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Type D travelling wave fault location on branched underground low-voltage networks

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Abstract: Low voltage cable faults are frequently associated with arcing at the fault which creates 2 high frequency transients which propagate away from the fault towards opposite ends of the cable and whose difference in arrival times can be used to determine the fault's location using the Type D method. A variant of the Type D method, known as the Transient Recording System (TRS) using asynchronous data acquisition units (ADAU) has been used successfully in situations where multiple branches on a cable have precluded the use of other travelling wave methods. The range, and precision of location, of the TRS method is extended by the use of a Marker Unit (MU) which allows the distance and direction to a fault to be determined relative to the point of connection of the MU. The asynchronous data acquisition units operate in 'listening' mode and are triggered by the arrival of the transients created by the fault arc. Prior to triggering, the ADAUs continuously (over)write all received data into their cyclic buffers, including the low amplitude MU pulses. Shortly after triggering the (over)writing of the cyclic buffer stops and earlier (pre-trigger) data retained – including the received MU pulses.

1 Introduction

Fault location on low-voltage (LV) cables is notoriously difficult due to the impracticality of disconnecting customer loads to create an 'isolated' cable situation. Methods which combine measurements of the voltage and current at the supply point, known as 'impedance' methods, have proved useful in *estimating* the distance to faults – provided detailed information about the composition of the circuit being monitored is available. However, the calculated value of impedance, i.e. the ratio of voltage to current at a single frequency, is questionable when the voltages and currents are *non-sinusoidal* as happens in the case of arcing faults. Hence, *accurate* distances to fault can really only be expected for solid phase to phase faults where any uncertainties about the zero-sequence path are not an issue. Time-domain reflectometry (TDR) methods which use the reflections of injected pulses from the fault arc have proved more accurate, provided the reflection can be identified. Identification is simplified by comparing traces obtained during arcing and non-arcing times. In practice, even with comparison, it is sometimes not possible to identify the fault reflection on long cable circuits with multiple branches. Nevertheless, TDR remains the preferred 'first line' of attack as only one device is required to be connected to the cable.

Retaining the advantages of the TDR method's reduced dependence on detailed information on circuits containing mixtures of cable length, types and sizes can be achieved using the Type D method with synchronised data acquisition units, similar to those used on overhead transmission lines, but with more sophisticated, and costly, GPS receivers offering sub-microsecond accuracy. The use of GPS however entails the inconvenience of providing antennae with clear views of the sky.

The Type D method can also be applied using asynchronous data acquisition units (ADAUs) if the recorded data contains a signal injected by a device connected at a known point on the cable being monitored. This is the basis of the transient recording system (TRS) where the injected signal is produced by one or other of the ADAUs. A further development of this technique where a separate movable marker unit (MU) is used is presented in this paper.

2 Behaviour of LV cable faults

Unlike situations where a cable can be completely isolated from its source of supply and from ALL connected loads, LV distribution cables require a completely different approach. It is impossible to check the condition of the cable insulation using an insulation resistance tester due to the presence of the connected loads and the only practical method of detecting/confirming the existence of a fault is by re-energising the cable at normal working voltage. *Stable* short-circuit and open-circuit faults are very apparent with this approach and can be located relatively easily with the supply disconnected. In reality, many faults are *unstable* and produce non-sinusoidal voltages and currents due to the non-linear characteristic of the arcing process.

2.1 LV cable fault characteristics

LV cable faults have been classified according to the way in which they respond to the application of normal working voltage as follows [1]:

i. *Transitory*: irregular sub-cycle voltage dips
ii. *Intermittent*: irregular fuse operation
iii. *Persistent*: fuse operation on re-energisation
iv. *Permanent*: e.g. open circuits and solid welds

Transitory, *Intermittent* and *Persistent* faults are only detectable and locatable *whilst the cable is energised* and produce non-sinusoidal voltages and currents. Such faults therefore require the use of 'on-line' equipment for their location. *Transitory* events do not cause supplies to be interrupted but result in flickering lights and malfunction of industrial and domestic equipment. *Permanent* faults can be located using either 'on-line' or 'off-line' devices since they are present whether or not the cable is energised.

2.2 Arc behaviour during LV cable faults

The non-sinusoidal voltage and current recorded during a typical single phase 'transitory' fault are shown in Fig. 1 – the most obvious features of the recording being that the fault arc has *ignited* as the A phase voltage has approached its negative peak value at which time fault current starts to flow. The arc has extinguished ~6 ms later and it is only during this period that the fault is active, and therefore locatable.

The recording of a typical A phase to B phase 'intermittent' fault is shown in Fig. 2, where it can be seen that the fault initially

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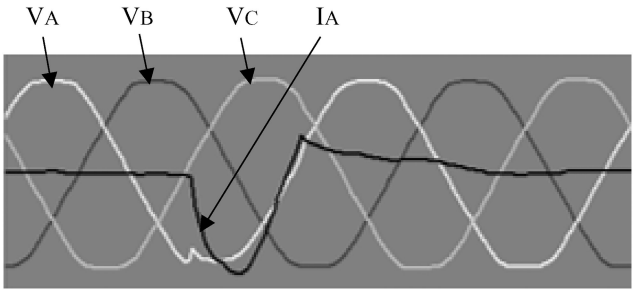

Fig. 1 *Source end voltage and current during a 'transitory' A phase to ground fault*

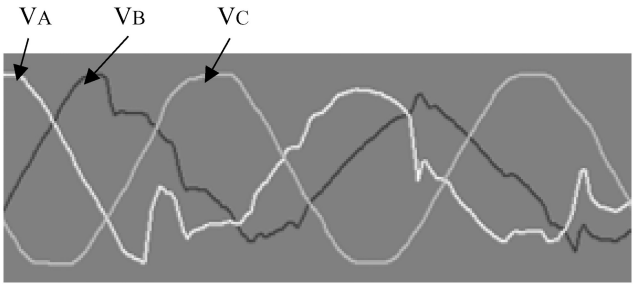

Fig. 2 *Source end voltage during an 'intermittent' A to B phase fault*

involves only B phase with A phase becoming involved a few milliseconds later.

The voltages (and currents) recorded at the source end of a cable clearly show the non-sinusoidal nature of the fault arc but do not show what has actually occurred at the fault point itself. To appreciate this it is necessary to examine the voltage created on the cable at points beyond the fault, as shown in Fig. 3. This shows that the voltage at the fault point dropped instantaneously to ~150 V when the arc ignited and, that although the fault current increased from zero to maximum before falling back to zero, the voltage across the arc changed very little from its initial value of 150 V.

Only 'on-line' fault location methods can be used to locate faults which behave in the manner described above of which there are two basic *travelling wave* versions. The first of these is 'triggered TDR' where identification of *the reflection of the low amplitude injected pulses from the transient low resistance of the fault arc* is used. The second is the TRS method which uses the much higher amplitude *transients produced in the cable by ignition of the fault arc*.

3 Travelling wave methods

3.1 Theory

Travelling waves are produced when impulses are applied to pairs of conductors. The energy in the wave travels in the dielectric between the conductors at a speed governed by the permittivity of the insulation (ε) and is not affected by the material or geometry of the conductors. The speed is defined as the cable's velocity factor (VF)

$$\mathrm{VF} = \frac{c}{\sqrt{\varepsilon}} \tag{1}$$

where c is the speed of light in a vacuum (300 m/μs).

The impulse currents flowing in the conductors, and the voltage between them, are related through the characteristic impedance (Z_o) which, ignoring any losses in the conductors and insulation is purely resistive and defined as

$$Z_o = \sqrt{\frac{L}{C}} \tag{2}$$

where L is the inductance per unit length and C is the capacitance per unit length.

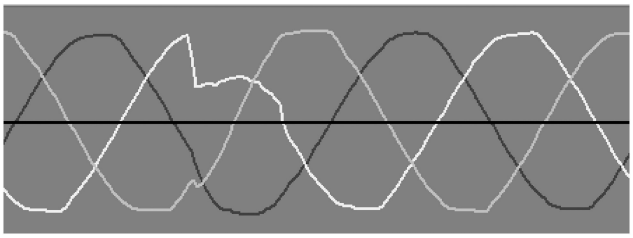

Fig. 3 *Remote end voltage during a single phase 'transitory' fault*

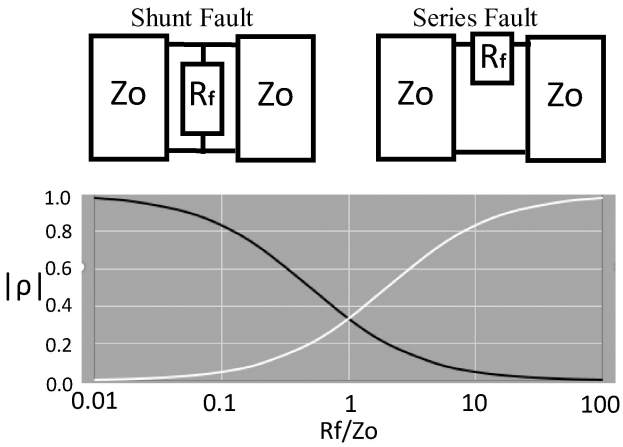

Fig. 4 *Variation of fault reflection factor (ρ) with R_f/Z_o*

When the impulse arrives at a termination of a cable, or at a junction to a cable with a different surge impedance, a reflection is produced with an amplitude and polarity determined by the reflection factor (ρ), defined as

$$\rho = \frac{Z_\mathrm{T} - Z_o}{Z_\mathrm{T} + Z_o} \tag{3}$$

where Z_T is the terminating impedance and Z_o is the surge impedance of cable.

The amplitude of the reflection factor from a fault is determined by the fault resistance (R_f) whilst the polarity depends on whether the fault is in 'shunt' with the cable insulation, or in 'series' with either of the conductors. The black curve in Fig. 4 shows the variation in amplitude of the fault reflection factor for a shunt fault against a 'normalised' base of $R_\mathrm{f}/Z_\mathrm{o}$. The white curve in Fig. 4 shows the variation for a 'series' conductor continuity fault.

Whenever a reflection occurs some of the energy within the impulse is transmitted beyond the discontinuity and, in the case of a fault, dissipated in the fault resistance. The fraction of the impulse voltage transmitted, or applied to the fault, is defined by the transmission factor (τ) as

$$\tau = (1 + \rho) \tag{4}$$

Hence, when an impulse arrives a discontinuity such as a branch joint which produces a reflection of, say 33%, it is attenuated by the same amount but still 67% is transmitted forward along the main cable (and also into the branch).

3.2 Triggered TDR

TDR fault location using injected pulses (triggered or non-triggered) is dependent on being able to identify the reflection from the fault amongst the reflections caused by other discontinuities in the section of cable between the point of injection and the fault. LV cables will frequently have many such discontinuities: where two cables of different size or construction are joined together and at single or three phase branch joints. Where the branch cable has the same surge impedance as the main cable the reflection amplitude and polarity will be exactly the same as that produced by a fault where $R_\mathrm{f} = Z_\mathrm{o}$ (0.33 as shown in Fig. 4). The magnitude of the fault

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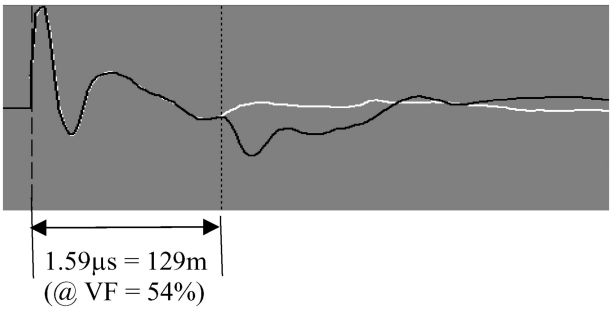

Fig. 5 *TDR traces before (white) and during (black) for an arcing fault located beyond several tee joints*

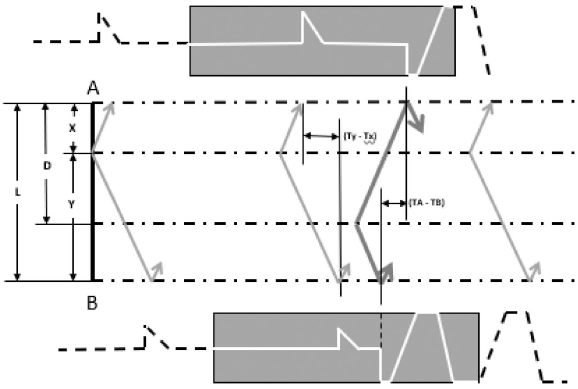

Fig. 6 *Rotated lattice illustrating the paths and timings of the travelling waves created by a fault and 'MU'*

reflection 'seen' at the point of injection is determined by the fault resistance and by the number of branch joints that the injected pulse has to pass on both its outward and return journeys. Fig. 5 shows the amplitude of the reflection produced by a fault with $R_f = Z_o$ situated beyond a number of branches.

3.3 Using fault generated travelling waves

Arcing faults and other sudden disturbances impressed on cables produce travelling waves which propagate away from their point of origin towards all the cable terminals. This is the basis of the Type D method of fault location used on overhead lines and also the TRS method used on LV cables [2]. The TRS method has proved to have several advantages over TDR methods as all the travelling waves, whether injected as synchronising pulses or generated by a fault, have to travel in only one direction. Although the waves still travel through branch joints they only do so once and are therefore not attenuated as much as reflected TDR pulses. The TRS method has shown a high success rate provided the injected synchronising signal has been visible at the opposite terminal. Injecting a pulse at an intermediate point, as described below, extends the length of circuit that can be covered and since it is based on identifying *transmitted* rather than *reflected* signals TRS data is simpler to analyse.

3.4 Event filtering using AC voltage waveforms

When first introduced TRS devices used a simple hardware trigger preceded by a low-pass filter to reduce triggering from 'non-fault' disturbances. This did not always prove effective so the low-pass filter was removed and all triggered events processed using 'post-event' analysis of the system voltage(s) any time the hardware trigger operated to eliminate unwanted 'non-fault' disturbances. The transient data, and the system voltage records, from the two TRS devices, are sent via GPRS to a server where the two sets of data are checked to confirm they are the result of the same fault disturbance and then the transient data is manipulated to determine the fault location. In the event of remote communication not being possible with either of the devices, the data can be retrieved locally

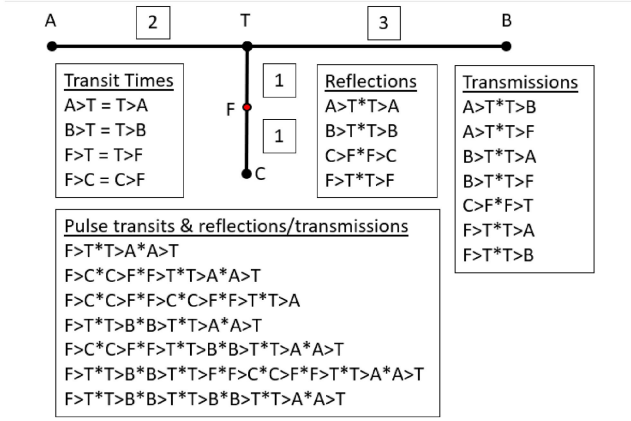

Fig. 7 *Timetree diagram for a branched cable with an arcing fault showing the decomposition of the pulse transits into reflections, transmissions and transit times*

from the device(s) over a Bluetooth link to a smartphone or tablet and then forwarded to the server.

4 Representation of travelling wave phenomena

The traditional method of representing travelling waves is with Bewley lattice diagrams which, when rotated through 90°, as shown in Fig. 6, represents time on the horizontal axis and distance on the vertical axis.

Lattice diagrams become difficult to analyse when a circuit contains sections with different values of Z_o and/or velocities of propagation. They become even more complex when the circuit contains branches and a simpler method is to use Timetree diagrams. Timetree analysis is easily implemented in software and allows the source of each received pulse at a node to be identified. Fig. 7 shows how a Timetree is produced when an arcing fault occurs on a branched circuit.

The pulse sequences shown in Fig. 7 are generic for any cable with a single tee and so once prepared can be quickly processed either manually or by computer. The pulse sequences consist of transit times represented by $x > y$ elements which summate to the total transit time delay from the pulse origin to the final node in the sequence. The pulse sequences include reflection factors for each node, represented by $x > y*y > x$ elements, and transmission factors, represented by $x > y*y > z$ elements. Multiplying all the reflection and transmission factors in a sequence provides the relative amplitude of the pulse at the final node relative to its initial. The diagrams presented in the following section are based on a simple 'timetree' representation.

5 Type D method applied to LV cables

Timetree representations of the simple cable shown in Fig. 6 are used in the following section to provide a clearer, non-mathematical, explanation of the use of the 'MU'. Figs. 8–12 show how the *asynchronous* recordings at ends A and B are *synchronised* by shifting and superimposing the record at end B to align the arrival of the fault disturbance with that recorded at end A. The distance to the fault from the MU MF is obtained by

$$\mathrm{MF} = (\mathrm{MB}' - \mathrm{MA}) * v/2 \tag{5}$$

where (MB′−MA) is the effective time separation after alignment and v is the velocity of propagation.

Figs. 8–12 illustrate cases where the MU is connected at 0, 25, 50, 75 and 100 along the cable for a fault located at 75%.

Fig. 8 is approximately equivalent in operation to the original TRS technique with the unit at end A using its own internal pulse generator instead of the MU to provide the synchronising signal received by unit B. However, in the TRS case the lengths (transit times) of the testleads must be deducted.

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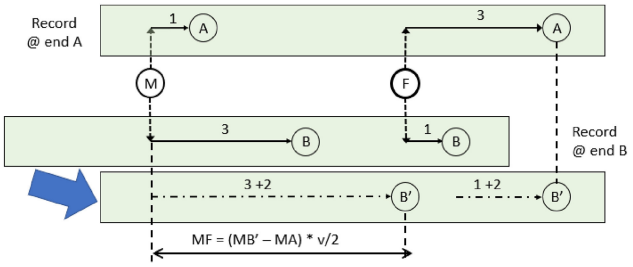

Fig. 9 *Marker at 25%, gives marker to fault = 50%*

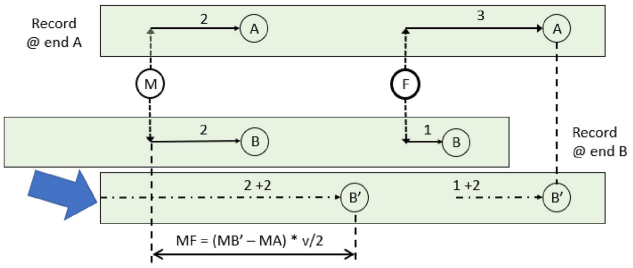

Fig. 10 *Marker at 50%, gives marker to fault = 25%*

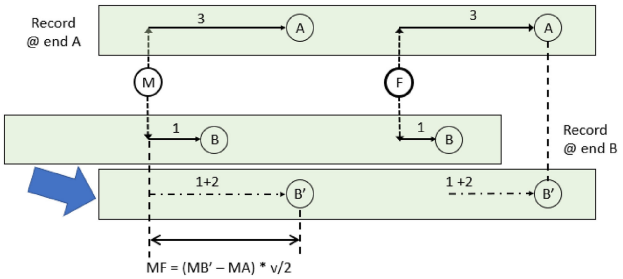

Fig. 11 *Marker at 75%, gives marker to fault = 0%*

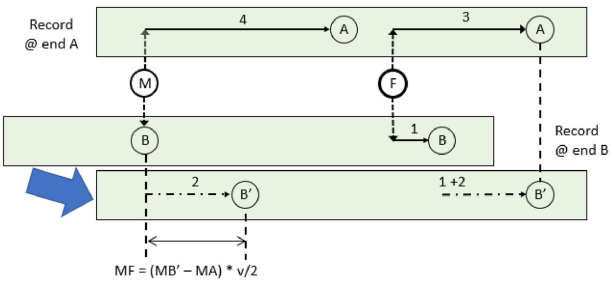

Fig. 12 *Marker at 100%, gives marker to fault = −25%*

In Fig. 9, the MU has been connected 25% of the cable length away from end A giving a marker to fault distance of 50% of the cable length.

Fig. 10 is effectively equivalent to using two separate GPS receivers to provide synchronising signals to the units at end A and B, as in the original Type D application on overhead transmission lines, as an alternative to using the MU.

In Fig. 11, the marker signal has been applied so that it appears to be co-incident with the fault. This can arise when the MU is connected at the end of a branch and the fault is in, or close to, the branch joint itself.

Fig. 12 shows the case where the MU is further from end A than the fault producing a negative distance to fault.

6 Experimental results

6.1 TRS method

The TRS method is identical to using the marker at 0% of the cable length. The test cable was nominally 200 m long with the fault at ~67.5%. Figs. 13*a* and *b* show the cable voltages at ends A and B, respectively, during a transitory fault.

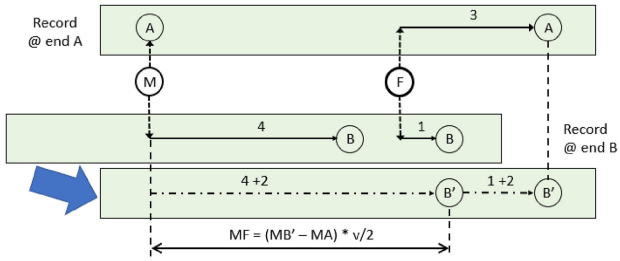

Fig. 8 *Marker at 0%, gives marker to fault = 75%*

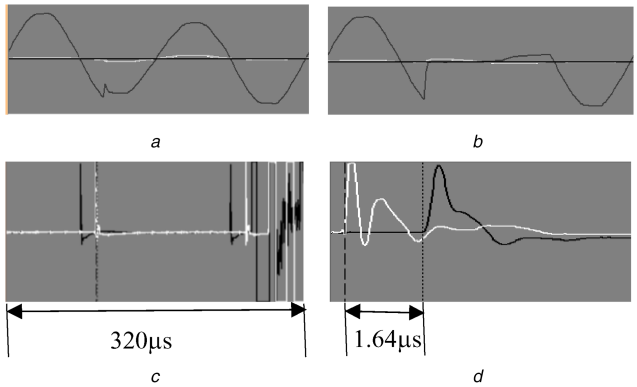

Fig. 13 *TRS method using the 'internal' pulse injectors of the ADAUs*
(a) Voltage at end A, ***(b)*** Voltage at end B, ***(c)*** Unaligned records from A (white) and B (black), ***(d)*** Aligned and expanded records from A and B

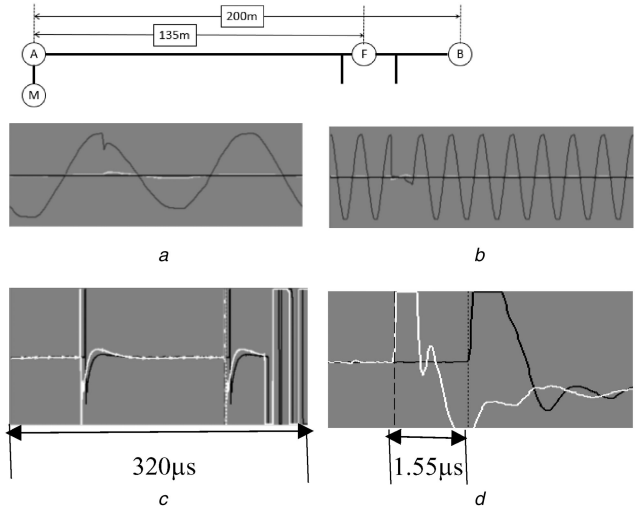

Fig. 14 *TRS method with the MU connected at end A*
(a) Voltage at end A, ***(b)*** Voltage at end B, ***(c)*** Unaligned records from A (white) and B (black), ***(d)*** Aligned and expanded records from A and B

Fig. 13*c* shows the complete transient records from ends A and B with the injected pulse(s) and fault disturbance both visible. Fig. 13*d* is an expanded view of the injected signals at A and B after alignment of the records on the fault disturbance giving a transit time from A to the fault of 1.64 µs (133 m atVF = 54%).

6.2 Marker method – position 1

Same cable and fault position as for the TRS test but with the marker connected at end A are used. With the same cable and fault position used for the TRS test, but with the MU connected at end A, Figs. 14*a* and *b* show the cable voltages during another transitory fault. Fig. 14*c* shows the complete transient records from ends A and B. Fig. 14*d* is an expanded view of the injected signal at A and B after alignment of the records on the fault disturbance giving a transit time from the marker to the fault of 1.55 µs (126 m).

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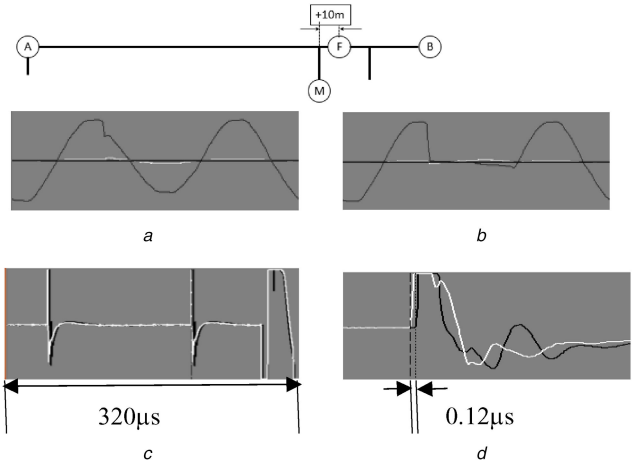

Fig. 15 *TRS method with the MU connected between end A and the fault*
(a) Voltage at end A, ***(b)*** Voltage at end B, ***(c)*** Unaligned records from A (white) and B (black), ***(d)*** Aligned and expanded records from A and B

6.3 Marker method – position 2

Same cable and fault position as in the TRS test but with the marker connected at M are used. With the same cable and fault position used for the TRS test but with the MU connected at M *before* the fault, Figs. 15*a* and *b* show the cable voltages during a further transitory fault. Fig. 15*c* shows the complete transient records from ends A and B with the injected pulse and fault disturbance both visible. Fig. 15*d* is an expanded view of the injected signal at A and B after alignment of the records on the fault disturbance giving a transit time from the marker to the fault of 0.12 µs (10 m at VF = 54%).

6.4 Marker method – position 3

Same cable and fault position as for the TRS test but with the marker connected at M are used. With the same cable and fault position used for the TRS test but with the MU connected at M *after* the fault, Figs. 16*a* and *b* show the cable voltages during the final transitory fault. Fig. 16*c* shows the complete transient records from ends A and B with the injected pulse and fault disturbance both visible. Fig. 16*d* is an expanded view of the injected signal at A and B after alignment of the records on the fault disturbance giving a transit time from the marker *back to the fault* of −0.19 µs (−16 m at VF = 54%).

6.5 TDR versus TRS and use of the MU

TDR is most effective when applied to a cable which is 'isolated' from all other cables connected to the same busbar. For arcing to occur at the fault, and the cable 'isolated', it must be energised via a high-frequency 'blocking coil' in series with the fuse, or by 'back-feeding' from another source. Even when a triggered TDR device is connected at an open end of an energised cable problems may still arise if the cable is supplying large non-linear loads which can cause additional TDR reflections to appear at various points-on-wave of the system voltage concealing, or confusing,

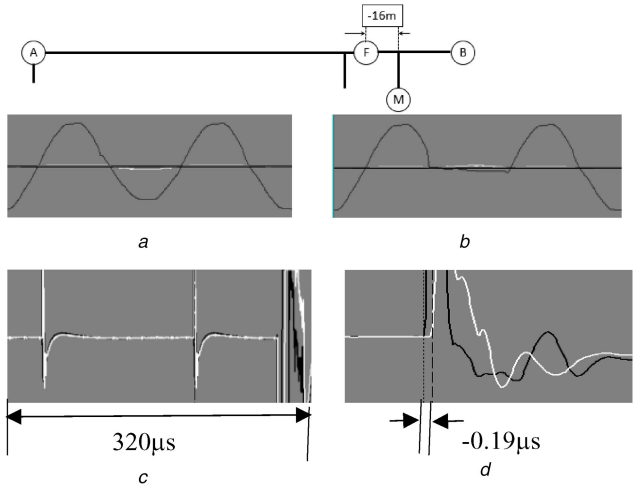

Fig. 16 *TRS method with the MU connected between end B and the fault*
(a) Voltage at end A, ***(b)*** Voltage at end B, ***(c)*** Unaligned records from A (white) and B (black), ***(d)*** Aligned and expanded records from A and B

identification of the reflection from the arcing fault. Non-linear loads do not affect Type D fault location as the technique is based on recording *transmitted* signals. Post-event filtering allows discrimination between fault generated transients and those created by non-linear loads. The MU can be used to produce either a 'calibration' reflection for TDR devices or a transient disturbance for synchronising and/or calibrating Type D fault locators.

When the cable characteristics and/or cable route are uncertain, the point of connection of the MU can be changed so that the time interval between the injected pulses and the fault transients recorded by the ADAUs become smaller thereby minimising errors arising from the use of an inappropriate velocity of propagation. The branches on a LV cable provide possible points of connection for the MU – for example at customer's terminals or in street lamp columns. The nearer to the fault point that the MU is connected the paths travelled by the injected pulses and the fault transients become comparable therefore they experience similar amounts of attenuation and distortion of their rise times.

7 Summary

The paper has presented a method of using fault generated transients in combination with an injected marker signal to determine the precise location of faults on branched underground cables. Rather than being an unwanted complication, the branches can be used to allow the marker signal to be injected close to the suspected location of a fault thereby reducing errors and increasing fault location accuracy.

8 References

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