephones simultaneously over the same lines, and some of these took the form of phantom circuits; we have already mentioned in Section 2 the phantom system of van Rysselberghe which superposed a telegraph circuit (with earth return) on the two wires of a metallic-loop telephone circuit. Generally, in those early days, the main object was to provide long-distance telephone communication over existing telegraph lines.[46] After an initial burst of enthusiasm for combined working, its use declined as the demand for telephone lines increased, and most of these were provided on a telephony-only basis. Then, around 1900, it seemed attractive to use these telephone lines, when not required or not suitable for telephone phantom working, for superposed telegraph circuits, a complete reversal of the previous philosophy. The methods used were basically those used earlier by van Rysselberghe, and were of two types:

(*a*) 'composited' circuits, in which a telegraph circuit was superposed on each telephone wire by what was essentially a lowpass-highpass filter arrangement

(*b*) 'simplexed' circuits, in which a telegraph circuit was superposed as a phantom on each telephone pair. Most countries used both systems during the two or three decades after 1900.

It is believed that in the USA the composited system was dominant and was used very widely by the A.T. & T.Co. to provide leased telegraph circuits (i.e. leased to telegraph companies or private renters) on its very extensive long-distance telephone network (Reference 2, pp. 343 and 357). A total of 630 000 mile (about 1 million km) of composited telegraphs, out of a total telegraph mileage of about 700 000 mile (about 1·1 million km) was quoted for the Bell Companies (including A.T. & T.) in 1922.[47]

In Germany, the second system, using the phantom principle, was tried out from 1897, and by 1901 was widely adopted and standardised in the form shown in Fig. 11.[48] Routes on which it was then working were Berlin–Vienna, Berlin–Budapest, Posen–Breslau, Dresden–Chemnitz, Frankfurt–Strasburg, and Hamburg–Lubeck. The circuit arrangement, using the differential iron-cored coil, was in principle the same as that patented by Jacob in 1882 and already shown in Fig. 4*c*. The capacitor C was nominally 2 μF, but was not always needed. It was reported that, on the Berlin–Vienna line, no capacitor was used at Berlin and only 0·25 μF was found necessary at Vienna.

In Britain, both composited and simplexed systems were used. Hill[49] reported that in 1908 there were 200 circuits on the simplexed (i.e. phantom) system in Britain. In addition to these, there were also 'a large number' of similar circuits in which a single-wire telegraph circuit and a single-wire telephone circuit on the same pole route were combined on a phantom-circuit basis to give a double-wire circuit carrying both telegraph and telephone. The extent to which this system had been adopted since its first trials in 1900[50] can be gauged from the following statement in 1902[51]:

> This method has been so completely developed as to permit in some cases of two or more metallic telephone circuits being obtained on different sections of independent telegraph circuits.

and from the report in 1903[52]:

> Circulars have been written standardising the appropriation of telegraph wires to provide metallic telephone circuits and superimposing telegraphic apparatus thereon by the use of transformers. The development of this system has been continued from the previous year and its use has been largely extended.

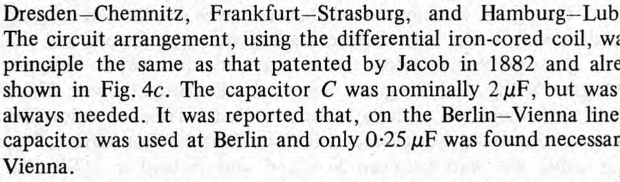

Fig. 11
German system for simultaneous telegraph and telephone working on double-wire line (1901)

Another use for a telegraph circuit as a phantom on a telephone circuit was to provide a 'call wire' for the use of operators controlling a group of trunk circuits. Previously, one of the speech circuits had to be allocated for this purpose, but, in 1905, the use of a superimposed telegraph circuit was found to be a satisfactory substitute on the London–Manchester route, thus enabling all speech circuits to be revenue earning; and the system was extended to other routes.[53] Soon afterwards, the same principle was applied to provide communication circuits for maintenance staff for use in localising and clearing of faults.[54] In addition to use in the public telecommunications network, these composited and simplexed methods were widely used on the railways.[55]

Phantom working on purely telegraph systems was also practised. A later example, from 1925, was the provision of seven double-wire telegraph circuits on eight wires of the London–Penzance cable.[56] In this case, bridge circuits were used in which the arms each comprised a resistance and capacitance in parallel; evidently, transformers could not be used when the side circuits carried d.c. telegraphs.

One advantage the simplexed or phantom circuit had over the composited circuit became of potential significance when loading coils were inserted in telephone lines. For phantom working, as we have seen, the side-circuit coils were arranged so that the superposed currents produced no flux. Therefore, superposed telegraph currents, which were large, had no effect on the magnetic properties of the core. But with composited circuits, the individual telegraph currents flowed in only one winding of the coil, and, being relatively heavy currents, were able to reduce the permeability and generally modulate the telephone currents. This interference was found very damaging in the USA (Reference 2, p. 365). Whether the advantage of the phantom arrangement was appreciated at the time, and any action taken, is not known.

9 Phantoms for music transmission

As radio broadcasting developed through the 1920s and 1930s, the need arose for special line circuits between studios or outside broadcasting points and transmitters, and between one transmitter and another, so that music and programme material generally could be transmitted with minimum distortion. Ordinary telephone circuits were quite unsuitable because of their very limited frequency band, restricted because of the system of loading coils used. Various methods were adopted for meeting this special need for circuits with extended frequency response: open-wire circuits, special screened and very lightly loaded pairs in cables, and, later on, the use of the band below 12 kHz in the new carrier-transmission cables, which used only the range above 12 kHz for telephony. However, extensive use was also made of phantom circuits.

One such application was on star-quad audio cables. The British Post Office had started, in the early 1930s, using star-quad-type cables, instead of the multiple-twin type, because these were much smaller and cheaper for a given number of pairs; but as these cables gave much higher attenuation to the phantom circuit, the British Post Office did not use the phantoms. They were thus left unloaded, and available for use by the BBC for programme transmission.[57]

Another application was on the carrier cables, which used separate cables for each direction of transmission and employed, as we have said above, only the band above 12 kHz for the carrier-telephony system. To use the band below 12 kHz for music transmission on the ordinary pairs necessitated expensive lowpass and highpass filters; to use the phantoms was much cheaper. This became the standard practice during and after the Second World War. The phantoms were also used by the BBC for its own low-frequency carrier-telephony system (Reference 57, p. 269).

10 Some theoretical considerations of phantom circuits

10.1 Transmission

The transmission characteristics of a phantom circuit depend very markedly on the type of line used. Let us consider first of all some open-wire arrangements. With open wires, the Heaviside distortionless condition $R/L = G/C$ is closely approached in most cases. Here, R is resistance in Ω/m, L is inductance in H/m, G is leakage in S/m, and C is capacitance in F/m. With this condition, the propagation constant is

$$P = \alpha + j\beta = \sqrt{(R+j\omega L)(G+j\omega C)}$$
$$= \sqrt{C/L}(R+j\omega L)$$

Thus, the attenuation constant is $\alpha = R\sqrt{C/L}$ neper/m.

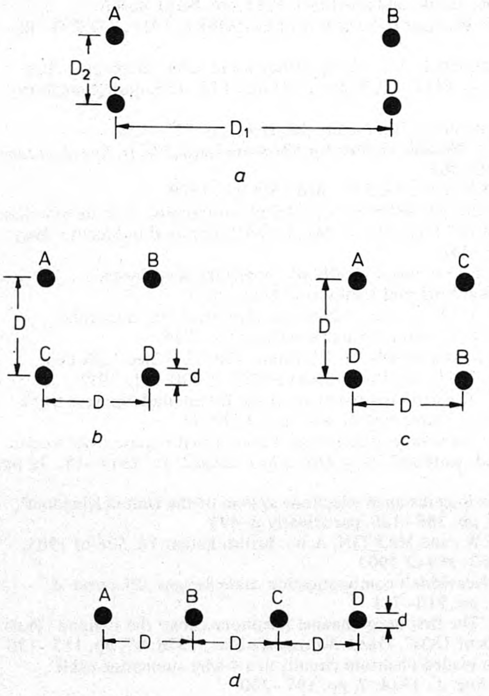

Fig. 12
Four cases of open-wire arrangements

A, B is one side circuit, C D is the other.
It is assumed that suitable transposition arrangements take care of crosstalk problems
a Case (*a*), $D_1 \gg D_2$
b Case (*b*)
c Case (*c*), as case (*b*), but side circuits on diagonals
d Case (*d*), all wires in same plane

Case (a) If the two wires of each side circuit were very widely spaced compared with the separation of the pairs, see Fig. 12*a*, then the phantom circuit is formed by the parallel connection of two virtually isolated circuits. In these circumstances

$$C_p = 2C_s \quad \text{and} \quad L_p = \tfrac{1}{2}L_s$$

where subscripts p and s denote phantom and side circuit, respectively,

In all phantom arrangements, of course, $R_p = \frac{1}{2}R_s$ and $G_p = 2G_s$. Thus, for this case, $\alpha_p = \frac{1}{2}\sqrt{2/\frac{1}{2}}\,\alpha_s = \alpha_s$. However, this is not a practical case.

Case (b) If the four wires are arranged at the corners of a square, as in Fig. 12*b*, with the side circuits formed from adjacent wires as shown, then it can be shown that

$$C_p = \frac{24}{\log_{10}(2\sqrt{2}D/d)} = \frac{24}{A+0{\cdot}45} \quad \text{pF/m}$$

where $A = \log_{10}(D/d)$, and numerical factors are approximate. Also

$$C_s = \frac{12}{\log_{10}(2D/d)} = \frac{12}{A+0{\cdot}3} \quad \text{pF/m}$$

The transmission effects are best seen by taking a numerical example. Take $D/d = 100$, which is a typical figure. Then, $A = 2$ and $C_p = 1{\cdot}9\ C_s$. (L_p and L_s are in inverse proportion.) Thus, $\alpha_p = 0{\cdot}95\alpha_s$; i.e. the phantom has 5% less attenuation than the side circuits.

Case (c) If the four wires are arranged at the corners of a square, as before, but, this time, the side circuits are formed from the diagonally opposite wires (a better arrangement from the point of view of crosstalk) as in Fig. 12*c*, then it can be shown[58] that

$$C_p = \frac{24}{\log_{10}(\sqrt{2}D/d)} = \frac{24}{A+0{\cdot}15} \quad \text{pF/m}$$

and

$$C_s = \frac{12}{\log_{10}(2\sqrt{2}D/d)} = \frac{12}{A+0{\cdot}45} \quad \text{pF/m}$$

With $D/d = 100$, $C_p = 2{\cdot}28\ C_s$ and $\alpha_p = 1{\cdot}14\ \alpha_s$. This is therefore a bad arrangement from the point of view of the phantom, which has 14% higher attenuation than the side circuits.

Case (d) If the four wires are arranged in the same plane, i.e. on the same arm of the pole, as in Fig. 12*d*, then the formulas given by Hill (Reference 59, especially p. 681) are, in effect,

$$C_p = \frac{24\log_{10}(\sqrt{3}D/d)}{\log_{10}(2D/d)\log_{10}(6D/d)} = \frac{24(A+0{\cdot}24)}{(A+0{\cdot}3)(A+0{\cdot}78)} \quad \text{pF/m}$$

$$C_s = \frac{12}{\log_{10}(2D/d)} = \frac{12}{A+0{\cdot}3} \quad \text{pF/m}$$

With $D/d = 100$, $C_p = 1{\cdot}61\ C_s$ and $\alpha_p = 0{\cdot}81\ \alpha_s$. With nearly 20% less attenuation in the phantom than in the side circuit, this is clearly a good arrangement when phantoms are used.

If we now turn to underground-cable arrangements, we can see immediately that the star-quad cable uses effectively case (*c*) above. Even on open wires, this gave 14% higher attenuation to the phantom circuit than to the side circuits. As the conductors are brought closer, i.e. D/d is made smaller, the ratio α_p/α_s increases. One cannot press the formulas into service for the cable case, because, not only do they assume $D \gg d$, but, of course, the distortionless condition does not apply to cables, and lump loading was generally employed anyway. However, it is clear that phantom working could not be satisfactory on star-quad cables.

The multiple-twin cable does not lend itself to exact analysis at all, because the relationship between the four conductors of a quad is infinitely variable throughout the length of the cable, ranging from something like case (*b*) to something like case (*d*) above. It never takes the form of case (*c*), and thus always corresponds to a condition in which the attenuation of the phantom is less than that of the side circuits. Hill states, from experience, that C_p has a mean value of about $1{\cdot}5\ C_s$, and that, when the cable is loaded, α_p is significantly lower than α_s. It is now clear why multiple-twin cable was always used when phantom circuits were to be provided.

Finally, let us consider early types of submarine telephone cable, made up of a number of cores (generally four or a multiple of four) each comprising a conductor surrounded by a dielectric/insulant and immersed in sea water. In this case, the capacitance of a metallic-loop (double-wire) circuit is one-half of that of a single-wire (earth-return) circuit, and the capacitance of the phantom circuit, formed by using each pair of conductors as each of its effective conductors, is twice that of the side circuits. The capacitance of the super phantom, formed from the four conductors as one conductor with earth return, is four times that of a single conductor with earth return, i.e. eight times that of a side circuit. Without loading, the attenuation of the phantom is the same as that of a side circuit; with loading, it is approximately the same. The attenuation of the super phantom is, however, significantly higher (Reference 59, p. 682).

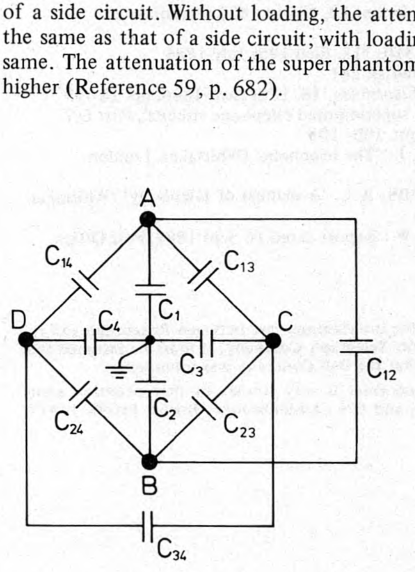

Fig. 13
Capacitances of a 4-wire group or quad

10.2 Capacitance unbalances

The capacitances of a 4-wire group, or quad, are shown in Fig. 13. For phantom working there are three cases to consider:

(i) Open lines. No published or manuscript statement has been found as to which of the capacitances were responsible, in practice, for crosstalk troubles. The capacitances between the wires of a side circuit, C_{12} and C_{34}, evidently have no bearing on crosstalk. In practice, the interwire capacitances were generally of the same order of magnitude as the wire-to-earth capacitances, but it seems likely that the unbalances of the latter would be greater than those of the former. It therefore seems likely that the practical condition for low crosstalk between side and phantom circuits was

$$C_1 = C_2 \quad \text{and} \quad C_3 = C_4$$

(ii) Underground cable. Here, the wire-to-wire capacitances are greater than the wire-to-earth capacitances. As before, C_{12} and C_{34} have no bearing on crosstalk, and it was usual, therefore, to adjust only the four capacitances C_{13}, C_{14}, C_{23} and C_{24} to be as nearly as equal as possible. There was, however, a school of thought in favour of balancing earth capacitances as well (Reference 59, p. 705).

(iii) Submarine cable. For the construction adopted in the early decades of the twentieth century, with each wire as a separate core, surrounded by its own insulation, each wire acted as a separate earth-screened cable. Thus, the interwire capacitances were negligible, and only the wire-to-earth capacitances significant. The condition for low crosstalk between side and phantom circuits was then

$$C_1 = C_2 \quad \text{and} \quad C_3 = C_4$$

11 Acknowledgments

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*This editorial report refers to the interference case between Rosebrugh and the electricians of the Western Union Telegraph Company. It must be assumed that this is an editorial mistake and that the Bell Company was intended

‡Note that this design of transformer is very similar to that patented some years earlier by S.Z. de Ferranti and G.L. Addenbrooke, British Patent 14917, 1885

†This paper concluded that loading of aerial lines was not worth while in Britain; it would appear that serious consideration had not previously been given to the matter