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AMPLIFIED TELEPHONE LINES BEFORE NEGATIVE FEEDBACK

with particular reference to zero-loss two-wire lines in 1934

By D.Gordon Tucker

Introduction

The thermionic valve was applied to the amplification of signals in long telephone lines in the first trans-continental telephone line from New York to San Francisco in 1915.(1) By analogy with telegraph repeaters, which did literally repeat the signals, the package of equipment which incorporated a thermionic-valve amplifier for telephone lines was called a telephone repeater. Repeaters were an integral part of the new underground telephone-cable network which was constructed in Britain from 1920.(2) From then until the introduction of negative-feedback amplifiers after 1934,(3) repeaters were subject to inconstancy of gain and nonlinear effects which hampered progress. This paper is concerned with my own experience in this matter, and is based largely on my official notebooks, most of which have fortunately survived.

I joined the Post Office Engineering Department at 17 in 1932 and had a training course of about 18 months duration, mostly in the North East of England. In October 1933 I was appointed to the Research Station at Dollis Hill and put in the Line Transmission Group. My immediate supervisor was J.G.Straw, who had the invaluable merit of giving me clear instructions and then leaving me alone to get on with the job. In this way I both did what was required and learnt a lot in the process.

Most of my work at the end of 1933 and through 1934 was in connection with the upgrading of lines between zone centres to zero overall loss. By October 1933, 90% of all main (i.e. zone-to-zone) long-distance telephone lines were in cable, and 65% were fitted with repeaters, incorporating valve amplifiers, at intervals averaging about 40-50 miles. 274 such repeatered lines were of four-wire type, and 378 were still of two-wire type.(4) The nominal standard had been 3 dB (sometimes 5 dB) overall loss for both types and this had not led to much difficulty. It was generally believed that zero overall loss could be attained with a reasonable margin against instability or self-oscillation and with adequately-low speech echo-effects only by the use of four-wire line circuits fitted with echo-suppressors.(5) In October 1933 only 88 lines had been upgraded to zero loss in this way. The basic protection from self-oscillation in these lines was the use of a differential transformer at each end, as shown in Fig.1, in which a 600-ohm resistance gave a nominal balance to the impedance of the line through the zone exchange, this balance being normally good enough to ensure several decibels loss round the go/return loop

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However, there were two conditions in which this protection could fail:

(1) when the exchange circuit was open, i.e. not connected to any extension line, and

(2) when the gains of the various repeaters along the line had a large net upwards fluctuation.

The first condition was easily dealt with by connecting a 600-ohm resistance across the inner contacts of the exchange jack, so that when no line was connected there was a balancing resistance on the exchange side. The second condition - gain fluctuations - was one about which little was known, and one of the jobs I was given was to investigate this. There was reason to think that fluctuations of gain could be large, because complaints had been received from the renters of lines for picture transmission (e.g. newspapers) about pictures being spoilt by transmission fluctuations. I had to look into this too.

I stated above that of the 652 zone-to-zone repeatered lines, no fewer than 378 (i.e. 58%) were two-wire lines - see Fig.2. These had been set up with balance return losses (BRL)* at each repeater adequate only for working with an overall loss of 3 dB (or sometimes 5 dB). (See Appendix for a further discussion of the modus operandi of two-wire repeaters.) However, it was going to be expensive to convert these lines to four-wire working, and there was one school of thought that supported a sort of rear-guard experimental project to see if it was feasible to design better impedance-balancing (or matching) networks and upgrade these two-wire lines to zero loss. That this school of thought was not very influential is indicated by the fact that I was given this job too. Actually I succeeded and had a zero-loss two-wire line in traffic without serious complaints; but by then the decision had been made that all zone-to-zone lines should be four-wire.

It is worth mentioning that while the conversion of existing two-wire lines to four-wire would be expensive, as twice as much copper conductor would be used, the situation was different in the planning of new cables. Since four-wire circuits could have higher amplifier gains, much lighter wire could be used than for two-wire circuits, so that for new lines there could actually be a saving of copper.

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* The BRL was defined as the loss from A to B (or C to D) minus the 6 dB loss which would be measured across the differential transformers even when completely unbalanced. For operation without self-oscillation or serious echoes, it was necessary that

$$BRL_{AB} + BRL_{CD} \gg G_{UP} + G_{DOWN}$$

where G_{UP} and G_{DOWN} are the repeater gains measured between the two-wire lines on each side of the repeater. The BRL was infinite if the impedance match was perfect.

Transmission fluctuations

The reason that little was known about transmission fluctuations was almost certainly that accurate, direct-reading and easily-used transmission measuring equipment was not available before 1934. The man who contributed most to improvement - one might call it a revolution - in this field was Dr.L.E.Ryall, who had fairly recently obtained his Ph.D. for research into the applications of neon lamps in electronic circuits. Some of his many ideas are embodied in an important paper presented in 1934 (6) However, these did not include the observation of fluctuations over a period of days or weeks; for this an automatically-recording apparatus was needed, and the circuits Straw suggested for me to make up were those shown in Figs.3 and 4. The neon-controlled or constant-output oscillator was an arrangement devised by Ryall.(7) The oscillation voltage across the neon-lamp circuit (i.e. lamp with resistance and capacitance in series) was made sufficient to cause the lamp to flash, and with suitable adjustments to the filament current of the valve and to its grid bias, I found the amplitude of oscillation could be made independent of the likely variations (say $\pm$ 5%) in filament and H.T. voltage to within $\pm$0.5% (or $\pm$0.05 dB). The receiving apparatus incorporated a paper-chart recorder with a movement of about an inch per hour. By using a large zero-offset, the scale could be made about one inch per dB. It is interesting that the valves (in this case with indirectly-heated cathodes) had undecoupled cathode resistances as stabilising devices - i.e. negative feedback before it had been published by Black! The circuit was later improved, but it worked quite well.

Normally, for observation, the oscillator was installed at the remote end of the repeatered line, and the recorder in London. It was considered desirable to observe the lines while they remained in traffic, and consequently the test frequency was made 2820 Hz in order
- (a) to be above the required range of the speech spectrum, and
- (b) to ensure that intermodulation interference with 18-channel voice-frequency telegraph systems would fall in the frequency-gaps between telegraph channels.

High- and low-pass filter pairs were used to separate the test tone from the traffic signals.

Tested without a repeatered line, the test system itself gave an output record constant to a small fraction of a decibel. The first records taken on a London-Manchester line (TSX-MR66) were as shown in Fig.5, with numerous fluctuations approaching 1 dB and an overall variation of nearer $\pm$ 1 dB. Since the margin against self-oscillation (or 'singing') of both 4-wire and 2-wire circuits was often less than 1 dB, clearly fluctuations of this magnitude were serious from this point of view. Furthermore, the circuit under observation happened to be one regularly used for picture transmission, and tests we made on picture transmission through an artificial line (see Fig.7) showed that fluctuations of 1 dB could have a catastrophic effect on a picture.

At this time, valves with indirectly-heated cathodes had only very recently become available, and all repeater valves had directly-heated cathodes, or filaments, some of bright-emitter type taking about 1A at 4V and some of dull-emitter type taking about 0.25A. Repeater stations were provided with a pair of massive L.T. batteries, the nominal L.T. voltage was 21V, and four filaments were fed in series. H.T. for the anode circuits was provided by a pair of batteries at a nominal 130V. A charge-discharge system was used, and it was not difficult to prove that most of the transmission fluctuations were due to the variations in L.T. and H.T. which this system produced. Probably for quite different reasons, a float-charge system later replaced the charge-discharge system. In the meantime it was necessary to improve the constancy of transmission with the existing system.

It was found that some individual valves were more sensitive to L.T. voltage changes than others. By systematic replacement of such sensitive valves by relatively insensitive ones, the transmission fluctuations in the London-Manchester line were greatly reduced, and Fig.6 shows a typical section of the record after this overhaul. Fluctuations were now only about $\pm$0.25 dB.

A systematic investigation of 170 valves taken from working repeaters, with hours of service from almost zero to 50,000, showed that sensitivity to L.T. fluctuations was unrelated to age, and was confined almost entirely to second-stage (i.e. output) valves. A simple test set and regular tests in repeater stations could enable sensitive valves to be rejected. Sensitivity to H.T. fluctuations, again restricted to second-stage valves, was more-or-less the same for all such valves, being about 0.5 dB for 10V change. The situation here could be improved by changing-over batteries before discharge was complete; the voltage variation was halved by foregoing the last 10% of the discharge period.

I mentioned, at the beginning, the matter of non-linearity. Now the transmission records shown hitherto were obtained when the line was not in use. With speech on the line, the effect shown in Fig.8 was obtained. This was due to intermodulation of the test tone and the speech. While this sort of non-linearity did not prevent the operation of the 18-channel V.F. telegraph system owing to its narrow and carefully-chosen channels, it did make the operation of carrier systems for speech very difficult. The only successful carrier systems at that time worked over open lines without repeaters. There were a few carrier channels on repeatered lines operated on a basis of one carrier channel above the audio channel, with intermodulation crosstalk reduced to a tolerable level at the time of installation by one of Dr. Ryall's non-linear compensation devices. This comprised a rectifier circuit inserted in the repeater input to introduce non-linearity opposite to that of the valves. Unfortunately the rectifiers and the valves aged at different rates, and I found one or two cases where, after a period in use, the intermodulation was actually being worsened by the compensating device!

Zero-loss two-wire circuits

In two-wire lines working with an overall loss of 3 or 5 dB, the balance return loss aimed at in designing the impedance-matching networks was a minimum of about 15-20 dB. For upgrading to zero loss, it was considered this minimum should be 30 dB. For the experimental zero-loss two-wire line, the London-Leeds route was chosen and a line allocated early in 1934. Intermediate repeater stations were Fenny Stratford, Leicester, Derby and Sheffield. The cable was coil-loaded for audio working, with coils at intervals of about a mile. The distance between repeater stations was unrelated to the coil spacing, so that it was chance at what point in a loading section the cable was terminated at a repeater station; thus the impedance at the cable terminals might be that of a half-section if the repeater came half-way between coils, it might be that of a half-coil-plus-section if the repeater coincided with the loading coil, and in general it could be anything in between and quite different on the two sides of the cut; see Fig.9. At the far end of the repeater section the cable was effectively terminated by a 600-ohm resistance (i.e. the input impedance of a repeater), and if the repeater section was a short one, there could be reflections from this which caused irregularities in the impedance/frequency curve. Consequently a different impedance-matching network had usually to be designed for each side of every repeater station.

Some examples of impedances for which matching networks were required are given in Figs.10-12. At Sheffield, the repeater station was more-or-less at the middle of a loading-coil section, and the impedances shown in Fig.10 were so nearly alike that a single design of matching network sufficed for both; the circuit is shown in Fig.13 and its impedance by dashed lines in Fig.10. The BRL exceeded 33 dB over the audio range (nominally 400-2400 Hz).

At Leeds, the cable from Sheffield was also cut more-or-less at mid-section, and the impedance/frequency relationship shown in Fig.11 can be seen to be only slightly different from those of Fig.10. It was less irregular, however, and was more easily matched, by a network only slightly different from that shown in Fig.13, as shown in Fig.14.

The Derby end of the Leicester-Derby section was quite different in that the repeater station came much nearer a coil. The impedance/frequency relationship, shown in Fig.12, is therefore different in nature to the previous ones, and required a different matching network as shown in Fig.15. This network gave a minimum BRL in the audio band of 33 dB.

I would like to be able to say that these networks were designed by some clever mathematical process, but the truth is that they were designed by trial and error, making intuitive additions and alterations to the circuits used for the poorer BRLs previously achieved, and using a Wheatstone bridge for the impedance measurement at each frequency.

It was found possible to set up the London-Leeds line on this basis to an overall loss of zero decibels, and I believe it functioned satisfactorily in service with an echo-suppressor fitted at one point. It is unfortunate that my notebook in which the operational tests would have been recorded is one of the few which are missing. The probability is that I lent it to Dr.Ryall and did not get it back. He was concerned with demonstrating that his design of 'stabilised repeater' could make a success of zero-loss two-wire circuits.(8) The stabilised repeater was like an echo-suppressor in that a signal passing through the amplifier in the UP-DOWN direction would operate a circuit in the DOWN-UP direction which would add considerable loss in that direction, and so prevent self-oscillation of the repeater; and vice-versa. This would make the stability of the two-wire circuit much less dependent on accurate impedance-matching and constancy of valve gains. To make his demonstration, with which I was not involved, he re-adjusted the 'line-up' of the London-Leeds line to omit the repeaters at Leicester and Sheffield and to have the highest individual amplification (namely 18 dB) at Derby, where he installed his stabilised repeater. (The overall loss of the cable between London and Leeds at 800 Hz was 37.3 dB.) He got a good result, but as stated earlier, this was only a rearguard action, and the decision to abolish two-wire circuits between zone centres had by then already been made.

References

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2. D.G.Tucker, 'The early development of the British underground trunk telephone network', Trans.Newcomen Soc., 49, 1977-78, pp.57-74.
3. H.S.Black, 'Stabilized feedback amplifiers', Bell System Tech.J., 13, 1934, pp.1-18.
4. J.Stratton and W.G.Luxton, 'Modern developments in telephone transmission over lines', Inst.Post Office Elect.Engrs., Paper No.153, Octr. 1933, pp.19.
5. F.E.A.Manning, 'Recent repeater station installations', I.P.O.E.E., Paper No.151, April 1933, pp.22-23.
6. L.E.Ryall, 'A few recent developments in telephone transmission apparatus', I.P.O.E.E., Paper No.155, 1934.
7. Ibid, p.14.
8. Ibid, p.34, and author's reply to discussion, pp.38-9.

APPENDIX. TWO-WIRE REPEATERS

(Extract from author's paper to Newcomen Society, see reference 2)

The technicalities of telephone repeaters cannot be very adequately discussed here, and only the critical problems will be taken further. The chief of these was the prevention of instability, 'singing', or self-oscillation of the amplifier system. Taking first the both-way or two-wire repeater, this had two forms, as shown in Figs. 16 and 17. In the single type, only one amplifier was used, coupled to the lines by means of a differential transformer as shown. It will be observed that the output of the amplifier is coupled to the same transformer as the input. Singing, or self-oscillation, will obviously be liable to take place unless (a) the transformer is accurately symmetrical and properly connected, and (b) the impedances of the 'Up' and 'Down' lines are identical at all frequencies at which amplification is effective. The more these conditions are departed from, the less amplification can be provided without singing. Reasonable balance of the transformer was not too difficult to achieve, but identical line impedances could be attained only if the lines were identical on both sides; this meant that the repeater must be inserted at the exact half-way point of the section of line, exactly half-way between loading coils, and that there must be no irregularity in the lines, and the terminating impedances at the far ends must be the same. Evidently this was impossible to achieve in practice, so that single-type two-wire repeaters could be operated only with quite low amplification. They were quickly displaced by the double type shown in Fig.17. In this system there was no need for the lines to be identical; each one was separately balanced by an artificial network of inductors, capacitors and resistors, carefully adjusted to match the line impedance with as much accuracy as the irregularity of the frequency response of the latter allowed.

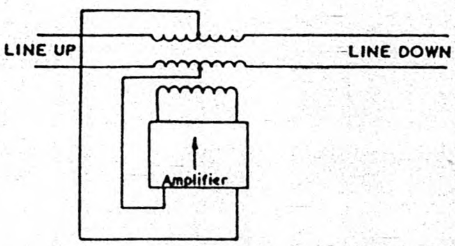

Fig. 16. Single type two-wire repeater.

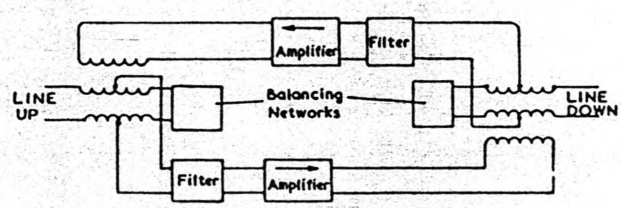

Fig. 17. Double type two-wire repeater.

This system allowed much more amplification to be used, and just before the final demise of the two-wire repeater on main routes in about 1935, it was found possible to operate two-wire trunk lines up to about 200 miles in length with no overall transmission loss between the terminal stations – i.e. with amplification equalling the loss of the line and transformers.

The need to maintain a relatively accurate balance of impedances made it difficult to operate two-wire repeatered lines at the level of overall transmission efficiency that soon became the aim. An overall loss of only 3 dB for main trunk lines became the basis of planning before 1930, and by 1933 zero-loss was the accepted aim. These standards could be much more easily and consistently maintained with four-wire repeaters, and since conductors of only 20 lb/mile could now be used, the cost of providing four-wire circuits was not prohibitive. Thus the four-wire system, which had been used on some routes since the early 1920s, became standard in the early 1930s.

On these low-loss circuits, problems arose from echoes. Although the overall circuit was stable, nevertheless there was sufficient backward transmission for a speaker's voice to be reflected back down the line at a quite audible level. Since on the long routes the time of transmission was considerable, these 'echoes' were significantly delayed, perhaps by 100-150 msec, and so interfered with the speaker's efforts to speak quickly and clearly. Thus 'echo-suppressors' had to be fitted on long routes; they were devices which used the speech power in one direction to suppress temporarily the amplification in the other.

Another matter worth mentioning is that in repeatered systems it was usual to insert electrical networks in the repeaters to correct the frequency-response of the system, so that the overall system had approximately the same transmission efficiency at all frequencies within the specified audio band. These networks were called 'equalisers'. The use of repeaters made the crosstalk requirements of cables much more severe because of the greater differences of signal level, and so better balancing techniques were necessary.

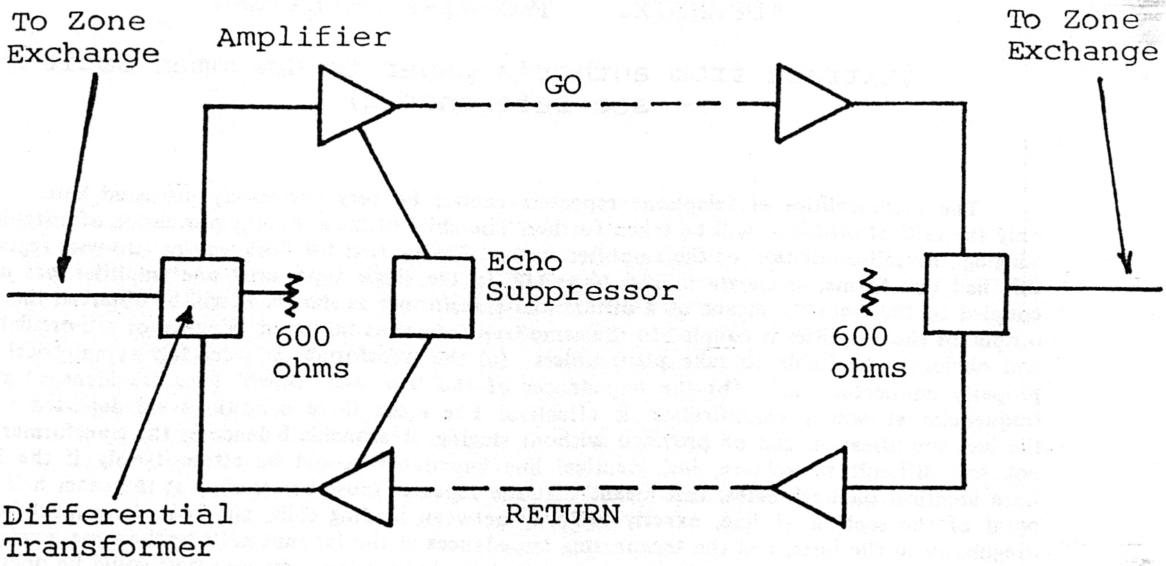

Fig.1. Four-wire zone-to-zone line with echo-suppressor

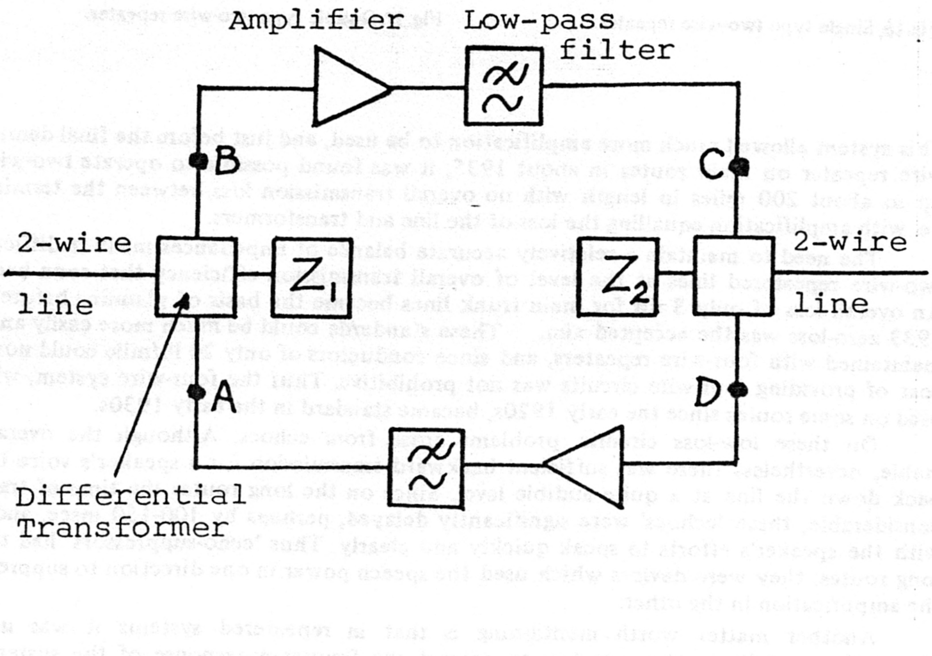

Fig.2. Two-wire repeater

(Z_1 and Z_2 are impedance-matching networks)

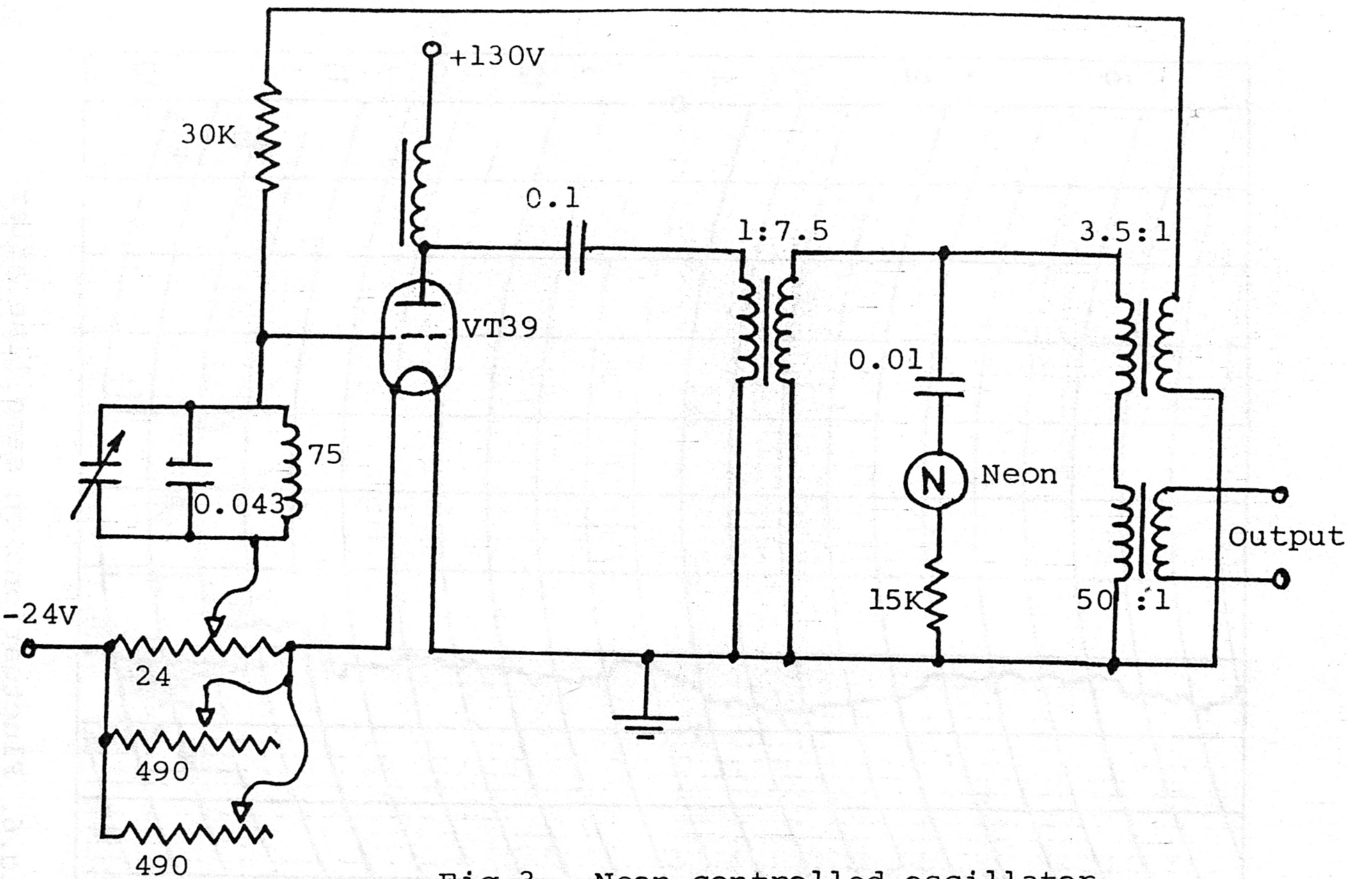

Fig.3. Neon-controlled oscillator

(Resistances in ohms, capacitances in μF, inductances in mH.)

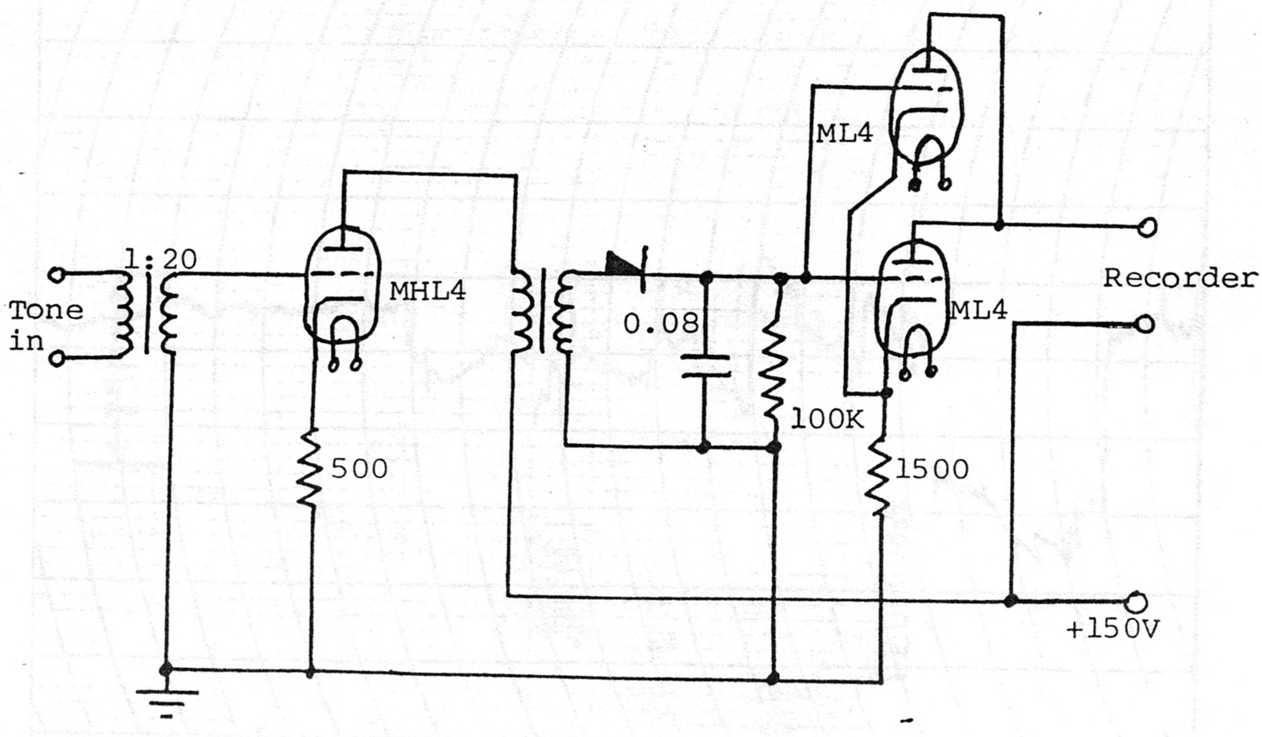

Fig.4. Amplifier-rectifier for recorder

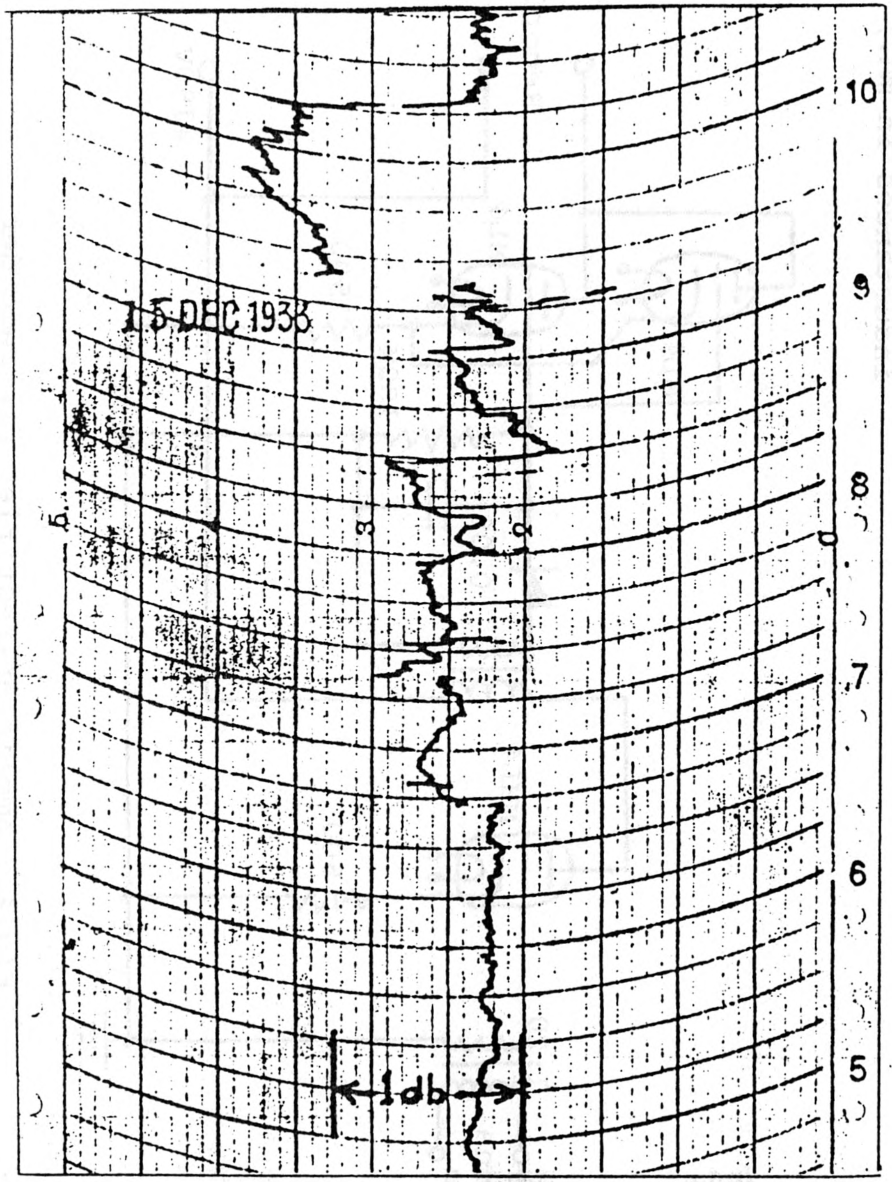

Fig.5. Transmission fluctuations on London-Manchester line before overhaul.

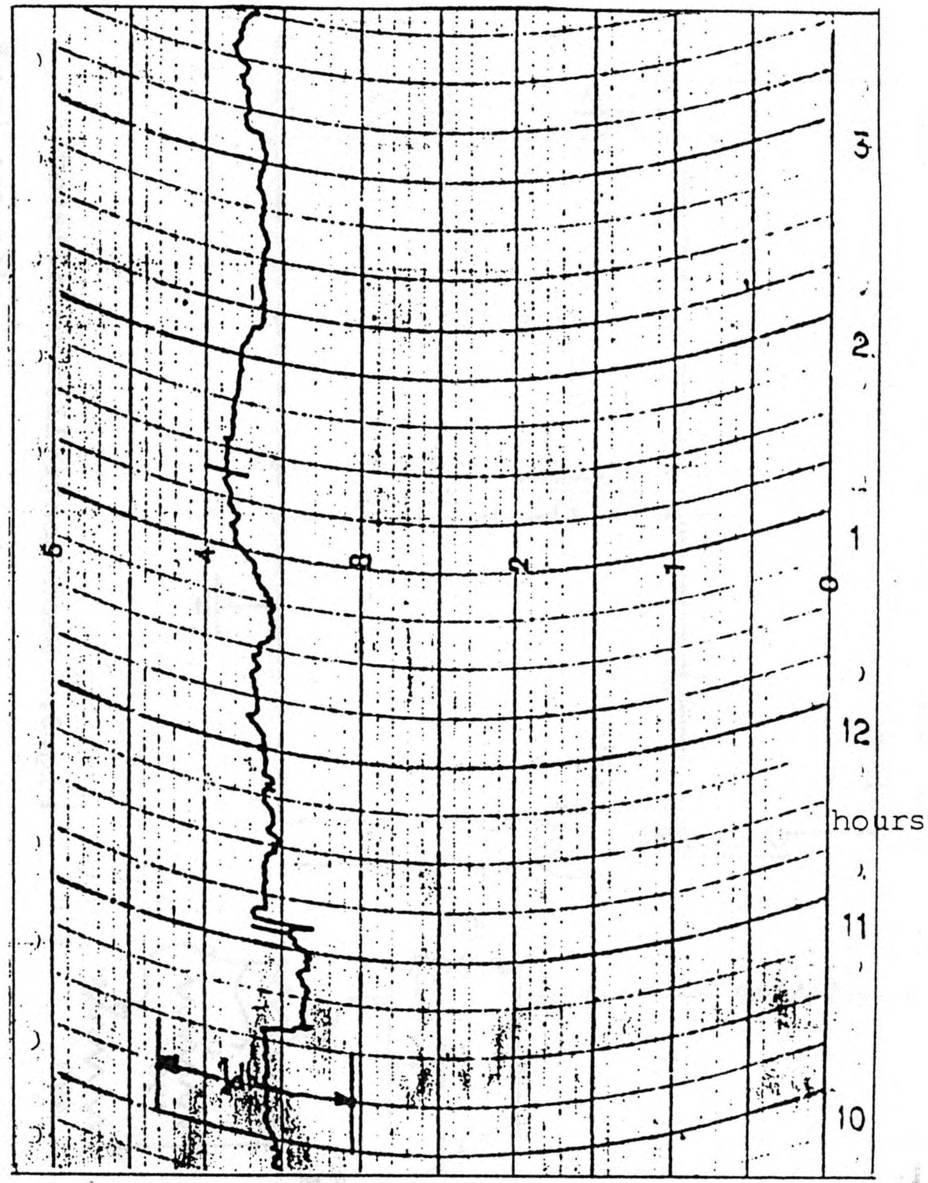

Fig.6. Fluctuations on same line after overhaul.

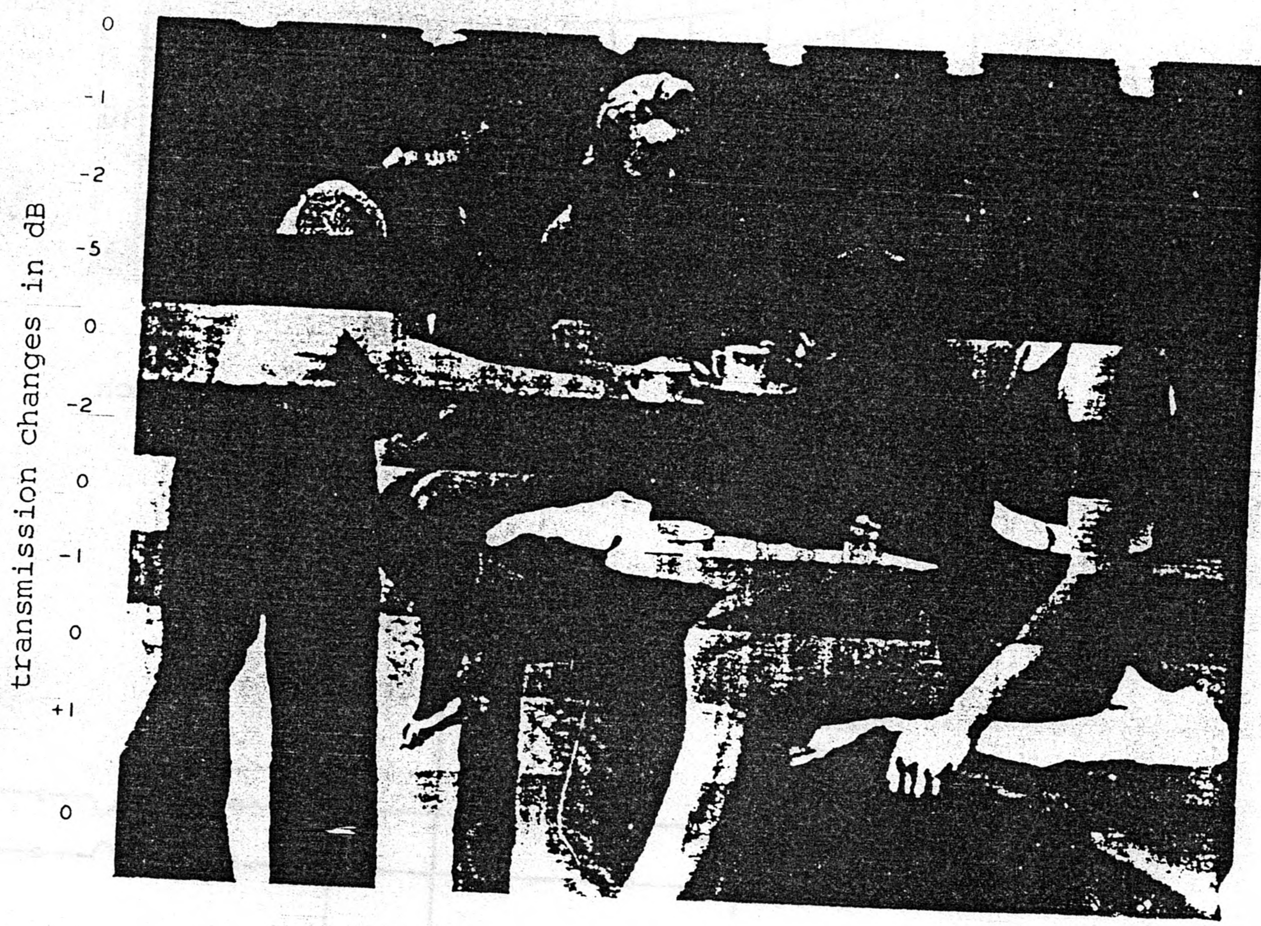

Fig.7. Effect of transmission fluctuations on picture transmission over a telephone line.

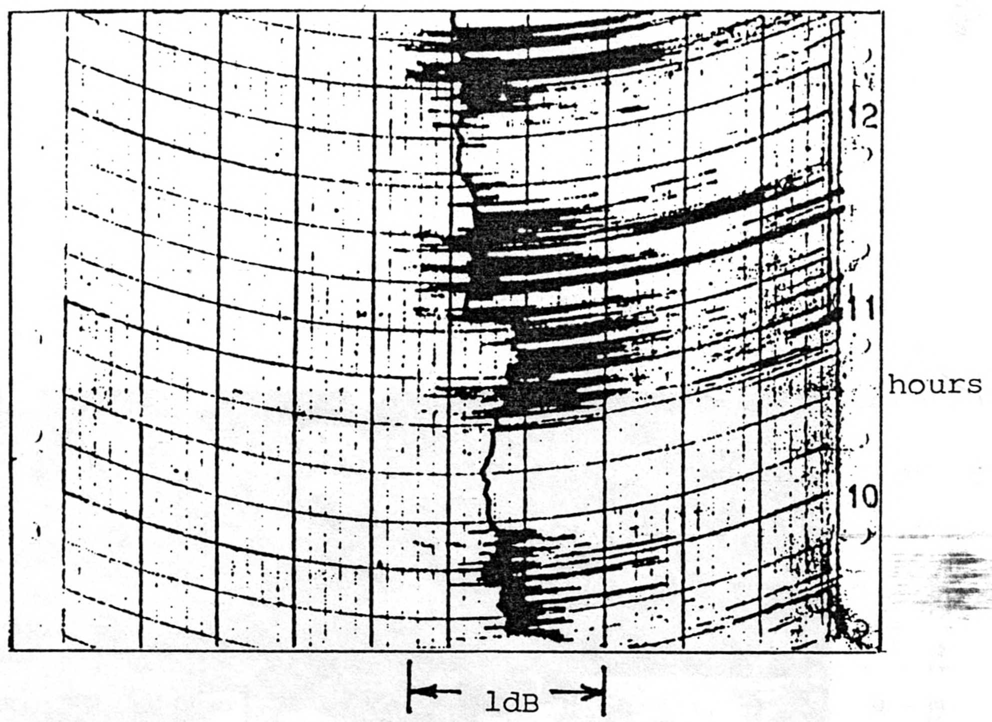

Fig.8. Showing intermodulation between speech and test tone.

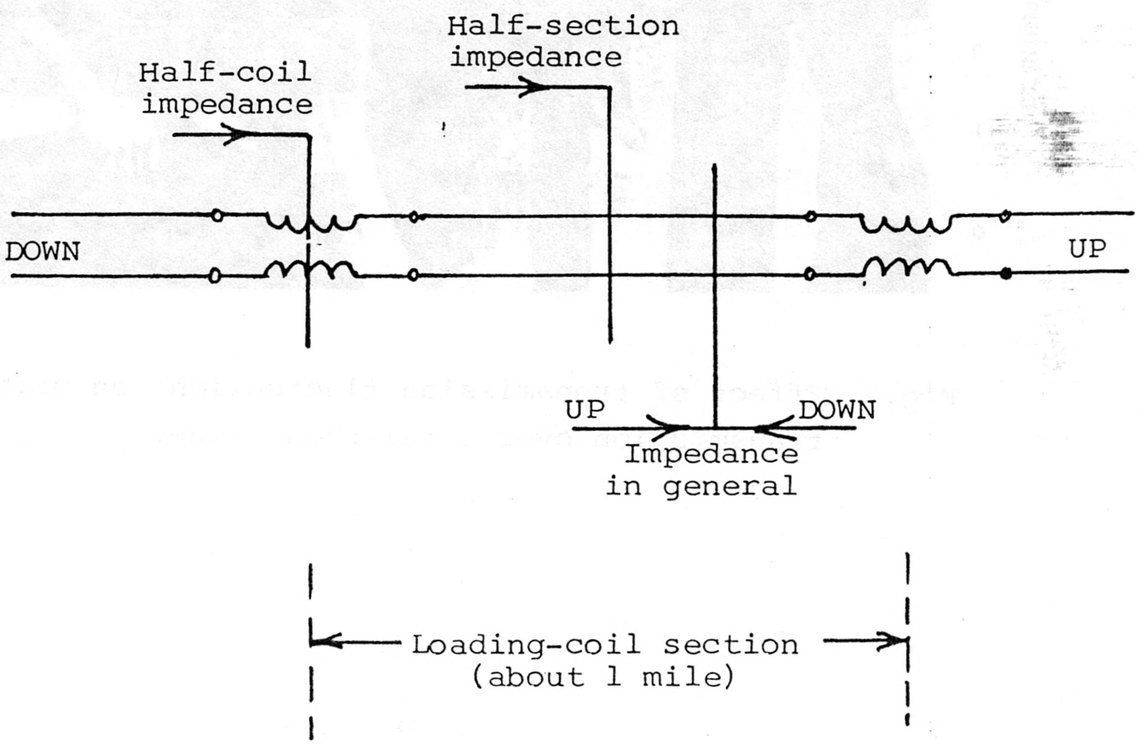

Fig.9. Showing the different kinds of impedance which could have to be matched.

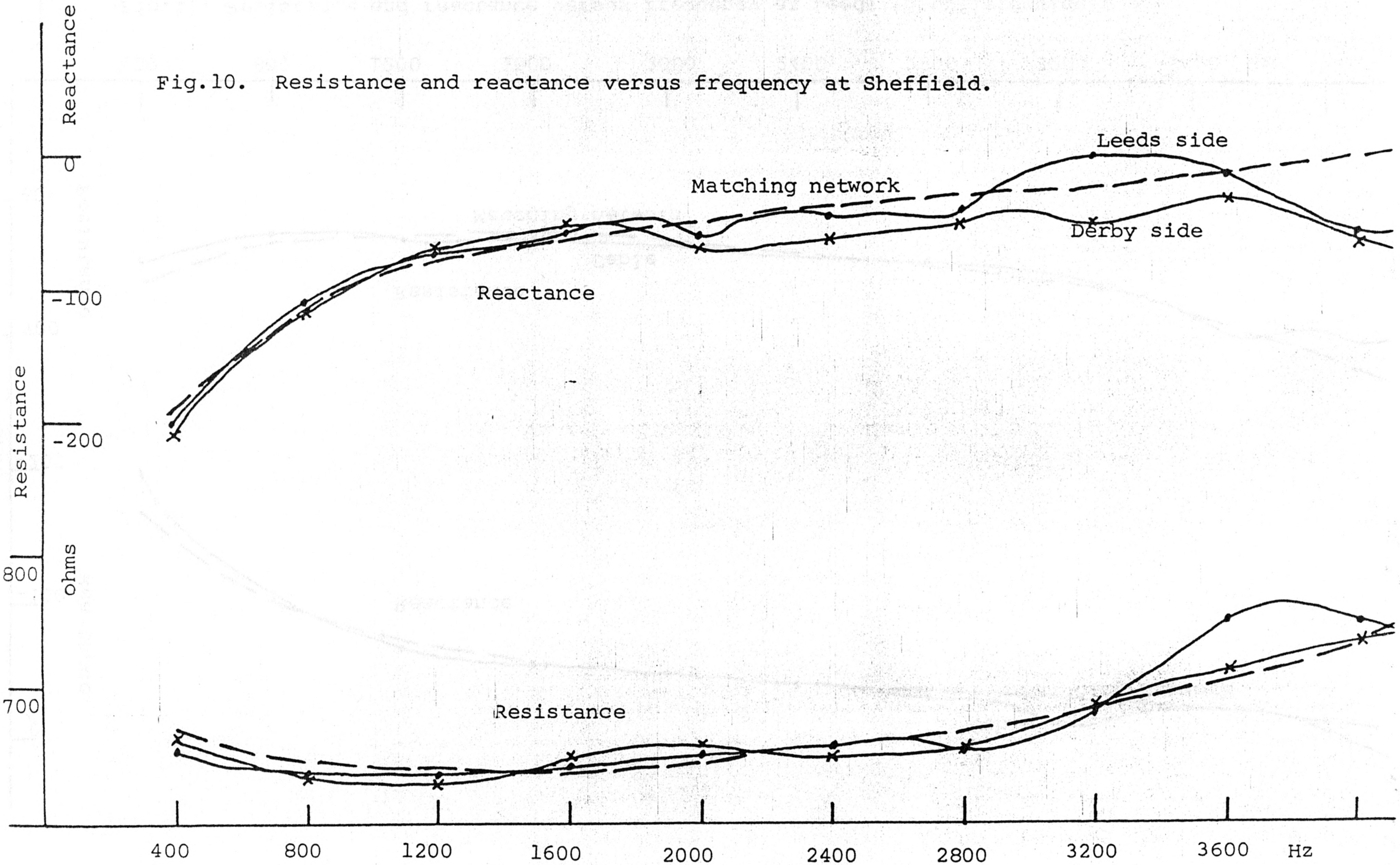

Fig.10. Resistance and reactance versus frequency at Sheffield.

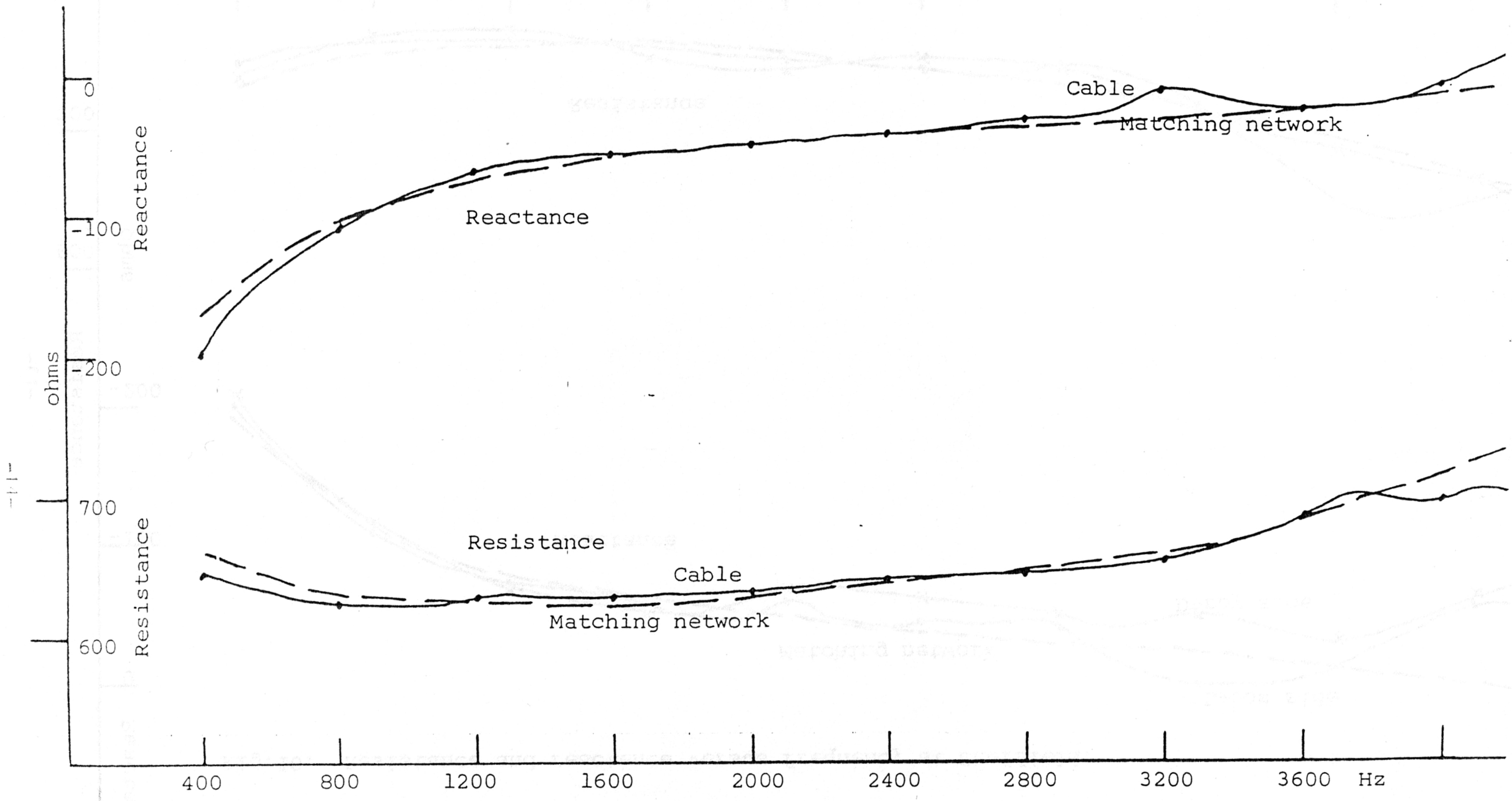

Fig.11. Resistance and reactance versus frequency at Leeds (Sheffield side).

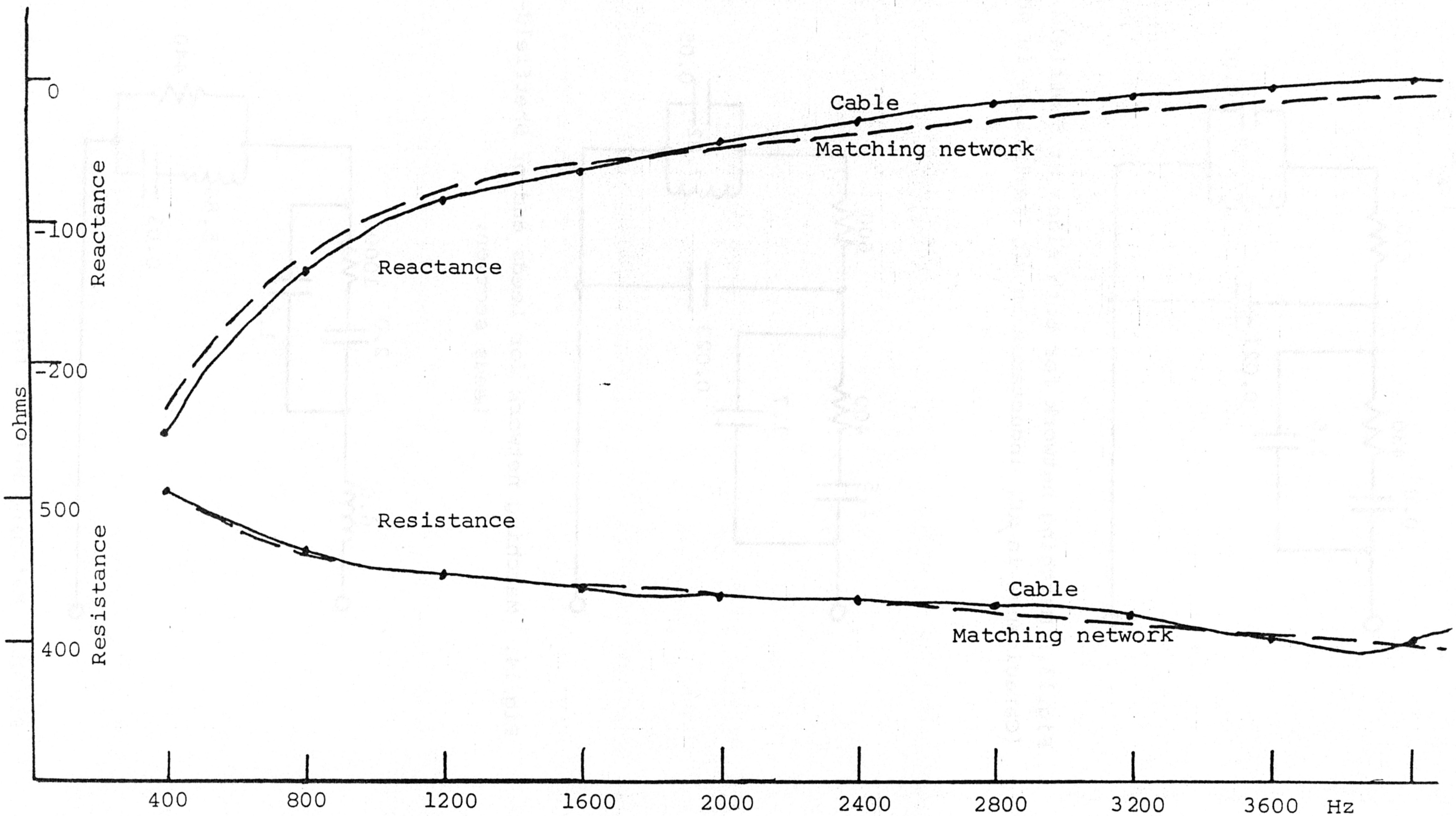

Fig.12. Resistance and reactance versus frequency at Derby (Leicester side).

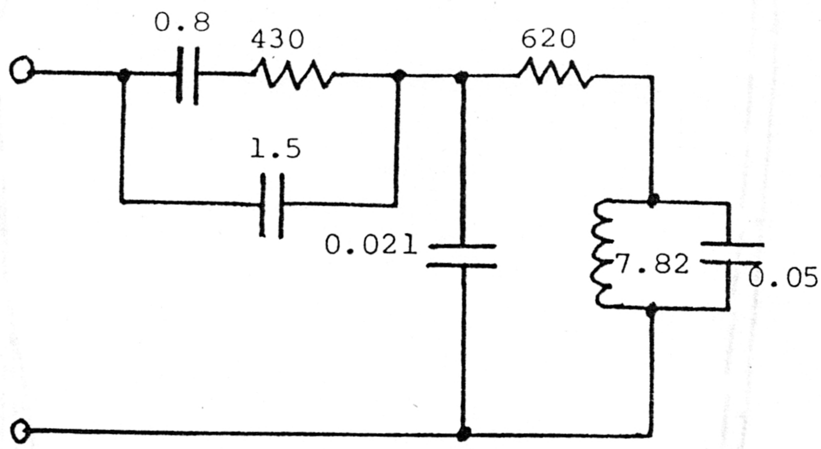

Fig.13. Matching network for both sides at Sheffield.
(Capacitance in μF, inductance in mH, resistance in ohms)

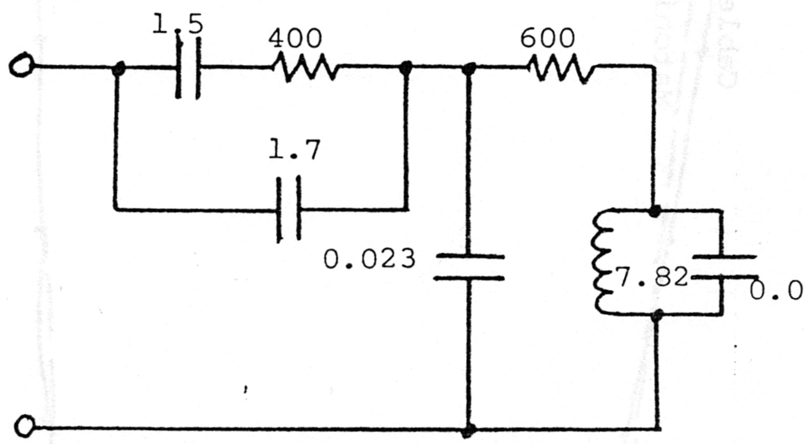

Fig.14. Matching network for Leeds end of Sheffield-Leeds section.

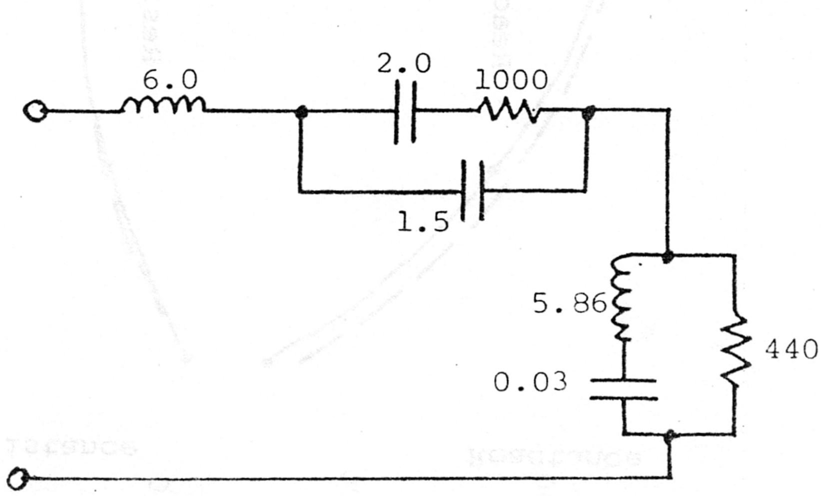

Fig.15. Matching network for Derby end of Leicester-Derby section.