THE INSTITUTION OF ELECTRICAL ENGINEERS

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

THE DESIGN AND USE OF RADIO-FREQUENCY OPEN-WIRE TRANSMISSION LINES AND SWITCHGEAR FOR BROADCASTING SYSTEMS

By

F. C. McLEAN, B.Sc., and F. D. BOLT, B.Sc., Associate Members

Reprint from

THE JOURNAL OF THE INSTITUTION, VOL. 93, PART III, NO. 23, MAY 1946.

THE DESIGN AND USE OF RADIO-FREQUENCY OPEN-WIRE TRANSMISSION LINES AND SWITCHGEAR FOR BROADCASTING SYSTEMS*

By F. C. McLEAN, B.Sc., and F. D. BOLT, B.Sc., Associate Members.†

(*The paper was first received* 12*th April, and in revised form* 31*st August*, 1945; *it was read before the* RADIO SECTION 5*th December*, 1945, *and the* HAMPSHIRE SUB-CENTRE 2*nd February*, 1946.)

SUMMARY

The paper describes the various types of transmission lines in use at transmitting stations of the British Broadcasting Corporation, their impedance, attenuation and power-carrying characteristics, together with results of various tests, general details of construction, and methods of matching the load to the transmission line. The major part of the work described was carried out before the end of 1943.

The paper is written primarily from the point of view of the engineer engaged on design and practical work in the field. Data are included enabling the most suitable transmission line for any practical purpose to be designed. The range of frequencies considered is from 0·2 to 25 Mc/s; of this range those up to 2 Mc/s are considered as medium waves and those from 2 Mc/s to 25 Mc/s as short waves.

(1) LIST OF SYMBOLS

a = Standing-wave ratio $= \dfrac{I_{max}}{I_{min}} = \sqrt{\dfrac{R_{max}}{R_{min}}} = \dfrac{R_{max}}{Z_0} = \dfrac{Z_0}{R_{min}}$.
$b = \tan 2\pi \dfrac{l}{\lambda}$.
E_c = Disruptive critical voltage between conductors, kV.
E_0, E_{min}, E_{max} = R.M.S. voltages corresponding to impedances Z_0, R_{min}, R_{max}.
f = Frequency, Mc/s.
$\mathscr{E}_c$ = Disruptive critical gradient, kV/cm(r.m.s.).
I_0, I_{min}, I_{max} = R.M.S. currents corresponding to impedances Z_0, R_{max}, R_{min}.
l = Distance along line measured from a known point, metres.
P = Power (watts) transmitted by a line $= \dfrac{E_0^2}{Z_0} = \dfrac{E_{min}^2}{R_{min}} = \dfrac{E_{max}^2}{R_{max}}$.
R_{max} = Resistance of transmission line at position of minimum current, ohms.
R_{min} = Resistance of transmission line at position of maximum current, ohms.
R_u = H.F. resistance per metre of line, ohms.
r = Conductor radius, cm.
S = Conductor spacing, cm.
Y_0 = Characteristic admittance of line, mhos.
Y_s = Admittance at sending point $= G_s + jB_s$.
Y_r = Admittance at load point $= G_r + jB_r$.
Z_0 = Characteristic impedance of line (ohms) $= \sqrt{(R_{min}R_{max})}$.
Z_s = Impedance at sending point $= R_s + jX_s$.
Z_r = Impedance at load point $= R_r + jX_r$.
α = Attenuation coefficient, nepers per metre.
λ = Wavelength, metres.
μ = Permeability, 1 for air and copper.
ρ = Resistivity, ohm-cm, $1{\cdot}78 \times 10^{-6}$ for copper.

The normalized impedance or admittance is the actual impedance or admittance at a point in a transmission line divided by the characteristic impedance or admittance of the line.

(2) OPEN-WIRE TRANSMISSION LINES

(2.1) Balanced Open-Wire Transmission Lines

(2.1.1) Two-Wire Lines.

The characteristic impedance of a two-wire open-wire line depends basically on the diameter of the conductors and their spacing. The variation of impedance due to these two factors is shown in Fig. 1. It will be seen from this curve that, from a mechanical point of view, it is difficult to construct a 2-wire line with an impedance lower than 200 ohms unless conductors of excessively large diameter can be used, or higher than 700 ohms without the use of very large spacing. The maximum power which can be transmitted by a given line is governed by the voltage at which the conductors will exhibit corona. Assuming that the line be electrically balanced, then this voltage will be twice the voltage above earth at which corona occurs. It is interesting to note that the corona voltage is practically independent of conductor spacing at spacing/radius ratios greater than 20.

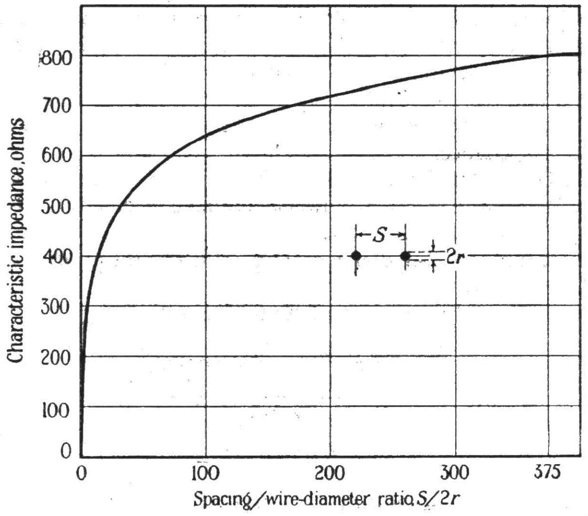

Fig. 1.—Characteristic impedance of 2-wire transmission line.

The smallest spacing between the conductors of open-wire lines is, of course, determined by mechanical considerations. In practice, for powers up to 100 kW a 2-wire line spaced to give an impedance of 500–600 ohms is found to be most suitable.

The slow change of impedance with change of spacing in a 500-ohm line is a useful characteristic, because it permits quite a large out-of-phase swing in the wires, which gives the designer much greater latitude in the mechanical desigd. It is found that even with spans up to 300 ft the variations due to this effect are negligible.

The total attenuation of a balanced transmission line depends on the copper loss, the insulator loss, the earth-current loss and the radiation loss. In balanced lines which are correctly ter-

---

* Radio Section paper.
† British Broadcasting Corporation.

minated, the radiation loss is small for frequencies up to 24 Mc/s, and losses due to insulators and the capacitance effects of the supporting structures are reduced by the correct choice of the insulating material and the dimensions of the frames. The earth-current loss is kept low by suspending the line at a height not less than ten times the line spacing above earth, and by ensuring that the voltage on each conductor is accurately balanced with respect to earth. The copper loss can, of course, be reduced only by increasing the diameter of the conductors, and the radiation loss by keeping the conductor spacing small relative to the wavelength of transmission, and by ensuring equal currents in the conductors at the same distance from the transmitter.

Using the method given in Section 2.1.3, the copper loss of a 2-wire 6 s.w.g. line is $0\cdot27\sqrt{f}$ db/km. The proportion due to leakage losses increases with characteristic impedance and, on a 550-ohm line, amounts to 67% of the copper loss. This gives the total loss as $0\cdot46\sqrt{f}$ db/km.

(2.1.2) Four-Wire Lines.

When practical considerations limit the maximum spacing between the conductors of a line, an increase in power-handling capacity can be obtained only by increasing the amount of copper used. A given increase in the weight of copper may be employed in two ways: (*a*) to increase the conductor diameter, thus raising the corona voltage limit, and (*b*) to increase the number of conductors of the original diameter, thus lowering the characteristic impedance.

The best utilization of the available copper must be considered from the point of view of power-handling capacity and attenuation. Consider first the power-handling capacity, and take as an example four 0·192-in diameter wires which have the same weight as two of 0·272-in diameter:

From Peek's formula for disruptive critical voltage[1]

$$E_c = \frac{2\mathscr{E}_c r\left(\frac{S}{2r} - 1\right) \operatorname{arc\,cosh} \frac{S}{2r}}{\sqrt{\left[\left(\frac{S}{2r}\right)^2 - 1\right]}}$$

where

$$\mathscr{E}_c = 29\cdot8\left[1 + \frac{0\cdot3}{\sqrt{r}} \Big/ (1 + 230r^2)\right]$$

E_c for 0·192 in conductors spaced 10 in = 68·6 kV
E_c for 0·272 in conductors spaced 10 in = 87·0 kV

The above formulae are accepted for frequencies of 50 and 60 c/s, and it has been shown[3, 12] that the voltage gradient for corona at radio frequencies is only slightly less than that for power frequencies.

The impedance of four 0·192-in conductors is 320 ohms, and the impedance of the 0·272-in conductors is 515 ohms. From this it follows that:

$$\frac{\text{Power-handling capacity } 0\cdot272 \text{ in}}{\text{Power-handling capacity } 0\cdot192 \text{ in}} = \frac{87\cdot0^2 \times 320}{68\cdot6^2 \times 515} = 1 \text{ very nearly}$$

That is, the maximum power-handling capacity is the same for the same amount of copper used.

If consideration is given to the effect shown by Peek (p. 72, Reference 1), that there is an additional increase in corona voltage on any wire owing to the presence of a second wire at the same potential, then by using the four lighter conductors the power-handling capacity will be increased by from 10 to 40%.

The resistances for a frequency of 20 Mc/s are found by calculation from the formulae given in Section 2.1.3 to be

H.F. resistance, two 0·272 in wires = 108 ohms/km of line.
H.F. resistance, four 0·192 in wires = 76 ohms/km of line.

The above figures give copper-loss attenuations of 0·91 db/km for two wires (Z_0 = 515 ohms), and 1·03 db/km for four wires (Z_0 = 320 ohms).

In Section 2.1.3 it is shown from measured results that the total attenuation is approximately 39% higher than that of the copper loss, chiefly owing to insulator and leakance losses.

Total attenuation, four wires = 1·03 + 0·4
= 1·43 db/km at 20 Mc/s.

Insulator losses will increase directly in proportion to line impedance, and for a 2-wire 515-ohm line will therefore be 0·4 × 515/320 = 0·64 db/km, giving

Total attenuation, two wires = 0·91 + 0·64
= 1·55 db/km at 20 Mc/s.

Although the superiority of the 4-wire line over the 2-wire line is not clear-cut, both the above considerations tend in its favour.

In running two wires parallel, the effect on the impedance will, of course, depend very largely on the spacing of the wires. If they are close together, their combined capacitance and inductance will not be very different from that of a single wire and hence the characteristic impedance will not be much changed. If they are well spaced, they will appear almost as two separate wires and the characteristic impedance will be halved.

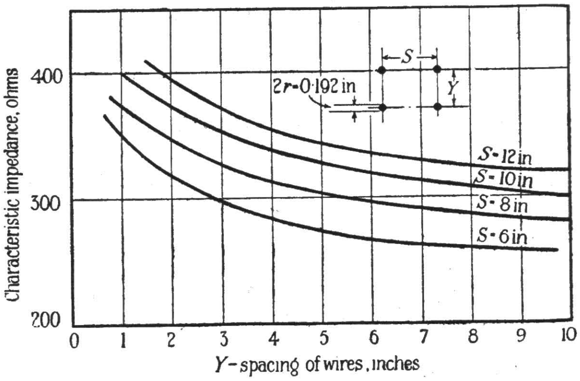

Fig. 2.—Characteristic impedance of 4-wire transmission line.

This effect is shown in Fig. 2. The curve shows that by the time the two wires on one side of the transmission line are separated by a distance somewhat less than the spacing between sides, the greater part of the impedance reduction has been realized. For convenience in mechanical rigging it is advantageous to keep the spacing small, and with the spacing normally used an impedance of 320 ohms is obtained. With a line of this impedance and using No. 6 s.w.g. wire with 10-in and 6-in spacing, a power of 130 kW 100% telephone-modulated can be transmitted on 21·5 Mc/s without corona or flashover.

(2.1.3) Attenuation.

The attenuation of a transmission line can be measured by taking current readings at two points separated by a quarter-wavelength at the load end of the line, and comparing these with current readings taken at two points separated by a similar distance near the sending end of the line.[10] If the total loss is of the order of 3 db, this method is usually sufficiently accurate, but difficulties in measuring small current variations in the field introduce errors when the total loss is small. Parallel pick-up currents on the line may also vitiate the results of such tests.

Measurements giving more consistent results can be made with a h.f. bridge. Values of the input impedance of approximately 1 km of an open-circuited or short-circuited line, over a small frequency range about the frequency of measurement, are plotted and the attenuation constant is derived. A typical result is shown in Fig. 3.

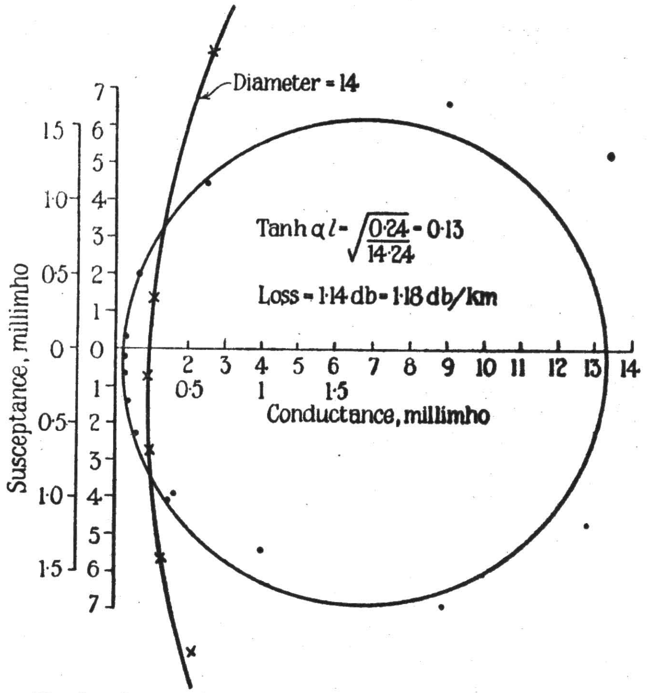

Fig. 3.—Attenuation of 4-wire transmission line; admittance circle on open circuit. Attenuation measurements: 15·2 Mc/s, 19 m, length 975 m.

Measurements on 4-wire lines of the type described show attenuations, when the standing-wave ratio on the line does not exceed 1·2 : 1, varying from 0·7 db/km at 6 Mc/s and 1·42 db/km at 17·8 Mc/s to 1·62 db/km at 21·0 Mc/s. Fig. 4 shows these losses and also the calculated loss arrived at from a consideration of the high-frequency resistance of the wire.

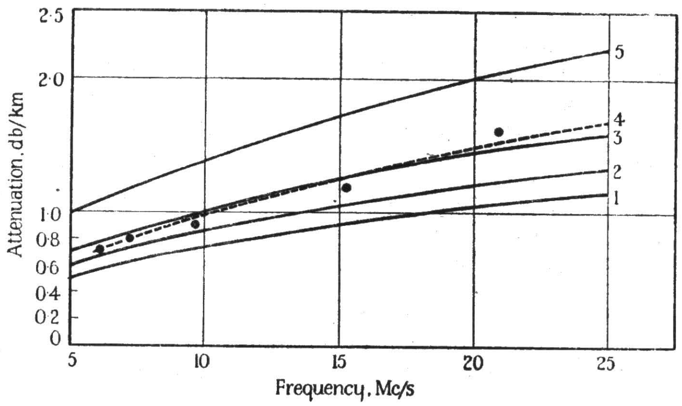

Fig. 4.—Variation of attenuation with frequency for 2-wire and 4-wire transmission lines.

Curve 1—Theoretical copper loss 320-ohm line = $0{\cdot}23\sqrt{f}$ Mc/s
Curve 2—Theoretical copper loss 550-ohm line = $0{\cdot}27\sqrt{f}$ Mc/s
Curve 3—Derived total attenuation 320-ohm line = $0{\cdot}32\sqrt{f}$ Mc/s
Curve 4—Measured attenuation 320-ohm line
Curve 5—Derived attenuation 550-ohm line = $0{\cdot}46\sqrt{f}$ Mc/s

The attenuation in db/km due to copper loss may be obtained from the following expressions:[2]

$$\frac{\text{R.F. resistance}}{\text{D.C. resistance}} = \frac{kr}{2\sqrt{2}} + \frac{1}{4} \quad \text{where } k = 2\pi\sqrt{\left(\frac{2\mu F}{\rho} \times 10^{-3}\right)}$$

$$\text{Attenuation (db/km)} = \frac{8{\cdot}68 R_u \times 10^3}{2 \times Z_0}$$

This gives the result

$$\text{Attenuation (db/km)} = 0{\cdot}23\sqrt{f} + 0{\cdot}0032$$

The constant is negligible for the frequencies under consideration.

The average length of transmission lines employed at B.B.C. short-wave transmitting stations is 0·6 km, so that at a frequency of 17·8 Mc/s the power loss is approximately 18 kW per 100 kW. By arranging the layout of the sites so that the highest frequency arrays are closest to the transmitters, the efficiency of all lines is approximately 82%.

When a standing wave is present on the line, the attenuation is increased and, assuming that the power transmitted per quarter-wavelength by the line is very much greater than the power dissipated in losses over the same length, the increase in the loss may be estimated as follows.

For a line of constant Z_0 terminated in a pure resistance of the same value, the current at any point will be $I = \sqrt{(P/Z_0)}$.

If the resistance per metre of the line is R_u ohms, the loss over any quarter-wavelength of line is

$$\frac{I^2 R_u \lambda}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the line is now terminated in aZ_0, the current at a point distance l from I_{min} will be

$$\sqrt{\frac{P}{\frac{a(b^2+1)}{a^2b^2+1}Z_0}} = I\sqrt{\frac{a^2b^2+1}{a(b^2+1)}}$$

The loss for a small length dl will be $I^2\left[\frac{a^2b^2+1}{a(b^2+1)}\right]R_u dl$

The loss over a quarter-wavelength of line will be

$$\int_{l=0}^{l=\lambda/4} I^2 R_u \frac{a^2b^2+1}{a(b^2+1)} dl = \frac{I^2 R_u \lambda}{2\pi}\left[\frac{\pi}{4}\left(a + \frac{1}{a}\right)\right] \quad . \quad . \quad (2)$$

Therefore the ratio $\dfrac{\text{Loss for standing wave} = a}{\text{Loss for standing wave} = 1}$

$$= \frac{\text{equation (2)}}{\text{equation (1)}} = \frac{1}{2}\left(a + \frac{1}{a}\right)$$

Comparing the calculated copper loss of a 4-wire line with the measured results, it is found, as to be expected, that the actual loss is greater owing to insulator and allied losses. These losses increase the constant in the expression for copper loss from 0·23 to 0·32, which means that 39% must be added to the copper loss and that the division of the total losses is: copper loss 72%, other losses 28%.

The general expression for the total attenuation of a 4-wire No. 6 s.w.g. line is therefore

$$\text{Attenuation} = 0{\cdot}16\left(a + \frac{1}{a}\right)\sqrt{f}\ \text{db/km}$$

It is of interest to note that the factor $\frac{1}{2}\left(a+\frac{1}{a}\right)$ for the increased attenuation due to the standing wave is of the same form as the expression for the centre of the circle on the impedance circle diagram, as will be seen from Appendix 8. It will be noted also that the increase in attenuation for standing-wave ratios up to 2 does not exceed 25%.

(2.1.4) **Flashovers and Corona.**

On high-frequency open-wire transmission lines of normal design where the wire spacing is much greater than ten times the wire diameter, excessive voltages tend to produce corona streamers and not direct flashovers between conductors. These streamers consist of flames projecting at right angles from the surface of the wire, the direction being determined by the force of the wind. These points of fire may travel along the wires until they reach a low-voltage point approaching a quarter-wavelength away, where they gradually fade out. Even if a flame blows right across the high-frequency line and appears to short-circuit the two wires no power arc follows.

A method of measuring these high voltages has been described by Alford and Pickles[3]; it consists of tuning a half-wave section of line into which a voltage of the required frequency is inductively fed. By measuring the current in the short-circuit and multiplying its value in amperes by the characteristic impedance of the line, the maximum voltage occurring on the test section is obtained. Measurements of this type have been confined to wires generally used in aerial and transmission line systems, together with qualitative tests on insulators, etc.

The results of a series of measurements on No. 6 s.w.g. copper wires spaced from 3½ in to 18 in are shown in Fig. 5. It will be seen that there is a considerable divergence between the results of successive applications of the same voltage, but that the corona voltage is affected only very slightly by the spacing between the wires down to the 3½-in limit of the tests. As a result of these tests and also on the basis of past experience, the maximum working voltage considered advisable on No. 6 s.w.g. wires is 21 kV r.m.s. equivalent to 30 kV peak between wires, or 15 kV peak to earth.

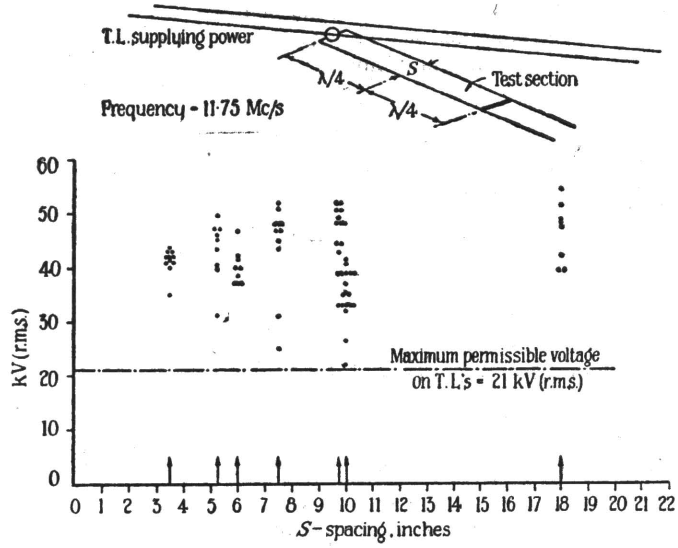

Fig. 5.—Corona breakdown results on No. 6 s.w.g. transmission lines.

Tests on 12 in rod insulators of the type normally used for supporting aerials and transmission lines[5] have shown that these have a corona limit between 26 and 47 kV, depending on the accuracy with which the packing between the end caps and the porcelain is set. In other words, this packing should not project beyond the end cap. Here again a good working maximum value is 30 kV peak. When these insulators are fitted with corona rings, the permissible voltage is greatly increased, and in tests made it has been found impossible to cause corona up to the maximum voltage obtainable, namely 60 kV r.m.s.

Various tests on the brass clamps, bolts, etc., used in the construction of the lines indicated that these also were satisfactory at 30 kV peak, no special care being taken to remove sharp points or to round off the edges cut by a guillotine or press tool, although when a breakdown did occur on such details it originated at those projections and sharp edges. The increased cost of these items if smoothed off would not, however, be accompanied by an equivalent increase in the permissible working voltage.

In general the effects observed in these tests were very similar to those mentioned by Alford and Pickles.[3]

The frequency at which these corona measurements were made was 11·75 Mc/s, but operating experience indicates that there is no appreciable change in flashover voltage with frequency.

Owing to the difficulty of making an adjustable short-circuit on a 4-wire line, similar tests have not been carried out with this configuration, although it is to be expected that such lines would have a slightly higher corona voltage than 2-wire lines of the same gauge of wire as stated in Section 2.1.2. It has been noticed that corona is less evident on stations employing 4-wire lines of 320 ohms characteristic impedance than on those employing 2-wire lines of 550 ohms characteristic impedance, when carrying powers calculated to give the same maximum voltage in the matched condition.

(2.1.5) Dissipative Transmission Lines.

Transmission lines having a large dissipation per unit length in the form of high-resistance conductors have been employed as test loads. The most satisfactory form is that in which the line is graded throughout its length in order to produce an approximately constant power-loss per unit length. By this means the size of the wire can be progressively reduced along the line, and hence the total length can be reduced.

Provided the attenuation of the line is sufficiently high it can be terminated in a short-circuit or open-circuit, as the reflected wave arriving back at the transmitter terminals will be attenuated by twice the forward attenuation. If the percentage change in impedance Δ at the transmitter terminals is not to exceed $\pm 5\%$, then the attenuation required is 16 db. For normal purposes, however, a forward attenuation of approximately 11 db, giving an input impedance variation of $\pm 15\%$, is adequate. The relevant expression is $\tanh \alpha l = 1 - \Delta$.

For a description of an exponential dissipative line, in which the length, for a given loss and power, is less than for a uniform line, see Burrows.[4]

(2.2) Unbalanced Medium-Wave Open-Wire Transmission Lines

(2.2.1) Impedance Curves and Results for Various Multi-Wire Lines.

As the aerial system at most medium-wave transmitting stations is unbalanced, unbalanced transmission lines of various types of construction are used. The choice of line is again largely determined by power, and hence voltage, considerations, but in view of the large power often involved the question of attenuation is also important. A loss of 0·5 db at a 10-kW station represents a loss of 1·1 kW of r.f. power, equivalent to 3·75 kW at the mains. The same loss at an 800-kW station would mean, however, 89 kW of r.f. power and 300 kW at the mains. It is therefore very necessary on high-power stations to keep the attenuation down to a minimum, even at the cost of heavier transmission lines.

The attenuation is caused by the following factors:

(*a*) *Copper loss* is one of the most important losses, but is readily reduced by increasing the copper section and by dividing up the conductors into a number of paths in parallel.

(*b*) *Insulator loss* is generally less than the copper loss, but it is desirable to keep the volume and number of insulators to a minimum.

(*c*) *Radiation losses* are usually small and are kept so by close spacing of the conductors and, of course, by correctly terminating the line.

(*d*) *Earth currents* can be a source of serious loss, as such currents are liable to flow through highly-resistive paths. The outer conductors should be arranged to screen the inner conductors efficiently from earth and metal supports; a number of small-gauge wires are therefore preferable, but this has the disadvantage of increased mechanical complexity. Where earth connections are necessary, as for example at supporting poles, these should be of low resistance. To ensure that the return current flows mainly in the outer conductors, their inductance must be small compared with alternative paths through earth.

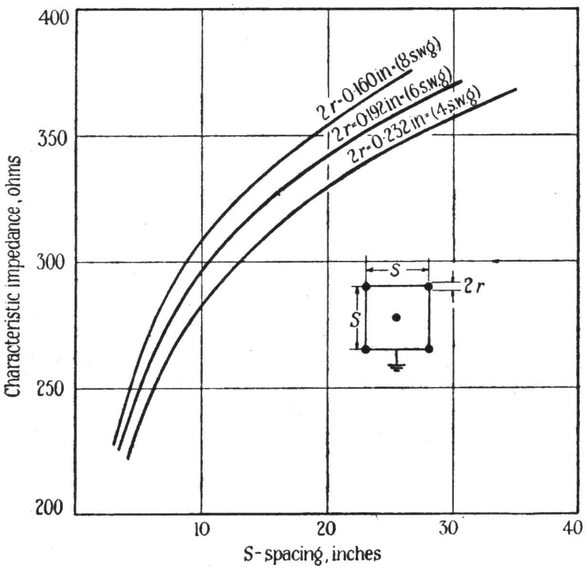

Fig. 6.—Characteristic impedance of 5-wire transmission lines.

Impedance values for 5-wire transmission lines are given in Fig. 6.

The multi-wire transmission lines in service are as follows:—

No. of wires	Outer wire spacing	Inner wire spacing	Wire size (s.w.g.)	Weight of copper per km	Impedance	Loss (1 Mc/s)	Power rating
				lb	ohms	db/km	kW
5-wire	12 in square		6	1 825	310	0·6	100
6-wire	15 in square	2½ in	6	2 190	220	0·5	150
12-wire	36 in dia.	8 in square	6	4 380	135	—	400
12-wire	36 in dia.	8 in square	4	6 400	125	0·27	800

(2.2.2) **Attenuation Values.**

Unbalanced transmission lines have been found to have a relatively greater loss than balanced transmission lines, and the attenuation of a 5-wire line of 310 ohms characteristic impedance consisting of four earthed outer wires on a 12 in square and a live central wire, all of No. 6 s.w.g., is 0·6 db/km at frequencies of the order of 1 Mc/s.

The average medium-wave line has a length of about 0·25 km, and for this length on frequencies of the order of 1 Mc/s the loss is 0·15 db, i.e. the efficiency of the line is about 96%.

For a high-power transmitter where it was necessary, owing to the high power and the longer length of line involved, to keep the attenuation at the minimum possible, a 12-wire line having four inner wires and eight outers, as shown in Fig. 14, was constructed. This line had the performance shown in Fig. 7; in particular, the attenuation at 1 Mc/s was 0·27 db/km. This line has approximately 3·5 times the amount of copper in the 5-wire line and, as shown above, the attenuation of the 5-wire line is 2·2 times greater. The 5-wire line has a copper weight of 1 825 lb/km, whereas the 12-wire line weighed 6 400 lb/km.

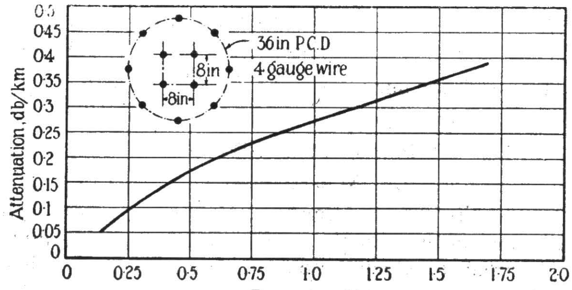

Fig. 7.—Variation of attenuation with frequency for 12-wire transmission line.

(3) CONSTRUCTIONAL DETAILS

(3.1) Balanced Transmission Lines

The 4-wire type of line is now in general use for powers above 50 kW. A typical transmission line route is shown in Fig. 9. The basic decisions reached for the Daventry station[5] have not been changed, but the method of construction has been steadily improved and at the same time its cost reduced owing to simpler mechanical construction and the use of longer spans. The main changes have been:—

(*a*) Use of four wires instead of two.
(*b*) Reduction of conductor tension from 400 lb to 150 lb, so that, while the same strength of conductor has been retained, it has been possible to eliminate the transmission-line counterweights.
(*c*) Increase of span lengths from 80 ft to 150 ft.
(*d*) Reduction in insulator length from 16 in to 12 in, and elimination of corona rings.
(*e*) Simple tubular construction used for supports.
(*f*) Simplification of bay-line switching and wiring.

All frameworks are made from standard scaffold-tube fittings, which are easily obtainable. Their use reduces the cost of the job and considerably shortens the time required for delivery. Wherever possible, standard l.v. distribution fittings are employed.

The possible difficulty of maintaining correct conductor spacing in a 4-wire line under wind conditions did not materialize, and a line of the configuration shown in Fig. 2 has proved satisfactory for spans up to 180 ft without horizontal insulating spacers, but vertical conducting spacers have been used at suspension points and at intermediate points.

Ground clearance has been maintained at 10 ft minimum, thus requiring, in view of the longer spans and lower stringing tension, somewhat higher supports. The type of support shown in Figs. 10 and 11 is economical at this height, and without change of general design can be increased by some 2 ft in special cases.

The frames have a height when erected of 12 ft for the tension frames and 14 ft for the suspension frames, and a width of 6 ft. They are made of steel scaffold-tubing 1·29/32 in o.d. and 9-s.w.g. wall. The tubes are interlinked by a patented scaffold-tube clamp which has proved very satisfactory in service.

A test on a frame set in good ground showed that the legs buckled at a side pull of 1 ton and that the foundations loosened at a slightly lower figure. Under the worst working condition, when the line turns through 45°, the maximum side force is 450 lb.

The bay transmission lines, that is the transmission lines connecting the aerial bays, were simplified and reduced in cost by the substitution of a direct short-circuit across the lines, as shown in Fig. 12, for the quarter-wavelength line switches originally used. This device was not only cheaper than the switches it replaced, but also allowed the lines to be brought down to a height of 10 ft above ground level, thus permitting shorter supports.

It is, of course, important to maintain the characteristic impedance as nearly constant as possible throughout the whole

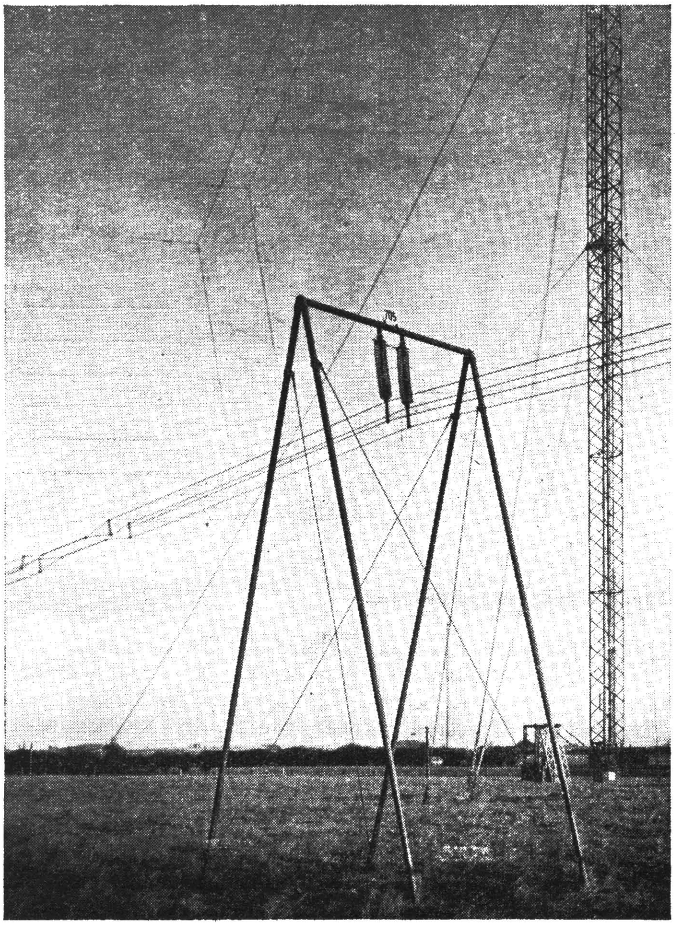

Fig. 11.—Support frame used for 4-wire transmission line, showing static leak coil and line-matching section.

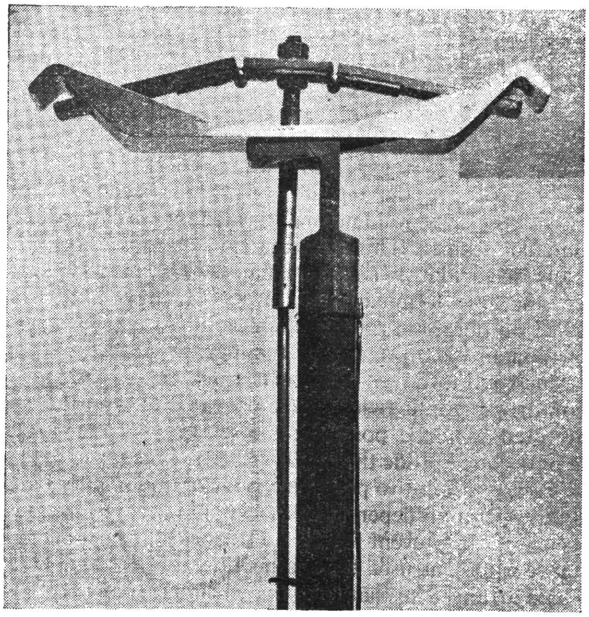

Fig. 12.—Transmission-line short-circuiting switch.

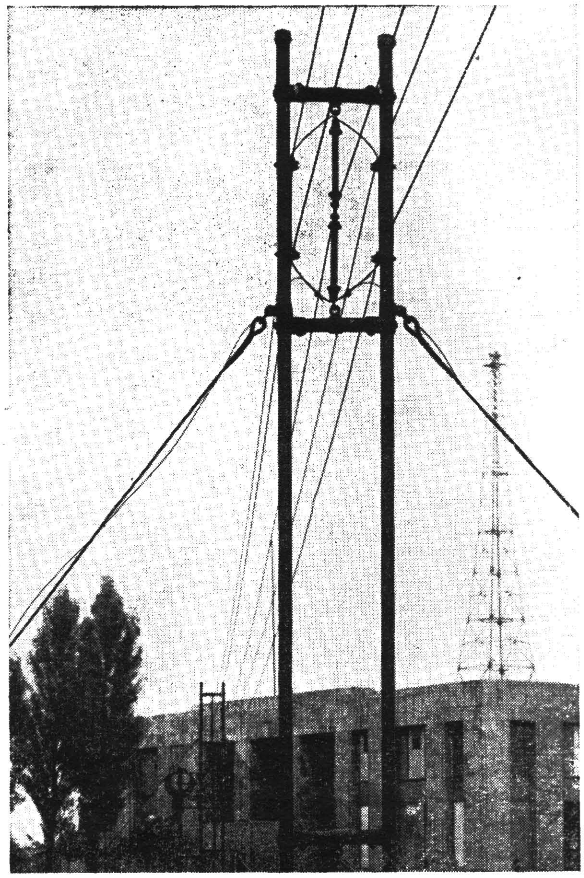

Fig. 13.—Medium-wave 5-wire transmission line.

With this system a 2-h.p. driving motor has to be used, and as the location of the switch in each position depends on friction, a reliable braking system must be incorporated so that the amount of travel after the limit switches have operated shall be the same in both summer and winter. That is, the braking force available must outweigh any variation in friction due to weather conditions.

The system has been in use for several years and has proved quite successful; but it requires regular maintenance and has in new installations been replaced by an improved design, where switch positioning does not depend on friction for its accuracy. The arrangements for terminating the lines and for bringing them into the tower are as previously described, as these have proved entirely satisfactory. The modification lies in the means used for locating the line switch itself.

The general design of the mechanical selector is shown in Fig. 16; a photographic view is reproduced in Fig. 17. The rotating arm of the line switch is carried on a boom fixed to a horizontal turntable mounted on the deck of the tower. Fixed to the turntable is a large Geneva wheel with slots at intervals of 45°. The striker arm for the Geneva wheel is rotated by a motor and moves the plate through 45° at each step. This gives a positive location to the moving contacts of the switch, and the accuracy is such that the switch is located to within 1/8 in of its correct position at each movement. The movement is mechanically correct in that the driver arm enters the slot in the Geneva wheel radially, and the plate is then accelerated uniformly from rest until it reaches a maximum velocity after a movement of $22\frac{1}{2}°$, when it decelerates until, after a further movement of $22\frac{1}{2}°$, the driver arm leaves the slot and the plate is once more at rest. The driving motor is then tripped by limit switches and, since

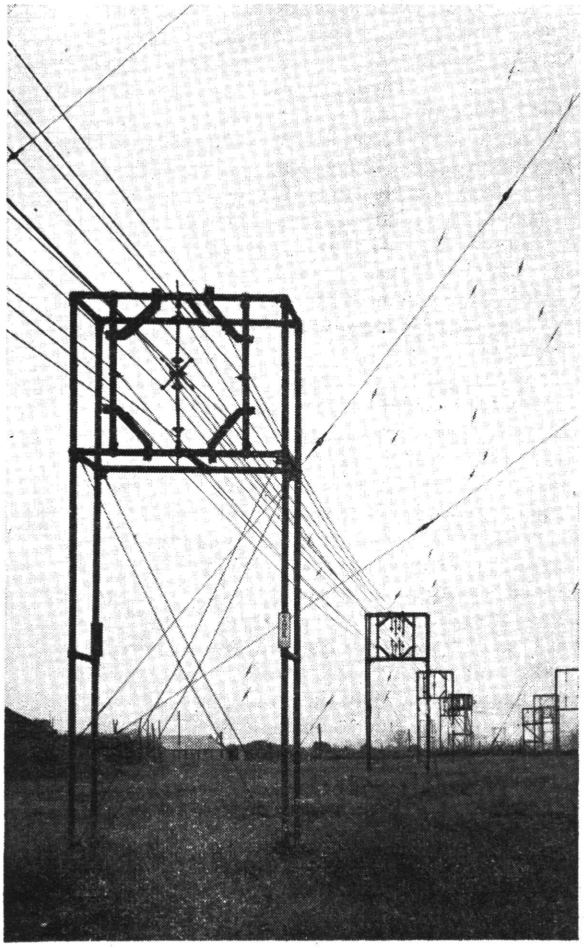

Fig. 14.—12-wire transmission line.

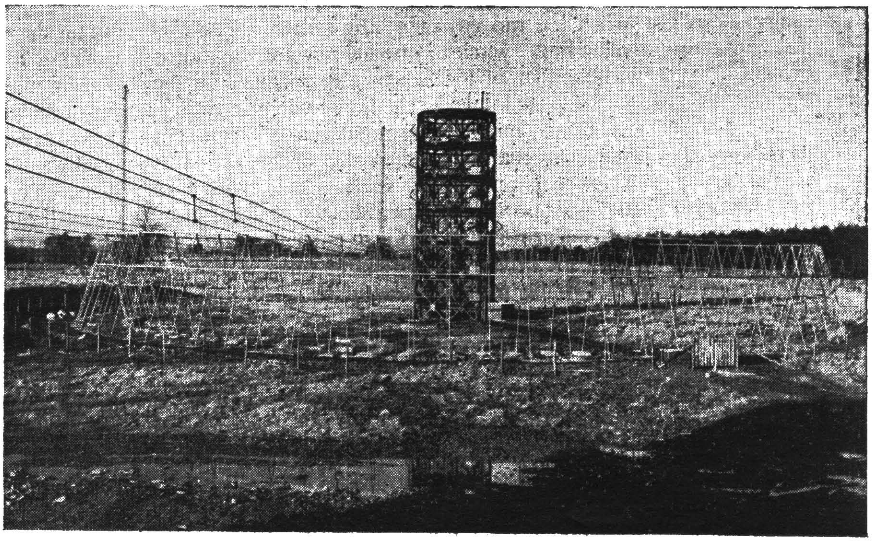

Fig. 15.—General view of automatic switching tower and circular terminating frame (H.T. frame).

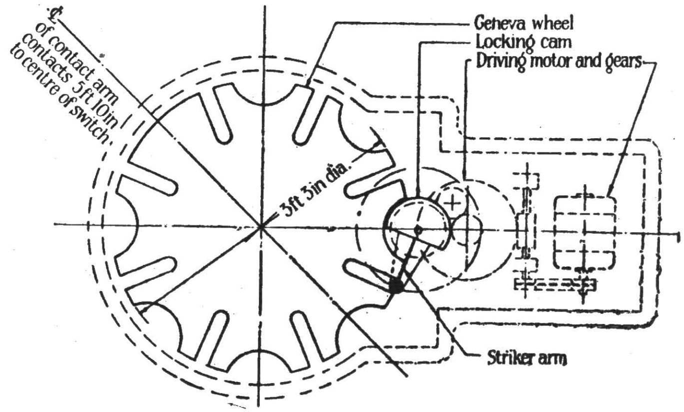

Fig. 16.—Simplified diagram of switching-tower mechanism.

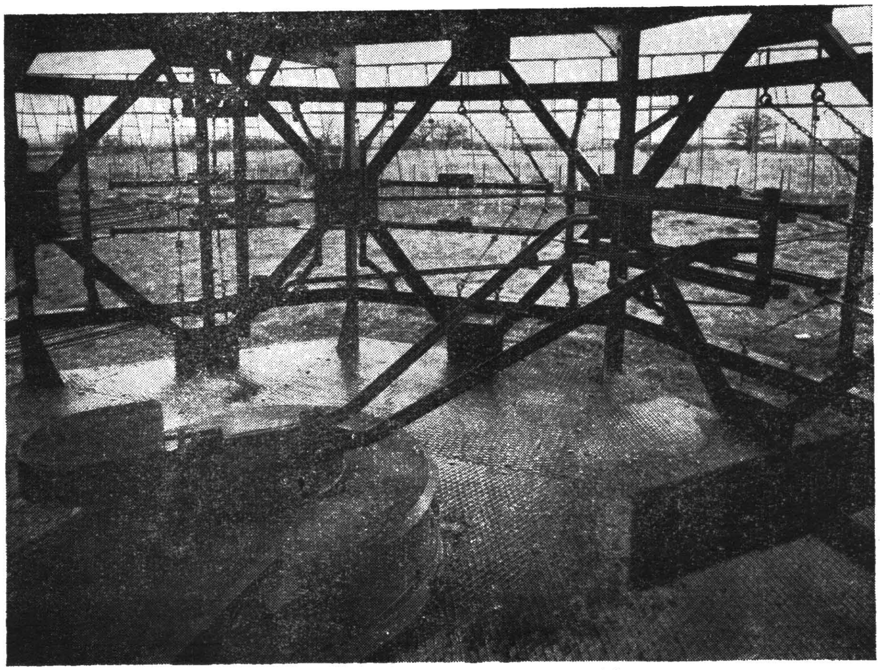

Fig. 17.—General view of one level of switching tower.

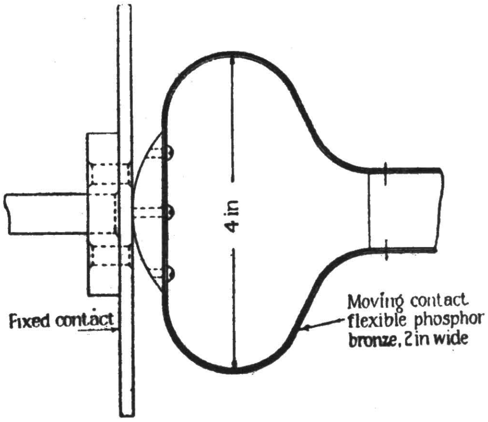

Fig. 18.—Switching-tower contact.

the striker arm is then disengaged, the time taken for the motor to stop does not affect the movement of the switch. There is thus ample time for the limit switch to operate and for the motor to come to rest, without fear of the driver arm engaging in the next slot, so giving a wide tolerance in the limit-switch setting.

As the whole mechanism might be brought out of alignment by moving the switch arm manually when the striker arm was disengaged, a cam on the driver-arm shaft was provided to interlock with a cut-away portion of the Geneva wheel, rigidly locking it until the driver arm is just about to enter the next slot. For manual operation, the driving motor can be put out of mesh and the striker arm can be rotated directly by a tommy bar through its shaft.

The complete mechanism is enclosed in a weatherproof housing, and by careful design the total height from the deck has been kept down to 15 in. It is, of course, important to reduce the metal of the switch mechanism to a minimum in order to avoid an appreciable capacitance across the line which would introduce a standing wave.

The hook-and-eye type of contact is obviously unsuitable for any mechanically-operated switch, and experiments were carried out to determine the best alternative type. It was found that a tangential contact having fairly high pressure and good thermal conductivity gave the best results. The contact used is shown in Fig. 18. The contact pressure is about 2–3 lb. This type of contact has proved entirely satisfactory and will break and remake contact on iced surfaces.

Line selection is controlled by relays and selector switches of the type used for lift controllers. In addition to the line-selector relays, a second relay has been added at each position. The contacts of this second relay are included in the transmitter interlock circuit so that power cannot be applied to the transmitter unless a manually-operated key switch controlling this relay is closed, the line selector being at the required position. Anyone working on a line takes the associated key with him, thus preventing power being put on that line.

(4.3) Bay Transmission-Line Switching

Short-wave aerials can be slewed by advancing the phase of one half of the array a given amount in front of the other half.[5] The method of carrying out the necessary switching to effect this phase advance is shown in Fig. 9. Each tapping is brought to a common switching point, known as a C-frame, at which a flexible section of line, attached to the main line, can be connected to any one of a maximum of six taps. The C-frame is shown in Fig. 19.

One end of each of the tap lines is permanently attached to the bay line, so that, when not in use, their lengths must be so adjusted that they will have the minimum effect on the characteristic of the bay lines. This is done by short-circuiting them one quarter-wavelength from their point of junction with the bay lines, using the short-circuiting switch shown in Fig. 12. The C-frame switch is of simple design and consists of flexible leads and contacts as already described. Tension is applied to the contact by means of a spring insulated from the live lines and anchored to the ground.

Each position on the C-frame is labelled with the bearing of the maximum radiation from the array when fed from that position. On a six-bearing array, the C-frame has six positions, and four short-circuit switches are used, two to short-circuit the tap lines connected to the same side of the array as the working tap, and two to short-circuit the lines of the reflector curtain in the tuned position. These switches are carried into new positions when the bearing of the array is changed.

At Daventry and certain other stations, the system of switching used was that of open- or short-circuited subsidiary quarter-wave lines. This had the advantage that all switching operations were carried out at ground level, but it was complicated by the additional lines required, and, what is more important, it was necessary to raise the bay lines to accommodate a quarter-wavelength of wire between them and ground level. This represented a very considerable expense, particularly in the case of the longer wavelengths.

It was therefore decided to carry out the line short-circuiting directly on the line and so simplify the mechanical construction. After experiments the pole-operated switch referred to above was evolved. The position for the switch is marked by means of wire bound to the line, and it is quite a simple matter to connect the short-circuiting switch directly across the line at this mark and to clamp it into position. A further advantage of the later method is that when an array is operated on any one of, say, six bearings, i.e. three bearings in the forward direction and three bearings in the backward direction, it is readily possible, with the quarter-wave type of line switch, for an unskilled operator to make a mistake and to have several of the quarter-wave switches in the wrong position. With the direct-operated switch, it is still possible for the operator to make a mistake, but the number of possibilities is smaller, in that for a six-bearing array there are only four short-circuiting switches and one hook switch to operate, instead of fourteen quarter-wave switches.

Direct short-circuiting has an added advantage when an aerial array has to work on a band of frequencies, as only the position of the short-circuit is affected by the frequency change. Both position and length of a quarter-wave switch are affected.

(5) TRANSMISSION-LINE MATCHING (BALANCED LINES)

(5.1) Permissible Standing-Wave Ratio

In general, the impedance of the aerial array into which a line delivers power will not equal the characteristic impedance of the

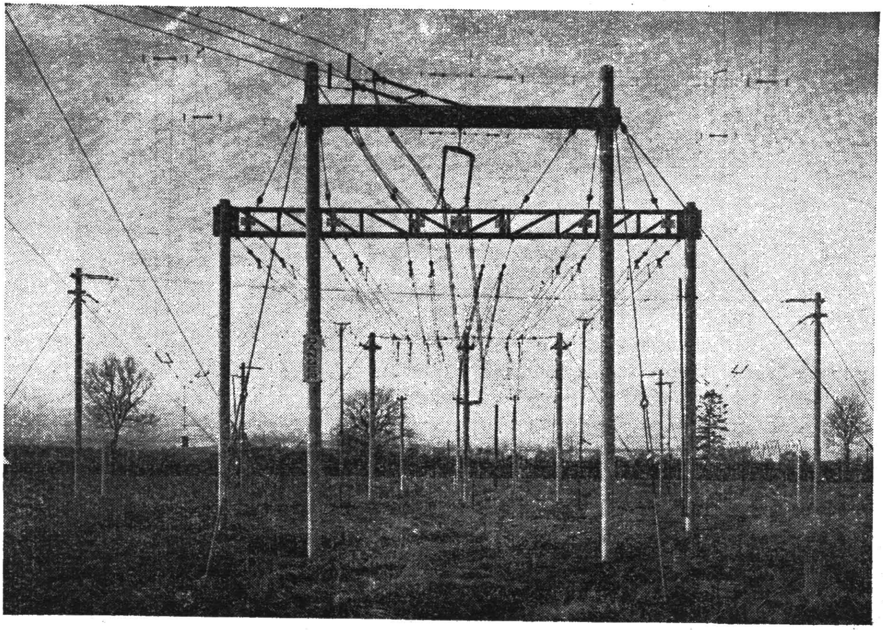

Fig. 19.—General view of C-frame, showing transmission-line short-circuiting switches.

line. If no steps are taken to match the load impedance to the line Z_0, the well-known effect of a standing wave is produced, resulting in higher voltages and currents than necessary for the power transmitted, as well as increased losses and a varying input impedance.

The problem of matching is fairly simple when only one frequency need be considered, but when an array must accept power over a band of frequencies, say ±2% about a mean, it becomes very much more involved. In fact, a true match cannot be obtained over the whole band, and some standing wave must be tolerated.

The standing-wave ratio *a* which can be tolerated on a 320-ohm line carrying 130 kW is determined as follows:

Maximum voltage across the line
= 30 kV peak (see Section 2.1.4) = 10·5 kV r.m.s.

Therefore maximum standing-wave ratio $a = \frac{E^2_{max}}{P.Z_0} = 2\cdot65$

The increase in attenuation would be $\frac{1}{2}\left(2\cdot65 + \frac{1}{2.65}\right) = 1\cdot5$,

or 50% for this ratio of standing wave. Fig. 20 shows that the range of resistance and reactance into which the output circuit of the transmitter would have to work would be very large. A limit to the permissible ratio is set by the range of coupling and tuning available in the transmitter output circuit.

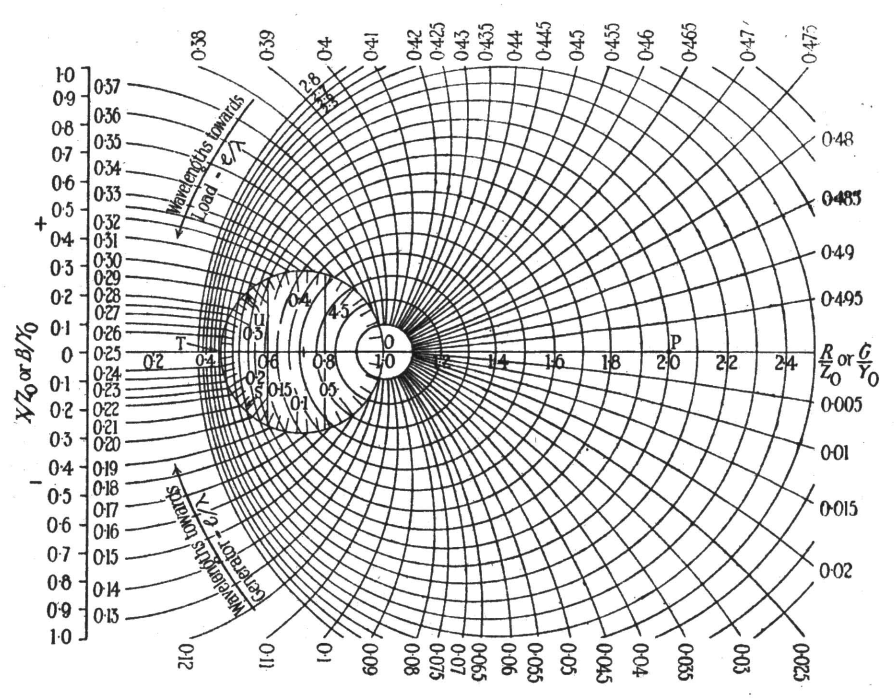

Fig. 20.—Circle diagram for matching on 4-wire transmission line.

The following conclusions have been drawn:

The standing-wave ratio at the transmitter must not exceed 1·9 in order to meet the transmitter output-circuit limitations. This calls for the standing-wave ratio on the major portion of the system to be not greater than 1·4, but it is generally not worth while trying to obtain a ratio less than 1·1.

If the line meets the above conditions, then the maximum power-handling capacity will be increased from 130 kW to $\frac{2\cdot65}{1\cdot9} \times 130 = 180$ kW.

(5.2) Matching with Stub Lines

A full account of how a load differing from the characteristic impedance of a line may be matched to a given line is given by Sterba and Feldman.[6] The curves in their paper are not in a very suitable form for general use, and in practice we now use the diagram shown in Fig. 20, which is also applicable to other types of matching.

Briefly, the method adopted is to establish where on the line the apparent admittance has a conductive component equal to that of the characteristic admittance of the line, and to cancel out the remaining susceptance by means of a stub line having a susceptance of equal value and opposite sign. Referring to the simplified diagram of Fig. 21, if the load into which the line is required to work produces a standing-wave ratio $a = 3$, then at points B and C the apparent admittance will be $1 - j1\cdot16$ and $1 + j1\cdot16$ respectively. It will be seen that, moving towards the transmitter, point B is $0\cdot083\lambda$ and C is $0\cdot417\lambda$ from the position of maximum current A. These admittances will be repeated every $0\cdot5\lambda$, so that if distances are measured from A towards the load, C will occur at an interval of $0\cdot083\lambda$ and B at one of $0\cdot417\lambda$.

If, therefore, a stub having a susceptance of $+j1\cdot16$ is attached to the line at point B, or alternatively one of $-j1\cdot16$ attached to the line at point C, then the result will be an admittance $=1 \pm j0$, and from that point up to the transmitter the line will be matched. If the stub has the same characteristic impedance as the feeder, its required length is also found from the diagram by treating it as a line terminated either in zero or infinite admittance, the standing-wave ratio on it then being infinite, and the *a* circle coincident with the *y* axis of the diagram.

If it is decided to use a short-circuited stub, then its termination will be infinite conductance and, measuring from the termination towards the generator, a length of $0\cdot12\lambda$ will give an admittance $-j1\cdot16$, which should be added at point C. If the length of the stub is increased to $0\cdot38\lambda$, its admittance will be $+j1\cdot16$, and this added at point B will give a match. Similarly for an open-circuited stub on which the terminating admittance is zero, the lengths will be $0\cdot38 - 0\cdot25 = 0\cdot13\lambda$ for a susceptance of $+j1\cdot16$, and $0\cdot25 + 0\cdot12 = 0\cdot37\lambda$ for a susceptance of $-j1\cdot16$. Space considerations will usually decide in favour of one of the shorter stubs being used.

This method is very convenient and easy to adopt; but it suffers from the disadvantage that stubs must be suspended from the lines, so that, if the resulting ground clearance is to be maintained, higher supports will be required, or alternatively protective fences provided round the stubs. For these reasons other methods are preferable.

Obviously an open-circuited stub could be replaced by a lumped capacitance connected across the line at the same point. When the required susceptance is small and positive, a lumped capacitance consisting of an insulator fitted with large corona rings can be conveniently employed.

(5.3) Matching by Changing Transmission-Line Impedance

It is well known that if a purely resistive load is to be matched to a line, this can be easily effected by inserting between the load and the line proper a quarter-wave section whose characteristic

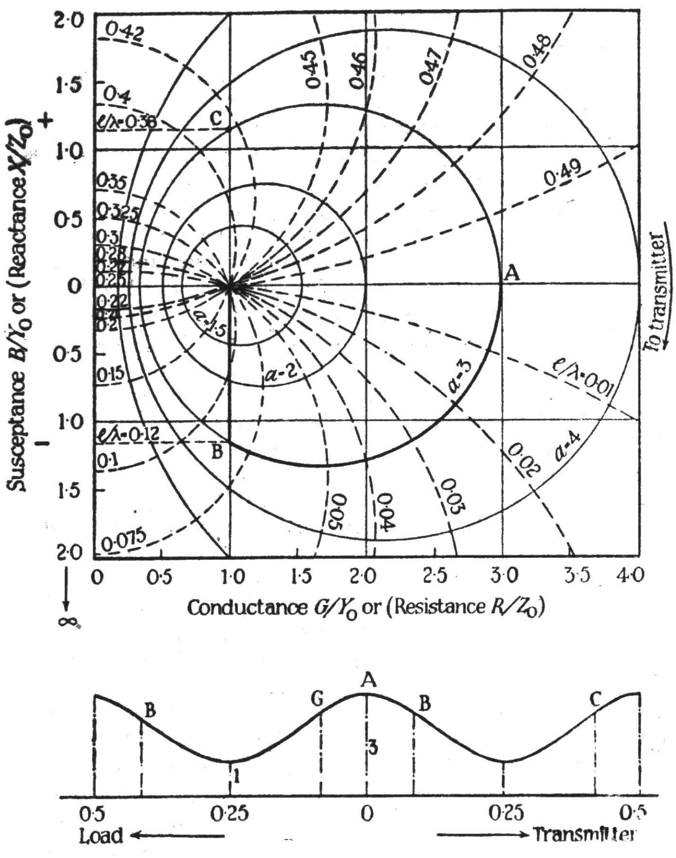

Fig. 21.—Simplified circle diagram.

impedance is the geometric mean between the impedance of the line and the impedance of the load. This method can be extended to match loads which are not purely resistive, by inserting an appropriate length of line differing in impedance from that of the line to be matched. The amount of mismatch that can be corrected by this means depends on the difference of the two characteristic impedances employed, as will be seen from Section 8.

Thus, on a 2-wire line with a spacing of 10 in, if a further pair of wires is hung 6 in below the line of characteristic impedance 510 ohms, the resulting characteristic impedance will be 320 ohms, being equivalent to the 4-wire line already described. On 4-wire lines of characteristic impedance 320 ohms, by pinching the wires together on the 6 in dimension, the resulting line has an impedance of approximately 480 ohms. By inserting a suitable section of modified impedance in the correct position, standing waves up to that which would be cancelled out by a quarter-wave section, i.e. $(480/320)^2 = 2{\cdot}25$, can be eliminated. The required position and length of the modified section are found from the curves in Fig. 20 or 25; the method is described in Section 8.

The impedance diagram of the form shown in Fig. 20 has been used by the B.B.C. since 1936; it can be plotted on a mesh of orthogonal circles instead of the rectangular mesh shown. The *a* circles are then concentric and the *b* circles equally-spaced radials.[7]

Another example of the circular form is given by P. S. Carter,[8] who plots the reflection coefficient $\frac{I_{max} - I_{min}}{I_{max} + I_{min}}$.

For a full description of the theory of the circle diagram, see Reference 13.

(5.4) Re-entrant Loop Matching

A further method of matching has been described by Alford.[9] It is based on the principle that if two points on a line on which there is a standing wave are joined together by a subsidiary line of a given length, then the two points and the length of the subsidiary line connecting them can be so chosen that the standing wave is cancelled out. This method has no practical advantages over that described in Section 5.3 for matching, except for matching high standing-wave ratios; it is chiefly of interest in its application to filters.

It is interesting to note, however, that the additional pair of wires described in Section 5.3 can be considered either as a modification to the line impedance or alternatively as a re-entrant loop, since it consists of a section of line separated by 6 in from the main line; it is therefore connected between two given points and is approximately 1 ft longer than the main line. It is found that these two ways of regarding it give results in very close agreement.

(5.5) Transmission Lines as Filters

As indicated in Section 5.4, line lengths can be used as filters and will give a very sharp frequency discrimination. Full treatment is given by Alford.[9] For normal sites, however, it is not usually worth while to put more than one frequency at a time on a line, as the additional complication outweighs the saving in the cost of another line, especially as the double voltage will require a radical change in the design if the power on each frequency is to be greater than 180/4 = 45 kW.

The short-circuiting bars connected across the 4-wire line do, however, form a type of filter, as when, for any given frequency, the bars are very near to a half-wavelength apart, the two conductors in parallel form a resonant circuit and introduce a high impedance in series with the line. For the operating frequency, it is, of course, necessary to ensure that the short-circuiting bars are never at this spacing. If the bars are located at the right spacing for any undesired frequency, then a very efficient filter is obtained.

If a short-circuited stub line of the type described in Section 5.2 is connected to the line and its length adjusted to $\frac{1}{4}\lambda$ of the frequency carried by the main line, it will have little effect on the line conditions, since its reactance will be extremely high. To any in-phase voltage of a different frequency, the stub line will have a relatively low impedance to earth, and hence the unwanted in-phase voltages will be reduced.

This use of stub lines has been of value in reducing the amplitude of sum and difference frequencies radiated by transmitters owing to unwanted-frequency voltages being fed into the anode circuit of one transmitter by a coupling existing between its transmission line and the aerial of another transmitter.

(5.6) Matching over a Band of Frequencies

A development of matching is that it is possible to match on two frequencies. That is to say, should the impedance of the aerial vary over a band of frequencies ± 2% of the mean frequency on which it is required to work, then it can be matched on two frequencies in the band. Further, subject to certain conditions, the mismatch remaining on frequencies in the band between the two for which exact matching has been applied, will be less than it would have been in the unmatched condition.

Briefly, the parameters of the matching section used, i.e. the distance from the load (or known point on the line close to the load), and length, are so chosen that they are correct for the two frequencies on which exact matching is applied. That this is possible will be evident when it is remembered that, at a single frequency, these parameters are unchanged when increased in steps of $\frac{1}{2}\lambda$, but their effect at a different frequency is progressively altered. At a certain calculable length, they will have altered sufficiently to give the necessary parameters to match the line-load conditions on a second frequency, while their corrective effect on the first frequency remains.

The B.B.C. Research Department have investigated this question for the different types of matching described above, and have established the requirement to be met in order that matching at the two chosen frequencies will also lead to approximate matching in the intermediary band of frequencies. Fig. 22 shows what is theoretically possible; practical tests have given encouraging results.

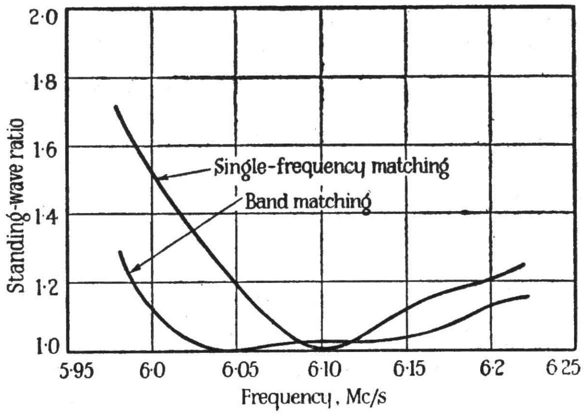

Fig. 22.—Calculated results for band matching.

(5.7) **Field-Matching Methods**

The method adopted in matching a six-bearing array to the standard 4-wire line and employing bay lines of the type already described uses a r.f. bridge as follows:

With the reflector curtain correctly tuned, the admittance at the exact centre of the interconnecting bay lines is measured. This is usually done by connecting a known, short length of line between that point and the bridge terminals, this line having characteristics similar to those of the bay lines. The admittance is normalized, and the result plotted on the curves (Fig. 20). The distance of the bridge in wavelengths from the centre point of the bay line being known, the relevant standing-wave circle is followed round in the direction "towards load" for that distance, and the new point so found gives the admittance at the centre of the bay lines. Since the two sides of the array are mechanically and electrically symmetrical within close limits, as has been checked by measurement, each side has half the admittance of that at the centre. The magnitude of the standing wave on each branch of the bay lines, and its position relative to the central point, are thus determined.

It is now required to match these lines along the tapped portion of the bay line, so that each tap sees the same admittance. The length and position of the required section are found from the curves in Fig. 20, and this section is put on to each half bay line outside the section used for tapping. A check reading is taken on the bridge; any remaining standing wave should not exceed 1·05, although usually 1·02 can be obtained without further adjustment of the matching sections. It is necessary to match to closer limits on the bay line than on the main line, in order to obtain similar conditions at each tapping-in point. The impedance at the junction will now be half the Z_0 of the bay lines, i.e. $510/2 = 255$ ohms. A 320-ohm line connects to this point with a resulting standing wave of $320/255 = 1 \cdot 25$ on the 320-ohm line. This can be readily matched for every tap, and thus at the C-frame all taps show 320 ohms. This matching section will be attached more than a quarter-wavelength from the junction, so that it is outside that section of the tap line which is short-circuited when the tap is not in use. A check measurement is made with the bridge at the C-frame switch.

This matching is carried out for the mid-band frequency, but, when the final check is made at each point of the C-frame switch, readings of admittance are taken for some five frequencies in the band, including the two limit frequencies; similar readings are taken at the transmitter terminals. Typical results are plotted in Fig. 23.

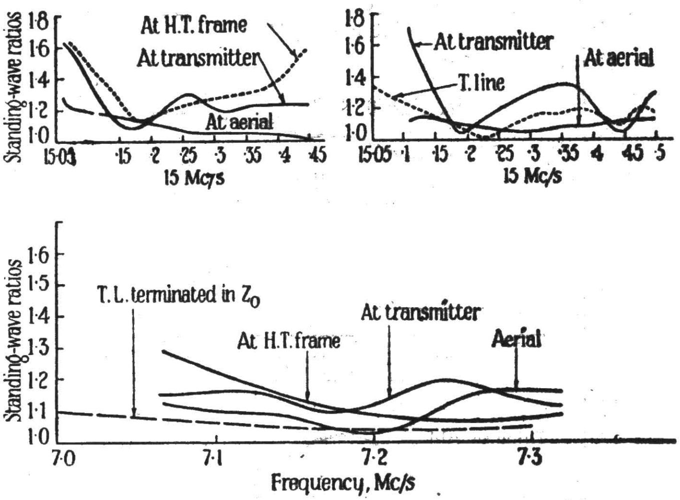

Fig. 23.—Measured performance of single-frequency matching over a narrow band of frequencies.

It is usually possible to omit any corrective matching along the main length of a 4-wire line, such as might be required to cancel the effect of irregularities of the characteristic impedance. If such matching is put on the line, it will be frequency selective and may have an adverse effect on other frequencies in the band. If the line itself introduces a considerable standing wave, this can usually be traced to either (*a*) incorrect spacing of connections on one or more tension frames, or (*b*) the distance between vertical (6 in) spacers approaching a resonant length.

The degree of uniformity of characteristic impedance obtained in a given line can be conveniently examined by terminating it with its theoretical Z_0, measuring the sending-end admittance or impedance, and deriving the corresponding standing-wave ratio. Typical results are given in Fig. 24.

The spacing of the line frames varies between 140 and 160 ft; for example, on line 813 the spacing is such that the frames are approximately 2 wavelengths apart. The insulator capacitances therefore all tend to add up and give a 1·5 standing-wave ratio at the sending end of the line. On the other hand, at the same wavelength on line 815 of approximately the same length, there is a slight and random change in the frame spacing, with the result that the capacitances are not additive and the standing-wave ratio is reduced to 1·27.

The effect is less between 17·6 to 18·2 Mc/s and at 21 Mc/s, even though the individual effect at each frame is greater owing to the decreased reactance of the insulator capacitance, since slight departures from a constant frame spacing are relatively longer in terms of wavelength.

Insulators in concentric-tube lines have similar effects on 45 Mc/s, as shown by Cork and Pawsey for the Alexandra Palace television lines.[11]

(6) RELATION BETWEEN GENERATION AND TRANSMISSION COSTS

As in all distribution systems, the cost of losses in the distribution system must be considered in relation to the cost of

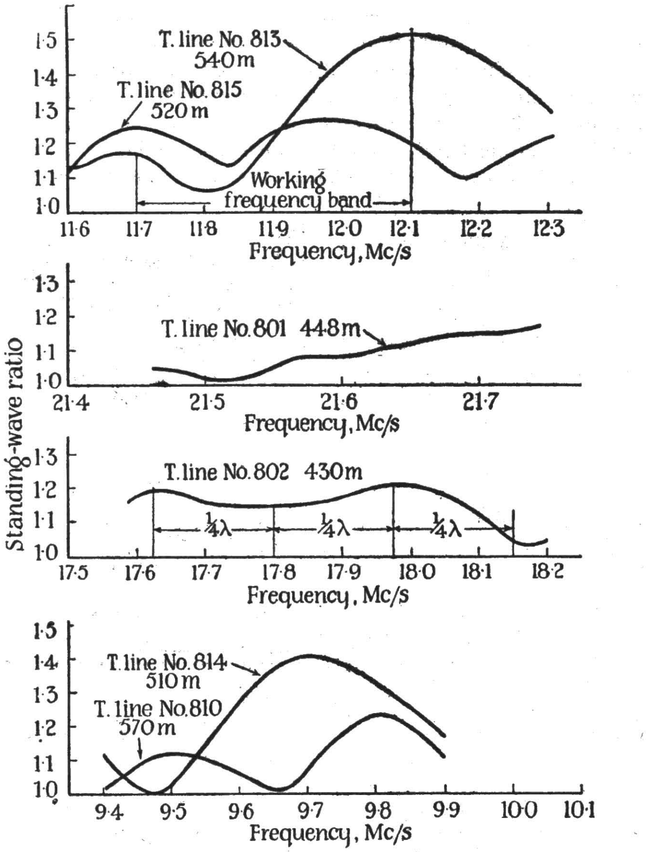

Fig. 24.—Standing wave produced by insulator capacitances. Measured values of input impedance of a transmission line terminated in its characteristic impedance, showing effect of insulators.

producing the power. In a radio system, the cost of the power consumed can be estimated within close limits, but the cost of the valves depends very much on the care with which they are operated and the conditions of output power and allowable distortion. To run with a low distortion means a high filament emission and consequently a shorter life. The costs for personnel and for plant depreciation do not alter appreciably for power-output variations of the order of the losses in the line, and hence need not be taken into account in assessing the investment to be made in the line.

In addition, however, to the pure economics of the question, there is a physical limit to the maximum power obtainable, which is imposed by the valves available; hence if, for any reason, it is necessary to employ the maximum radiated power, then the line losses must be kept to a minimum regardless of whether this shows an economic gain.

To generate 1 kW of modulated h.f. power delivered to the transmission-line system, it is necessary to take 3·25 kW from the mains. Assuming that the power costs 0·75d. per unit and that the transmitter is operating 7 000 hours per annum, the total charge will be £71 per annum. Valve costs may be taken as approximately 1·25d. per kWh of h.f. output; on the basis of 7 000 hours' operation, 1 kW will cost £36 6s. per annum. The total cost of 1 kW of power is therefore roughly £100 per annum.

The cost of h.f. power does not vary greatly between medium-wave and short-wave stations, although generally speaking the cost in medium-wave stations will be slightly less than the above figure, and that in short-wave stations slightly higher.

It will be of interest to consider a typical line for each wavelength.

(6.1) Short-Wave Transmission Line Handling 100 kW

Consider the gain in changing from a 2-wire No. 6 s.w.g. line to a 4-wire line of the same gauge.

Attenuation of 2-wire line at 11·75 Mc/s = 1·5 db/km (from Fig. 4):

Average length of line	0·6 km
Total loss	0·9 db
Output power	100 kW
Power loss	18·7 kW
Cost of power loss	£1 870 per annum

The above loss is, however, incurred only if the line is in use throughout the day. On short waves any line is not usually in use for more than 33% of the total time, and the loss on any one line therefore reduces to £623 per annum.

Attenuation of 4-wire line at 11·75 Mc/s = 1·1 db/km (from Fig. 4):

Average length of line	0·6 km
Total loss	0·66 db
Output power	100 kW
Power loss	14 kW
Cost of power loss	£1 400 per annum
Correction for time of operation	£466 per annum

Net saving by using 4-wire line = £623 − £466 = £157 per annum.

The erection costs of the two lines are approximately

2-wire line = 1s. 7d. per ft. .. .. £155 for 0·6 km
4-wire line = 2s. per ft. .. .. £195 for 0·6 km
Increased cost = £40

The increased cost is therefore saved in the first three months' operation, and there is a decided case for increasing further the amount of copper invested in the system.

(6.2) Medium-Wave Transmission Line Handling 100 kW

Length of line = 0·25 km
5-wire line loss at 1 Mc/s
$$0{\cdot}6 \times 0{\cdot}25\ \text{db} = 0{\cdot}15\ \text{db} = 3{\cdot}5\ \text{kW}$$
12-wire line loss at 1 Mc/s
$$0{\cdot}27 \times 0{\cdot}25\ \text{db} = 0{\cdot}0675\ \text{db} = 2{\cdot}8\ \text{kW}$$
Total saving from use of 12-wire line = 0·7 kW
On basis of 7 000 hours per annum = £70

The erection costs of the line are:—

12-wire line 10s. 6d. per ft, hence 250 m cost £430
5-wire line 2s. 6d. per ft, hence 250 m cost £102

For an extra investment of £328, there is therefore a saving of £70 per annum. Thus, for a power of 100 kW on medium waves it is not justifiable to put in a larger line than the 5-wire 6-gauge line. It will be clear, however, that for greater powers there is a considerable saving in using the larger line.

(7) ACKNOWLEDGMENTS

The authors wish to thank the Controller (Engineering) of the British Broadcasting Corporation for permission to publish this paper, which is based on work carried out by all departments of the Engineering Division. The mechanical design of the Geneva-wheel motion on the transmission-line switching tower was due to Clarke Chapman and Company, Ltd., of Gateshead. The authors wish to make particular acknowledgment of the part played by Mr. B. N. MacLarty, O.B.E., head of the Design and Installation Department, B.B.C., who contributed many ideas on which the designs were based.

(8) APPENDIX

Method of using Diagram (Fig. 20).

The diagram represents solutions for the equation

$$x + jy = \frac{Y_s}{Y_0} = \frac{\dfrac{Y_r}{Y_0} + j\tan 2\pi\dfrac{l}{\lambda}}{1 + \dfrac{Y_r}{jY_0}\tan 2\pi\dfrac{l}{\lambda}} = \frac{G}{Y_0} + j\frac{B}{Y_0}$$

and from it the normalized impedance at any point in a line can be found if either (*a*) the ratio $\frac{I_{max}}{I_{min}}$ and the position of either I_{max} or I_{min} is known, or (*b*) the admittance at any point on the line is known.

A set of curves can be readily drawn up since, if the substitutions $a = Y_r/Y_0$ and $b = \tan 2\pi\frac{l}{\lambda}$ are made,

$$x = \frac{a(b^2 + 1)}{a^2b^2 + 1} \qquad y = \frac{b(1 - a^2)}{a^2b^2 + 1}$$

When a is a constant, b varies from 0 to ∞, and the relationship between x and y is a circle of radius $\pm\frac{1}{2}\left(a - \frac{1}{a}\right)$ and centre $\left[\frac{1}{2}\left(a + \frac{1}{a}\right), 0\right]$.

When b is a constant, a varies between 0 and ∞, and the relationship becomes a circle of radius $\frac{1}{2}\left(b + \frac{1}{b}\right)$ and centre $\left[0, \frac{1}{2}\left(b - \frac{1}{b}\right)\right]$.

Thus the complete solution is a family of circles as above. The a curves (full lines) give the two components of the impedance at any point, and hence represent the variation in impedance with constant standing wave and variable distance. The b curves (dotted lines) give the variation of impedance at a fixed distance from a variable load.

The axes x and y can be the resistance and reactance of a complex impedance without affecting the form of the diagram, but it is more convenient to work in admittance, since matching and discontinuities are in parallel with the line; also it is easier to work in these units as r.f. bridges give parallel values.

A simplified form of the diagram is shown in Fig. 21. Using admittance terms, for a line having a characteristic admittance of Y_0 the x axis is the locus of all points of I_{min} and I_{max}, and gives the range of the normalized conductance component G/Y_0 of all complex admittances represented by $G + jB$.

If we wish to consider the case where two lines of different admittances are joined, then at the junction the impedance at the end of one line is found to have a definite plot, and to transfer to the other line using the same scale will involve changing the normalizing factor, and hence the admittance will be represented by a different point on the diagram. If, however, the scale is changed instead, then it is unnecessary to replot the point. For example, if we change from a line Y_0 to one KY_0 then the normalizing factor is correspondingly changed, and the scale must be considered as multiplied by Y_0/K instead of Y_0. Any point (x, y) will represent one admittance $G + jB$ equivalent to the normalized admittances:

$\frac{G}{Y_0} + j\frac{B}{Y_0}$ on the Y_0 transmission line, and

$\frac{G}{KY_0} + j\frac{B}{KY_0}$ on the KY_0 transmission line.

By this means we can pass from one line to another merely by changing the scale of the rectangular co-ordinates. The circular co-ordinates will change correspondingly, and hence will be based on a new focal point which will be centred on the point $(K, 0)$, instead of $(1, 0)$ to the scale of the Y_0 series.

The use of the chart for deducing the matching of Section 5.3 will require only one a circle of the KY_0 series to be drawn, namely that one which passes through the point $(1, 0)$ on the Y_0 series, for this point is the admittance which will correctly terminate the Y_0 line. This follows from the fact that, to match a 320-ohm line, it is more convenient to use only suitable lengths of a 480-ohm line, rather than to make both the length and impedance variable.

Thus any admittance $G + jB$ occurring on Y_0, as G/Y_0, which also lies on the circle OST in Fig. 20, can be transduced to $Y_0 + j0$ by introducing a certain length of line of admittance $0{\cdot}67Y_0$, the length being represented by the circular arc between points $\left(\frac{G}{Y_0}, \frac{B}{Y_0}\right)$ and $(1, 0)$ of the circle OST, measured on the b lines associated with OST, i.e. not the b lines of the Y_0 diagram.

As an example, $K = 0{\cdot}67 = 320/480$; $a = 2$

Starting from I_{max}, point P, on a 320-ohm line, the "$a = 2$" circle cuts the auxiliary circle at S, $0{\cdot}21\lambda$ towards the generator. If the line is now changed to 480 ohms, further movement towards the transmitter will follow the auxiliary circle along STUO. By making this distance equal to arc STUO and then changing back to 320 ohms, the remainder of the 320-ohm line from O to the transmitter will be correctly matched.

In the example it would be better to continue on the 320-ohm line until the second intersection at U, at a distance of $0{\cdot}29\lambda$ from P, as the necessary 480-ohm length would then be UO = $0{\cdot}16\lambda$. This will apply generally, and the semicircle in the positive half of the diagram is all that is required.

It will be noted that the maximum standing-wave ratio which can be eliminated by one impedance change of $0{\cdot}67$ is $2{\cdot}25$, because the "$a = 2{\cdot}25$" circle is tangential to OSTU at T and the required length of modified line = $0{\cdot}25\lambda$.

For the specialized use of matching, the distances PSU and UO are plotted on rectangular co-ordinates against the standing-wave ratio a, as in Fig. 25.

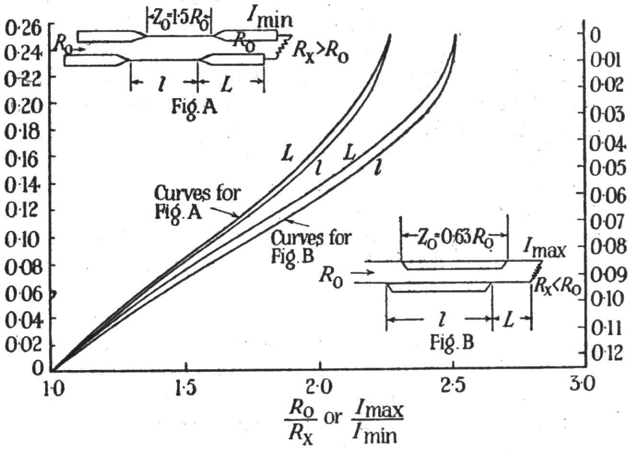

Fig. 25.—Transmission-line matching curves plotted to rectangular co-ordinates.

Numerical Example from Bridge Readings (Fig. 26).

Frequency = 12 Mc/s.
Bridge reading = 200 ohms in parallel with $-j780$ ohms.

$$\text{Therefore}\quad \frac{Y_r}{Y_0} = \frac{320}{200} - j\frac{320}{780} = 1{\cdot}6 + j0{\cdot}41.$$

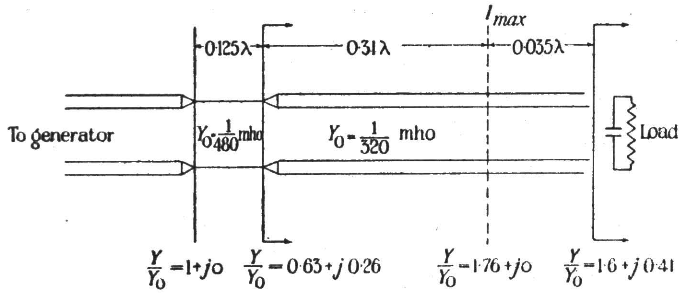

Fig. 26.—Example of matching applied to a 4-wire transmission line.

Standing-wave ratio on line from Fig. 20 = 1·76. I_{max} = 0·035λ towards transmitter. Point where matching section commences: 0·31λ from I_{max} towards transmitter. Length of matching section = 0·125λ.

Then the 6-in spaced wires are pinched together for a distance of 3·12 m, starting 8·6 m from the point of measurement of impedance.

(9) BIBLIOGRAPHY

(1) Peek, F. W.: "Dielectric Phenomena in High-Voltage Engineering," 3rd edition, 1929 (New York: McGraw-Hill).
(2) Warren, A. G.: "Mathematics Applied to Electrical Engineering," 1939 (London: Chapman and Hall).
(3) Alford, A., and Pickles, S.: "Radio Frequency High Voltage Phenomena," *Electrical Communication*, 1939–40, **18,** p. 135.
(4) Burrows, C. R.: "The Exponential Transmission Line," *Bell System Technical Journal*, 1938, **17,** p. 555.
(5) Hayes, L. W., and MacLarty, B. N.: "The Empire Service Broadcasting Station at Daventry," *Journal I.E.E.*, 1939, **85,** p. 321.
(6) Sterba, E. J., and Feldman, C. B.: "Transmission Lines for Short-Wave Radio Systems," *Proceedings of the Institute of Radio Engineers*, 1932, **20,** p. 1163.
(7) Smith, P. H.: "Transmission Line Calculator," *Electronics*, January, 1939, **12,** p. 29.
(8) Carter, P. S.: "Charts for Transmission-Line Measurements and Computations," *RCA Review*, 1938–39, **3,** p. 355.
(9) Alford, A.: "High Frequency Transmission Line Networks," *Electrical Communication*, 1938–39, **17,** p. 301.
(10) Walmsley, T.: "Beam Arrays and Transmission Lines," *Journal I.E.E.*, 1931, **69,** p. 299.
(11) Cork, E. C., and Pawsey, J. L.: "Long Feeders for Transmitting Wide Side-bands, with reference to the Alexandra Palace Aerial-Feeder System," *ibid.*, 1939, **84,** p. 448.
(12) Seward, E. W.: "The Electrical Strength of Air at High Frequencies," *ibid.*, 1939, **84,** p. 288.
(13) Jackson, W., and Huxley, L. G. H.: "The Solution of Transmission-Line Problems by Use of the Circle Diagram of Impedance," *ibid.*, 1944, **91,** Part III, p. 105.
(14) Duncan, R. D.: "Open Wire Transmission Lines," *Communications*, June, 1938, **18,** p. 10.
(15) Brown, G. H.: "Characteristics of Unbalanced Overhead Transmission Lines," *Broadcast News*, May, 1941.

DISCUSSION BEFORE THE RADIO SECTION, 5TH DECEMBER, 1945

Mr. C. E. Strong: Much can be done with relatively rudimentary transmission lines and transmission-line gear. In the early days, when it was necessary to concentrate a very heavy effort on the design of transmitters, there was a tendency—perhaps too great a one—to proceed on an *ad hoc* basis in the treatment of transmission lines. This, of course, was not good enough, especially when the power of transmitters increased, because trouble then came from two directions. First, it was found that the transmission lines themselves limited the power which could be passed to the antenna before the onset of corona. Secondly, the power lost in the lines, which was not considerable in smaller stations, now became an important factor. In any case there was justification for meticulous engineering on this equipment, because the lines had very often to be installed in out-of-the-way places and in very bad weather, and it became extremely important to plan them properly from the outset and to provide suitable methods for making corrections for matching, etc.

The paper is therefore a very welcome addition to our recorded information on this subject, the more so because it clearly represents the outcome of several years' practical experience and of close observation on the performance of this type of equipment. The important aspect of economics has been treated very fully, and I agree with the authors that probably the right economic balance between power loss and copper weight has perhaps not yet been struck. I should have thought that such a calculation made it necessary to take into account the capital value of the increase in transmission power necessary to make up for the loss in the lines. I gather that the authors feel that in future they would go to larger copper weights.

Can the authors give some information on the change of impedance which occurred with various kinds of weather—for example with rain, and with ice? Are these changes of impedance an embarrassment in practice, and has any action to be taken to correct the situation accordingly?

The switching of feeders has always been difficult. At first sight it seems to be an easy problem, which is probably one reason why it turns out to be such a nuisance in the long run. It seems to me that the solution indicated here is a very good one, if there are a large number of transmitters and very many antennae. I should like to ask the authors what would be the minimum size of installation to which this particular method is applicable. For example, would it apply, from their knowledge of the costs of this kind of equipment, to two transmitters and a maximum of ten antennae?

The very brief Section on matching to two frequencies simultaneously whets my appetite, and I hope that in the discussion this topic will be elaborated.

The authors evidently strongly favour the concentric cage type of unbalanced line for medium-wave transmitters. No doubt that is a very good solution for very-high-power transmitters. I should like to know whether their preference for this kind of line applies also to the lower-power sets—for example, between 20 and 100 kW—as compared with the copper-tube and other coaxial types of line.

Mr. B. N. MacLarty: The authors have stated that some 40 miles of the four-wire type of feeder described in the paper have been erected in various short-wave broadcasting stations in this country. I am now able to say how this amount of line was used.

Between 1940 and 1943 the B.B.C. built and used open-wire feeders for the following 100-kW short-wave transmitters:—

3 at Daventry.
4 at Rampisham, Dorset.
12 at Skelton, Cumberland.
1 at Lisnagarvey, Northern Ireland.

and for 50-kW short-wave transmitters:—

1 at Start Point, Devon.
6 at Woofferton, Ludlow.

These 27 transmitters are additional to those in service on the outbreak of war, and they fed a total of 150 additional aerials.

In addition to the short-wave stations, a large transmitter capable of an output to the aerial of 800 kW was erected at Ottringham, near Hull. This transmitter was designed for operation on either the medium- or long-wave broadcasting band. The 12-wire unbalanced feeder described by the authors was designed specifically for this station.

The foregoing indicates the extent of the expansion of the Overseas Service, but is by no means a complete picture. Many other transmitters were erected.

Such an extension programme carried out under war-time conditions necessitated the most careful attention to economy of material and ease of construction. I think it will be agreed that the information contained in the paper will be useful to engineers who are concerned with this type of construction.

I should like to draw attention to the authors' statement that a large proportion of the losses on the lines can be attributed to leakage. I suggest that they do not mean ordinary surface leakage but probably dielectric loss, which is not mentioned in the paper.

In connection with these losses it is possible that dark brushing may account for a fair proportion of the total loss. Visible brushing is mentioned in the paper, but the authors do not mention the possibility of loss due to dark brushing. If such dark brushing did occur, it could be minimized by radiusing the sharp edges of the mass-produced fittings. It is possible that a very small loss due to this cause at each insulator could add up to a considerable figure in a long line. The authors point out that, when a brush discharge occurs owing to an excessive voltage on the lines, the arc does not flash across to the opposite corner but tends to go away from it. As the opposite conductor is at opposite polarity, one would naturally expect the arc to flash across to it, but I have never seen this happen.

I should like to draw the authors' attention to the question of terminology. I note that in certain cases they use the terms "bay" and "bay transmission lines," which terms are peculiar to the B.B.C. I think they should be further explained.

The type of contact used on the tower consists of a single tangential contact formed of a piece of copper about $\frac{1}{8}$ in thick. This design was arrived at after many tests in connection with the switches designed to carry heavy currents at frequencies up to 23 Mc/s. Two parallel contacts of this type will carry about 250 amp at this frequency; a switch of this description has been in use at Daventry for many years and has given no trouble. It has been found in general that a simple contact using the minimum number of tangential contact points is the most effective for carrying heavy currents at radio frequency.

There is one point in connection with the 12-wire concentric feeder which was designed to feed 800 kW into an aerial at the Ottringham station. The insulators in this line are of the same type as those used on short-wave lines. When the line was being designed, tests on an experimental section at Droitwich indicated that these relatively small insulators had a perceptible effect on the impedance/frequency characteristic of the line. In view of the fact that the tests were carried out at 200 kc/s, it is somewhat surprising that the small capacitance of these insulators should have any effect, and it is a point to which I think the attention of engineers should be directed.

(*Communicated*): The protagonists of the tubular feeder have again called attention to it, but I think it should be made quite clear that this type of feeder received careful consideration when the Daventry short-wave station was designed, and the matter is referred to in the paper which I wrote in association with Mr. L. W. Hayes on the Daventry Broadcasting Station in 1938.*

The overground type of concentric feeder to which Mr. Smale particularly refers is much more expensive than the open-wire type described by the authors. It is less flexible and more difficult to repair, a point to which special attention had to be given under war conditions. With this type of feeder it is also a much more difficult job quickly to add compensating stubs or other devices to compensate for mismatch of the load.

The matter of switching a large number of aerials to any one transmitter is difficult with any type of concentric feeder, and I have never been impressed with the types of switching systems which have been devised for this purpose.

One can summarize by saying that for frequencies up to, say, 25 Mc/s the open-wire feeder is satisfactory for the purposes described in the paper, but for higher frequencies there is no doubt that the concentric feeder is the only type suitable. It is good engineering to choose the most economical and convenient feeder for a specific job, which was done in this case after the most careful consideration of all available types.

With regard to the buried-cable type of feeder, while this would probably be a little more expensive than the overhead line, I do not think that it has been developed to carry powers of 100 kW or more.

Mr. E. O. Willoughby: The paper contains a wealth of useful practical data and gives an interesting account of a good engineering solution of a formidable switching problem. One wonders, however, how much the system was affected by the tremendous war-time expansion of B.B.C. services under conditions of urgency, and by existing equipment, and whether the extreme switching flexibility provided is normally necessary. In particular, do the long lengths of exposed lines allow icing to cause degradation of performance below the usual B.B.C. standards?

The four-wire transmission lines provide "go" and "return" paths for de-icing currents on each side of the feeder system which would be extended through the individual aerial units, but power consumption will be very high unless the lengths of the exposed feeders are reduced and the heating capacity switched on at ambient temperatures of 34 to 36° F so that air-convection currents can prevent the formation of ice.

There might be a case for breaking up a large short-wave transmitting system into units of convenient administrative size with, say, 7 to 10 transmitters in a building at the centre of a half or three-quarter circle of arrays, thereby effecting a large reduction of the lengths of the feeders. This would permit a simple indoor switching unit on the roof of the transmitter building, and the aerial groups could be so arranged on site as to reduce firing-through between adjacent circles of arrays, although a moderate amount of firing-through would not seem to be a serious disadvantage.† It would be interesting to hear the authors' opinions on the magnitude of the icing difficulties and practical methods of coping with them.

Referring to Section 2.1.5, data of the resistivity and permeability of suitable available wire for dissipative lines would be useful.

Perhaps the short-wave loading unit in Fig. A will prove of interest. It is capable of absorbing up to 150 kW and is simple to tune and match. The circuit is a parallel-tuned transmission-line unit, and sufficient damping is provided if high-grade wrought-iron tube is used. For the open load shown, about 20 kW in 100 kW is radiated, but if it is surrounded by a lagged screening trough and an adequate flow of water is used through

---

* Item (5) of Bibliography.

† See PAGE, H.: "The Measured Performance of Horizontal Dipole Transmitting Arrays," *Journal I.E.E.*, 1945, **92**, Part III, p. 68.

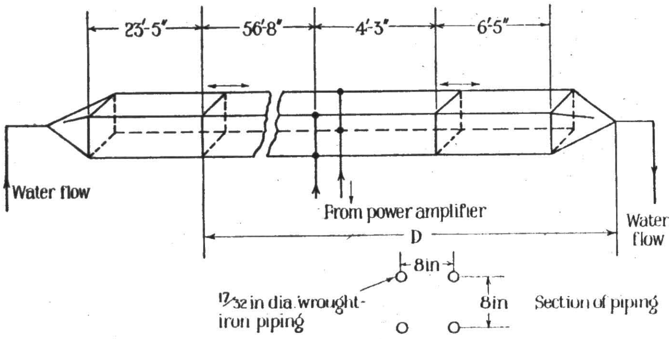

Fig. A

the tubes it should form a reliable load for power measurement. It is possible on lower powers that a similar load of much reduced dimensions could be made with an iron-wire tuned transmission-line unit under the surface of the water in a trough through which a continuous flow was maintained.

Referring to Section 2.2.1, it would be interesting to have a fuller discussion of unwanted earth currents, as the authors show in Section 6.2 that large radiated powers justify detailed study of losses which on lower powers would be negligible.

It would seem that in addition to the currents due to imperfect screening of the centre conductors and imperfect earthing of the outer conductor, appreciable coupling can occur between aerial and overall transmission line, owing mainly, for $\lambda/2$ aerials, to the Beverage effect caused by a resistive earth thereby setting up lossy currents between the outer cage and earth. Losses due to any of these effects should be reduced by running a few spaced earth-return wires parallel to the transmission lines and near the surface of the earth, and connecting them to the earth mat of the aerial. Spacing of earth connections on the outer cage at intervals of $\lambda/4$ should help to reduce standing waves at fundamental frequencies and thereby reduce earth losses.

It would be interesting to know what special precautions have been taken to reduce earth losses for 800 kW of radiated power, as these too would assume a new significance.

Mr. A. Cook: The switching frame is rather an extensive and elaborate arrangement, and no doubt meets the B.B.C.'s requirements fairly well. Its size, however, is obviously dependent on the spacing which has been adopted for the feeder systems at the point of connection to the frame. I should like to ask the authors whether they have any information on the amount of crosstalk or other factors affecting the spacing between the transmission lines.

In the switching arrangement adopted at the tower, the complete circle around the tower has been used, which seems to imply that when the transmitter feeder is being switched to an aerial feeder connected on the side of the octagon adjacent to the side to which the transmitter is connected, there is a kink in the transmission line which is very severe, the lines forming an acute angle of some 45 deg. I should like to see measurements made on the transmitter side of the frame, and to know whether the impedance changes occurring in the transmission feeder, as it passes from the tower, cause big bumps in the impedance/frequency characteristic. It would appear that, by utilizing a semicircle or some smaller fraction of a circle, such a kink in the transmission line could be avoided; the kink must have an effect on the impedance of the line comparable to that of a large number of insulators.

The B.B.C., like the Post Office, have used open-wire feeders almost from the start of the service. Have they considered the use of coaxial feeders in a balanced-twin arrangement for the purpose of switching the outputs of the transmitters, and using matching networks between the twin coaxial feeders and the open-wire system? Such an arrangement would appear to be much more compact than the radial switching system, without increasing the overall cost of the transmission lines to the extent which would be involved by using coaxial cables throughout.

Although my main interest has been in the switching system, many points arise from consideration of the results of the transmission-line measurements. Section 5.5 states that the use of stub lines reduces the effect of unwanted-frequency voltages being fed into the anode circuit of one transmitter by a coupling between its transmission line and the aerial of another transmitter. When I read that sentence, I was not very clear whether it referred specifically to transmitters and transmission lines connected to the medium-frequency equipment, or whether this had been experienced in the 3–25 Mc/s range. If the latter, I shall be most interested, because in the Post Office records there is a case in which two transmissions from Rugby were reported to be interfering with another transmission from France, the three transmissions being received at one station. The spacing between the frequency allocations of the Rugby transmitters being 110 kc/s, and that between the French transmitters and one of the Rugby transmitters being 110 kc/s, a third-order intermodulation product of some sort was obviously involved. The engineers at the receiving end claimed that their receivers did not contribute to the effect. We listened at a point four miles from the Rugby transmitters and could find no trace of the spurious emission reported to be causing interference; if both statements were correct, we might have to look for the Luxemburg effect on the short-wave range as well as on the medium-wave range. Such a case has been reported by the Dutch engineers on the Kootwijk–Bandoeng circuit, and they are quite convinced about the effect; but so far I have heard of no other case. If the B.B.C. have reports of cross-modulation at the transmitting end in the 3–25 Mc/s range, they would be of very considerable interest.

Mr. J. A. Smale: Except in connection with medium waves, no mention is made in the paper of concentric feeders.

The paper describes the consolidation of design and installation of open-wire feeders, which hitherto may have received much less attention than other parts of the whole transmitting equipment; but at a much earlier date concentric copper-tube feeders had been carefully designed and installed, and long experience shows that this system has a very high degree of reliability, largely due to immunity from weather conditions.

The paper confirms the fact that switching of open-wire feeders calls for elaborate and expensive arrangements; here again the compact indoor switching units possible with concentric feeders are no small advantage.

Regarding the design of switching tower, it would be interesting to know whether commutation of an aerial to a plurality of transmitters is also possible, and, if so, what arrangement is made to avoid the "dead-end" effect; the paper appears to deal only with commutation of a transmitter to a plurality of aerials, in which case the effect does not arise.

In concentric-tube feeders there is an optimum ratio of inner and outer conductor diameters for any given conductor material; it is about 3·6 for copper. Has any similar relation been used in the design of open-wire feeders dealt with in the paper?

Regarding the statement that aerials are so arranged that the shortest feeders are employed on the highest frequencies, have considerations of propagation and static at the receiving station been fully considered in relation to frequency?

Is it not possible that the attainment of maximum radiated power is more important on low frequencies, on which static is so much more severe? On the higher frequencies the increase of attenuation at the fade-out period is so rapid that little extension of working period is obtained by increase of power.

The amount of crosstalk between transmitting feeders and the pick-up on feeders from other aerials is very important and calls for maximum balance or screening in transmission lines; otherwise serious spurious beat-frequencies can be radiated and cause interference to other circuits.

Dr. E. W. Smith: Section 2.1.1 says that the leakage losses are 67% of the copper losses. I cannot imagine how this figure can arise, especially on a dry summer day. As I am more used to thinking in terms of cable than of open-wire line, anything above a few per cent seems high.

One advantage of cables, which has not been mentioned, is the possibility of filling them with inert gas at high pressure. The flashover voltage, the initiation of corona, can be very materially increased, and in any case the inclusion of dry air in a cable under pressure is the best insurance against the ingress of moisture. Damp cannot get in when there is air inside to get out, and a small pressure gauge to give continuously the conditions of the pressure inside the cable is all that is required.

I was privileged before the war to witness the trials of a small transmission cable which the B.B.C. had undertaken to test. The conductor was of about ¼ in diameter, and the inside diameter of the sheath was 1½ in. There was no nitrogen or air under pressure in the cable. After some interesting trials the cable was eventually taken to breakdown, which occurred at something between 80 and 90 kW, at approximately 1 Mc/s, with 75 or 80% modulation. Just before the war we were concentrating on cable which could be treated and handled as such, as opposed to the open-wire feeder or to the cable which really amounted to a plumbing job. The object was to make cables substantially larger than the 1½ in one I have just mentioned, capable of being delivered on site on drums.

Do the authors really think that the open-wire line will be regular enough, especially if frequency has to be increased? The regularity of transmission lines is becoming more and more important, and extreme measures are contemplated in order to improve it. I have expressed considerable surprise at the 67% leakage loss. The standing-wave ratios given in the paper strike me as being very much on the high side. In some cases it may be necessary to reduce both these factors to lower levels, but I doubt whether the open-wire line is the medium by which this can be done.

Regarding power transmission limitations, it is implied in Section 2.1.4 that corona does not occur at 130 kW. This would correspond to about 12 kV or, say, up to 25 kV for the actual occurrence of corona. There may well be a point, however, when frequency increases, where the limitation of power-handling capacity is neither in voltage breakdown nor in corona initiation, but is determined by the maximum current which the wire will stand without damage. I should be glad if the authors would indicate the current limitations in terms of frequency of some of the open-wire lines that they have described.

Mr. W. West: The first paragraph in Section 4.1 deserves underlining. I agree that when the number of transmitters increases above four and the number of aerials is more than some 10 to 15, it becomes virtually impossible to have complete flexibility, if an open-wire transmission line is used throughout. But the twin-coaxial-cable system of switching mentioned by Mr. Cook does seem to offer a possibility of complete flexibility.

At Rugby radio station there are some 13 short-wave transmitters and over 100 aerials. Mr. Strong asked the authors what was the minimum number of transmitters and aerials for which they would consider the switching system they have described to be suitable. I should like them also to give the maximum number.

The switch contact in Fig. 18 appears to present a rather severe discontinuity in the transmission line. Whether its effect is appreciable in practice I do not know, and I should like to ask whether the authors have any information about the reflection caused by the discontinuity.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Mr. F. C. McLean and **Mr. F. D. Bolt** (*in reply*): Replying to Mr. Strong, although the change in impedance at the sending end on a 4-wire is much less than on a 2-wire transmission line, it is still sufficient to affect transmitter output conditions. Since rain and ice affect the parameters C and G rather than L and R on the transmission line, their relative effect will be less as the Z_0 of the line is lowered. Hence the 4-wire line is inherently superior. The greater part of the change seen at the transmitter terminals is, however, considered to be due to a change in load termination on the transmission line, namely a change in aerial impedance. In practice, with modern transmitters, it is possible to accommodate these impedance changes by the coupling control, but in cases of severe icing it is necessary to operate transmitters at low power for periods of up to half an hour in order to melt the ice. Severe icing on a line and aerial which have been out of service may cause a standing-wave ratio up to 4 : 1 with equivalent sending-end impedances. We agree that the particular switching system described is more applicable to a large number of transmitters and aerials and would tend to be expensive for a smaller number of combinations. We think, however, that for 2 transmitters and 10 aerials its use would be justified if the operating requirements were similar to those of the system described in the paper.

It is not possible in this reply to deal adequately with the matching of two frequencies simultaneously, but it is hoped that further information on this matter will be included in a future paper. Useful information is given in item 3 of the Bibliography. With regard to the use of concentric cage-type transmission lines we are of the opinion that the advantages of these hold down to comparatively low powers, and we consider that the lower limit would be certainly not higher than 5 kW.

We are indebted to Mr. MacLarty for his amplification of the reasons which lay behind the work described in the paper. We do not mean ordinary surface leakage when referring to leakage losses, but all losses which are shunt losses. These include dielectric losses, radiation losses, losses in frameworks, earth losses, etc., and would more accurately be described as "leakance" losses, i.e. associated with the G of the line.

We agree with Mr. MacLarty and with Dr. Smith that there is probably an upper limit to the frequency on which an open-wire line will be satisfactory. We think, however, that this frequency is certainly well above 25 Mc/s.

Replying to Mr. Willoughby, we agree that it would be possible to use the go and return sides of the transmission line for de-icing currents. As mentioned in the reply to Mr. Strong we have, however, found that quite a short period of h.f. heating of the transmitter is sufficient to remove the ice, and have therefore not considered it necessary to go to direct ice melting. Also, it would be a very expensive matter in such a very large system, since each transmission line is in use for only a comparatively short period.

We agree with Mr. Willoughby that there is a tendency for a Beverage effect to be set up in a transmission line due to earth currents flowing, and in the case of medium-wave lines we endeavour to keep these to a minimum by earthing the outer of the transmission line at each supporting frame. We would incline to the view that, if any extra wires are to be run, it would be advantageous to run these as additional outer conductors for the transmission line rather than to run them in parallel with the earth. With regard to the reduction of earth losses for the 800-kW radiating system, special attention was paid to the earth system; this will be described in a paper to be presented to The Institution shortly.

Replying to Mr. Cook, our experience has been that, provided the transmission lines are separated by a distance not less than 6 times the side-to-side wire spacing, then the crosstalk is negligible no matter over what distances the lines are parallel, provided of course that the lines are balanced within the limits mentioned in the paper. Crosstalk naturally increases at lesser spacings, but we have not experienced crosstalk or allied effects which could not be cured by simple methods even with spacings of the order of three times the side-to-side spacing. Running transmission lines in too close proximity one to the other also gives rise to effects due to mutual impedance, and these may be troublesome when the line operating frequencies are varied.

It is agreed that in certain positions there is a very sharp bend in the transmission line as it passes through the switch, and this sharp bend could be reduced if the switch were made in semicircular form. To do this and still retain the same number of transmission line positions would, however, considerably increase the size of the main framework. In actual practice it is found that the discontinuity introduced by going through a sharp angle in the transmission line is less than would be expected, and no difficulty is experienced in keeping the overall standing wave within the limits laid down.

It is agreed that the completely open-wire switching system described takes up more space than an arrangement using balanced twin coaxial conductors. It has to be realized, however, that this is an open-air construction and that space is not a very important or costly requirement. Section 5.5 referred to frequencies in the 3 to 25 Mc/s range.

We have had many experiences of cross-modulation occurring at the transmitting end. The causes of these have been various, from mixing of transmitter input frequencies to actual coupling between aerials and transmission lines. In all cases, however, it has been possible to get rid of the intermodulation frequencies by taking appropriate steps.

Replying to Mr. Smale, we would point out that, although the outdoor switching gear is large, it is not a very expensive item. It is doubted whether it would be possible to produce an indoor switching arrangement for concentric lines which would be actually cheaper than the arrangement described. Section 4.1 describes the means that are used to switch an aerial to a number of transmitters. It will be seen that in this switching there is no dead end of transmission line.

Replying to Dr. Smith, the explanation of the relatively high leakage losses is that the copper losses are very low and, as pointed out in the reply to Mr. MacLarty, the term "leakage" loss includes all shunt losses.

One of the advantages of the open wire is that with this line it is possible to accept a considerably higher standing-wave ratio than would be permissible with a cable-type line. This permits a greater latitude in operating, both as regards accuracy of matching the aerial and in operating the whole system over a wide frequency range.

Regarding Dr. Smith's point on change in corona voltage with frequency, as pointed out in the paper, we could find very little difference between 50-c/s and 20-Mc/s operation in this respect, and while we have no accurate data we should expect that the increase in frequency would have to be quite considerable before any appreciable reduction of corona voltage occurred. With regard to the current-carrying capacity of open-wire lines, we think that a No. 6 s.w.g. copper wire may safely dissipate a maximum of 50 watts/ft at 300° C, and the current to which this corresponds for any given frequency can be deduced from Fig. 4. From this it will be seen that a single No. 6 copper wire at 16 Mc/s will carry a maximum current of 50 amp.

Replying to Mr. West, we think that it would be difficult to make a switching system on the lines described in the paper for more than 8 transmitters and 60 aerials in a single system. For numbers greater than this it would be necessary to have separate switching systems with interconnecting lines following on the precedence of the subdivision of telephone switching systems into a number of exchanges.

We have not found it possible to observe any discontinuity introduced into the line by the contact shown in Fig. 18.

Printed in Great Britain by
UNWIN BROTHERS LIMITED, LONDON AND WOKING