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THE RECALCULATION OF THE ORIGINAL PULSE PRODUCED BY A PARTIAL
DISCHARGE, TAKING INTO CONSIDERATION THE DISTORTION CIRCUITS
INSERTED BETWEEN THE "POINT OF THE EVENT" AND THE "POINT OF
MEASUREMENT"

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16. Abstract

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A number of analytical and graphic methods are presented, and computer simulations are used which were developed by the author for specific cases of a few measurement circuits. It turns out to be possible to determine the effect of each circuit element and thus make some valid corrections.

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THE RECALCULATION OF THE ORIGINAL PULSE PRODUCED BY A PARTIAL DISCHARGE, TAKING INTO CONSIDERATION THE DISTORTION CIRCUITS INSERTED BETWEEN THE "POINT OF THE EVENT" AND THE "POINT OF MEASUREMENT"

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Summary   /3*

The loads on a dielectric or an insulation arrangement cannot be precisely rated without properly assessing the manner in which a pulse produced by a partial discharge is transmitted from the point of the event to the point where it is recorded.

A number of analytical and graphic methods are presented, and computer simulations are used which were developed by the author for specific cases of a few measuement circuits. It turns out to be possible to determine the effect of each circuit element and thus make some valid corrections.

1. Introduction

With an accurate recording of the pulses which indicate a partial discharge it is possible to precisely rate the loads on a dielectric or an insulation arrangement. Unfortunately, however, the display of this discharge on an oscilloscope allows s · some distortions due to circuits inserted between the recording instrument and the point at which the error occurs. Owing to their time constant these circuits change the rise time of the pulse and reduce the amplitude.

Thus an incongruity appears between the actual load on the dielectric and the load which is estimated to be much smaller according to the pulse displayed on the oscillograph.

In recent years the ever-increasing use of oscillographs

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* Numbers in the margin indicate pagination in the foreign text.

with wide-band amplification has made it possible to precisely determine the shape parameters and pulse parameters [1,2]. The problem will become even more important in the future if the measurement of partial discharges using narrow-band measuring devices is supplemented by wide-band measurements in order to gain additional information about the pulse [3].

In this connection -- except when using circuits with reduced time constants which cause only slight distortion -- the problem arises concerning the creation of some analytical or graphoanalyticamethods with which one can recalculate the original pulse from the pulse, recorded on the oscillograph, which is then distorted by the measurement circuit. These methods would have to enable one to determine the effect of any circuits in the instruments used, thus allowing appropriate corrections to be made.

In what follows, the author proposes some considerations for possible methods to be used for recalculating a pulse. In so doing, these methods are applied in some actual measurement situations involving partial discharges.

2. Analytical Methods

If the transfer function of a circuit and one of the input and output variables is known, it is possible to analytically determine the other variables in the case of a simple circuit. The problem becomes more and more complicated with circuits consisting of several distortion circuits[1] or with the production of some pulses which, in terms of shape, appear more complicated. (Instead of a step function, an exponential or double exponential function). By solving the equations for these circuits and calculating the function maximum, although difficult to do, it is

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1. By distortion circuit is meant a circuit with R and C inserted between the "point at which the event occurs" and the "point at which it is measured."

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definitely possible to determine the pulse amplitude and the time at which the pulse reaches the maximum amplitude.

2.1 General Case: Two Distortion Stages, Input Vairable, a Double Exponential Function of the Form: $u_{Eing} = U_{Eing}[\exp(-\alpha t) - \exp(-\beta t)]$

This is the most general case which might be encountered in practice both from the standpoint of the number of elements used and from the standpoint of the form of the input variable. Other cases encountered during testing are derived from this case by introducing particular quantities. For such a circuit with two elements (Fig. 1) the transfer function assumes the form:
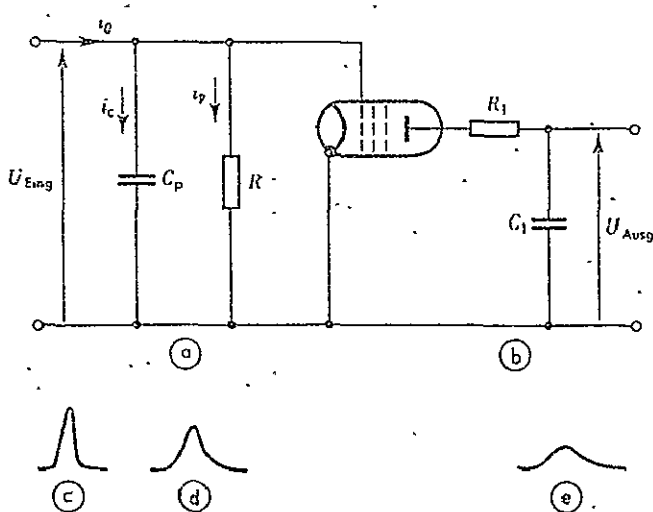
$$G(p) = \frac{\mathscr{L}(u_{Ausg})}{\mathscr{L}(u_{Eing})} = \frac{1}{(1+pT)(1+pT_1)} \quad (1)$$

We define our terms as follows:

$$\gamma = \frac{1}{T} \quad (T = RC_p)$$

$$\delta = \frac{1}{T_1} \quad (T_1 = R_1 C_1) \quad (2)$$

Fig. 1. The distortion stages between the point where the discharge is produced and the point at which it is recorded.
a. measurement stage
b. oscillograph amplifier
c,d,e. qualitative appearance of the pulse distortion (reduction in amplitude and change in front shape) after passing through the stages.

Provided that the variable used for the system input is a double exponential function of the form:

$$u_{Eing} = U_{Eing}[\exp(-\alpha t) - \exp(-\beta t)] \quad (3)$$

with α and β as time constants for the two exponential functions, then this function can be expressed

as follows:

$$\mathscr{L}(u_{Eing}) = \mathscr{L}(u_{Eing})[\exp(-\alpha t) - \exp(-\beta t)] =$$

$$= U_{Eing}\frac{\beta - \alpha}{(p+\alpha)(p+\beta)} \quad (4)$$

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Taking into consideration Eqs. (1) and (4), the picture of the output voltage will be the following:

$$\mathscr{L}(u_{Ausg}) = G(p)\mathscr{L}(U_{Eing}) = \frac{U_{Eing}(\beta-\alpha)\gamma\cdot\delta}{(p+\alpha)(p+\beta)(p+\gamma)(p+\delta)} \qquad (5)$$

where the expansion theorem is used successively: p = -α; p = -β; p = -γ; p = -δ. The values of the constants A, B, C and D are determined. These are given by the following equations:

$$A = \frac{\gamma\cdot\delta}{(\gamma-\alpha)(\delta-\alpha)} U_{Eing}$$
$$B = -\frac{\gamma\cdot\delta}{(\gamma-\beta)(\delta-\beta)} U_{Eing}$$
$$C = \frac{(\beta-\alpha)\gamma\cdot\delta}{(\gamma-\alpha)(\gamma-\beta)(\delta-\gamma)} U_{Eing}$$
$$D = -\frac{(\beta-\alpha)\gamma\cdot\delta}{(\delta-\alpha)(\delta-\beta)(\delta-\gamma)} U_{Eing} \qquad (6)$$

With this information the function u_{output} assumes the form:

$$u_{Ausg} = A\exp(-\alpha t) + B\exp(-\beta t) + C\exp(-\gamma t) + D\exp(-\delta t) \qquad (7)$$

a function which, when solved, gives the solution for the most general case encountered in making measurements.

The method of solving Eq. (7) is based on the use of a computer, with the determination of some additional conditions.

The results obtained for the maximum amplitude of the pulse (when it occurs) and for the time were in agreement with results obtained by other methods.

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2.2 Cases Derived from the General Case

2.2.1 A single distortion stage, the exponential input variable of the form: $u_{Eing} = U_{Eing}[\exp(-\gamma t) - \exp(-\beta t)]$.

This case can be studied using the equations for the general case if $T_1 = 0$ (or $\delta = \alpha$).

Substituting these conditions into Eqs. (1), (2), (5), (6) and (7), we obtain values for the case in point, (6') and (7'):

$$A = \frac{\gamma}{\gamma - \alpha} U_{Eing}$$

$$B = -\frac{\gamma}{\gamma - \beta} U_{Eing}$$

$$C = \frac{\gamma(\beta - \alpha)}{(\alpha - \gamma)(\beta - \gamma)} U_{Eing} \qquad (6')$$

The equation which gives the maximum for the output variable u_{output} assumes the form:

$$u_{Ausg} = A \exp(-\alpha t) + B \exp(-\beta t) + C \exp(-\gamma t) \qquad (7')$$

2.2.2 A single distortion stage, the exponential input variable of the form: $u_{Eing} = U_{Eing} \exp(-\gamma t)$

This case can be studied from the general case wherein

$$T_1 = 0 \quad (\delta = \infty), \quad \beta = \infty$$

Thus Eqs. (6) and (7) become:

$$A = \frac{\gamma}{\gamma - \alpha} \qquad\qquad C = -\frac{\gamma}{\gamma - \alpha} \qquad (6'')$$

$$u_{Ausg} = A \exp(-\alpha t) + C \exp(-\gamma t). \qquad (7'')$$

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This case was studied by Kreuger [4;5] who successfully determined the variation curve for the ratio of the input variable and the output variable as against the ratio of the time constants for the circuit and for the pulse. With his equation it is possible, if one knows the input variable and the circuit parameters, to very easily determine the output variable in a functional manner. The reverse procedure is also valid.

3. Graphic Methods

Assuming a partial discharge source consisting of a "point-plate" electrode system with a precision resistor R connected in series and with the point at the negative polarity of the voltage
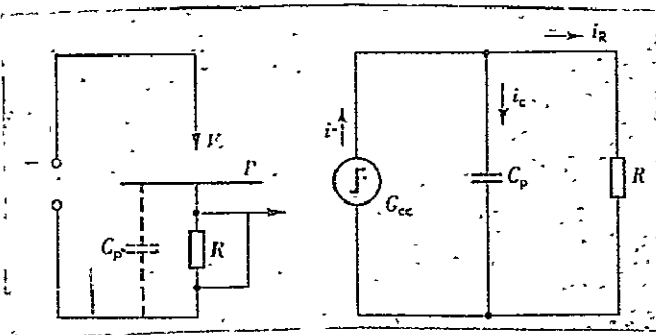

Fig. 2. Diagram of a point-plate system with a constant current generator.

source, König [6] considers this system with a constant current generator which transmits pulses of constant amplitude and with a rectangular front into the test apparatus (Fig. 2).

The Trichel pulses which are found with an electrode arrangement of this type are distinguished by their constant amplitude and frequency for a given voltage [7,8].

Fig. 3 shows the regularity of the curve for such a discharge mechanism in a "point-plate" electrode system.

An arrangement with two distortion stages inserted between the "point of the event" and the "point of measurement" shows that in Fig. 1 R stands for the precision resistor and Cp the interlinking capacity between the plate and ground, while R_1 and C_1 represent the amplification elements of the oscillograph. As the pulse passes through each stage its shape changes, affecting
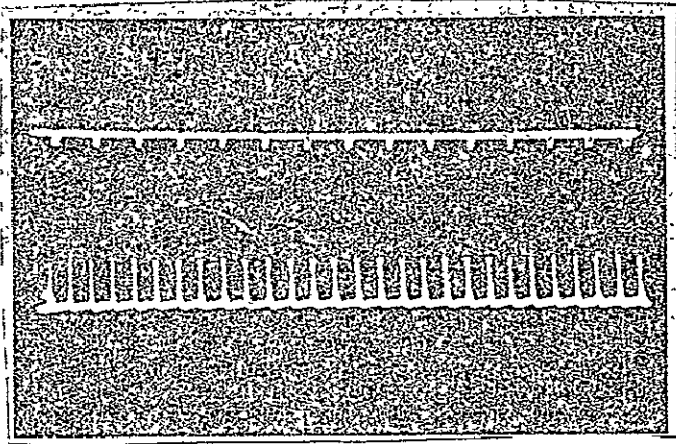
Fig. 3. Trichel pulses in a point-plate electrode system, current pulses of constant amplitude.

both the front and amplitude, precisely as shown qualitatively in Figs. 1c, d and e.

The current supply by the generator has two components, i_c and i_R, which passed through the voltage [sic] and the precision resistor. Provided that a pulse stage is produced at the input, the current i_R will increase exponentially according to the following equation:

$$i_R = i\left[1 - \exp\left(-\frac{t}{T}\right)\right]$$

(8)

with $T = C_p R$ as the time constant and $u_m = R i_R$ as the voltage applied at the oscillograph.

This already distorted pulse i_R reaches the second stage (oscillograph amplifier) and as a result an even more distorted curve is produced.

Based on the Duhamel reconstruction theorem, König [6] breaks down the recorded pulse into a series of step pulses of width $\Delta t < T$ (T stands for the time constant of the circuit transited) on the basis of which the input variable is determined using a few graphs and some proportionality equations. The smaller the time interval Δt into which the pulse is divided and the greater the operating stage, the greater is the precision.

Fig. 4 shows the recalculation of the original pulse for an exemplary case from a pulse recorded on an oscilloscope.

for curve 2:
$T = R\,C_p = 280 \times 200 \cdot 10^{-7} = 56\,ns$
$\Delta t = 10\,ns$
$\dfrac{\Delta t}{T} = 0.138$

for curve 3:
$T_1 = R_1 C_1 = 11\,ns$
$\Delta t = 4\,ns$
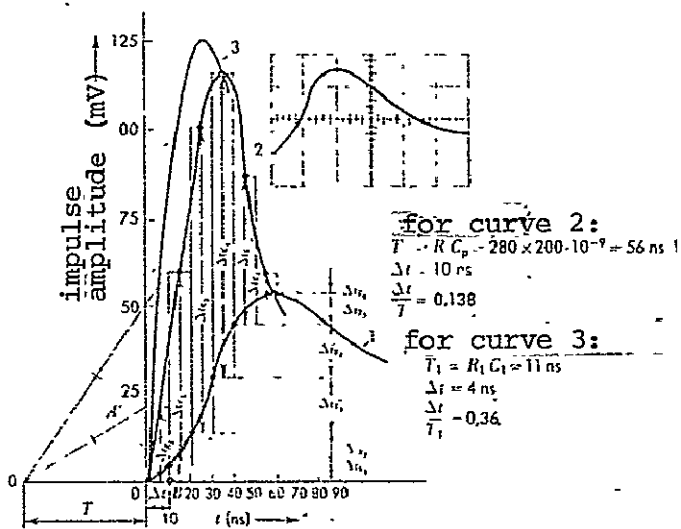$\dfrac{\Delta t}{T_1} = 0.36$

Fig. 4. Recalculation of the original pulse from the pulse recorded on a oscillograph.
1. Recorded pulse.
2. Recalculated pulse, taking into consideration the influence of the measurement circuit.
3. Original pulse, recalculated before it passes through the 2 circuits.

The series expansion of Eq. (8) which gives the current i_R leads to an approximate equation of the form:

$$\frac{\Delta i_{R_v}}{\Delta t} = \frac{\Delta i_{K_1}}{T} . \qquad (9)$$

in which T is the time constant of the circuit transited by the pulse, Δt is the partial interval, Δi_{K_v} is the change in the recalculated pulse. The polar curve P is selected at the original distance T from which Eq. (9) is geometrically determined from the similarity of triangles O' OA' and OAB and also from the similarity similarity of the other triangles which are formed in succession. Eq. (9) included the elements be

being sought.. If we know three variables then in a very simple manner the fourth variable Δi_K can be derived if the construction[1] is continued. In section 4 we will outline the technique employed by König using a concrete, recorded example.

This method, which was also used by the author in his work, gives sufficiently precise results in comparison with the results produced by other methods (not as precise as the results given by the analytical or adaptive methods, but they can be obtained much more quickly).

1. In so doing, different points i_K are determined through which the curve passes and which represent the recalculated pulse.

4. Computer Simulation Method

With respect to this problem, Schwab [9] has made a valuable contribution by using a computer for studying a detection circuit and test circuit for partial discharges.

With the knowledge of the pulse parameters at the output of the measurement system and the characteristic curves for the distortion circuits which are inserted between the point at which the events occurs and the point of measurement, research carried out at the Institute using the same technique [10] has shown that /200 appropriate vairations of the system can be simulated in order to study pulse transmission. If the input variable, e.g. front, amplitude, etc., is adjusted, then a pulse resembling the pulse obtained on an oscilloscope when measuring partial discharges can be [word missing]. In this case a clear connection between the parameters of these two pulses can be determined, e.g. the distortion caused by a circuit, the corrections which are effected, etc.

If we let RC_p stand for the time constant of the measurement circuit, and $R_1 C_1$ the time constant of the oscillograph amplifier (the second distortion stage); with $i_0(t)$ standing for the current produced by the partial discharge which is divided between R and C_p (i_R and i_C); with $u_1(t)$ standing for the distorted pulse of the first stage which is conveyed to the amplifier and with $u_2(t)$ standing for the pulse recorded on the oscillograph (see Fig. 1), then we can proceed to the actual simulation.

Equation (10)

$$i_0 = i_R + i_C \tag{10}$$

can be simulated if we take into consideration the fact that

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$$i_C(t) \doteq C_p \frac{du_c}{dt} \qquad \text{and} \qquad i_R = \frac{U_R(t)}{R} \qquad (11)$$

This can be transformed into the following equation:

$$\frac{du_1(t)}{dt} + \frac{u_1(t)}{RC_p} = \frac{i_0(t)}{C_p} \qquad (12)$$

which gives the solution for $u_1(t)$, i.e. the pulse after the first distortion circuit which will undergo a second change caused by the circuit R_1C_1.

It can be shown that the equation for $u_2(t)$ can be derived from a similar equation of the form:

$$\frac{du_2(t)}{dt} + \frac{u_2(t)}{R_1C_1} = \frac{i_1(t)}{C_1} \qquad (13)$$

The solutions for these two equations contain the desired values of $u_1(t)$ and $u_2(t)$.

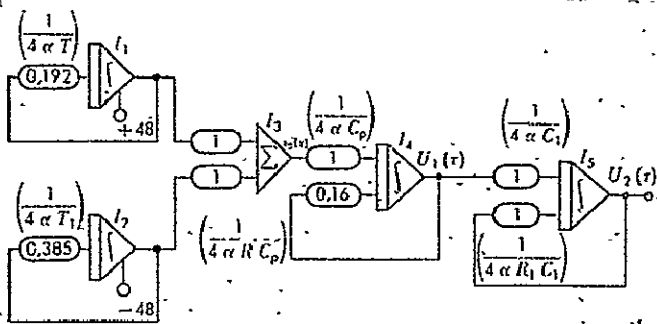Fig. 5 shows a diagram of the simulation procedure.

Fig. 5. Diagram of the simulation procedure for pulse transmission using an analog computer

The integrators I_1 and I_2 attain voltages at their outputs which change exponetially with the time constants T and T_1 so that at the output of sumator 3 a quantity proportional to the following equation is obtained:

$$i_0 = A\left[\exp\left(-\frac{t}{T}\right) - \exp\left(-\frac{t}{T_1}\right)\right] \qquad (14)$$

Using integrator I_4 the first distortion produced by the RC_p group is obtained. At the output of integrator I_5, after the distortion produced by the group R_1C_1, one obtains a quantity

proportional to $u_2(t)$, i.e. at another stage precisely the pulse which is recorded on the screen of the oscillograph.

In order to simulate and observe the curves for the variables on an analog computer these variables were converted into slow, very easy to observe changes which leads to a transformation of the time scale:

$$\tau = \alpha t \tag{15}$$

ThussEq. (12) takes on the following form in the new time scale:

$$\sigma \frac{du_1(\tau)}{d\delta} + \frac{u_1(\tau)}{RC_p} = \frac{i_0(\tau)}{C_p}. \tag{12'}$$

Annumber of coefficients (shown in Fig. 5) was obtained for the simulation procedure as a function of the computation parameters (R = 0.5 M , C = 0.5 F). With these it is possible to exactly observe the pulse transmission process. The coefficien. ficients are plotted as elements of the system.

The basic diagram used for the different cases is shown in Fig. 5. The only changes are in the values of the coefficients which differ for each case studied.

If the behavior of the measurement circuits with pulses having a steep front was observed, rectangular pulses of variable width were produced by a generator G. The simulation setup used is shown in Fig. 6. With the proposed simulations it was possible to check the measurement circuits. The type of pulse transmission and the connection between the input and output parameters were determined.. The problem of reproducing the input pulse on the basis of the pulse recorded by the oscillograph has not yet been completely solved.

Table 1. The Parameters of the Circuit and of the Recording Instrument

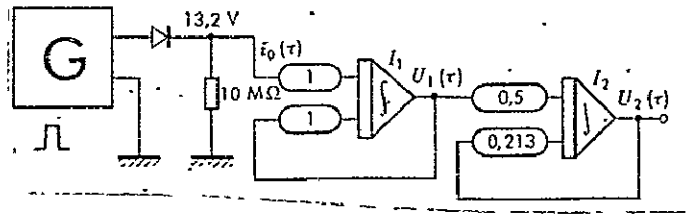| R Ω	C_p pF	B MHz	$T_1 = \frac{1}{2\pi B}$ ns	$T \sim RC_p$ ns	type of oscillograph
280	200	14	11	56	Philips GM-5602
37.5	200	30	5.3	7.5	Ribet-Desjardins

Fig. 6. Analog computer simulation diagram of measurement circuits with rectangular pulses passing through them.

5. Test Results

Two measurement circuits and two oscillographs were used by the author, T_1 stands for the time constant of the amplifier and T the time constant of the measurement circuit. The parameters for the recording instrument are given in Table 1. When using the first circuit the shape of the recorded pulse was that shown in the upper right corner of Fig. 4. This was enlarged with another scale to allow for easier treatment (curve 1).

The graph can be explained by a single distortion circuit and the same procedure is followed for the following circuit.

In accordance with the method discussed in section 3, a time interval Δ = 10 ns is selected, i.e. a ratio of $\Delta t/T$ = 0.138 < 0.3, and the curve recorded on the oscillographs is divided up into triangles of width Δt. The segments $\Delta i_{R_1} \ldots \Delta i_{R_n}$ which indicate the change in current through the resistor are determined by reading the curves, and T is determined by the choice of the ratio $\Delta t/T$. It remains to determine the fourth variable Δi_k which is calculated from Eq. (19) and in so doing a new amplitude is obtained. The triangle of width Δt and height Δi_{k_1} is drawn in; the recalculated curve passes through the middle of Δt. The other points of curve 2 are determined in a similar manner.

It is clear from Fig. 4 that the greatest distortion is

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produced by the current with the greatest time constant, both in terms of the shift in the amplitude maximum and in the steepness of the pulse. Thus in comparison with the recorded pulse, the amplitude of the recalculated pulse 3 is larger by a factor of 2.3, while the maximum is shifted by an amount of 23 ns as against the original 60 ns. Therefore even larger insultation loads are produced than those derived from the values recorded on the oscillograph, a fact which requires careful recalculation of the original pulse.

Figs. 7 represents the second case in which a wide-band Ribet-Desjardins oscilloscope was used. The time constants from the diagram had values of 5.3 ns and 7.5 ns. In this case, because of the small time constants, the distortion caused in both circuits was minimal. The ratio of the original pulse maxima and the distorted pulse may not exceed 11.5%. Just as in the first case, a maximum shift of a similar value, approximately 25 ns, was determined. Hence we see that the results obtained are similar for the different recording instruments used in the two cases.

Using the computer and the basic diagram shown in Fig. 5 it was possible to study the effect of the circuit elements during the measurement process.

for curve 2:
$T = R\,C_p = 37.5 \times 200 \cdot 10^{-9} = 7.5$ ns
$\Delta t = 2.2$ ns
$\frac{\Delta t}{T} = 0.29$

for curve 3:
$T_1 = 5.3$ ns
$\Delta t = 1.5$ ns
$\frac{\Delta t}{T_1} = \frac{1.5}{5.3} = 0.284$

1. auf Oszilloskop eingetragener Impuls
2. unter Berücksichtigung des Meßkreis-einflusses umgerechneter Impuls
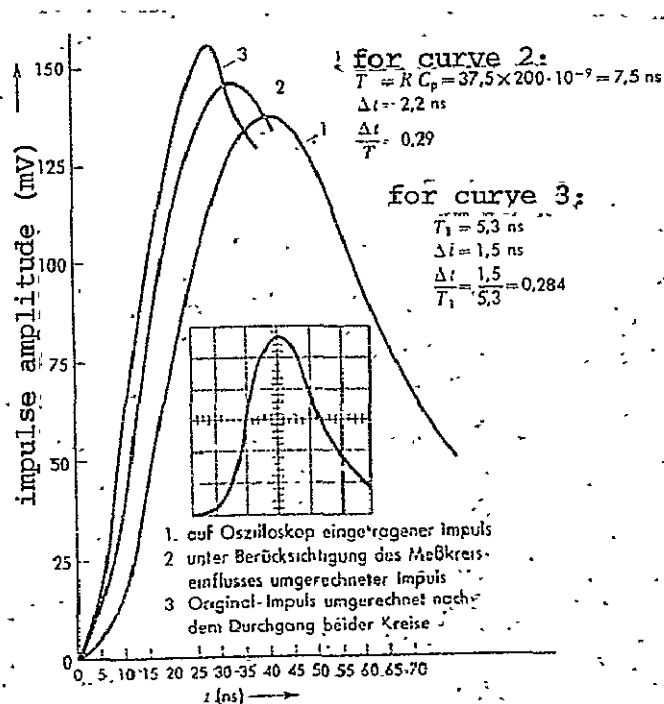3. Original-Impuls umgerechnet nach dem Durchgang beider Kreise

Fig. 7. Recalculation of the original pulse from the pulse recorded on wide-band oscillographs.
1) Pulse plotted on an oscilloscope. 2) Recalculated pulse taking into consideration the effect of the measurement circuit. 3) Original pulse recalculated after passing through both circuits.
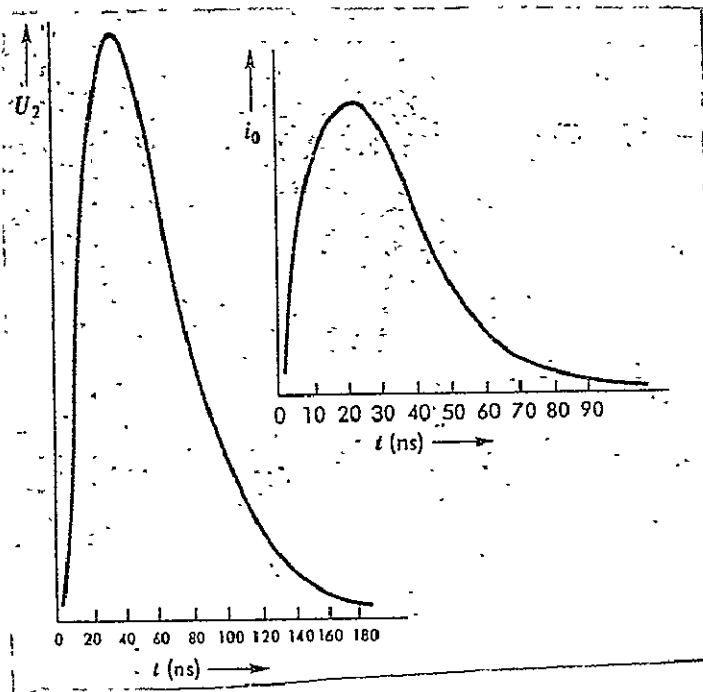
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Fig. 8. The input pulse (i_0) on an analog computer recalculated from the pulse recorded at the output of the measurement system u_2.
U_2 = Final pulse recorded on the oscilloscope
i_0 = Pulse recalculated on the computer.

Simulating different situations -- precision resistors ranging between 37.5 Ω and 1000 Ω and corresponding to different oscillographs -- it was possible to determine the way in which a circuit affects the pulse transmission. In so doing, the smallest distortions were determined in the case of the circuit with small time constants. From the series of results obtained, the results given are those corresponding to the case in which R = 37.5 Ω, C_p = 200 pF, RC_p = 7.5 ns and $R_1 C_1$ = 5.3 ns. If the pulse at the system output is known then the input pulse can be determined.

Simulating the two exponential functions at the integrators I_1 and I_2, which are afterwards substracted from the sum Σ_3, and varying the parameters I_1 and I_2 which are determined by the two distortion stages, it was possible to obtain a pulse similar to that recorded on the oscillograph. Because of the similarity between the curve obtained and the curve recorded using the computer it can be stated that the pulse i_0, which had such an appearance after passing through the distortion circuit, is the non-distorted original pulse. Fig. 8 shows the curves recorded in this case. Similar results were obtained with other methods. The peak of the original pulse likewise falls in the 23-ns range, just as in the graphic or analytical methods. (Analytically, solving the transcendental equations [11] in section 2 gives the amplitude maximum for the specific case of

the circuit used. Other methods give an approximate value of
25 ns for the time maximum.) If the circuit is once simulated   /202
in this way then the necessary corrections from one stage to
another can also be made.

Likewise, in case a rectangular pulse generator G is being
used, the distortion of the front at each stage and also the
reduction in amplitude can be determined.

When using rectangular pulses of a width of 20–25 ns we see
that the greatest amount of distortion is caused with the pulses
of the smallest width. Likewise the rationbetween the pulse
amplitudes apply and those recorded are smaller, the larger the
pulse width.

6. Conclusions

6.1 When the characteristic curves for the circuits and
the output variable are known, the analytical methods for
determinging the input variable, which are easy to use for
simple circuits, become difficult methods to handle in the case
of several complicated circuits or with the input of complicated
functions. Solving these equations requires expert knowledge
and, under certain conditions, a computer.

6.2 The results obtained using the graphic methods showed
that the shape of the original pulse can be recalculated with
sufficient accuracy with respect to the distorted pulse. This
is independent of the measurement system and the oscillograph
used, taking into consideration the indications of scale selection.
Moreover, data can be obtained on the pulse parameters at the
discharge point even in the case of a highly sensitive instrument
when using the corrections mentioned above. The graphic method
offers the possibility of making a quick evaluation of this
phenomenon.

6.3   The simulation of the pulse transmission circuits from the point at which the event occurs to the point at which it is measured using an analog computer gives exceedingly valuable indications for the selection of the characteristic curves of a measurement system which is supposed to transmit the input quantity as accurately as possible.   Exact simulation of the distortion circuits makes it possible to reproduce the input pulse if the output variable $u_2(t)$ is known.

By applying pulses of different shape and varying their parameters until a pulse is obtained which resembles that recorded on the oscilloscope it is possible to approximate the input pulse and obtain some information on the front time, the half-amplitude time and the maximum.

6.4   The results obtained using the different methods mentioned in the paper are similar so that one is free to choose any one of the methods.   It is recommended, however, that, if possible, at least two methods be used for more exact determinations.