WINDING CAPACITANCE

By N. H. CROWHURST

THIS data sheet assists in computing the various winding capacitances of multilayer windings used in the construction of audio-frequency transformers, chokes and other equipment. They apply to windings in which turns are wound on layer by layer, either interleaved or random wound, so that the P.D. between adjacent turns belonging to consecutive layers will be much greater than that between adjacent turns in the same layer. The capacitance effect between adjacent turns in the same layer is neglected, only that between layers being considered. Capacitance between winding and core, and electrostatic screens, if used, must also receive attention.

Fig. 1 illustrates a cross section of a piece of winding in which layer interleaving is used. It is seen that the dielectric between adjacent conductors in consecutive layers is complex both in shape and material. The turns on the top layer shown fall so that each turn drops in the space between two turns on the second layer, corrugating the interleaving material with a slight resulting increase in capacitance compared with that between the middle and bottom layers shown. Due to the spiral form of each layer, the position of turns in consecutive layers to one another will change at different points round the direction of windng, thus the capacitance between any pair of layers will automatically take up the average value. The composite dielectric is made up of conductor insulation, most commonly enamel, interleaving material and the triangular shaped spaces left between adjacent turns and the interleaving material. These spaces will be filled with dry air if the windings are dried out and hermetically sealed, or with impregnating compound if the windings are vacuum impregnated. The latter procedure will give rise to a somewhat higher capacitance.

In practice the major controlling factor determining the total capacitance between two adjacent layers of winding is the thickness of the interleaving material, thus distributed capacitance may conveniently be estimated in terms of the thickness of interleaving material, giving this material a value of dielectric constant empirically obtained, allowing for the average effect of the other dielectrics in the composite arrangement.

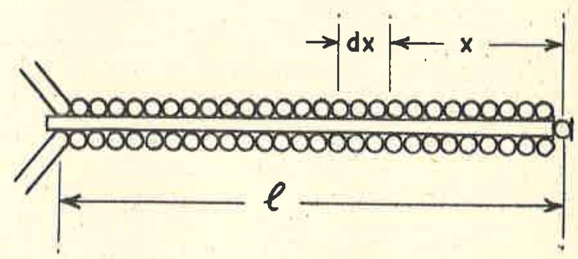


Fig. 2. Effective capacitance of a pair of layers

Effective Layer to Layer Capacitance

Take a winding having only two adjacent layers, its turns distributed uniformly throughout the two layers as shown in section at Fig. 2. Consider an element dx at a distance x from the end of the winding where the conductor steps up from one layer to the other. In the complete winding the elemental capacitance due to the section dx will be transformed so that it can be represented as an equivalent value across the whole winding. If the length of the whole layer is l and the capacitance per unit layer length C, then the effective capacitance of the element referred to the whole winding will be $(x/l)^2C.dx$ The capacitance due to the whole winding will be

$$\int_0^l (x/l)^2 C.dx = \frac{1}{3} l.C$$

Thus the effective capacitance of such a two-layer winding is one-third of the capacitance between two layers measured when their far end is unconnected.

Take now a winding consisting of n whole layers: there will be $(n-1)$ adjacent pairs of layers throughout the winding and the effective capacitance of each pair of layers, referred to the whole winding will be a capacitance of $(2/n)^2$ times their capacitance referred to the high potential and considered as a pair. Thus the capacitance of n whole layers referred to the whole winding becomes

$$\frac{4}{3} \cdot \frac{(n-1)}{n^2} .Cl$$

For large values of n the capacitance becomes inversely proportional to the number of layers. Fig. 7 illustrates a typical winding shape together with the dimensions as used in the data sheets. The capacitance per layer, given in the foregoing formula as Cl, is proportional to the product of the length per mean turn L_{MT}, and the length of layer L_W.

Vertical Sectionalising

It is sometimes of advantage to sectionalise the winding as shown at Fig. 3, each vertical space being filled completely before proceeding to fill the next one. Although physically the winding will have the same overall cross-sectional dimen-

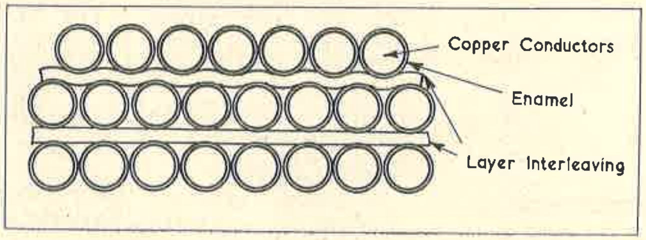


Fig. 1. Section through layer interleaved winding

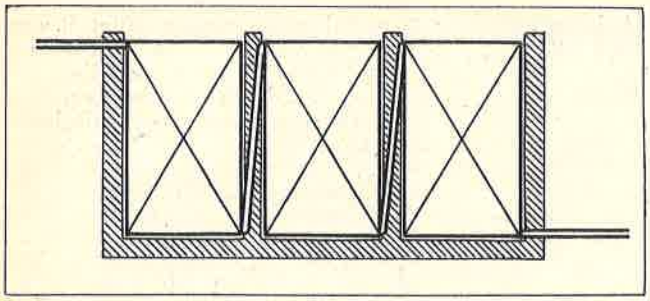


Fig. 3. Sectionalising to reduce capacitance

sions its self-capacitance will be equivalent to that of a winding having $1/N \times$ layer length and $N \times n$ layers, where N is the number of vertical sections. The distributed capacitance of the winding due to such sectionalising thus is reduced by the factor $1/N^2$. Note that this rule applies only to referred interlayer capacitance and does not apply to capacitance between the top and bottom of the winding and adjacent windings or screens. The various reduction factors for vertical sectionalising are given in Table 1.

Effect of Mixing Windings

In the design of a transformer it is often necessary to mix the primary and secondary windings in order to reduce leakage inductance. This arrangement will generally be a disadvantage as regards minimising winding capacitance, since it exposes greater surface area of winding in proximity to either the other winding or an earthed screen. If the ratio of the transformer is fairly high, then from the high impedance winding the whole of the low impedance winding appears at common audio potential, usually earthy. But if the ratio of the transformer is not very high, capacitance between points at differing audio potentials in the two windings may have serious effects, and it is generally best to arrange the windings so as to avoid such capacitance.

Fig. 5 shows a cross-section suitable for an inter-valve transformer designed to operate two valves in push-pull from a single valve on the primary side. The H.T. end of the primary is earthy and is therefore diagrammatically earthed. The high potential end of the primary is adjacent to the earthy end of one of the half secondaries so that the capacitance between windings at this point is effectively from anode to earth. The two high potential ends of the secondary are remote from the primary and so minimise the possibility of unbalanced capacitance transfer from primary to one half secondary.

Another problem which often arises is in the design of push-pull output transformers, particularly for Class AB or Class B circuits, where it is essential that each half of the primary be well coupled to the whole secondary. From the viewpoint of leakage inductance and winding resistance, it is unimportant whether the secondary sections are connected in series or parallel. Fig. 6 illustrates three arrangements for a transformer of this type, each of which may be best suited under different circumstances. At (a) is an arrangement which gives minimum primary capacitance, but suffers from the defect that leakage inductance and winding resistance are unequal for the two primary halves. For Class A operation using valves requiring an optimum load of high impedance this arrangement is sometimes the best. At (b) is an arrangement intended to equalise winding resistance and leakage inductance from each half-primary to the whole secondary as well as primary self-capacitance. This arrangement is particularly suited to circuits employing low loading Class AB or Class B operation. The alternative arrangement shown at (c) results in a slightly lower referred capacitance across one half only of the primary. In general this unbalance is not desirable, but if leakage inductance is adequately low, the coupling between all the windings may be so good that the reduction in capacitance may be apparent across the whole primary.

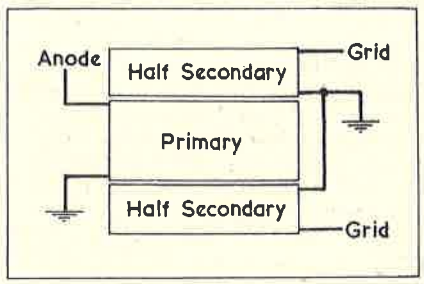


Fig. 5. Push-pull secondary intervalve transformer secondary arrangement

Table 2 gives a pictorial representation of various ways in which high impedance windings may be arranged in relation to earthy points shown as screens. The table is equally applicable if these points are earthy low impedance windings. The capacitance factors for alternative connexions of the winding, with either one side or the centre point at earth potential, are given relative to the average capacitance between one end layer of the winding and one screen. The two arrangements marked with an asterisk indicate that it is necessary to reverse the direction of winding in order to achieve the capacitance factor shown.

Random Winding

In what is known as random winding, no interleaving material is

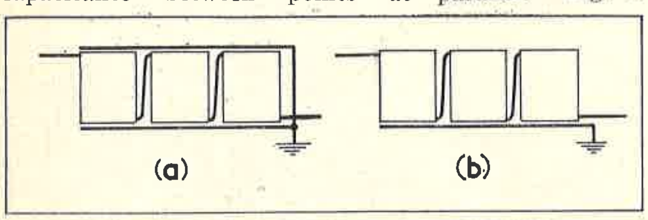


Fig. 4. Arrangements using vertical sectionalising. See Table I (*below*)

Number of Vertical Sections	Distributed Capacitance Component	Winding to Screen Capacitance Arrangement as]Figure 4		
		(a) One side earthy	(a) Centre point earthy	(b) One side earthy
1	1	1	0.5	0
2	0.25	0.75	0.25	0.125
3	0.111	0.704	0.185	0.185
4	0.0625	0.6875	0.1875	0.219
5	0.04	0.68	0.168	0.24
6	0.0278	0.676	0.176	0.255
∞	0*	0.667	0.167	0.333

* The method of winding is here changed so that for the purposes of this column, the dimensions Lw and Tw will change places.

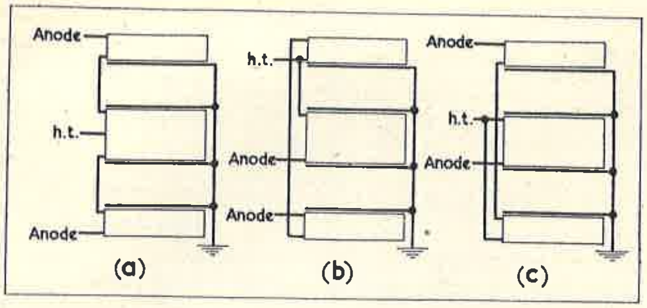


Fig. 6. Arrangements for push-pull output transformer

used. For ideal random winding the layers should be built up so that at all times during winding the top surface is level. Failure to do this will not greatly affect the self-capacitance, but will result in increased danger of breakdown due to electrical or mechanical stresses. As the number of layers is always large, it is convenient to reduce the calculation to simple terms of the winding dimensions.

The essential variables are: length of winding L_W, length of mean turn L_{MT}, winding thickness T_W (see Fig. 7), and number of turns, T. Considering variation of each of these quantities in turn, the others being taken as constant: variation of L_W will vary the referred capacitance per layer as before, and additionally the effective number of layers will vary inversely as $L_W^{\frac{1}{2}}$; variation of L_{MT} simply varies the layer size, as before; variation of both T_W and T varies the number of layers in direct proportion to $T_W^{\frac{1}{2}}$ or T. Thus the whole expression for variation of capacitance can be written,

$$C_P \propto \frac{L_{MT} L_W^{3/2}}{T_W^{\frac{1}{2}} T^{\frac{1}{2}}}$$

The lower half of the data sheet is based on this relation and empirical values obtained from average results with random windings.

Example 1

A push-pull output transformer is arranged as at Fig. 5: primary winding has a total of 12 layers, $T_D = 3$, $k = 2$; insulation between primary and screen, $T_D = 15$, $k = 5$; main dimensions, $L_W = 2''$, $L_{MT} = 8''$.

Distributed capacitance, using upper data sheet, $L_W = 2''$, $L_{MT} = 8''$, $T_D = 3$, $k = 2$ and $n = 12$, is $C_P = 240$ pF.

Capacitance from each primary to screen, substitution $T_D = 15$, $k = 5$, is $C_P = 1200$ pF. The capacitance factors for the arrangement of Fig. 5 are: (a) 0.25; (b) 0.5; (c) 0.375. Thus the total capacitance referred to the whole primary for each method of connexion is,

(a) 300 pF + 240 pF = 540 pF.
(b) 600 pF + 240 pF = 840 pF.
(c) 450 pF + 240 pF = 690 pF.

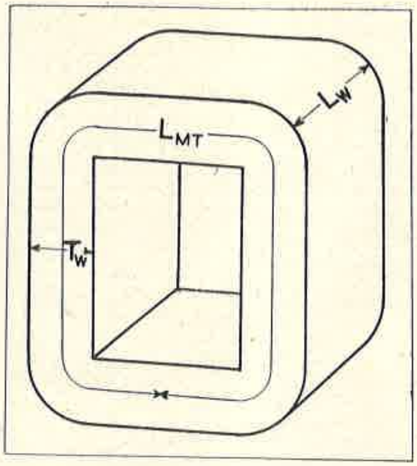


Fig. 7. Dimensions used on data sheets

Example 2

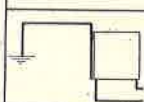
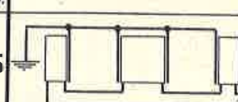
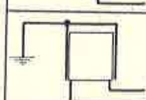
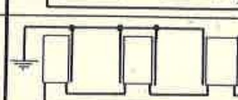
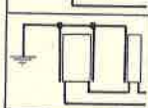
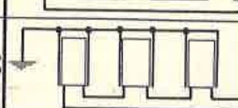
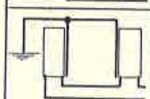
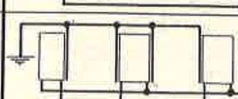
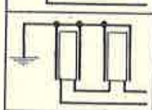
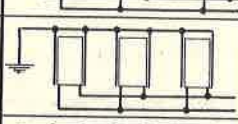
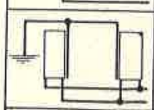
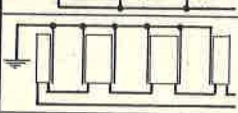
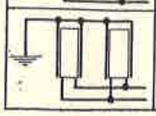
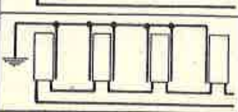
An intervalve transformer, to operate from push-pull to push-pull, uses a simple arrangement having both windings all in one section: $L_W = 0.6''$, $L_{MT} = 2.5''$, T_W (each winding = $0.1''$; insulation between windings, T_D, $k = 3$; Turns, 4,000 c.t./12,000 c.t.

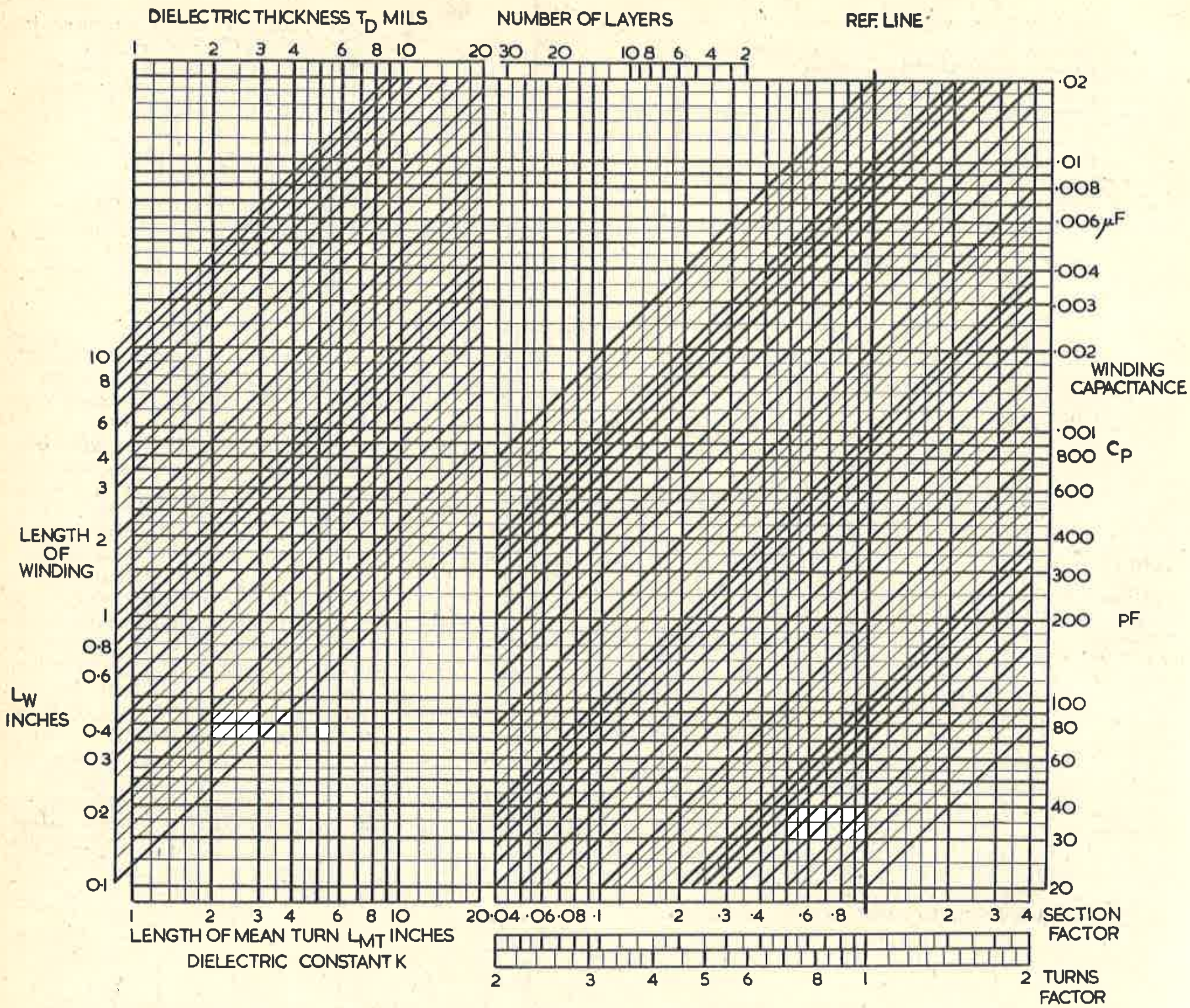
Distributed capacitance, using lower data sheet, $L_W = 0.6''$, $L_{MT} = 2.5''$, $T_W = 0.1''$, T (primary) = 4,000, is $C_p = 58$ pF. For secondary, $T = 12{,}000$, $C_p = 34$ pF.

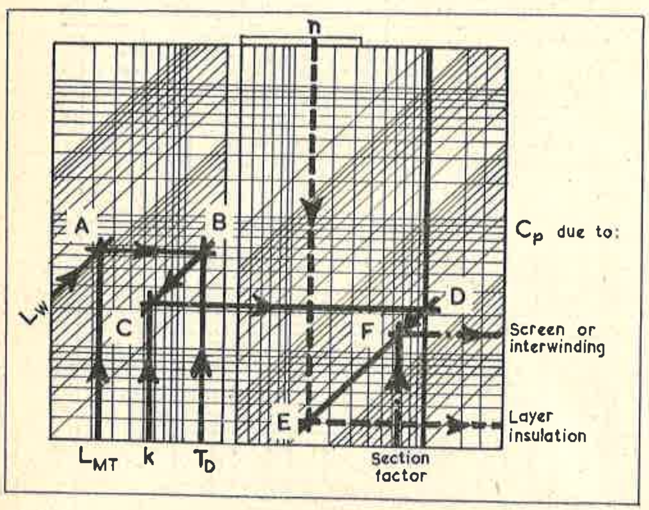
Capacitance coupling between one-half primary and one-half secondary, using upper data sheet, actual capacitance, $L_W = 0.6''$, $L_{MT} = 2.5''$, $T_D = 10$, $k = 3$, is $C_P = 100$ pF. Both windings wound in same direction, turns factor across this capacitance referred to whole primary is $\frac{1}{2} + 1\frac{1}{2} = 2$, so referred capacitance is 400 pF. Windings wound opposite directions, turns factor referred to primary is $1\frac{1}{2} - \frac{1}{2} = 1$, so referred capacitance is reduced to 100 pF.

(*Continued on page 431. Data sheets overleaf*)

Table 2. Effect on referred winding-to-screen capacitance of various arrangements

WINDING & SCREEN ARRANGEMENT & CONNEXION	CAPACITANCE FACTOR One side earthy.	CAPACITANCE FACTOR Centre point earthy.	WINDING & SCREEN ARRANGEMENT & CONNEXION	CAPACITANCE FACTOR One side earthy.	CAPACITANCE FACTOR Centre point earthy.
	—	·25		1·25	·25
	1	·5		1·11	·11
	·22	·055		2·11	·611
	·5	—		1 *	1
	1·5	·5		3	1·5
	— *	·5		1·94	·44
	2	1		1·75	·25



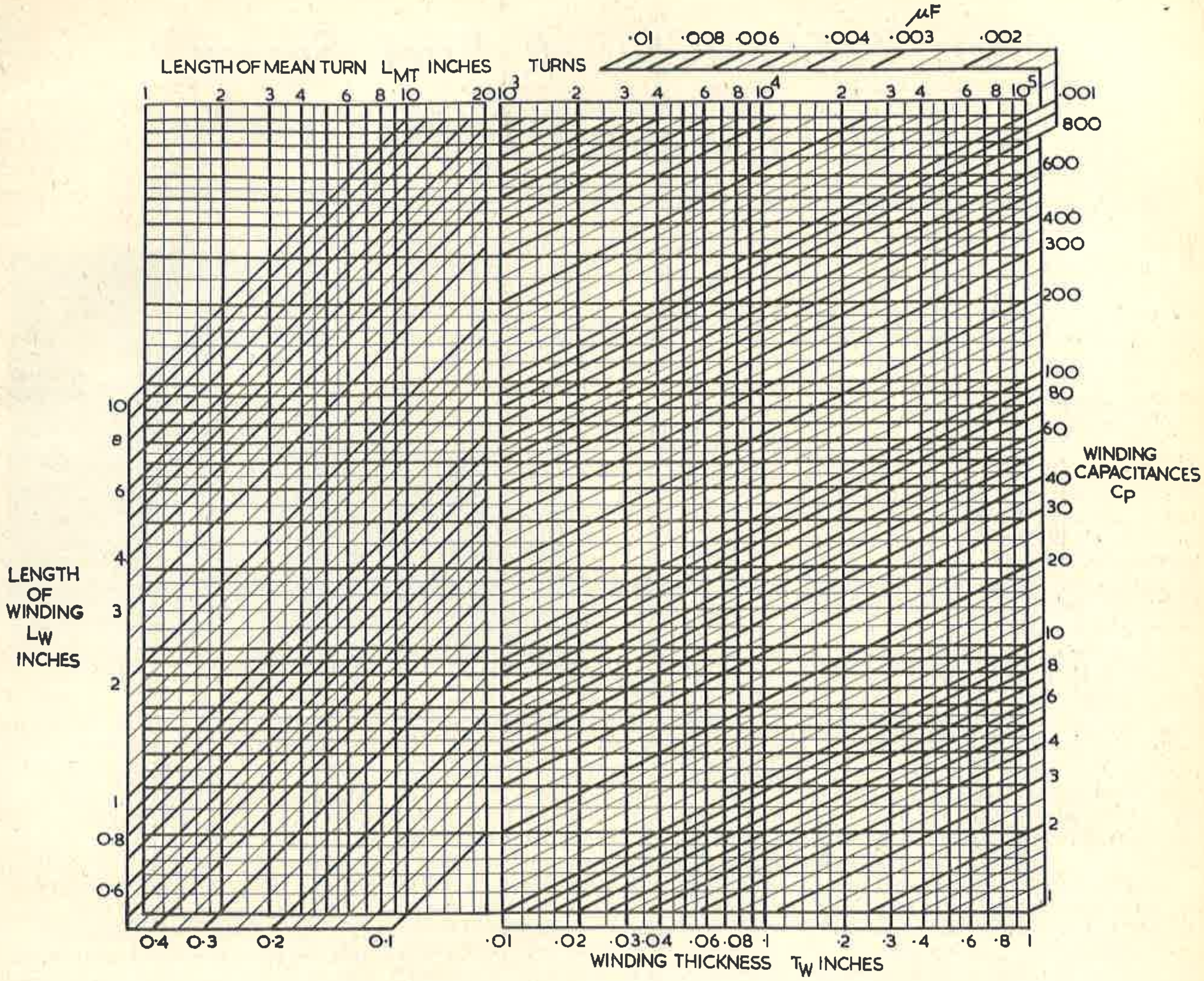


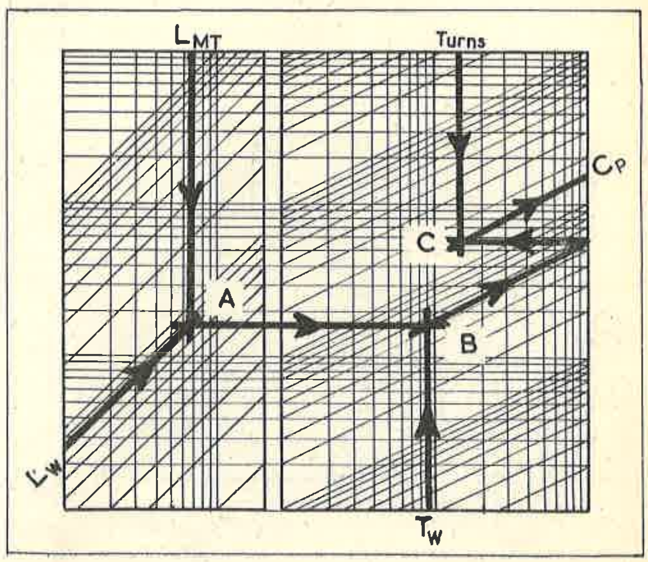
For Distributed Capacitance due to Layer Winding:

Refer length of winding L_W, and length of mean turn L_{MT}, on their respective scales, to intercept at A (figure 8 left), then along the horizontal reference lines to intercept with the thickness of dielectric material T_D, at B. From this point refer along the slanting reference lines to intercept with the empirically determined value of dielectric constant *k*, at C, then along the horizontal reference lines to the unity reference vertical at D. From this point refer down the slanting reference lines to intercept with the number of layers *n*, at E, whence the referred capacitance is read off on the scale at the right.

For Interwinding, or Winding to Screen Capacitance:

As above, for the winding dimensions and dielectric thickness to a point corresponding to D, whence, for winding to screen capacitance, or interwinding capacitance when the other winding is all at low potential, refer down the slanting reference lines to intercept with the section capacitance factor obtained from Table No. I. For interwinding capacitance where there is appreciable potential in the adjacent portions or both windings, individual attention will be necessary for each interwinding space, and the turns factor scale will assist here.





For Distributed Capacitance due to Random Winding:
Refer length of winding L_W, and length of mean turn L_{MT}, on their respective scales, to intercept at A (figure 9 right), then along the horizontal reference lines to intercept with the vertical line for thickness of winding T_W, at B. From here refer up the slanting reference lines to the right-hand edge of the data sheet, and then back along the horizontal lines to intercept with the vertical line for the number of turns at C, from which referred capacitance is read off along the slanting lines at C_P.