Basics and Application Of the Pulse-Echo-Method

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Basics and Application of the Pulse Echo Method

1.1. Measuring method

A pulse fed into a cable will be reflected at a point of change in the characteristic impedance of the cable to its near end. Hence, if the propagation velocity of the pulse in the cable is known, the distance to the point of reflection can be calculated from the transit time of the pulse. Changes in the characteristic impedance are short-circuits and breaks or series faults. For the measurement of the transit time of the pulse, one uses a pulse generator, an amplifier and an oscilloscope for representation and time measurement.

1.2. Test pulse

For the pulse echo measurement, voltage or current impulses are fed to the near end of the cable. With regard to their period, these are short voltage or current impulses with square, triangular or bell-shaped pattern. Sine- and cosine-shaped pulses are also found. As per Fourier, any such pulse represents the sum of a multitude of AC voltage components of various frequencies which coincide in a defined assignment of their phases and amplitudes. Hence follows, that due to frequency-dependent attenuations of a cable, the same appears as a low pass and a pulse fed into the cable will change its shape after a longer distance.

1.3. Characteristic impedance

The characteristic impedance of a cable is the resistance value which would be measured at the near end of an indefinitely long cable. For the practical application, it has been approximately defined as :

[1] $$Z = \sqrt{\frac{L}{C}} \text{ Ohm}$$

Since both numerator and denominator are geometrical values, the characteristic impedance itself is independent of the length of the cable.

In order to recognize limiting cases - e.g. measurements in a telecommunication cable with very small core diameters - or other deviations, one uses the more precise formula [2]

[2] $$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \text{ Ohm}$$

Additionally, the equivalent circuit of an electrical transmission line has to be taken into consideration.

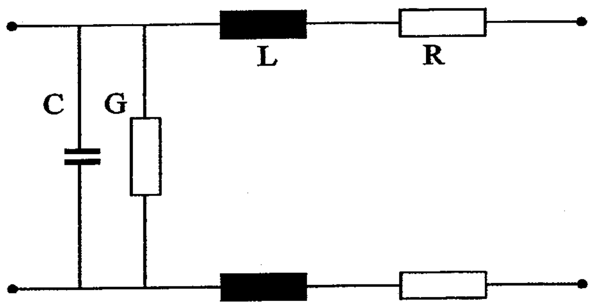

Figure 1 : Equivalent circuit of a cable

Whereby :

C	=	Shunt capacitance in nF
G	=	Leak resistance in Ohm
L	=	Series inductance in mH
R	=	Series resistance in Ohm

In the case of telecommunication cables with a small diameter, e.g. 0.4 or 0.6 mm, the series resistance R is a considerably stronger factor in the formula, which means that the resulting characteristic impedance can be largely determined by this value. The leak resistance G however can be considered relatively constant for a healthy cable and of no consequence for the characteristic impedance.

∅	0.4	0.6	0.8	1.2	mm
R/km	300	130	73	32.5	Ω
C/km	36	42	34	35	µF
L/km	0.7	0.7	0.7	0.7	mH
N/km	150	105	76	53	mN

Table 1. Data of telecommunication cables

1.4. Propagation velocity

The propagation velocity of electrical signals in cables corresponds to approximately half the speed of light and is largely independent of the measuring frequency, although in the case of long telecommunication cables with small diameters, the dispersion must not be neglected. For tasks of fault location, half the propagation velocity (v/2) is used. This value is mainly dependent on the type and construction of the insulant and hence of the dielectric constant ε and of the speed of light **c**. Formula [3] shows these interrelations.

[3] $$V = \frac{c}{\sqrt{\epsilon\ rel}} \quad \text{m/µs}$$

The total transit time from the near end to the far end of the cable and back is measured in µs. The distance to the point of reflection (fault) is calculated by the formula [4].

[4] $$l_x = t\frac{v}{2} \quad \text{m}$$

Some typical v/2 values are listed in table 2, whereby special attenuation should be paid to the differing stray values.

Cable type	v/2	Stray value
A2Y (FL)2Y	95	low
A2Y (St)	100	low
A02Y(LCo)	116.5	115-118
PMpc	118	110-120
NAKBA	80	77-83
NAYY	78	70-82
NA2XY	85	low

Table 2. v/2 values in m/µs

The v/2 values listed in this table are quantities, but no constants. Even within a manufacturing batch, variations may appear. In the case of plastic insulated cables, variations in v/2 occur between cores of different colours.

1.4.1. Dispersion in cables

The dispersion of a telecommunication cable is due to the frequency - dependent group delay time and makes itself felt as a length-dependent change in v/2. This means, that the test pulse looses constantly speed during its travel on the cable. For example, the v/2 value of a 0.4 pair reduces by 10 % at a measuring length of 30 - 40 µs. Figure 2 shows different wire diameters.

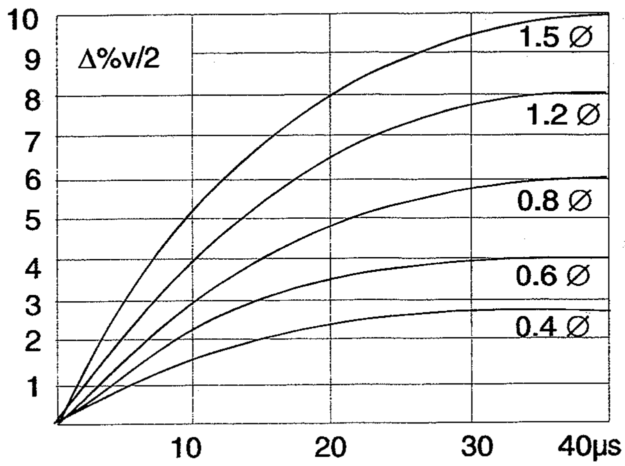

Figure 2. Dispersion on telecommunication cables

1.5. Cable attenuation

When using the pulse echo method with its high frequency components in unloaded cables, the attenuation formula [5] (at ω L ≥ R) is valid.

[5] $$l_x = t\frac{v}{2} \quad Np/km$$

For the low frequency component of the test pulse, the formula [6] (at ω L ≤ R) is to be used

[6] $$\alpha = \frac{R}{2Z} + \frac{GZ}{2} \quad Np/km$$

Therefore, the ohmic component of a cable determines largely its attenuation so that in the case of cores with a diameter of e.g. 0.4 mm, the attenuation will be considerably higher than in cores of e.g. 1.4 mm. Hence, the covering range of a pulse echo measurement in an unloaded cable is also dependent on its diameter. In a cable with a diameter of 0.4 mm, a maximum range of approx. 2 - 3 km can be expected.

1.6. Reflection factor

Any change in the homogenous structure leads to a change in inductance and/or capacitance - but also in the leakance G - at this point and hence to a change in the characteristic impedance Z. This reflection point with the change in characteristic impedance reflects a certain portion of the incoming test pulse in the direction of the feeding point. If only part of the pulse is reflected, the remaining pulse proceeds to the next reflection point and returns to the near end of the cable. The portion of the reflected impulse voltage is defined through the reflection factor r and is expressed in per cent. The following terms are valid :

r	=	reflection factor
Rf	=	fault resistance
Z	=	characteristic impedance of the cable

For parallel faults, the formula [7] is applied

[7] $$r = \frac{-Z}{2R_f + Z} \quad \%$$

This means, that in the case of a parallel fault, the reflected pulse changes its polarity.

For series faults, e.g. breaks or assembly faults, however, the formula [8] is valid :

[8] $$r = \frac{R_f}{2Z + R_f} \quad \%$$

In this case, the test pulse returns with the same polarity.

1.7. Fault Location

The test pulse which has been fed at the near end of the cable, travels to the reflection point at the propagation velocity typical of the cable and is reflected there in whole or in part to the near end of the cable. The required time **t** is used for the determination of the fault position. The determination of the fault distance has already been described in formula [4] using the following terms :

l_x	=	**fault distance**
t	=	time in µs
v/2	=	propagation velocity

[9] $$lx = t\frac{v}{2} \quad \text{m}$$

The measurement criterion is the time between the leading edges of the test pulse and of the reflected pulse. In the case of long cables, the test pulse is flattened through the attenuation so that the rise of pulse cannot be measured accurately. In this case, one uses the core or pair comparison, provided healthy cores or pairs are available.

2. Types of faults

The pulse echo measuring technique deals with a multitude of faults. However, these are always due to a change in the homogeneity of the cable. The effect of the malfunction caused by a fault is dependent on the cable or its operating mode. Any fault, be it the drop-out of a fuse due to a short-circuit in a power cable, cross-talk on a telecommunication cable or the incomplete transmission of pulses in a message transmitted with PCM technique, is a change in the characteristic impedance Z.

2.1. Parallel faults

In the case of parallel faults (contacts) with a reflection facor **r** = 100 % , all incoming AC voltage components, independent of the frequency, are reflected with the same amplitude, however with opposed phase position Figure 3a shows an ohmic parallel fault and figure 3 b the pertaining trace.

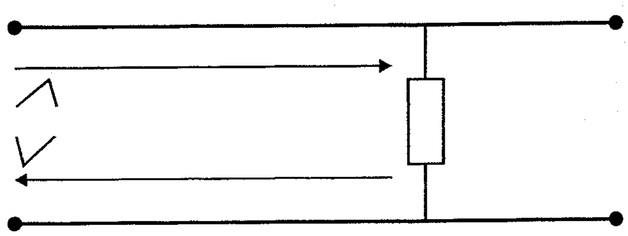

Figure 3 a. Parallel fault

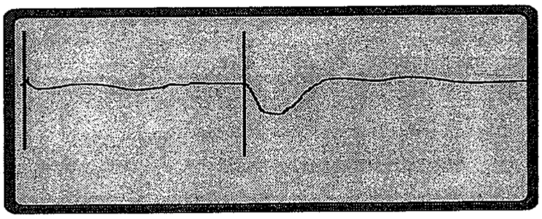

Figure 3 b. Trace of figure 3 a.

Provided that the cable is homogenous up to the point of fault, fault resistances can still be determined if the real fault resistance is < 10 Z. Imaginary or complex fault resistances will also render the reflection factor complex. In this case, in addition to the change in amplitude, differing phase displacements of the individual frequency components will occur which might distort the reflected pulse.

2.2. Series Fault

In the case of a series fault, e.g. a core break and hence a series fault resistance of infinite magnitude, all incoming AC voltage components are also reflected with the same amplitude and phase position. Hence, in the trace, the reflected pulse has the same polarity as the transmitted pulse. Figure 4 a and 4 b show a series fault and the pertaining trace.

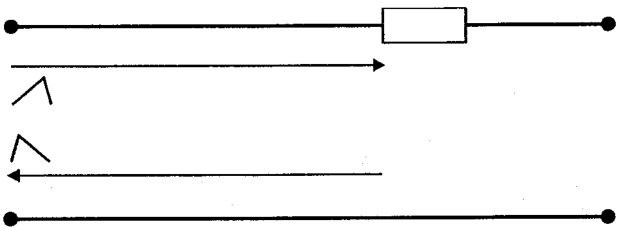

Figure 4a. Series fault

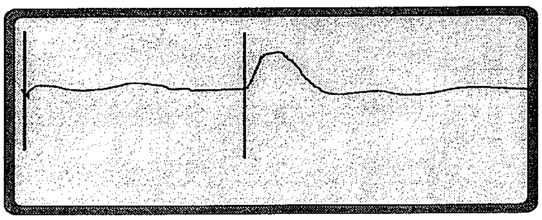

Figure 4 b. Trace of series fault

Provided that the cable is homogenous up to the series fault reflection, reflections due to a fault can still be measured if the fault resistance is > 1/10 Z.

2.3. Reflection Point

If two cable sections of different characteristic impedances are spliced together, so-called reflection points are generated which cause a partial reflection. The energy and communication flow will not be disturbed, with the exception of PCM operated communication cables. Hence such a "fault" is mainly of importance in pulse carrying cables.

A peculiarity of reflection points is the difference between the traces. They are totally different when viewed from the near end or from the far end.

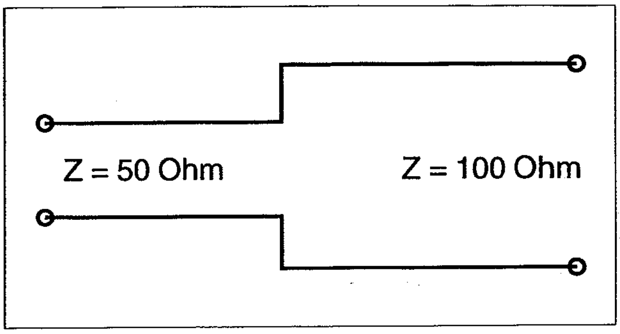

Figure 5 a. Reflection point

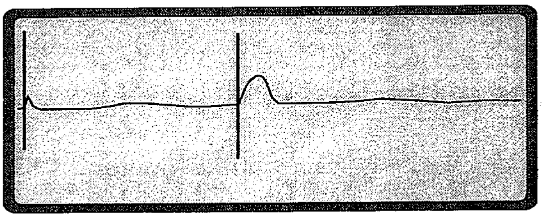

Figure 5 b. Reflection point viewed from the near cable end

The transition of the characteristic impedance from 50 to 100 Ohms is shown as a positive reflection

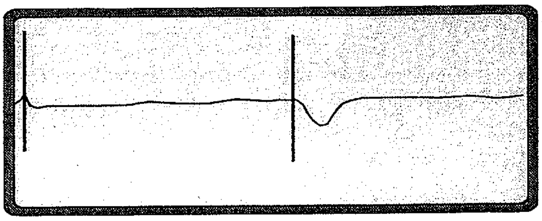

Figure 5 c. Reflection point viewed from the far end of the cable

2.4. Coupling Fault

Coupling faults are not reflection points and are very difficult to classify. Coupling faults can be real, imaginary or complex. The following types of coupling faults can be found in telecommunication cables : ohmic, inductive and capacitive coupling. With an ohmic coupling, the resistance should be < 1 kOhm. Coupling measurements with the pulse echo method do not measure the degree of coupling, but the distance of the coupling point. This measurement mode is of advantage when dealing with core transpositions and pair ruptures. Figures 6a and 6 b show a coupling fault and the pertaining trace.

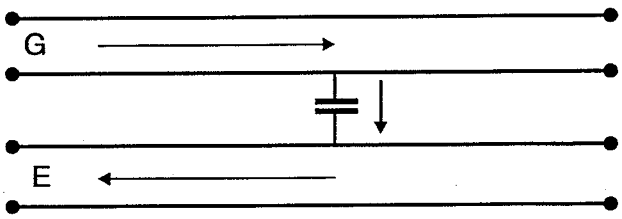

Figure 6 a. Capacitive coupling fault

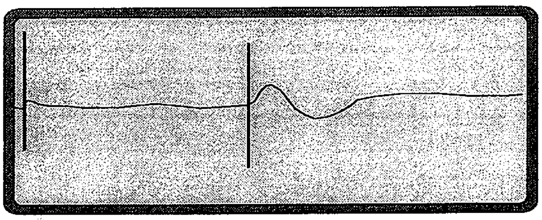

Figure 6 b. Trace of a capactive coupling

Figure 6 a shows that the method applied is not a pulse echo method. The pulse generator G and the receiver A are separated. Although the transmitter pulse is reflected at the far end of the cable, it returns to the generator without being indicated there. Part of the pulse, however, couples into the receiver line via the capacitor and, after having returned to the near cable end, is shown on the display unit. This measurement does not determine the degree of coupling, but the distance of the coupling point.

2.5. Intermittent Faults

Intermittent faults, i.e. changes from high to low resistance in an undetermined time sequence, can be located with pulse reflection instruments only when using special methods viz:

a. Arc reflection method
b. Impulse current method
c. Oscillation method

Since normally, each of these methods lasts only a few milliseconds and is non-recurrent, the necessity exists of recording this process in a transient recorder so that the evaluation can be carried out on a standing picture.

2.5.1. Arc Reflection Method

The arc reflection method is mainly applied in cases where the cable fault cannot be burned down to a low resistance value by means of a burn down instrument. Lately, this method is also used each time burning down is to be dispensed with. As shown in figure 7, the method consists of generating an arc through the ignition of the fault by a surge from the shock discharge generator SWG. For the purpose of maintaining the arc for approx. 20 ms, the arc stabilisation unit LSG feeds a sufficiently high current via the buffer diodes GL into the arc. During this time, a standard pulse echo measurement is carried out in the faulty cable. Coupling is made via the high voltage coupling capacitor CK.

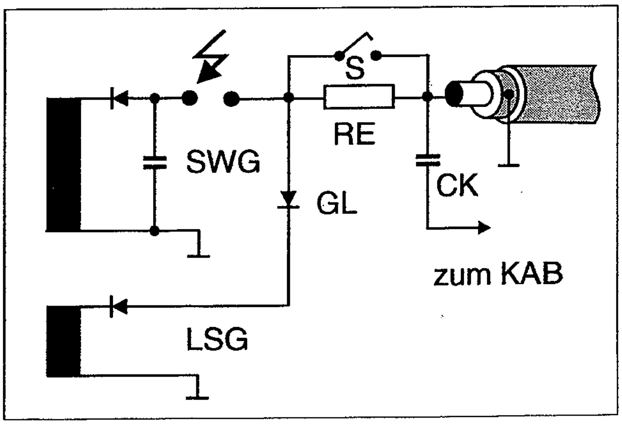

Figure 7. Arc stabilisation

The actual pulse echo measurement takes only a few ms and is recorded in the transient recorder of the pulse reflection instrument. Normally, a single breakdown is sufficient to carry out a prelocation of the fault. It is of special advantage to record a trace of the connected core prior to the arc reflection measurement. When comparing the two traces, the fault stands out very clearly as shown in figure 8. The measurement of the fault is carried out in the usual way. For a pinpoint location of a cable fault using the acoustic method, the switch S over the decoupling resistor RE is closed in order to obtain the full energy of the shock discharge generator at the fault.

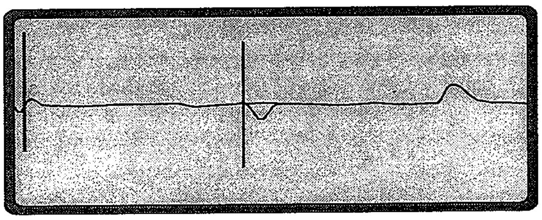

Figure 8. Double trace in the arc stabilisation method

2.5.2. Impulse Current Method

The application of this very simple method for the location of transient flashovers or breakdowns at the fault requires only a shock discharge generator SWG with a linear coupler LK and a pulse reflection instrument with a transient recorder (see figure 9). The advantage of this method lies in the fact that no high voltage carrying components are required for the generation of the test signal. The heterogeneities in a cable test van can be compensated through comparator circuits.

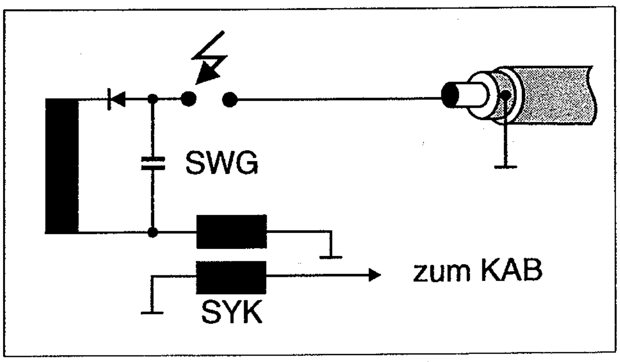

Figure 9. Impulse current methode

When a surge pulse is released, the transient phenomenon is transmitted to the transient recorder of the pulse reflection instrument and is recorded there. However, the fault trace is not evaluated by the rules of the standard pulse echo technique. Figure 10 shows the relevant connexions.

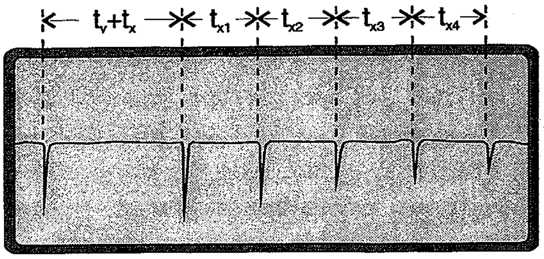

Figure 10. Representation of a flashover fault with the impuls current method

The distances in time of t_{x1}, t_{x2} and t_{x3} are identical. For the location of the fault, the formula [10] is used

$$[10] \qquad lx = tx_1 \frac{v}{2} \quad \text{m}$$

In addition to the transit time of the pulse, the measuring section tv+tx also includes the ignition delay time tv of the fault. Therefore, the first measuring section must not be used for the fault location.

2.5.3. Oscillation Method

Flashover faults in medium and high voltage cables can also be measured with the voltage oscillation method. This requires a very good insulation value of the point of fault up to the flashover. There must not be a resistance - not even very high - in parallel to the point of flashover, since a charging of the cable capacitance would not be possible. Figure 11 shows the schematic circuit diagram of the voltage coupled oscillation method.

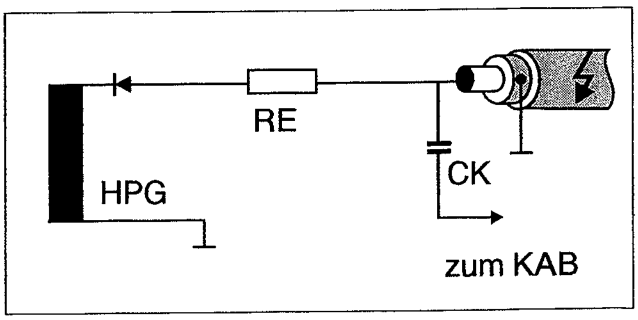

Figure 11. Schematic circuit diagram of the voltage oscillation method

For charging of the cable capacitance, a high voltage test instrument HPG is connected to the faulty core via the decoupling resistance RE. The high-voltage resistant coupling capacitor CK is connected to the same point. The test voltage is increased and on reaching the flash-over voltage, will generate a flashover at the fault. The resulting transient phenomena are fed to the transient recorder of the pulse reflection instrument via the coupling capacitor and can then be evaluated as a standing picture. Picture 12 shows an oscillation process

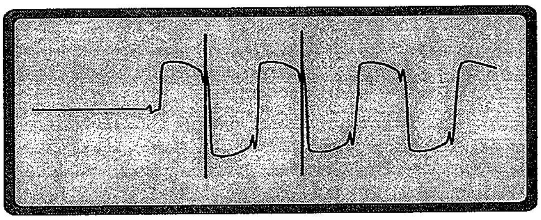

Figure 12. Oscillation result

The duration of the oscillation process depends on the cable capacitance on the one hand and on the cable attenuation on the other. The period T is measured, whereby as shown in figure 12, the individual periods are identical. For fault location, the formula [11] is used :

[11] $$lx = T\frac{v}{4} \quad \text{m}$$

3. Practical Pulse Echo Measurement

Pulse echo measurements can be classified in three different categories :

a. Direct measurement
b. Comparison measurement
c. Differential measurement

3.1. Direct Measurement

For a direct measurement, only two test leads are connected to the faulty cable. The success of the measurement is however mainly dependent on the homogeneity of the cable and of the fault resistance. Short-circuit faults or total breaks stand out very clearly. Examples of these simple measurements are shown in figures 3 a - 3 b - 4 a - 4 b. A measurement of non-homogenous cables or cables with T-joints is very difficult as shown in figure 13. These cables compose of part sections of different structures, thus generating a multitude of reflections. The fault itself can hardly be recognized.

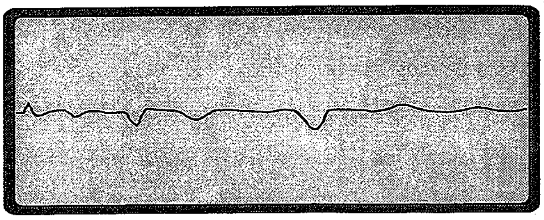

Figure 13. Fault in a non-homogenous cable in the direct measurement

3.2. Comparison Measurements

Here it has to be differentiated between a real time trace and a recorded trace.

3.2.1. Real time comparison measurement

In the real time comparison measurement, a healthy and a faulty pair of cores of the telecommunication cables are connected alternately via a relay circuit in the output of the pulse reflection instrument. Hence, the term "pair comparison" is used. In the case of power cables, a comparison is made between a healthy and a faulty core. The second reference point is the common screen or the neutral of the cable. This measurement is called "core comparison". A trace of a core comparison is shown in figure 14. Although all heterogeneities as in the direct measurement are present, the point of fault marked by the cursor can be easily recognized.

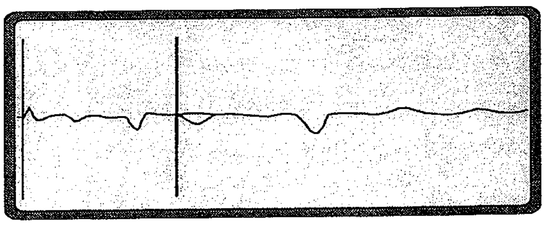

Figure 14. Core comparison measurement

3.2.2. Time-displaced comparison Measurement

If only one double lead is available, a pair or core comparison is not possible. The use of the recording technique however enables a comparison measurement. For this purpose, one proceeds as follows : First a trace of the cable section in question is recorded. Then the fault is pre-conditioned using burn down or shock discharge instruments. In most cases, this will be successful. Now a second trace is recorded and compared with the first record. The point of fault stands out clearly. Figure 15 shows a time-displaced comparison measurement. In this case, the fault could be made low resistance e.g. by means of a shock discharge generator.

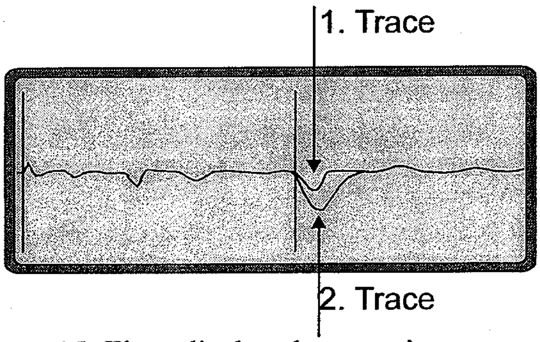

Figure 15. Time-displaced comparison measurement

3.3. The Differential Measurement

If two symmetrical pairs are available, then the possibility exists of applying the differential method as shown in figure 16.

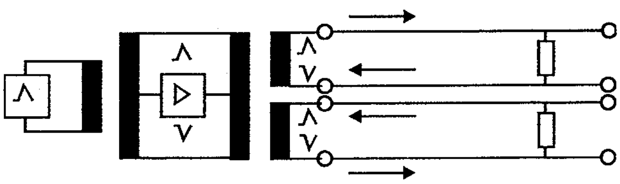

Figure 16. Differential measurement in symmetrical telecommunication cables

For the purpose of applying the differential method in power cables, one proceeds as per figure 17. The screen or neutral serves as a return conductor.

For the purpose of applying the differential method in power cables, one proceeds as per figure 17. The screen or neutral serves as a return conductor.

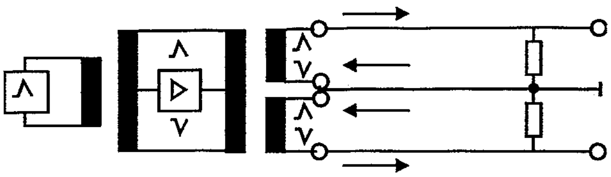

Figure 17. Differential measurement in power cables

In the differential measurement, all heterogeneities occurring at the same point cancel out so that only the real difference - the fault - is visible. Figure 18 shows the difference to figure 16 with the same fault.

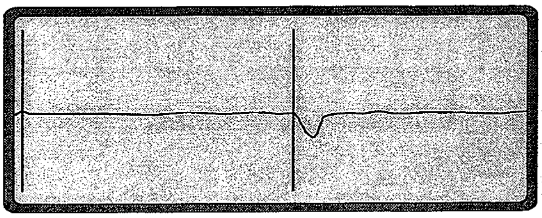

Figure 18. Differential trace

In the differential measurement, the usual initial reflections at the start of the trace disappear. This offers the possibility of measuring faults even at short distances. This method is applied with great success in cables with T-joints.

4. Length-dependent amplification

Especially when dealing with long telecommunication cables, the attenuation of the fault pulse is troublesome since even relatively low resistance faults cannot be recognized. Modern pulse echo test sets normally work with the sampling method in order to trigger the LCD display. This variant also offers the possibility of using a length-dependent amplification. Figure 19 shows the trace of a measurement in a long telecommunication cable. The fault reflection is very faint and can hardly be measured.

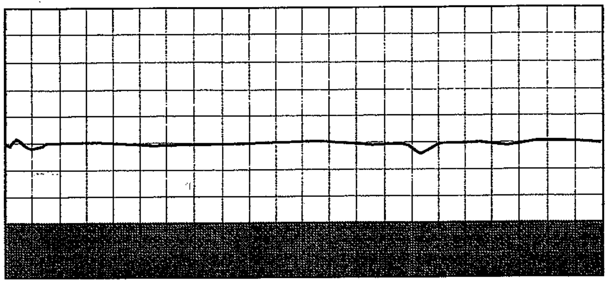

Figure 19. Trace with linear amplification.

By using a higher gain, the fault reflection could be recognized more easily, however, the initial reflections would also be amplified which could lead to an override which would overdrive the screen. Figure 20 shows this behaviour at a higher gain.

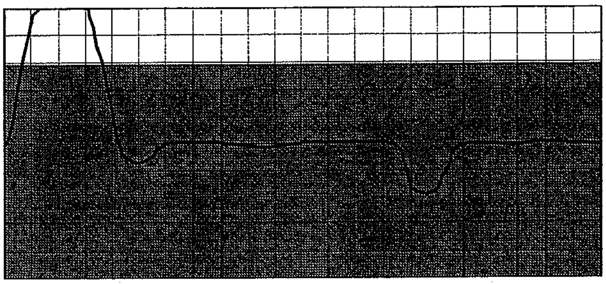

Figure 20. Trace with override.

Instruments with a length-dependent amplification avoid an override and simultaneously amplify the fault reflection. Figure 21 shows the length-dependent amplification and the results that can be achieved.

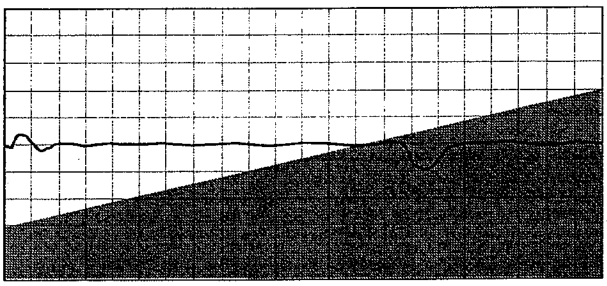

Figure 21. Trace with length-dependent amplification.

5. Recording of Traces

Due to the digital signal processing, modern pulse echo instruments are mostly equipped with internal or external recorders. The idea of recording traces mainly lies in supporting practical fault location. If for instance at the commencement of a measurement a trace of an untreated faulty core is recorded, then this trace is permanently available for comparison purposes. Even the slightest changes, caused by the application of high voltage or current, can be recognized and measured. Normally, these records are only temporary and can be erased after the successful measurement.

For a medium-term recording which is to be recommended if a cable section has failed repeatedly, the traces can be stored in external memories. The advantage of this kind of trace recording is that in addition to the trace with all its heterogeneities, also the setting parameters of the instrument are recorded. For the next measurement, the setting values used are immediately available.

The long-term recording of traces can serve for a cable surveillance with cable records. It is however to be noted that for the surveillance of a cable, several traces with different amplification have to be recorded. In addition to the total trace of a cable, traces of part sections should also be recorded. Practice has shown that a 3-core power cables of 2 km length requires approx. 12 traces to be recorded before changes can be recognized in time. External memories relieve the internal memory which is meant for short-term and medium-term records. External memories in the form of floppy discs or PCMCIA cards are more and more accepted by PCs and can be integrated in a cable data bank. For most of the good pulse echo instruments, a corresponding software is available.