Cable Fault Location in Power Cables

Fault Location in Low Voltage Networks
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1. Introduction

Problems in medium voltage networks are usually handled by redundancies in the setup and appropriate switching measures, which usually ensures a relatively uninterrupted continuation of the supply. A lengthier wait until the fault can be corrected results mostly only in an increased risk due to the possibility of consequentially occurring disturbances. In low voltage networks, which usually have no redundant power supply, the time intervals until the customer can be reconnected to the power supply greatly depend on the speed in locating the fault. The longer waiting periods due to a more remote fault location system are very problematic. However, a low voltage installation also has advantages. The distances are relatively short and easily manageable. In many cases, the joint position can also be very clearly delineated based on the known positions of the private connections. Since cable faults occur 80–90% in joints, an anticipatory localisation of the fault is possible.

2. Type and behaviour of cable faults in the low voltage network

<table>
<thead>
<tr>
<th>Type</th>
<th>Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient</td>
<td>irregular, short-term voltage drops without fuse triggering</td>
</tr>
<tr>
<td>Intermittent</td>
<td>irregular triggering of fuses at longer intervals</td>
</tr>
<tr>
<td>Ongoing</td>
<td>repeated triggering of fuses at shorter intervals</td>
</tr>
<tr>
<td>Permanent</td>
<td>interruptions and serious shorting</td>
</tr>
</tbody>
</table>

Many LV cable faults change from transient to permanent (“flickering lights” are possible signs of a transient fault).

In addition, LV cable faults are often unstable / non-linear and can therefore only be located when the cable is conducting live voltage.

Only once a fault has become permanent can it be located using conventional techniques with the cable in a voltage-free state.

All unstable LV cable faults require a change in their fault state in order to be located. The only way of doing this – with consuming devices connected – is to reconnect the mains voltage.

If the time period between re-energising and the fault occurring is too long, the more efficient and easier method is re-energising via a mains fuse. If the intervals are shorter and where there is sufficient space, automatic reconnection devices such as PowerFuse can be used to maintain the mains supply and effect a change in the fault state.
3. The technical problem of fault location in branched networks

Since, in order to locate high-resistance cable faults, DC and surge pulse voltages must be used, the private connection fuses must be removed. The problem of access to the service box arises, which is not always a given.

A real problem in prelocating faults on cables with many T-branches arises from the pronounced attenuation of the reflection measurement signals and the complexity of the reflectogram due to the jumps in impedance on the joints and branchings. Often, faults arising after the third or fourth T-joint are no longer recognisable due to these effects. Even more difficult is the situation with faults in branch joints, since these create a strong self-generated reflection themselves. Even the tried and tested arc reflection method (ARM®) is equally affected by these limitations.

In view of this, even experienced technicians today must often locate the fault by measuring various end points of the branched cable. In certain cases, the cable is actually cut in order to limit the test stretch.

In this article, we would like to present you with an overview of the proven test methods for low voltage networks. Further basic information can be found in the already published information on prelocation of cable faults.

4. Network structures

4.1. TN System (Fr. Terre Neutre)

In the TN system, the star point of the feeding transformer is earthed. In contrast to the TT system, the TN system introduces a protective multiple earthing at this point.

Depending on the version of the protective earth, a distinction is made between the TN-C system, the TN-C-S system and the TN-S system.

4.2. TN-C System (Fr. Terre Neutre Combiné)

In a TN-C system, a combined PEN conductor fulfils the functions of both a protective earth (PE) and a neutral conductor (N).
4.3. TN-C-S System (Fr. Terre Neutre Combiné Séparé)

The TN-C-S system is structured similar to a TN-C system from the transformer. At a certain point, the PEN conductor is divided into neutral conductor and protective earth.

4.4. TN-S System (Fr. Terre Neutre Séparé)

In a TN-S system, a separate neutral conductor and protective earth lead from the transformer to the consuming devices.

4.5. TT System (Fr. Terre Terre)

In a TT system, the star point of the feeding transformer is earthed. The protective earth of the consuming device does not lead up to this star point, but is instead earthed separately.

4.6. IT System (Fr. Isolé Terre)

In an IT system, the star point of the feeding transformer is not earthed. The protective earth of the consuming device is earthed separately. This type of network is used, for example, in areas at risk of explosion, in the operating rooms of hospitals, and by Deutschen Bahn AG.
5. Overview of test methods

### Prelocation based on impulse reflection methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Impulse reflection</th>
<th>LV monitoring</th>
<th>ARM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer need not be disconnected from mains</td>
<td>Consumer need not be disconnected from mains</td>
<td>Consumer must be disconnected from mains</td>
<td></td>
</tr>
<tr>
<td>Coupling via separation filter 400 V</td>
<td>Coupling via integrated separation filter 400 V</td>
<td>Localisation of high-resistance faults Comparison of OK and fault pattern</td>
<td></td>
</tr>
<tr>
<td>Localisation of impedance changes short-circuit interruption joints</td>
<td>Localisation of faults transient intermittent ongoing permanent</td>
<td>The structure of the network determines the level of surge voltage (max. 4 kV)</td>
<td></td>
</tr>
<tr>
<td>In branched networks, evaluation only through wire comparison</td>
<td>Comparison of OK and fault pattern</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Prelocation based on transient methods

<table>
<thead>
<tr>
<th>Method</th>
<th>TRS – LV Monitor</th>
<th>ICEPlus</th>
<th>ICE, three-phased</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer need not be disconnected from mains</td>
<td>Consumer must be disconnected from mains</td>
<td>Consumer must be disconnected from mains</td>
<td></td>
</tr>
<tr>
<td>Localisation of high-resistant transient faults according to the travelling wave method through synchronisation of two Teleflex LV Monitors</td>
<td>Localisation of low- and high-resistance parallel faults in branched networks</td>
<td>Localisation of low- and high-resistance parallel faults in branched networks</td>
<td></td>
</tr>
<tr>
<td>The structure of the network determines the level of surge voltage (max. 4 kV)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Additional methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Powerfuse</th>
<th>Voltage drop</th>
<th>Measuring bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer need not be disconnected from mains</td>
<td>Consumer must be disconnected from mains</td>
<td>Consumer must be disconnected from mains</td>
<td></td>
</tr>
<tr>
<td>Electronic fuse for bridging with intermittent faults Prelocation and pinpointing only conditionally possible</td>
<td>Localisation of low-resistance faults by measuring the voltage drop in the service box. Feeding of a high current</td>
<td>Localisation of low- and high-resistance faults using the bridge method</td>
<td></td>
</tr>
</tbody>
</table>
6. Prelocation based on impulse reflection methods

6.1. Basic principles

The use of T-branches in low voltage networks makes the evaluation of reflectograms considerably more difficult. Only through comparative measurements of fault-free and defective wires can evaluable results be achieved. The test pulses of Teleflex are partially reflected on the T-joint with a negative algebraic sign while test pulses that continue are simultaneously reduced in amplitude. The amount of reflection depends on the impedance in the main line and the continuing line. The T-joint is, according to the theory of transmission lines, a parallel switching of the impedance of two conductors.

\[
Z_X = \frac{Z_L^2}{2 \times Z_L} = \frac{1}{2} Z_L
\]

**Fig. 2: Equation for calculating the impedance**

With identical impedance of both continuing lines, Z is reduced by 50% at the T-joint. However, this seldom occurs in practice. As a rule, the main line has a larger cross-section than the secondary line and thus a different impedance.

The reflection factor “r” can be derived using the following equation:

\[
r = \frac{Z_X - Z_L}{Z_X + Z_L} = \frac{1}{2} \frac{Z_L - Z_L}{Z_L + Z_L} = \frac{-1}{2} \frac{Z_L}{Z_L} = -\frac{1}{3}
\]

**Fig. 3: Equation for calculating the reflection factor**
The result shows that with identical impedance, 33% of the test pulse is reflected with a negative algebraic sign and 33% of the pulse continues in each of the two continuing lines. Due to the different cross-sections of the main and secondary lines and the therefore varying impedance, the reflections at the T-branches are principally between 10% and 30%. Actual test results show that in singly branching networks, positive results can still be achieved even after 10 T-joints. In networks with multiple branchings however, the situation is more complicated.

This diagram shows a branched LV network with 12 T-branchings and two connecting joints. The end of the red line corresponds to the distance of the fault, which could be located on the straight line or in the T-branch.
The following diagrams depict the branches and joints shown above as a graphical representation and as reflections.

Fig. 7: Fault after the 7th T-joint

By graphically transforming the cable ends of the T-branches in the main line, the possible reflections of T-branches and cable ends can be seen.

Fig. 8: Fault after the 7th T-joint, graphically adapted

The following figure serves as the basis for comparing a reflectogram with the network.

Fig. 9: Idealised reflectogram and network
The end reflections of branches and negative reflections of the T-joints overlap and cannot be clearly designated as to their source. The following figure shows the reflections still in idealised form and without attenuation or dispersion.

![Fig. 10: Idealised reflectogram without attenuation and dispersion](image)

Depending on the construction of the cable and the number of joints, the test pulses are attenuated in their amplitude to various degrees.

![Fig. 11: Idealised reflectogram with attenuation](image)

Higher frequencies (steep slopes) are reduced with increasing distance (dispersion).

![Fig. 12: Idealised reflectogram with attenuation and dispersion](image)

Fault detection is very difficult from a measurement curve such as this. By short-circuiting the cable ends in the service or distribution boxes, it is possible to determine whether one’s position is before or after the fault.

Extensive knowledge about the faulty low voltage cable network simplifies the locating of the cable fault significantly. The technician should know the following:

1. Number of sections (cable types, different cross-sections)
2. Type of insulation: PVC or Paper/Mass (PILC)
3. Type of shield: copper, aluminium, none
4. Type of armour: lead, steel, plastic
5. Number of wires and cross-section: 3-, 4-, 5-lead cables
6. Position of fault: wire/wire, wire/shield
7. Fault resistance
8. Number of joints, length of sections, etc.
The diffusion speed \( v/2 \) changes depending on the type of coupling of the reflectometer on the cable.

Crucial for the diffusion speed of the test pulse, and thus also for the measuring accuracy, is the arrangement of the wires, but also the differences or changes in the dielectric. Typical known effects involve:

1. The position of the conductors to each other
   a. wire/wire adjacent
   b. wire/wire diagonal
   c. wire/shield
2. The construction
   a. colour of the PVC insulation
   b. material
3. The humidity content (e.g. in wet joints) – reduction of the \( V/2 \) by up to 30%

7. Examples and test results

In branched low voltage networks, low-resistance faults, interruptions and large changes in impedance can only be located by comparison of fault-free and defective wires.

7.1. Change of the pulse width
Wide test pulses generate more clear-cut reflections in the wire comparison mode. However, the resolution diminishes.

Fig. 13: Pulse width 50 ns
7.2. Wire comparison

With a wire comparison, small impedance changes can be made visible. L1 – fault-free wire is compared with defective wires L2 and L3.
The following example will demonstrate the difficulty of prelocating with the reflection method in a heavily branched network. The cable faults were located outside of Melbourne in an area of 150 to 200 single-family homes. The feeding could be undertaken from two sides. After removing all fuses (always outside the house), all three phases were measured and recorded with the Teleflex Compact System. The fault resistance was in the range of about 100 Ohm. Only by comparing the wires of all three phases could the fault position be prelocated at a distance of 193 m. The reflections between fault-free and defective wires were, due to attenuation at every T-joint, so limited that only by short-circuiting a phase near the service box (201 m) could the fault location be confirmed. The prelocation was made even more difficult by additional reflections of cable ends and branches. Prelocation without a comparison of the fault-free and defective patterns is hardly possible in a branched network. Acoustical pinpointing confirmed the prelocation.

Fig. 16: Wire comparison of L1/L2/L3 in a heavily branched low voltage network in Melbourne, Australia (Fault at 193 m, short-circuit created in service box at 203 m, opened joint link to service box)
7.3. IFL – Intermittent Fault Locating

Intermittent faults are very difficult to locate. Due to numerous joints and connections, these faults occur frequently in low voltage and street lighting networks. Corrosion in lamp masts and poor connections in joints lead to these faults. The Digiflex Com and Teleflex MX have therefore been equipped with “IFL mode”. Both devices perform continuous measurements and record them. Every impedance change, short-circuit and interruption is automatically saved and represented in a reference curve.

Advantages of the IFL mode:
- No time synchronisation required, every change is automatically recorded.
- The operator can perform the measurement unassisted and determine the end of a line.
- The reflectometer can be connected with the faulty cable over a lengthier period. All events are graphically shown.
- In “Difference mode”, even small changes in the impedance are visible.
- No triggering device is required.
- No high voltage is required.

Fig. 17: IFL mode for Digiflex (on left) and Teleflex MX (on right)
8. Measuring low voltage networks while under voltage

Separation filters (400 V) enable the direct connection of a reflectometer on the low voltage network while under voltage. The measurement should always be performed from the cable end or service box in the direction of the supplying station. Transformers, switchgears and distribution boxes generate large reflections which overlap the measurement signals. In addition, the test pulse travels through all outgoing lines and also receives multiple returning signals from them. This greatly increases the difficulty in evaluating the actual fault reflections. A measurement from the end that is distant from the distribution generally has only a defined direction of diffusion.

![Diagram of Digiflex Com connection](image)

Interruptions and short-circuits up to the T-joints can be localised very well due to the small pulses

In some countries, such live measurements are used to detect illegal consumers. The requirement for this is a comparative measurement with previously recorded reference patterns. A measurement made in the immediate vicinity of the service box and the meter contains so many reflections that the detection of additional lines and consumers is only possible via a comparative measurement. Such a measurement requires however the observance of certain safety criteria, e.g. of connection lines. These safety criteria are described in the next section.

8.1. Safety for measurements made on live networks

Measurement circuits are subject to load due to the operating voltage and the transient loads of the electrical system to which they are connected during the measurement. The use of measuring devices on live networks requires certain constructional safety measures and a corresponding label. These are defined by the engineering standard VDE 0411 / IEC 61010 and divided into the categories of CAT 1 to CAT 4.

The defining element here is the hazard arising from surges and peak voltages in the corresponding CAT range. The insulation in the device and the corresponding measuring lines must reliably insulate these voltages. In the case of an arc igniting due to a surge, several thousand amperes could be generated, depending on the connection zone, before the upstream safety elements trigger.
8.1.1. Category IV
Three-phase connection to the LV voltage source as well as the low voltage overhead lines: suitable for measurements at the source of the low voltage installation. Examples are meters and measurements on primary overcurrent protection devices and ripple control devices.

8.1.2. Category III
Three-phase distributions as well as public / industrial single-phase lighting systems: suitable for measurements in the building installation. Examples are measurements on distributors, circuit breakers and cables. Railway distributors, distribution boxes, switches, sockets of the fixed installation, devices for industrial use and other equipment as well as fixedly installed motors.

8.1.3. Category II
Single-phase plug-operated applications: suitable for measurements on circuits that are directly linked electrically with the low voltage network. Examples are measurements on household devices, portable tools and similar devices.

8.1.4. Category I
Electronic system: suitable for measurements on circuits that are not directly linked with the network. Examples are measurements on circuits which are not diverted from the network and specially protected circuits which are diverted from the network.

<table>
<thead>
<tr>
<th>Operating voltage</th>
<th>CAT IV</th>
<th>CAT III</th>
<th>CAT II</th>
<th>CAT I</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 150 V</td>
<td>4,000 V</td>
<td>2,500 V</td>
<td>1,500 V</td>
<td>800 V</td>
</tr>
<tr>
<td>up to 300 V</td>
<td>6,000 V</td>
<td>4,000 V</td>
<td>2,500 V</td>
<td>1,500 V</td>
</tr>
<tr>
<td>up to 600 V</td>
<td>8,000 V</td>
<td>6,000 V</td>
<td>4,000 V</td>
<td>2,500 V</td>
</tr>
<tr>
<td>up to 1,000 V</td>
<td>12,000 V</td>
<td>8,000 V</td>
<td>6,000 V</td>
<td>4,000 V</td>
</tr>
</tbody>
</table>

Fig. 20: Voltage ranges and corresponding categories with the required insulation values
9. ARM method

High-resistance cable faults in low voltage networks can be localised with the arc reflection method. This method requires both OK and fault patterns for evaluation. The disadvantages in branched networks, such as attenuation of the test pulses at the T-joints and additional reflections from the cable ends, also apply to this method of prelocation. The cable must be disconnected and all fuses must be removed from the service box. If the cable fault is located after several T-joints, the difference between the OK and fault pattern will be very slight. By enlarging the pulse width, the difference can be made more noticeable. The fault location system should be implemented as needed. In the following figures, several test examples are shown.

Fig. 21: OK / fault pattern, fault at 167 m after 6 T-joints in a branched low voltage network, the Netherlands

Fig. 22: OK / fault pattern, fault at 270 m after 12 T-joints in a branched low voltage network, the Netherlands
In principle, practically every measuring system can be employed with the ARM method. A restriction is presented by the lowest available surge voltage level. Three to maximally 4 kV is optimal, whereby “less is more”!

If, for example, the voltage in an 8 kV level needs to be reduced to 3 kV, only a limited surge energy remains available. \((W = 0.5 \times C \times U^2)\). For prelocation, this is not so important, but for pinpointing at least 300–500 J should be available.

### 9.1. EZ Thump

A compact, practical system for this application is the EZ Thump, which offers a complete fault location system.

The EZ Thump has a 4 kV level (alternatively, 12 kV as well), which is used for testing, breakdown detection, prelocation and pinpointing. An automatic routine allows the locating of faults with “hardly any” expertise with the equipment. The system guides the operator automatically through the diverse applications, detects the situation in the test object and informs the user accordingly.

The test results are given directly as alphanumeric values on the display. Also shown are the joint positions, the end distance and the fault location. For checking purposes, the reflectograms of both the OK and fault patterns are displayed. A cursor marks the fault location.

**Fig. 23: OK / fault pattern, fault at 23 m**

With the voltage adjustable from 0 to maximally 4 kV, EZ Thump offers the ideal solution for fault location in lighting and low voltage networks.
9.2. Teleflex LV Monitor – online reflectometer monitoring

The Teleflex LV Monitor serves in locating all faults on low voltage networks, but particularly intermittent faults. In doing so, the LV Monitor operates under voltage without shutting off the consuming devices. In the reflectometer/TDR mode, a conventional reflection measurement is performed with a device. The same principles of transmission line theory apply here as in classical reflection measurement.

In contrast to regular reflectometer fault location devices, the Teleflex LV Monitor is connected online simultaneously with all three phases of an operating low voltage cable and enables the operator to perform the reflection measurement either locally or remotely on any phase combination. The Teleflex LV Monitor is supplied with power through a line with a three-phase connection in which at least one phase must be under voltage.

With the Teleflex LV Monitor, the measurement is always made on the cable which is under voltage. After setting all the basic parameters such as amplification, pulse width, measuring range and selection of the defective wire, the LV Monitor sends test pulses continuously to the defective cable. In the case of voltage drops or triggering of fuses, 64 reflectograms are recorded chronologically around the event. Fault location is done by comparing the measurement prior to the event (OK) and during the event (fault pattern). Since the measurement is performed on cables under voltage, the time intervals for the measurements between “OK” and “fault pattern” must be very brief, since otherwise the switching on of powerful consuming devices (short-circuit for reflectometer pulse) would lead to false interpretations. The type of voltage and the progress of the fault of individual phases as well as the current curve can be seen during the event time window and can be included for evaluation.

**Activation of Teleflex LV Monitor with voltage triggering**

![Diagram of Teleflex LV Monitor activation](image)

**Fig. 24: Teleflex LV Monitor – connection to service box with voltage triggering on cable end and service box**
Activation of Teleflex LV Monitor with voltage triggering

In reflectometer mode, one or two devices can be used. The devices are positioned on the service and distribution boxes of the low voltage network. In doing so, knowledge of the network should be applied and fault prelocation (flickering in houses) done if possible. After connecting the units, the test parameters should be adapted similar to a Teleflex through individual measurement.

- Selection of phase – “Fault”
- Internal model – “Balance internal”
- Calculation of the difference between two phases – “Balance external”
- Amplification – “Gain”
- Pulse width – “Pulse”
- Measuring range – “Range”, 400 m or 800 m
- Triggering of the results

Depending on the fault situation (Phase/N or Phase/Phase) shown on the voltage monitor, you can make settings for the subsequent tests in the Control Panel.
In the next figure, the monitor clearly shows that the voltages on the red and yellow phases drop simultaneously and the blue phase is involved shortly after. For this test, the LV Monitor was programmed with R-Y=Model. The voltage monitor shows important information on the nature and progress of the fault.

All variations of the Phase=N or Phase=Phase testing are possible with the Balance set against an internal Model. Select a “Model” setting so that the transient process of the reflection pattern is as short as possible. Typical values for Model are between 10 and 40.

Instead of the internal model, you can also set the Balance against a second Phase=N or Phase=Phase. With this setting, the difference between the selected phases is measured. This test setting allows increased gain, because only the differences in the reflectometer curves are shown. By offsetting the time window in the voltage monitor, the OK and the fault pattern can be displayed. The measurement of the distance is done as in the Teleflex with a cursor.
10. Prelocation based on transient methods

10.1. Teleflex LV Monitor – TRS mode (travelling wave method)

TRS mode also uses test pulses to locate transient faults, but only to synchronise the second device which is used for the measurement. In other words, the pulses must only travel one way between the two installed devices, thus doubling the range compared to the impulse reflection method.

Two LV monitors are installed in the network in such a way that the suspected location of the fault is between them.

![Diagram showing the TRS method with Teleflex Monitor](image)

*Fig. 30: Principles of the TRS method (travelling wave method) with Teleflex Monitor*

The illustration below shows the course of the transient recordings. In this example, only one unit (the master) sends synchronisation pulses:

![Diagram showing general principle](image)

*Fig. 31: General principle*

In this example, the travelling wave of the fault impulse (red diffusion line) reaches the slave unit before it reaches the master unit.
The LV Monitor software superimposes the fault impulses by offsetting the curves, and determines the fault distance from the master unit using the distance of the transmitted and received synchronisation pulses.

![Diagram](image)

**Fig. 32: General principle**

If both units send synchronisation pulses, the fault distance can also be determined from both ends of the cables.

After the master unit has been armed, a manual test should be performed on the slave unit to determine whether the synchronisation pulse of the master is received. If the master pulse is weak or undetectable, the pulse width and amplification should be increased in both devices and the test repeated. The TRS test cannot be evaluated without visible synchronisation pulses from the other unit.

**Evaluation**

In the voltage monitor, phase position and amplitude of the voltage drop can be seen. In this example, the voltage drop beyond the fault location (far end) is much greater than in front of the fault.

![Voltage monitor](image)

**Fig. 33: Voltage drop of two synchronised devices**
The following illustration shows an example of the fault distance from the “brown unit”:

Fig. 34: Measurement of the fault distance from the “brown unit”

The following illustration shows an example of the fault distance from the “blue unit”:

Fig. 35: Measurement of the fault distance from the “blue unit”

Click the **Locate #2** buttons to evaluate additional synchronisation pulses.
As the triggering reason for a measurement of the Teleflex LV Monitor, an actual fault can be used. This is done in situations in which faults occur often or with great regularity and there is little need for any specific action. In other words, in situations in which previous experience has shown that a further triggering can be expected shortly anyway.

Also in situations in which the tripping of a fuse poses a larger problem for the connected consumers, e.g. in industrial operations, but it is generally useful to combine the Teleflex LV Monitor with the later described Powerfuse.

The consumers are thus immediately back on the network after triggering, and the LV Monitor creates a measurement from each event. This allows results to be compared and the possible triggering factors to be identified based on the time point of the incident.

Permanent faults can be measured through deliberate switching on or off of the fuse (Powerfuse). In other words, a low voltage ARM fault location is performed with mains voltage. In this case as well, the consumers can remain connected to the mains, since this use does not cause the normal mains voltage to be exceeded.
10.2. ICEPlus method

The ICE method (Impulse Current Equipment) has been in use since the beginning of cable fault location. In this method, a surge pulse discharge from the ignition of a cable fault results in a transient current signal that is then recorded. This method can be applied very successfully for medium voltage cables without branchings. On cables with T-joints, the problem arises as with reflection measurement that the impedance pulse locations of the branchings only give a very complicated or unevaluable result.

The test signal arising from a fault disruption contains not only the known oscillating current pulses but also a second, likewise oscillating current (fundamental wave), which is superimposed on the transient current pulses (Fig. 24) with an oscillation frequency that is derived from the parameters of the measurement setup.

The known capacitance of the surge capacitor in use (e.g. in the SPG 5-1000) and the inductance per unit length of the cable up to the fault position are the dominating factors influencing the oscillating frequency of the fundamental wave (Fig. 25). The capacitance of the defective cable is insignificant in relation to the surge capacitance, while the self-inductance of testing system and connection cable are known and are taken into account accordingly in the evaluation.

Fig. 36: Transient current catching and total current with fundamental wave

Fig. 37: Surge capacitance and cable inductance as the dominating components of the oscillating circuit
By determining the oscillating frequency of the fundamental wave, the following equation

\[ f_o = \frac{1}{2\pi \sqrt{LC}} \]

can be used to calculate the inductance of the oscillating circuit.

\[ L = \frac{1}{\omega_o^2 C} \]

The evaluation of test signals with pronounced attenuation of the fundamental wave or even the evaluation of acyclical alternations or very noisy signal parameters (due to intermittent arcs) is done using a digital signal processor (DSP) and a multiple-stage approximation software as well as diverse analytical algorithms.

The measured circuit frequency \( \omega \) and the calculated oscillation circuit rate \( Q \) are used to calculate the inductance up to the fault position \( L_F \).

\[ L_F = \frac{1}{\omega^2 C_S (1 + 1/4Q^2)} \]

Using this inductance value \( L_F \), a kilometric inductance per unit of cable \( L_k \) is calculated, which depends on the line cross-section and the geometric configuration of the conductors.

To achieve a solid database for the calculation of the fault distance, comprehensive field tests to determine the typical inductance values of various cable types and conductor configurations have been performed.

Using a simple test configuration with known cable lengths, the parameters of “exotic” cable types, which are not yet contained in the unit file, can also be later deduced.

This patented ICEPlus method enables even unexperienced users to easily perform the prelocation of cable faults.

For the precision pinpointing of cable faults, conventional test methods are available as described in the following section.

**Simple fault location**

A turnable selector knob with enter function enables easy navigation in the menu and quick setting of parameters.

To quickly inform the user as to which fault situation is at hand, the test function includes a simultaneous display of the leakage current and insulation resistance values.

![Fig. 38: Main menu for selection of the test functions](image-url)
A further useful function is “Breakdown detection”. With this feature, the flashover voltage of the fault is automatically calculated in order to set the amplitude of the surge pulse voltage so that it is most effective in both prelocation and pinpointing. This ensures that the cable is not subjected to an unnecessarily high surge voltage and thus reduces the risk of secondary damages.

In the prelocation function with ICEPlus, the user follows the prompts on the display, which essentially entail entry of the conductor cross-section, the cable structure and the wire position when switching on the unit. The user is in each case provided with a selection list or graphical representation of the cable data (e.g. 4-conductor cable or 3-conductor cable with shield or the switching on of adjacent wires or opposite-lying wires).

Should the stretch of cable be composed of different cable types, the input can be entered in sections. The correct specification of the conductor cross-section and the type of connection are requirements for a precise calculation of the cable fault distance. If a fault lies in a branch, e.g. in the vicinity of the service box cable, the prelocation result will be offset by the change in cross-section which was not taken into account. However, this problem is within the inaccuracies that occur anyway when transferring the calculated distance to the actual physical site.

If the measured fault distance leads to the conclusion that the fault is in a branch with a length of more than 20 m, a supplemental measurement from the end of the respective branch is useful.

With ICEPlus, the fault distance is specified directly in meters and thus no interpretation of complicated reflection patterns is necessary.

To obtain stable oscillation frequencies, the surge voltage should be at least 2 kV and optimally 4 kV.
For a precise pinpointing of cable faults, the SPG 5-1000 offers the DC step voltage method and the acoustic field method. In the step voltage method, an adjustable direct current with selectable cycle intervals is used. The switching does not involve the surge capacitor. The acoustic field method uses voltage levels of 2 or 4 kV, each with 1000 W surge energy. This enables the acoustic field of the cable fault to be located effectively even under conditions with loud background noise.

10.3. Three-phase ICE (current catching)

Four current catcher switches have proven successful in prelocating high-resistance and intermittent faults in power cables. These are:

“Direct method”
“Comparison method”
“Differential comparison method”
“Loop On – Loop Off method”

10.3.1. Direct method

A surge wave generator or DC testing device is used as the source. Each branch between the cable beginning and the fault unavoidably leads to multiple reflections and thus interferes with the reflection method to be evaluated. The direct method is therefore only used for cables without branchings.

10.3.2. Comparison method

As generator, a high voltage testing device or a surge wave generator (with pulse buttons that are pressed) is used. This method is primarily used in branched networks. Requirement: An intact wire must be available and the cable must be able to withstand load (no parallel resistance).

10.3.3. Differential comparison method

A surge wave generator is used as the source. This method is primarily used in branched networks. Requirement: An intact conductor must be available.

10.3.4. Loop On – Loop Off method

As generator, a high voltage testing device or surge wave generator is used. This method is used in unbranched networks. Requirement: The high voltage connection cable must be of sufficient length (1’ >> 50 m).

Detailed information on the above testing methods can be found in the section on three-phase ICE.
11. Fault location via burning odour

In civil engineering work, one can often determine whether one is near the fault by the odour rising from the ground. Some utility companies use this burning odour to advantage, employing specially trained tracker dogs to pinpoint the location of the fault. Burning occurs in a cable fault when the ignited arc scorches the insulating material. This process releases a number of different combustion gases. These gases can then be smelled (or detected by dogs) or separated into their essential component parts and localised using a gas chromatograph.

Since cables, terminations and joints are made of very different materials, correspondingly different gases are created. Investigations have determined that some of these carbon compounds are released by all insulating materials, and most importantly, in the sufficient quantity. Based on this discovery a new technology has been developed, the FaultSniffer, which specialises in detecting precisely these gases.

The gases which occur at a fault are not volatile; in other words, they remain in the surrounding soil and can be measured even days later. The diffusion and thus the measurability of these gases depends heavily on the ambient conditions. Loose earth and lack of a sealed covering results in lower concentrations than, for example, compressed earth with a thick asphalt covering. A localisation of the gases thus depends not on their concentration, but on their distribution. The fault location is based on the maximum of the detectable concentrations.

As long as the fault itself appears only temporarily and the supply continues, no switching off is necessary for the fault location. The actual measurement only requires that gas samples be taken from the ground. If no solid surface exists, a small hole can be made and the gas samples removed from the soil through this by means of a sampling hose and a pump in the FaultSniffer. For solid surfaces such as concrete or asphalt, a cordless drill is used to make a sampling hole, which is then properly closed with a sealing compound following the removal of the sample.
A fundamental principle of this fault location method is the fact that faults mainly occur in joints or in the area of construction activities. Construction work is relatively easy to recognise. The joints are primarily found in the area of the house connection. Consumers are in part still supplied with power, while consumers behind the fault may no longer be supplied. Using such simple observations, conclusions and available data, e.g. layout diagrams, the general position of a fault can be fairly narrowly localised in advance.

Since the gases that occur are still measurable within an area of two to four meters, the need for an exact positioning of the sampling point is not very great. Drilling directly in a footpath is also unnecessary, since it often suffices to make a sampling hole in soil a couple of steps away and explore there first before beginning any actual drilling.

![Diagram of gas concentration and fault location](image)

When measuring, one first identifies where the gases are detectable and then centres the search at the point of the maximum value. This maximum then represents the fault position and is more precise than an excavation requires.

**Fig. 43: Fault location based on the maximum gas concentration**

**Advantages of this method:**

- Power to customers does not need to be switched off
- No prelocation required
- The user requires neither switching permissions nor electrical expertise

**Disadvantages:**

- Primarily useful for low voltage cables
- Requires that the gases be able to diffuse from the joint or the cable
- Depends on ambient site factors, such as density, sealing, etc.

**11.1. LV fault location kit**

In combination with the Teleflex LV Monitor described in section 10.1, the FaultSniffer offers the option of fault location without having to switch off consumers. Fault prelocation as well as pinpointing are performed under voltage.
12. Supplementary methods

12.1. Powerfuse

The Powerfuse serves as an automatic backup fuse and is used in prelocating intermittent faults in low voltage networks with connected consumers. Low voltage networks are largely protected with NH fuse elements. If the fuse drops out due to an insulation fault, the customer is disconnected from the network. Reconnection requires manual replacement of the defective NH fuse. Particularly with intermittent faults, the fuse is tripped in irregular intervals and replacing it requires a greater amount of work.

With the aid of the Powerfuse, the respective cable section is automatically switched back on.

In connection with a reflectometer, cable prelocation per OK / fault pattern can be done at the same time. After switching on 9 times within 5 minutes, the device shuts down. Tripping currents can be set incrementally from 125 to 315 A.
12.2. Prelocation in insulated networks (IT networks)

With faults in IT networks, control lines or, for example, signal lines in railways, the term used for this is short-to-ground rather than fault. IT networks are specially protected networks which are designed so that contact with a voltage-conducting line is harmless (hospitals) and that in the event of a short to the earthing, no current flows (explosion protection). Especially in industrial systems in which the cables are nearly always in an environment with good electrical conductance, short-circuits are one of the greatest potential hazards faced. Normally in an IT network, a short-to-ground initially does not trip any fuses, and thus does not interrupt any processes.

However, the short causes the formerly unearthed, potential-free system to set itself to the earthing potential which was created by the fault. As a consequence, the unaffected phases take up a defined potential against earthing.

An additional short of a different phase (double short-to-earth) can now cause a true short-circuit and thus lead to the total failure of the power supply. This could then, for example, halt critical manufacturing processes or create an arc due to the high current flow, which actually poses the highest danger in an explosion-protected environment.

Such installations have an insulation or short-to-earth monitoring system, which displays this state in the event of a short-to-earth, thus warning the operator. The operator can thus localise and resolve this short-to-earth as quickly as possible in order to restore the operating safety of the system.
One of the simplest and above all fastest options for localising this short-to-earth is using the technology of Geolux. The location method is devised so that an earth contact point can be located without interrupting the network function or affecting the signalling and control circuits. In the Geolux system, a low frequency signal current of 5 Hz is directly coupled to the conductor afflicted with the short-to-earth.

![Geolux with accessories](image)

The integrated separation filter enables a direct galvanic coupling of up to 660 V AC and DC. The electromagnetic field of this signal current is traced with inductive sensors and thus leads to the fault position. A pulse is used to better identify the signal current and the signal flow time of the generator is displayed by means of a synchronising circuit on the test receiver. A compensating circuit enables interfering cable capacitances to be compensated so that fault resistances of up to 200 kOhm can be localised.

The user follows the path of the signal current against earthing with a pair feeding pliers (or, where the cable bunching does not permit this, with an inductive clamp-on sensor) until reaching the position of the fault. There, the signal divides and can no longer be traced.

![Fault signal tracing in the IT network](image)

A detailed description of this application will be appear again separately in a special article on the subject of sheath faults / faults due to contact to earth.
12.3. Prelocation with the voltage drop method

This testing method’s main area of application is heavily branched low voltage networks (private connection networks, lighting networks). The focus of this method is finding a low-resistance cable fault with nearly galvanic connections (such as faults in connecting joints or branch joints).

The voltage drop that occurs at high currents is used in prelocating these very low-resistance faults in the low voltage network. The high current can be fed from a burner device (such as the BT 5000). At the service box, either a digital voltmeter to measure the voltage drop or an ammeter to measure the current is used. A voltage level (max. 400 V) is set depending on the operating voltage of the cable system or the existing fault resistance. The result is a current flow through the fault resistance RF. From the cable distributor, parallel switching of the ammeter (indicator) to the fault resistance is made at the service box. The displayed current value is used for evaluation and is taken into account in assessing the fault position. A measuring point after the defective branch will exhibit a significant drop in voltage. This indicates the type of fault in the previous branch.

A further application in connection with the voltage drop method is directly subjecting the cable to a load. Such a method creates a clear fall-off in the voltage behind the fault position.

With this method, longitudinal faults in particular are relatively easy to detect. Longitudinal faults in this context, depending on the situation, are e.g. corrosion or poor contact in the joints, direct breaks or fully corroded conductors, a process that particularly occurs in aluminium conductors. Due to the high current load, the transfer resistance of the fault position greatly affects the voltage after the fault. As with the already mentioned flickering of lights, the voltage in this case can sometimes fully drop out under load. In other words, such a fault can be reproduced in a relatively simple manner and its position localised to within the area of a service box.
12.4. Neutral conductor break – impedance measurement

The N conductor is the most important conductor in the network since it is required by all phases. Flickering lights can be indication of a neutral conductor break. Because of a higher phase voltage, damage to users cannot be excluded. The most frequent neutral conductor breaks occur in joints. Corrosion from humidity at the terminals, incorrect assembly and exterior mechanical damage from civil engineering work can be the catalysts and reasons for this fault. The neutral conductor break is a power disruption and leads to high imbalance in the network. Depending on the type of this fault, such as contact to earth, the following test methods for prelocation can be applied:

- Impulse reflection method (impedance change)
- Sheath fault location for contact to earth
- Impedance measurement

The conventionally available impedance measuring devices are generally combination instruments with which to measure the following:

- Z – Impedance
- $I_k$ – Short-circuit current
- R – Resistance loop
- $X_L$ – Induction loop
- $U_m$ – Network voltage

In the event of a neutral conductor break or a poor terminal connection, high resistance values appear for the loop. If there is not a conductor break, the values typically lie within the mΩ range.

At the farthest point of the network, the short-circuit current $I_k$ must reach the minimum required shutoff current $I_a$ of the upstream overload protection device.

**Shutoff requirements:**

- $I_k > I_a$
- $I_k = \frac{U_b}{Z_{\text{Loop}}}$

![Fig. 51: Impedance loop in the network](image-url)
13. Bridge measurement method

With a high voltage measuring bridge, faults due to contact to earth as well as insulation faults can be prelocated. Detailed information on this can be found in an article to follow on the subject of “Sheath fault location.”
### 14. Equipment configurations (examples)

#### 14.1. Unbranched networks

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## 14.3. Online fault location for branched and unbranched networks

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