LAYER-THICKNESS MEASUREMENT OF ENAMEL-COVERED WIRE

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1. Production of enamel-covered wire

In the machines and instruments of the electrical industry and of the electronics the insulation of the wires used may be different : one or more layers of textile, enamel cover, or a combination of the two. The advantages of enamelled wire against other insulated wires are its low production cost, relatively high heat resistance and its small space requirement.

The basic material of the enamelled wire is generally copper, sometimes aluminium. In an apparatus, at a given power and temperature, the cross-section of the aluminium wire must be greater because of its lower conductivity. If the insulation can stand higher temperature then aluminium wire of the same cross-section as copper can be used and this could be important in the question of price and weight reduction.

Some time before, solely oleo-resinous enamel was used for enamelling. The fundamental material for this is the China wood oil. The development in the production of the synthetic materials has brought about important changes also in the enamels used for enamelling wires. Several different enamels of excellent quality have been developed, which could more or less be included in one of the following groups of plastics :

polyurethane
polyvinylformale
polyesther
copolymer of vinylchloride vinylacetate
carbamide resin
polyamide (perlon)

These enamels have a much higher resistance against heat and chemicals, have higher mechanical strength etc., than those of oleo resinous ones. There is even now such an enamel which melts at the temperature of soldering and desoxidates the wire. This is especially advantageous in a multiterminal transformer, because the wire can be soldered to its place without preliminary cleaning.

The requirements for enamelled wires are different, depending on whether they are used in electrical or electronic engineering. The high number of turns common in electronic equipments demand that the thickness of the layer does not exceed the standard specifications. The continuity of the layer is also important, whereas by great dielectric strength is not, because of the small turn-to-turn voltage. Low dielectric loss is required of wires used in high frequency coils.

In the machines and equipments of electrical engineering more important points are high dielectric and mechanical strength of the insulation and its resistance against heat and oil. The trend towards the specified load emphasize these factors all the more.

The enamel layer must stick fast to the wire, this can be achieved by producing clean surfaces by using the proper enamel quality. The enamel layer must be flexible enough not to crack or split while spooling, because of the pulling and bending stress. The layer even under impregnation must be so hard that no short circuit should occur when two crossing turns cut into each other.

The method of enamelling is based on putting more and more thin enamel layers — the thickness of which is of the order of microns — on the wire, burning it in on an electric heated oven, then winding the finished enamelled wire on spools. The use of more than one layer is necessary, because the dissolvent must easily evaporate from the enamel-film. Should the layer be too thick, the dissolvent would evaporate with a burst and damage the smooth surface of the layer.

The proper temperature for burning in is secured by automatic temperature regulating of the oven. The colour and glossiness of the enamel layer indicates the proper stage of the stoving.

The thickness of the enamel layer is regulated by standard specifications. It is in the interest of the producing firm to stop the production of wires not fulfilling these specifications or to modify the thickness of the layer properly, even in the case of small deviation.

Wires thicker than 0,5 mm move relatively slowly between the stove and the winding spool and there is time enough for someone to check the diameter with a micrometer by slowly walking along the moving wire.

On the other hand, wires 0,05—0,5 mm in diameter are made by other types of machines, the speed of which are much greater. The greatest trouble in the micrometer measuring method is the necessity of again and again tearing the wire for measuring, until the enamelling is properly set. Moreover, the layer-thickness once adjusted does not remain constant either. As at a spool only once is there an opportunity to check the diameter — when taking the spool off — the thickness of the enamel layer cannot always be kept within the prescribed limits.

2. Continuous measuring of the layer-thickness

Continuous measuring can be achieved by capacitive method [1]. If the wire passes through a vessel filled with mercury, a cylindrical condenser

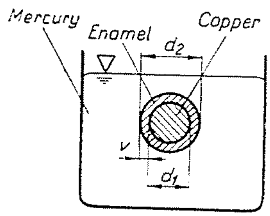

Fig. 1. Measurement of layer-thickness by capacitive method

is formed, one electrode of which is the wire itself, the dielectric is the insulating layer, while the other electrode is the mercury (Fig. 1).

The capacitance can be calculated from the equation

$$C = 0{,}55\, \varepsilon \cdot l \frac{1}{\ln \frac{d_2}{d_1}} \quad [pF] \tag{1}$$

where ε is the dielectric constant of the enamel, l the length of wire in cm merged in the mercury, d_1 the diameter of the base wire and d_2 the diameter of the insulated wire — these last two quantities should be substituted as the same unit otherwise any arbitrary measuring can be used.

The dielectric constants of the enamels mentioned above are between 2,8 and 4,0 at 800 c/s. The dielectric constant of an unknown enamel can be determined by way of the mercury filled measuring vessel, if we know the geometry of the wire.

Since the Standards in most cases contain the diameter of the copper and the layer-thickness, it is advisable to eliminate d_2 from the equation and have the layer-thickness (v) as the new variable. So — since $d_2 - d_1 = 2\, v$ —

$$C = 0{,}55 \frac{\varepsilon\, l}{\ln \left(1 + \frac{2\, v}{d_1}\right)} \quad [pF]$$

For the conversion of Standards [2]—[5] or rather to make quick estimations, the equation above is not easy to handle. If we consider the fact that — according to most of the Standards — between 0,05 and 0,5 mm nominal diameters the minimum diameter growth is not less than 5% of the copper diameter, the maximum diameter growth is not bigger than 50%, we get a good approximation with the relation :

$$C = 0{,}55\,\varepsilon \cdot l \left[\frac{d_1}{2v} + 0{,}48\right] \ [pF]. \tag{2}$$

At the mentioned limits the value of the amount in brackets is 20,48 and 2,48 ; the absolute value of the deviation from the exact relation never exceeds 0,015 (see Appendix). So the capacitance as function of the layer-thickness almost hyperbolically varies.

The Standard for enamelled wires gives the mean layer-thickness for every copper diameter and that tolerance range, inside which the thickness of the layer is acceptable. From these data one can calculate the minimum, mean and maximum capacitance belonging to the maximum, mean and minimum layer-thickness. The character of the relation between the copper diameter and the capacitances is shown in Fig. 2. One must note the heavy fluctua-

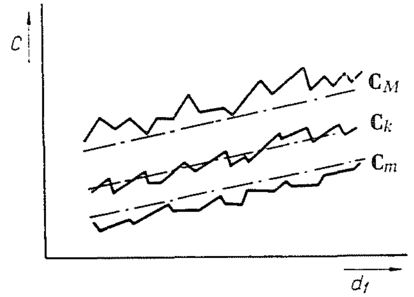

Fig. 2. Relation between the nominal diameter of standard wire and its layer capacity

tion of the curves and besides, the two capacitance differences : $C_k - C_m$ and $C_M - C_k$ are not equal. The reason of the fluctuation is due to the fact that the Standard supposes mechanical measuring device (micrometer) and, therefore, it prescribes the maximum, mean and minimum thickness of the layer — often arbitrarily — in whole numbers of microns. The discrepancy of the two capacitance difference, on the other hand, arises, because the thickness tolerance is symmetrical to the centre, but the capacitance is not a linear function of the thickness. In the capacitive layer-thickness measuring devices now in use, it was easy to realize the asymmetrical measuring range, but instead of the zig-zagging tolerance limit, a narrower limit had to be used (dash-and-dot lines in Fig. 2) since it would have been much more complicated to set in the exact limits on the apparatus.

From equation (2) one can calculate the capacitance variation corresponding with the minimum and maximum layer-thickness :

$$\Delta C_1 = C_M - C_k = 0{,}55\,\varepsilon\, l \left[\frac{d_1}{2\,v_m} - \frac{d_1}{2\,v_k}\right], \tag{3}$$

$$\Delta C_2 = C_k - C_m = 0{,}55\,\varepsilon\, l \left[\frac{d_1}{2\,v_k} - \frac{d_1}{2\,v_M}\right], \qquad (4)$$

where C_M is the maximum capacitance belonging to v_m, the minimum layer-thickness ; C_k is the mean capacitance belonging to v_k, the mean layer-thickness; and C_m is the minimum capacitance belonging to v_M, the maximum layer-thickness. The whole capacitance variation is

$$\Delta C_1 + \Delta C_2 = 0{,}55\,\varepsilon\, l \left[\frac{d_1}{2\,v_m} - \frac{d_1}{2\,v_M}\right], \qquad (5)$$

and the asymmetry

$$\frac{\Delta C_1}{\Delta C_2} = \frac{\dfrac{1}{v_m} - \dfrac{1}{v_k}}{\dfrac{1}{v_k} - \dfrac{1}{v_M}}. \qquad (6)$$

If the thickness tolerance is symmetrical, and so

$$v_M - v_k = v_k - v_m \qquad (7)$$

we get a simple relation for the asymmetry :

$$\frac{\Delta C_1}{\Delta C_2} = \frac{v_M}{v_m} \qquad (8)$$

If the measuring is made according to the capacitive method, it would be preferable to have the value of (5) and (8) constant. The latter is fulfilled in the well-known Standards but the first condition can be realized only if, according to :

$$\frac{d_1}{2\,v_m} - \frac{d_1}{2\,v_M} = \frac{d_1}{2\,v_M}\left(\frac{v_M}{v_m} - 1\right) \qquad (9)$$

$\dfrac{d_1}{2\,v_M}$ or as it comes from above, $\dfrac{d_1}{2\,v_k}$ is constant. According to the Standards, though, along with the increase of diameter the relative layer-thickness decreases. That is the reason why it is necessary in the already working instruments to use a special setting for the adjustment of the mean capacitance — that is : of the nominal wire diameter.

3. Constructing the ideal Standard

It is advisable to choose the ratio of the layer-thickness and the diameter, so that the electric load of the wire of different diameters

$$E = \frac{2\,U}{d_1 \ln\left(1 + \frac{2\,v}{d_1}\right)}$$

should be constant. With this solution it could easily be secured to have the outstanding layer-thicknesses eliminated, that is the over- and under-rated insulations.

The Standards [2]—[5] presently in use are — as mentioned before — accomodated to possibilities given by the mechanical measuring devices (micrometer). The layer-thickness is given in whole numbers of microns. It is to be noted that the relative layer-thickness decreases with the increase of the nominal diameter. As the steps of the layer-thickness are chosen from different aspects (easy to memorize, symmetrical tolerance range, etc.), the relative layer-thickness as function of the diameter, shows strong fluctuations instead of the desired steady character.

In order to realize a simple plant measuring method, it is more advisable to have such a Standard, in which the steps of diameter values are more or less smoothed to the capacitance curve. When forming the standard let us make the following conditions :

1. The difference of the maximum and minimum capacitance should be constant.

2. The ratio of the deviations from the mean capacitance should be constant.

3. The relative layer-thickness should decrease with the diameter, so that the electrical load should remain nearly constant.

All three conditions can be fulfilled only if we abandon the symmetrical thickness tolerance. The minimum, mean and maximum layer-thickness can be determined from the following equations :

from the 1st condition :

$$\frac{d_1}{2\,v_m} - \frac{d_1}{2\,v_M} = k_1, \tag{10}$$

from the 2nd condition :

$$\frac{d_1}{2\,v_m} - \frac{d_1}{2\,v_k} = k_2 \left[\frac{d_1}{2\,v_k} - \frac{d_1}{2\,v_M}\right]. \tag{11}$$

From the combination of (10) and (11)

$$\frac{d_1}{2\,v_M} = \frac{d_1}{2\,v_k} - \frac{k_1}{1 + k_2} \tag{12}$$

and

$$\frac{d_1}{2\,v_m} = \frac{d_1}{2\,v_k} + \frac{k_1 k_2}{1 + k_2}\,. \tag{13}$$

The value of $\frac{d_1}{2\,v_k}$ can be given, either by taking the 3rd condition, or by the conventional Standards so far used.

Fig. 3 shows the relation between capacitance and layer-thickness, according to the Hungarian Standard MSZ 1569. In the lower part of the figure a stepped diagram shows the layer-thickness as function of the diameter.

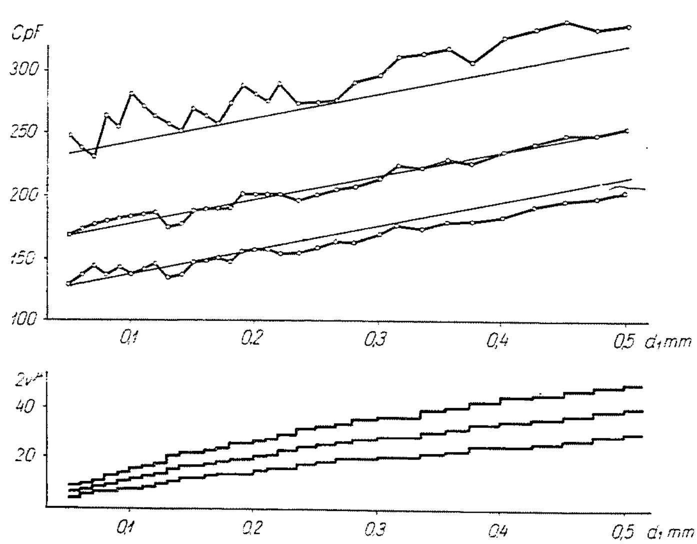

Fig. 3. Relation between layer thickness and capacity according to Hungarian Standard MSZ 1569

The curves in Fig. 4 were plotted in the following way: we prepared the function $\frac{d_1}{2\,v_k}$ osculatory to the middle curve in Fig. 3 ; then we determined the value of k_1 and k_2 from the positions of the exterior curves

$$k_1 = \frac{\Delta C}{0{,}55\,\varepsilon\,l} = 5{,}49$$

$$k_2 = \frac{\Delta C_1}{\Delta C_2} = 1{,}62\,.$$

The values of v_M and v_m from (12) and (13), rounded to whole microns, give the exterior curves of Fig. 4 and the stepped diagram, in which we can

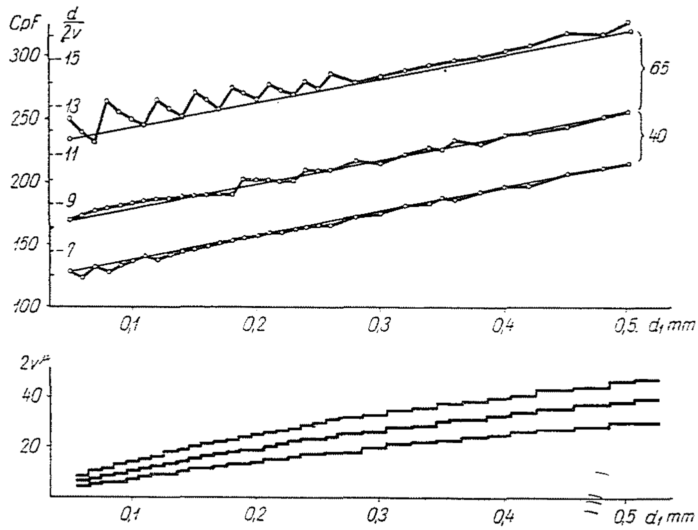

Fig. 4. Relation between layer-thickness and capacity according to ideal Standard

see, that we can design a standard very close to the ideal one, if we introduce a small change in the tolerance range.

4. The principle structure of the measuring apparatus

The main outlines of the measuring apparatus are shown in Fig. 5 The measuring is based on bridge-method : an oscillator with the approximate frequency of 1 Kc/s feeds the primary windings of a differential transformer.

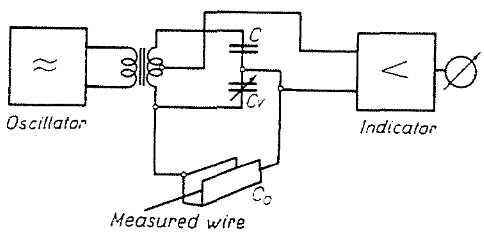

Fig. 5. Schematic block of measuring apparatus

The mercury of the measuring vessel is connected to one end of the centre-tapped secondary coil, that is the outer plate of the capacitance (C_o) to be measured. The other plate of the capacitance is the copper wire, which is grounded. A variable capacitance is also connected to these same points. The other end of the secondary coil is connected to a fixed capacitance.

The dial of the variable capacitance is calibrated to the values of the mean layer-thickness (v_k), so that when measuring a wire of the diameter d_1, we balance the bridge by setting the value of the capacity

$$C_v = C - C_0 = 0.55\,\varepsilon\, l \left(\frac{d_1}{2\, v_k} + 0.48\right) [pF] \tag{14}$$

which comes from equation (2).

The capacity of the measuring vessel, if the diameter of the merging wire is d_1, and its layer-thickness v,

$$C_1 = 0.55\,\varepsilon\, l \left(\frac{d_1}{2\, v} + 0.48\right) \tag{15}$$

The output voltage of the differential-bridge between the centre tap of the transformer and the ground is, by using equation (14) :

$$U_2 = U \left[\frac{1}{2} - \frac{C_1 + C_v}{C + C_1 + C_v}\right] = \frac{1}{2}\, U \,\frac{C_0 - C_1}{2\,C - C_0 + C_1} = -\frac{1}{2}\, U \,\frac{\frac{\Delta C}{C}}{2 + \frac{\Delta C}{C}} \tag{16}$$

Finally, equation (3) gives the connection between the capacity variation ΔC, and the deviation of the layer-thickness.

The phase of the voltage may be the same, or the reverse in respect to the bridge supply voltage, depending on whether the layer thickness is greater

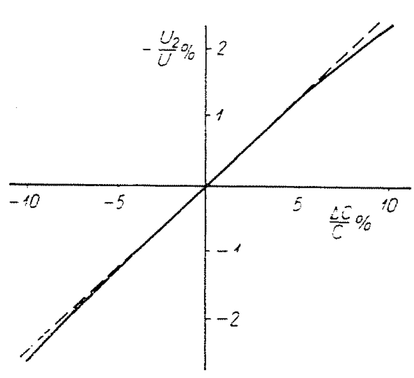

Fig. 6. The output voltage of the bridge plotted against the capacity variation

or smaller than the mean value. The relation between the voltage and the capacity variation is plotted in Fig. 6.

We can indicate the output voltage of the bridge by a vacuum tube voltmeter. The disadvantage of using a common type vacuum tube voltmeter is, that it only indicates the amplitude of the voltage (Fig. 7.), but does not give information on its phase. That is the reason why we have to use a phase-sensitive voltmeter.

We can get the reference voltage needed for the phase sensitive voltmeter from the same source, where we get the bridge supply voltage from. In this

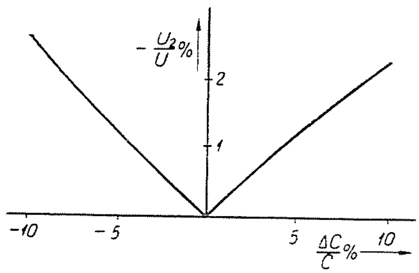

Fig. 7. The absolute value of the output voltage of the bridge, plotted against the capacity variation

way the polarity of the output DC voltage corresponds to the direction of the layer-thickness deviation, while its value is proportional to the greatness of the deviation. The indicating miliammeter of the phase sensitive voltmeter is fitted with specially shaped pole-shoes (Fig. 8*a*) in order to equalize the non-

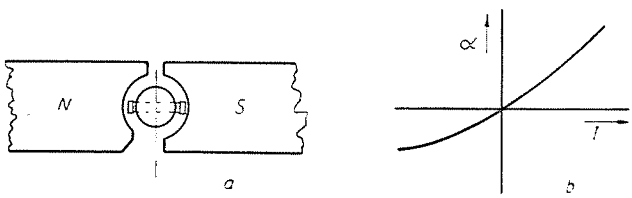

Fig. 8. Miliammeter with specially shaped pole-shoes *a)* outline, *b)* sensitivity character

linearity existing between the layer-thickness and the bridge voltage. So it has an asymmetrical sensitivity character (Fig. 8*b*).

In this way it can be achieved that the indication of the meter is an almost linear function of the deviation of the layer-thickness from its mean value.

5. Plant measuring equipments

The block diagram of the first plant measuring equipment, of this kind. is shown in Fig. 9.

A 6AU6 miniature pentode generates an A. C. voltage of 800 c/s, as a phase-shift oscillator. This is amplified by a 6AQ5 power pentode tube. A transformer, in its plate circuit, supplies the differential transformer and gives the reference voltage for the phase detector using a 6AL5 twin diode (Fig. 10) [6].

In one arm of the differential bridge is a fixed capacitance, in the other a variable one, the sum of the capacity to be measured and the other adjusting capacitances together have exactly the same value, as the former fixed capacitance. In place of the capacity to be measured any of the 8 measuring chan-

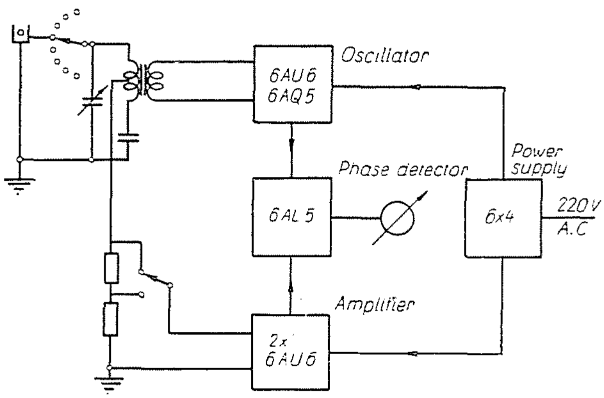

Fig. 9. Block-scheme of plant measuring apparatus

nels of the 8 simultaneous enamelling channels can be switched, one after the other. The output voltage of the bridge is directly connected to the input terminals of a two-stage amplifier in the case of double layer. If, however, the wire is covered by a simple layer, a voltage divider is used. The amplified

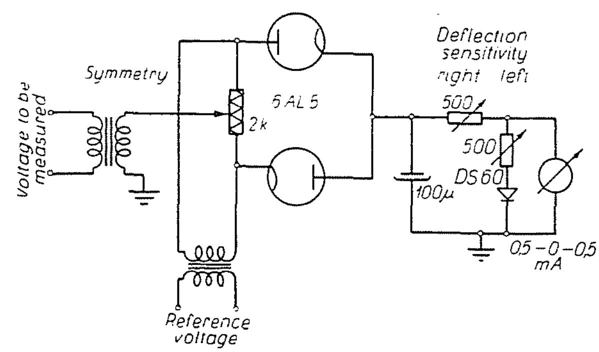

Fig. 10. Phase-sensitive detector

error signal goes on to the phase detector, which circuit can be seen in Fig. 10. In this version the linearity of the scale is not secured with specially shaped pole-shoes as mentioned above, but by a shunt crystal diode. The supply voltage needed for the instrument is taken from a mains-rectifier stage using a 6X4 miniature vacuum tube. In the Enamelled Wire Works (Albertfalva) instruments of this kind have been already used for several years and they made it possible to produce more enamelled wire of better quality.

By using the performance data and by introducing a new phase sensitive circuit stage [7]—[8], a new type of measuring instrument has been made for

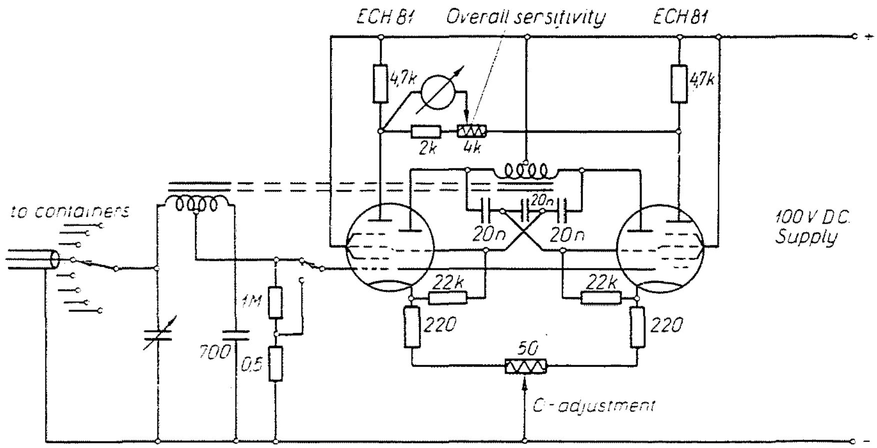

Fig. 11. Schematic diagram of new circuited plant measuring apparatus

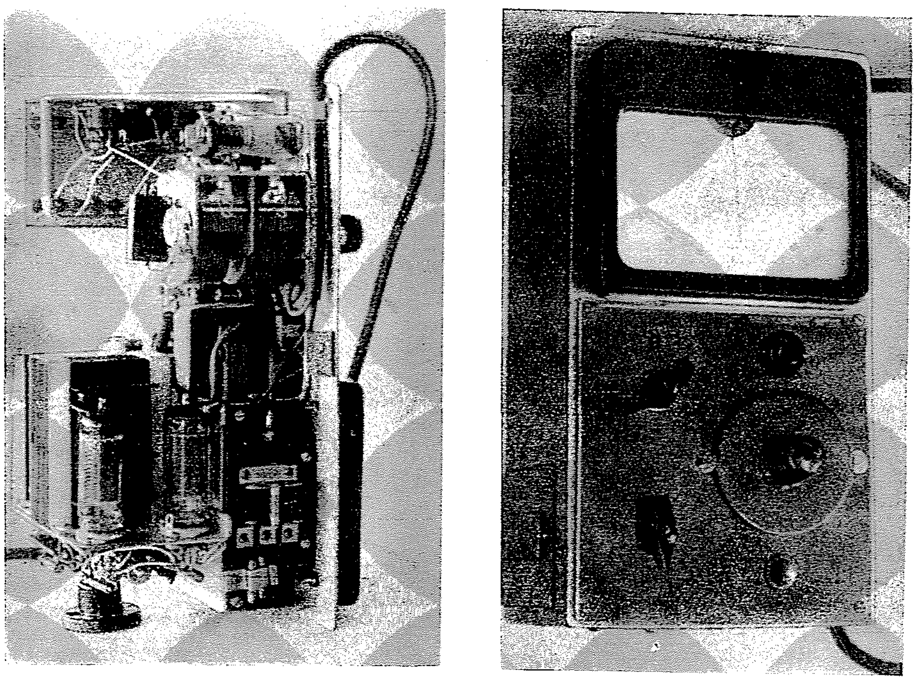

Fig. 12. Photo of new circuited plant measuring apparatus

export purposes, which contains only two vacuum tubes of the same type, besides the rectifier tube. The low number of tubes reduces the price of the instrument and greatly increases its reliability of service. The circuit diagram is shown in Fig. 11, while its photo can be seen in Fig. 12. Its working principle is as follows :

The oscillating systems of two mixer tubes (ECH 81) work in a push-pull oscillator circuit, so the mixer grids receive voltages of opposite phases. The transformer in the plate circuit of the oscillator supplies the previously discussed differential bridge. The output voltage of this controls the joined first grids of the mixer tubes. Multiple mixing takes place and the frequency difference results in direct current, which will increase the DC current in one of the tubes and a decrease in the other, because of the opposite phases of the voltages connected to the oscillator grids. A capacity deviation in the opposite direction will result in a plate current difference in the opposite direction. The plate circuits of both tubes form a DC vacuum tube voltmeter, a midposition miliammeter with specially shaped pole-shoes is connected to these points to indicate the unbalance.

Appendix

It is to be proved that equation (2) is a good approximation of equation (1) so

$$\frac{1}{\ln(1+x)} \approx \frac{1}{x} + 0{,}48$$

if $0{,}05 < x < 0{,}5$. Starting from equation (1) we can get equation (2) in the following way :

Let us expand in Taylor series the function $\ln(1+x)$ at the $x = 0$ place :

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots$$

So

$$\frac{1}{\ln(1+x)} = \frac{1}{x\left(1 - \frac{x}{2} + \frac{x^2}{3} - \dots\right)} = \frac{1}{x\left[1 - \frac{x}{2}\left(1 - \frac{2}{3}x + \frac{2}{4}x^2 - \dots\right)\right]}.$$

By a binomial series expansion it can be written :

$$\frac{1}{\ln(1+x)} = \frac{1}{x}\left[1 + \frac{x}{2}\left(1 - \frac{2}{3}x + \frac{2}{4}x^2 - \dots\right) + \right.$$

$$\left. + \left(\frac{x}{2}\right)^2 \left(1 - \frac{2}{3}x + \frac{2}{4}x^2 - \dots\right)^2 + \dots\right].$$

Let us take only the first two members of the series in [ ], and to continue the neglection, let us regard constant as the so far unknown multiplier of $x/2$. In this way:

$$\frac{1}{\ln(1+x)} \approx \frac{1}{x}\left[1 + A\frac{x}{2}\right] = \frac{1}{x} + \frac{A}{2}.$$

The error of the approximative formulae is given by the

$$h(x) = \frac{1}{x} + \frac{A}{2} - \frac{1}{\ln(1+x)}$$

error function (Fig. 13).

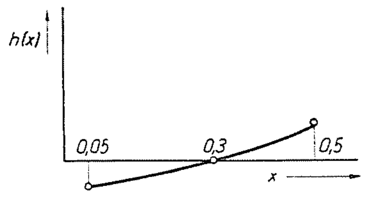

Fig. 13. Error function

The two functions smooth the best to each other, when the error integral

$$H(x_1, x_2) = \int_{x_1}^{x_2} h(x)\, dx$$

taken for the whole range is zero. This condition gives the zero place of the error, and the A multiplier, respectively

$$H(x_1, x_2) = \int_{x_1}^{x_2} \frac{dx}{x} + \int_{x_1}^{x_2} \frac{A}{2}\, dx - \int_{x_1}^{x_2} \frac{dx}{\ln(1+x)} = 0\,.$$

To solve the first two integrals is not difficult, but the third one can only be calculated numerically. This latter one is the logarithmic-integral function, which can be found in tables of higher functions [9] with the symbol : li $(1+x)$. So

$$H(x_1, x_2) = \ln\frac{x_2}{x_1} + \frac{A}{2}(x_2 - x_1) - [\text{li}(1+x_2) - \text{li}(1+x_1)] = 0$$

and at the given boundaries:

$x_1 = 0{,}05$	li (1,05) = −2,3935
$x_2 = 0{,}5$	li (1,5) = 0,1251
	ln 10 = 2,3026

So it comes that :

$$A = 2\,\frac{0{,}1251 + 2{,}3935 - 2{,}3026}{0{,}45} = 0{,}96.$$

The error is the greatest at the boundaries :

$$h(x_1) = -\,0{,}01,$$
$$h(x_2) = +\,0{,}015.$$

There is no error if x is equal to the root of the following transcendental equation

$$\frac{1}{x} + \frac{A}{2} - \frac{1}{\ln(1+x)} = 0.$$

Here $x = 0{,}3$.

Summary

Both the heavy-current and weak-current industry put up strong demands against the enamelled wires. The thickness of the enamel layer cannot be continuously checked, in production, with mechanical measuring devices. The paper discusses a new method and a plant measuring apparatus, which measures the layer-thickness non-destructively in a capacitive way. In connection with the new method a few questions of standardization are also discussed in this article.

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