LOCATING THE CAUSES OF RECURRENT SUPPLY INTERRUPTIONS AND FLICKERING LIGHTS ON SCOTTISH POWER'S LOW VOLTAGE CABLE NETWORK USING TRAVELLING WAVES

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ABSTRACT

Identifying the causes of recurring interruptions of supply and transient voltage distortions on low voltage cable networks requires 'on-line' monitoring equipment. For many years ScottishPower have used 'Triggered TDR' methods which have consistently provided accurate results but been limited in range on multi-branched circuits. TDR reflections from the growing number of 'energy saving' loads can be confused with the reflections from faults. The use of multi-point travelling wave techniques has proved to significantly extend the length and complexity of circuits which can be monitored and be immune to the effects of load non-linearity.

INTRODUCTION

In the 10 years since the presentation of a previous paper by the authors [1] Scottish Power have increased the number of 'on-line' low voltage cable fault locators in service fivefold and thereby accumulated extensive experience of the capabilities and limitations of the 2 most widely used methods of low voltage (LV) 'pre-location' methods, - *viz* 'impedance calculation' and time domain reflectometry (TDR).

Impedance methods, which combine measurements of the voltage and current at the supply point, 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 is the case with most 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.

By comparison TDR 'pre-locations', when the fault reflection has been identifiable, have always proved more accurate. Success with the TDR method is dependent on being able to 'see' the reflection of an injected pulse from the fault which is greatly simplified by comparing the traces obtained during fault and non-fault conditions. In practice, even with comparison, it is sometimes not possible to identify the fault reflection on cable circuits with multiple branches if the fault lies beyond several branch joints. In recent years a further complication has arisen as the number of 'energy saving' devices connected to the LV network has increased. These devices present input impedances which vary during a cycle of the supply voltage producing reflections which can obscure, or be confused with, reflections from the fault. Nevertheless, TDR remains the preferred 'first line' of attack as only one device is required – preferably connected at a remote open terminal rather than at the supply point of the cable..

Fortunately a means of overcoming the limitations of the TDR method is provided in the 'on-line' monitoring devices used by Scottish Power when the TRS mode is selected. This is not as convenient to apply as the TDR method since it requires the use of at least 2 devices but it retains the inherent accuracy and minimum dependence on detailed cable records.

BEHAVIOUR OF LV CABLE FAULTS

Fault location on LV distribution networks is complicated by the following:

1. Multiple branches
2. Single phase services
3. Access to customer's terminals
4. Connected loads

Taking account of the factors above, especially the presence of connected loads, it is rarely possible to even prove the existence of a fault without the application of normal working voltage to the cable. Only by detailed observation of the behaviour of the fault when it is (re)-energised can its condition be determined and the appropriate method of location selected.

LV Cable Fault Characteristics

LV cable faults can be divided into the following types:

1. ***Transitory***: irregular sub-cycle voltage dips
2. ***Intermittent***: irregular fuse operation
3. ***Persistent***: fuse operation on re-energisation
4. ***Permanent***: e.g open circuits and solid welds

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

Voltages and currents during LV Cable Faults

A faulty LV cable circuit consists of an ***upstream*** section through which the fault current flows, and a ***downstream*** section beyond the fault point Fig 1. The impedance between points of measurement along the ***upstream*** 'Go and 'Return' paths, and the point of supply, produces a progressively greater degree of voltage depression as the fault point is approached. Voltages measured anywhere in the 'downstream' section are not affected by the fault current and basically consist of the voltage across the fault itself, with minor reductions due to any connected loads.

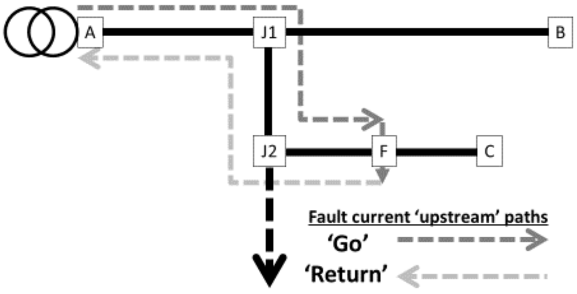

Fig 1 Showing ***upstream*** fault current paths

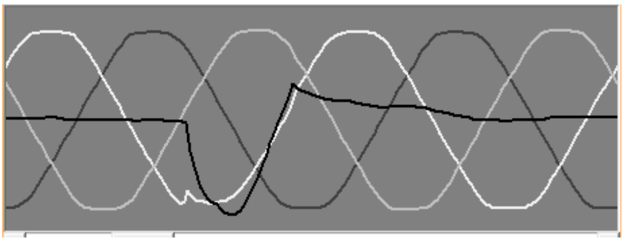

Fig 2a ***Upstream*** (source) voltages and current at A

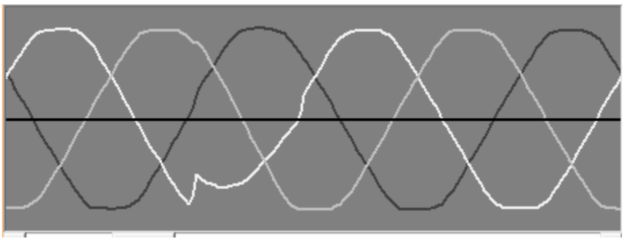

Fig 2b ***Upstream*** voltages at B

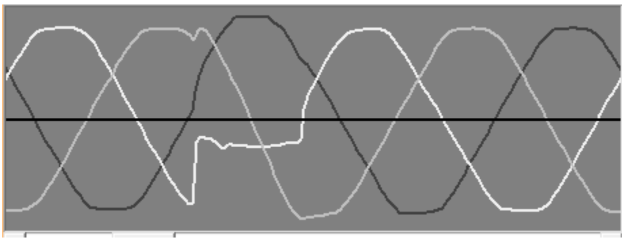

Fig 2c ***Downstream*** voltages at C

The important features to note from the simultaneous recordings of the single phase to neutral fault above are:

1. Virtually constant voltage (~100v) across the fault arc as recorded at C whilst the fault current recorded at A varies from 0 to a peak of ~1kA producing a fault resistance of < 1Ω for most the arc duration.
2. The large and rapid drop in the instantaneous voltage at the fault (~270v) caused by ignition of the fault arc
3. Instantaneous voltages recorded at points along the 'upstream' path are the result of the voltage drop between the source and the point of connection PLUS the voltage drop across the fault arc.
4. Displacement of the neutral voltage due to the single phase fault current and distortion of the healthy phase voltages.

Multi-phase faults

The example above is an illustration of a single phase to neutral fault. Many faults in practice are not so simple in their behaviour due to the presence of the 3 phase voltages acting on the insulation in the vicinity of the fault. It has frequently been observed that faults will ignite when the phase to neutral voltage on one phase is close to its peak value but the arc path then becomes phase to phase as shown in Fig 3.

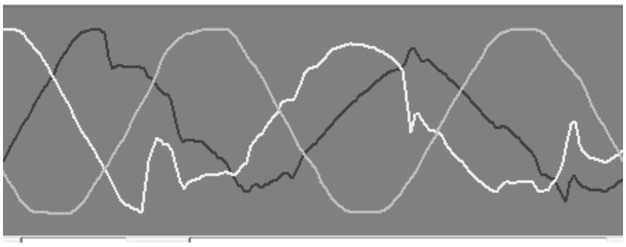

Fig 3 ***Upstream*** (source) voltages for phase to phase fault

The ***upstream*** (source) voltages shown in Fig 3, are more distorted than the ***upstream*** (source) voltages in Fig 2a as the fault was much nearer to the source and the fault current therefore much higher - resulting in the rupture of both fuses on the affected phases in less than 2 cycles. The voltage waveforms also show that the fault arc voltage was not as stable as in the previous example – an effect frequently observed when the fault is in a 'burning pot-end' as opposed to within the length of a cable as shown in Fig 4 below.

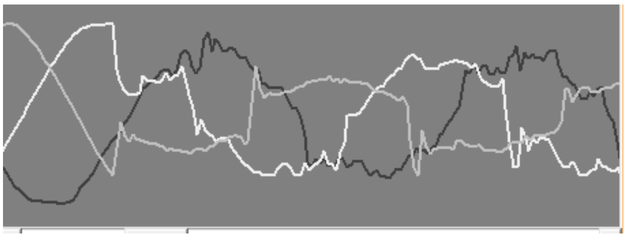

Fig 4 ***Upstream*** voltage from 'burning end'
on a short 'abandoned' branch

TRAVELLING WAVE METHODS

Theory

Travelling waves are produced when impulses are applied to pairs of conductors. The energy in the wave travels within the insulation 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):

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

Where c = the speed of light in a vacuum (300 m/µsec)

The impulse currents flowing in the conductors, and the voltage between them, are related through the Characteristic Impedance (Zo) which, ignoring any losses in the conductors and insulation is purely resistive and defined as:

$$\mathrm{Zo} = \sqrt{\frac{L}{C}}$$

Where L = inductance per unit length
C = capacitance per unit length

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:

$$\rho = \frac{Z_T - Z_o}{Z_T + Z_o}$$

Where Z_T = terminating impedance
Zo = surge impedance of cable

Reflections are also produced when the impulse encounters any discontinuity within the length of the cable, such as a fault or branch point resulting in a Reflection Factor (ρ) given by:

$$\rho = \frac{Z_D * Z_o}{Z_D + Z_o}$$

Where Z_D = 'effective' terminating impedance
Zo = surge impedance of cable

Whenever a reflection occurs some of the energy within the impulse is transmitted beyond the discontinuity or, 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:

$$\tau = (1 + \rho)$$

The amplitude of the reflection factor from a fault is determined by the Fault Resistance (Rf) 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 5 shows the variation in amplitude of the 'shunt' fault reflection factor against a 'normalised' base of Rf/Zo. The white curve in Fig 5 shows the variation for 'series' fault.

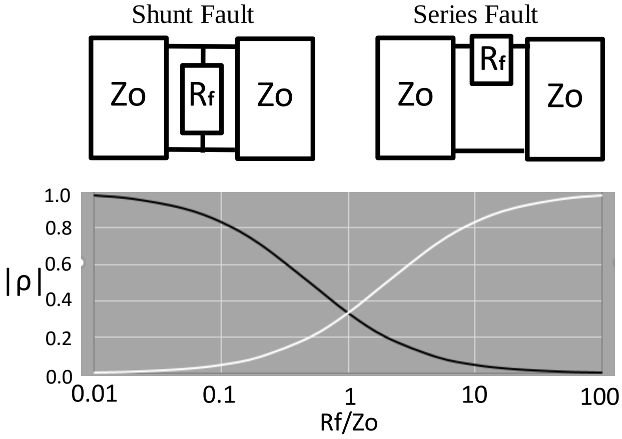

Fig 5 Variation of Fault Reflection Factor (ρ) with Rf/Zo

The foregoing analysis relates to a single pair of conductors e.g. a single phase LV service cable. Modern LV mains cables however consist of 3 phase conductors surrounded by a neutral/earth conductor. Older LV cables usually contain an internal neutral conductor which nowadays will be strapped to the outer sheath at various points along the cable route. Different values of surge impedance exist between every pair of metallic elements within a cable as shown for a 3 phase cable with an outer neutral/earth outer sheath in Fig 6.

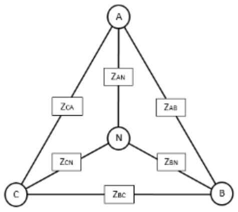

Fig 6 Surge impedance mesh of 3 phase LV cable

Calculation of the reflection and transmission factors associated with networks such as Fig 6 involves matrix algebra which is the basis of many transient analysis computer programmes such as *pSpice* and *EMTP*. The problem is simplified when the cable geometry is symmetrical as shown in Fig 7

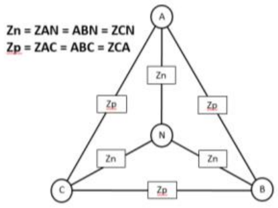

Fig 7 Surge impedance mesh for a symmetrical cable

Sources of travelling wave impulses

Travelling waves are produced when a low voltage pulse is injected at the terminals of a cable. The signal can be injected either between a phase conductor and neutral or between 2 phase conductors as shown in Fig 8.

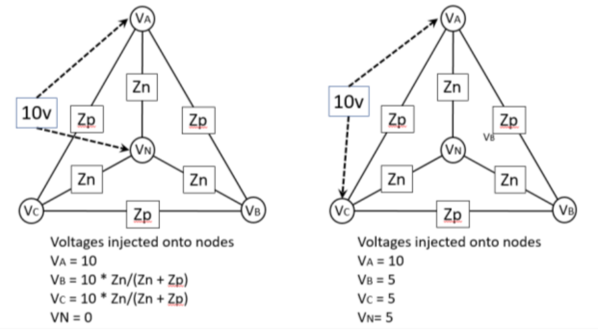

Fig 8 Impulse voltage distributions with phase-neutral and phase-phase injections

When a fault occurs in an energised length of a cable the 'injected' voltage is equal to the instantaneous voltage difference in the supply voltage between the 2 conductors involved minus the value of the arc voltage. This is shown in Fig 9 for a phase to neutral flashover at the peak of the phase to neutral voltage and for a phase to phase flashover at the peak of the phase to phase voltage.

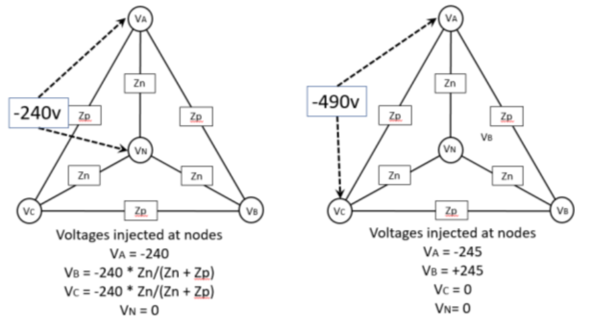

Fig 9 Fault generated voltage distribution at peak voltage flashover for phase to neutral and phase to phase faults with assumed fault arc voltage of 100v

When faults, or sudden changes in voltage due to point-on-wave switched loads, occur within a length of cable, the impressed voltage produces waves which travel in opposite directions away from the point of injection as shown in Fig 10.

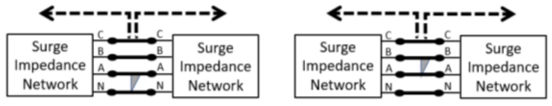

Fig 10 The pair of travelling waves produced by phase to neutral and phase to phase faults within a cable

The effects of branches

Fault location using injected pulses (ie TDR methods) is dependent on being able to identify the reflection from the fault from 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 2 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 is exactly the same as that produced by a fault where Rf = Zo (0.33 as shown in Fig 5). The magnitude of the fault 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 11 shows the amplitude of the reflections produced by 5 branch joints each with ρ= 0.33 and τ=0.67 and a fault where Rf = Zo also with ρ= 0.33 after each branch joint.

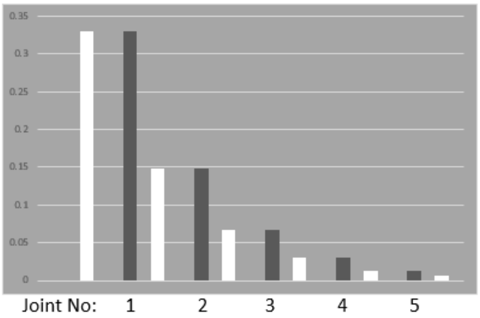

Fig 11 Reflections from branch joints (black) and from faults located between each joint (white)

The effects of variable impedance loads

The TDR traces produced by a transitory fault beyond several branch joints can be clearly identified in Fig 12a, with the associated voltage recorded at the feeding substation shown in Fig 12b.

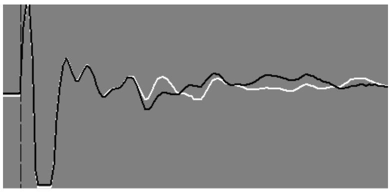

Fig 12a Triggered TDR traces from a transitory fault

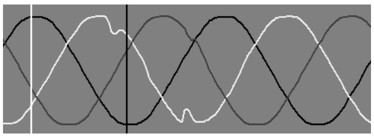

Fig12b Substation voltage during above transitory fault

By comparison Fig 13a and 13b show differences of a similar magnitude in the TDR traces obtained at different points-on-wave of the supply voltage due to changes in the impedances of ‘non-linear’ loads

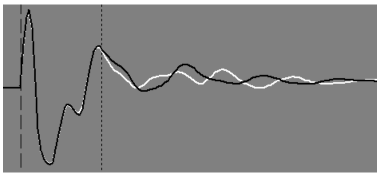

Fig 13a Point-on-wave changes in TDR traces

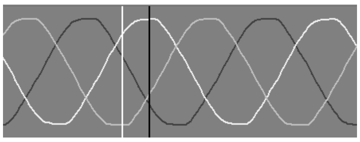

Fig 13a Point-on-wave markers for TDR trace

Using fault generated travelling waves

As is shown in Fig 10 faults, and other impressed disturbances, produce travelling waves which propagate away from their point of origin. This process has been the basis of fault location on ScottishPower’s overhead transmission system for many years using GPS signals to synchronise transient recording devices at the line terminals. A modified version of this technique for use on LV cables, the TRS method, was presented in [1]. The TRS method has proved to have several advantages over TDR methods as all pulses, 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 TDR reflections. The TRS method has shown a high success rate provided the injected synchronising signal has been visible at the opposite terminal. The addition of an injector at an intermediate point extends the length of circuit that can be covered and, unlike the TDR method, an increase in the amplitude of the injected signal extends the coverage even further. The lattice diagram in Fig14 shows the synchronising signal injected at an intermediate point.

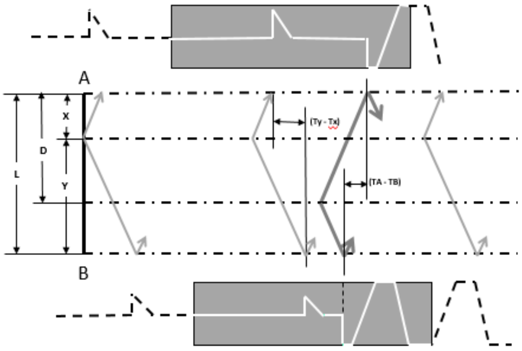

Fig 14 TRS method using intermediate synchronising pulse injection

The distance to the fault is determined by:

1. Align the arriving ‘fault’ pulses in the transient recordings at ends A and B.
2. After alignment, the time interval ΔT between the 2 ‘synchronising’ pulses.

Distance to fault from A = $\Delta T\text{x}V/2 – X$

Distance to fault from B = $\Delta T\text{x}V/2 - Y$

Recent improvements to the TRS method

Filtering

When first introduced the TRS device 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) every time the hardware trigger operated.

Auto-reporting

The original LV fault locators used ‘dial-up’ GSM modems and were remotely interrogated and controlled ‘on-demand’ from a desktop PC application. Now, with GPRS communications, the devices auto-report into a central server whenever they are triggered and early warnings of potential problems sent to the appropriate place. As the devices are ‘internet’ enabled they can still be polled ‘on-demand’ using any web browser. Auto-polling, at regular intervals, is used to check the integrity of the communication channel and the health of the remote devices.

CONCLUSIONS

Using a combination of the triggered TDR and TRS methods of fault location ScottishPower has been able to detect and locate the position of recurring faults on their LV network more accurately than with any other method. Modifying the design of the TRS hardware, and the manner in which the devices are used, has allowed longer and more complex circuits to be handled.

Both TDR and TRS methods have proved especially useful when addressing customer complaints of flickering lights, and equipment mal-functions, where there have been no supply interruptions reported. Flickering lights are usually an indication that transitory faults are taking place so their detection and location is essential to a ‘pro-active’ fault management strategy.

REFERENCES

[1] J. Livie , 2007, "Experience with on-line low voltage cable fault location techniques in Scottish Power", *CIRED 19th International Conference on Electricity Distribution*, Vienna, May 21-24, Paper 0696.