EXPERIENCE WITH ON-LINE LOW VOLTAGE CABLE FAULT LOCATION TECHNIQUES IN SCOTTISH POWER

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ABSTRACT

On-line fault location equipment has enabled Scottish Power to achieve significant improvement in the location of transitory and intermittent faults on low voltage power cables. The equipment has also proved useful in identifying the sources of other Power Quality affecting disturbances.

INTRODUCTION

The location of faults on UK low voltage (LV) cable networks has plagued electricity supply engineers for many years. Fault location techniques used on high voltage (HV) cables cannot generally be applied to LV distribution cables due to the multi-branched design of LV networks and the difficulty of disconnecting all the customers supplied from the faulty cable. The low operating stress in LV cable insulation results in many faults exhibiting an unstable/non-linear characteristic making them only locatable when the cable is energised at normal working voltage. On-line techniques of fault location are thus essential if multiple excavations, cable cutting and ground re-instatement are to be minimized.

Although LV cable fault location presents severe technical challenges, network operators require the equipment and procedures used by field staff to be simple. At the same time, incentives imposed by the Regulator have increased the urgency to restore supplies after ***permanent*** faults and to avoid outages by reducing the incidence of ***intermittent*** faults. To address these challenges Scottish Power has introduced a remotely controllable on-line LV cable fault locator which allows diagnosis and location to be performed by centrally located 'specialist' personnel. Examination of the transients produced by LV cable faults has confirmed that many ***intermittent*** (repetitive fuse blowing) and ***transitory*** (non-fuse blowing) faults occur and that these faults can be located without customers experiencing any (un)planned supply outages. Many faults, which from fuse operations were believed to affect only a single phase, were found to involve multiple phases – with the phases involved in the fault arc path often changing several times within a cycle of the supply frequency. In addition, some repetitive supply interruptions, suspected to be caused by cable faults, have been shown to be the result of excessive load or mal-functioning auto-reclosing devices.

LV CABLE FAULT CHARACTERISTICS

The operating voltage stress of LV cable dielectric is very low – the insulation thickness being determined by mechanical factors rather than electrical considerations. This results in LV cable faults exhibiting high levels of instability and non-linearity making them a major cause of Power Quality problems [1]. Fig 1 shows the voltage disturbance recorded at a substation during a ***transitory*** **AB** fault. Fig 2 shows a disturbance recorded on the same cable, a few days later, when an ***intermittent*** **AB** fault caused the **A** phase fuse to rupture. After the circuit was re-energised ***transitory*** and ***intermittent*** faults continued to occur until the fault position was confirmed and repairs completed. Both records show the non-sinusoidal and non-linear nature of the fault current in the **A** phase.

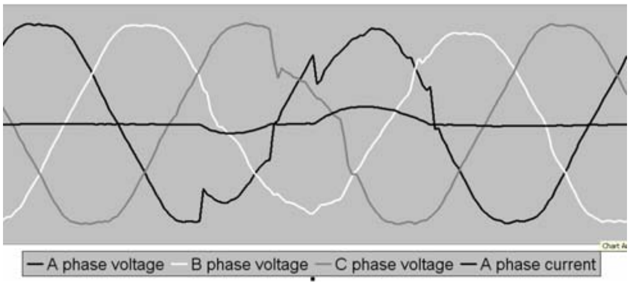

Fig 1. Transitory fault

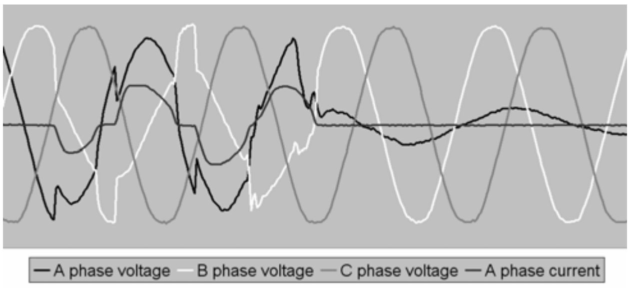

Fig 2. Intermittent fault

Transitory faults are often the pre-cursor of a developing ***intermittent*** fault and provide early warning of pending problems. Additionally they degrade PQ and can cause both industrial and domestic electronic equipment to mal-function. LV cable faults associated with deterioration and un-reported accidental damage often develop from the ***transistory*** condition through the ***intermittent*** condition before finally becoming ***permanent*** - at which time they must be located before supplies can be restored.

ON-LINE LV CABLE FAULT LOCATOR

Fig 3 shows the schematic diagram of the on-line LV cable fault locators used by Scottish Power. The locator incorporates ‘high speed’ data acquisition and triggering, a pulse generator, a differential TDR output stage with integral phase selection, ‘wireless’ local and remote communication hardware, status indicators and a power supply with automatic selection of energized phases(s). 4 channel ‘low speed’ data acquisition and triggering is implemented through the locator’s software.

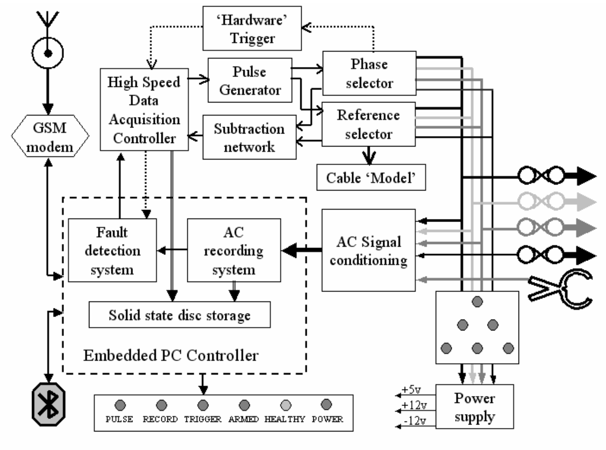

Fig 3 Schematic of On-line fault locator

The locator can operate as a triggered Time Domain Reflectometer (TDR) or as a high speed Transient Recording System (TRS) to capture the high frequency transient(s) generated by the fault itself. In both cases, AC waveform data is stored to confirm the fault characteristics and for use in a 3 phase Voltage Gradient System (VGS).

Triggered TDR mode

The first triggered TDR fault locator for LV power cables was developed in the 1980s at the UK Electricity Council Research Centre [2]. The new locator is connected to the energized faulty cable and the ‘high speed’ acquisition hardware is configured to inject a short duration pulse into the cable every 500µS. TDR waveforms produced by each pulse are recorded in a 64 section memory which is cyclically overwritten. Injection of the TDR pulses continues until the ‘low speed’ data acquisition software detects a trigger – typically a reduction in the voltage on one or more phases lasting for more than 750µS. Once the trigger is detected a further 32 TDR pulses are injected and then the process is stopped. Meanwhile, acquisition of ‘low speed’ data continues for 160mS and then stops. The locator therefore now has approximately half of the 64 TDR waveforms during the pre-trigger period and the remainder during the post-trigger period. The ‘low speed’ record, which is 10 cycles in length, has 2 cycles of pre-trigger and 8 cycles of post-trigger data. The 2 sets of data are then combined in an event file and stored in a cyclic non-volatile 20 record ‘event’ buffer for subsequent local or remote retrieval. The process is illustrated in Fig 4. The fault position is determined by identifying the first major point of difference between TDR pulses obtained when the fault is not active with those when the fault is present.

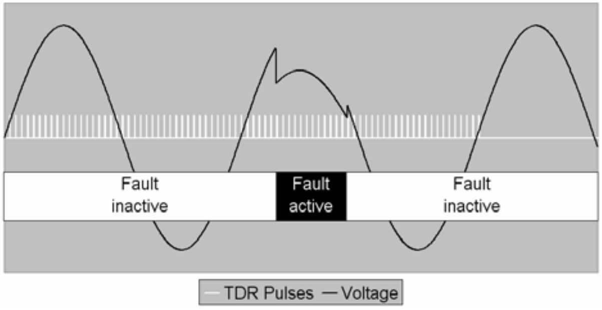

Fig 4 Principle of triggered TDR

The remote communication capability is essential, not only for retrieving event records but also for re-configuring the TDR hardware in light of the information about the fault characteristics derived from previous events. Fig 5 shows 2 of the TDR waveforms from a transitory **AB** fault with the TDR configured to inject between phase **A** and **N**(eutral). Comparison with Fig 6, which shows a subsequent transitory **BC** fault but with the TDR injection between **B** and **C** phases, clearly shows the benefits of setting the TDR output to match the fault behaviour.

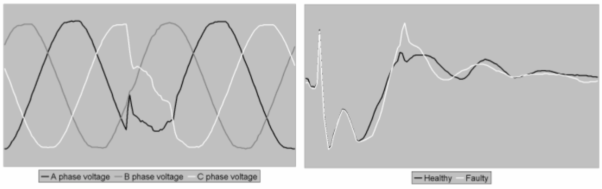

Fig 5. AB transitory fault with A-N TDR traces

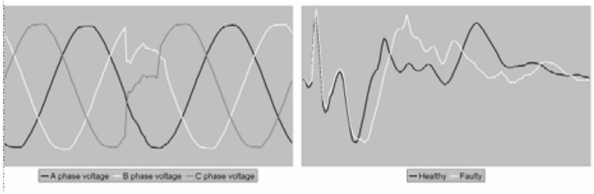

Fig 6. BC transitory fault with B-C TDR traces

TRS (Travelling Wave) mode

Scottish Power have a large number of Travelling Wave Fault Locators (TWS) installed on their 400 and 275kV EHV overhead line network [3]. These units operate by determining the difference in time of arrival of the fault generated transient at opposite ends of a transmission line. This requires the 2 units to be synchronized accurately – achieved by use of GPS clocks which provide timing accuracies in the order of ±1µSec which gives a theoretical fault location accuracy of ±150metres - less than the distance between 2 adjacent towers. For LV cable fault location much greater accuracy is needed and, although GPS clocks are capable of accuracies of a few nanoseconds, they are large and expensive. In addition they require the use of an antenna with a clear view of the sky.

A pair of on-line fault locators connected on either side of the fault position can act like TWS fault locators but with a timing accuracy appropriate for cable fault location. This is done by operating the hardware of the 'high speed' acquisition system as a hardware triggered transient recorder with approximately 280µS of pre-trigger and 40µS of post-trigger data. The TDR pulse generator provides a synchronizing pulse every 160µS to ensure that at least 1 pulse will be captured in the pre-trigger period of any 'high speed' transient record. The hardware trigger is adjusted so that it operates on receiving high amplitude fault generated transients but not the much small injected synchronising pulses. Injecting timing pulses onto a faulty conductor for synchronizing 2 fault locators was first reported in 1957 when it was classified as a Type B3 method[4].

If both on-line fault locators inject synchronizing pulses locations can be determined from both points of connection - but for simplicity Fig 7 shows only the upper unit injecting.

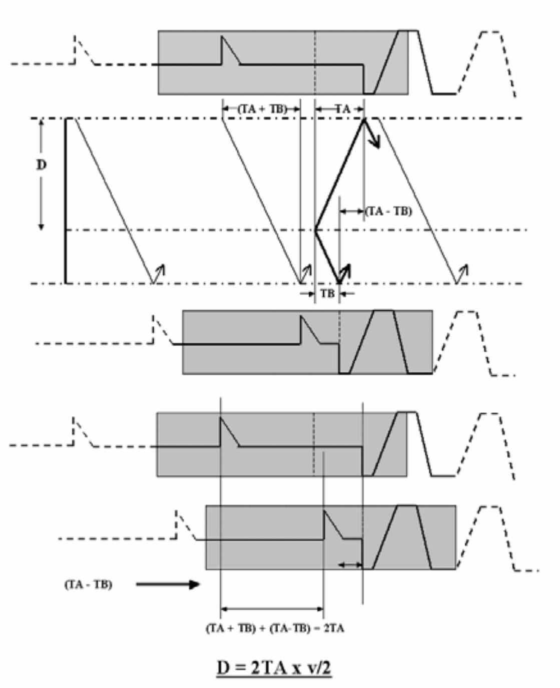

Fig 7 Theory of TRS mode of operation

When a fault breakdown occurs it produces 2 travelling waves which propagate away from the fault point in opposite directions. The arrival of these (relatively) high amplitude signals trigger the 2 on-line fault locators to capture a single 'high speed' record. Prior to the fault occurring the upper unit has injected a (relatively) small pulse which travels to the far end of the cable where it appears as a (much) smaller but still identifiable feature visible during the pre-trigger period of the 'high speed' transient record. When the edges of the fault breakdown on the records from the 2 on-line fault locators are aligned the location of the fault can be determined as shown in Fig 7.

In Figs 8, 9 & 10 one locator was installed in a substation and the other in an underground link box. Both units were set inject synchronising pulses. The difference in time between the injected and received pulses (after alignment), Fig 11, was used to locate the fault position which was confirmed using the EATL '*Fault Sniffer'*.

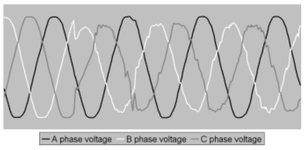

Fig 8a Substation voltages

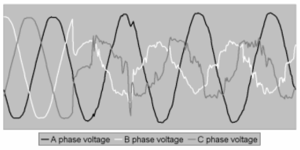

Fig 8b Link Box voltages

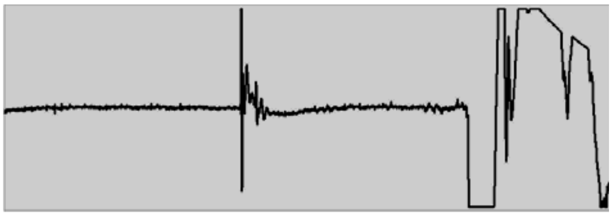

Fig 9a Substation 'high speed' record

Fig 9b Link Box 'high speed' record

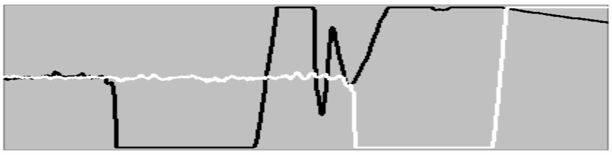

Fig 10a Expanded view of 'fault' edges

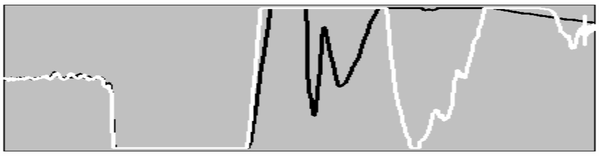

Fig 10b 'Fault' edges aligned

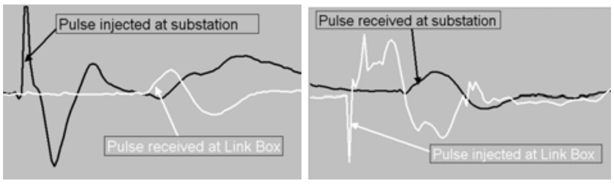

Fig11 Injected and received pulses

VGS mode

The Voltage Gradient System for locating non-linear LV cable faults from measurements of instantaneous voltages along the cable route using multiple recorders was first described in 1974 [5]. In practice the method proved difficult to apply as the units could only capture a single event and had no remote communication capability. A further limitation of voltage gradient fault locators has been that they are single phase devices and, as has been shown, many transitory and intermittent faults involve more than one phase with the phases involved frequently changing with each event.

When 2 or more on-line fault locators are connected to the same cable, for example when working in the TRS mode, the recorded AC waveform data can be used to provide an additional location using the VGS method. The multiple event storage provided by the on-line fault locators, together with the ability to interrogate them remotely plus the fact that they monitor all 3 phases, greatly increases the chances of obtaining a fault location. It is essential that 1 unit is connected 'downstream' from the fault to measure the fault arc voltage as shown in Fig 12.

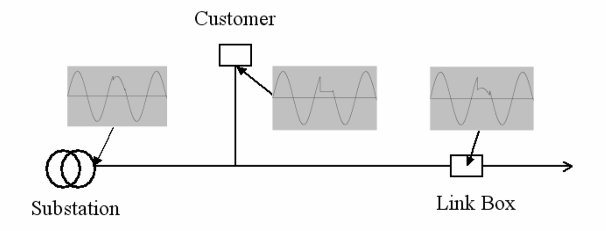

Fig 12 Voltage Gradient System

Comparison of modes

Each of the modes has its own advantages and disadvantages. Without doubt the TDR mode is the most convenient since only 1 unit is required but attenuation limits how far any TDR instrument can see along a multi-branched and loaded LV cable. Additionally, when the on-line fault locator is connected in a substation it is desirable to insert additional inductance in series with the connecting leads of the fault re-energising device so that the injected and reflected pulses are prevented from entering other cables connected to the busbar. The preferred point of connection for the TDR mode is therefore an open end.

The TRS mode does not require units to be connected at open ends but does, of course, mean that 2 units are needed. The main advantage of the TRS mode is that the recordings only contain received signals, i.e. no reflections are involved, and all the pulses have to make only 1 transit along all, or part, of the cable. The signals from the fault which are used for aligning the traces are always large.

The TDR and TRS modes share the advantage that they do not require as much information about the type, size and mixture of cables within the circuit on which they are used. The VGS mode does require detailed cable records but is not affected by attenuation.

FIELD EXPERIENCE

Scottish Power has successfully located numerous troublesome intermittent faults since the introduction of prototype on-line fault locators in 2003. Table 1 lists the outcome of the first 100 installations which included both prototypes and final production versions of the locator. In all cases the units were installed on difficult faults – often following failure to obtain a location by other methods.

Installations	Outcome
52	Confirmed and Repaired
11	Awaiting Confirmation
6	Identified as load/other cause - excavations avoided
2	Confirmed - after records found to be incorrect
21	No result - equipment removed before further triggers
8	Unsuccessful

Table 1 Results from first 100 installations

CONCLUSIONS

The need to use on-line equipment to reduce the cost and inconvenience of intermittent LV cable faults has been clearly demonstrated. Attention is now being directed to implementing procedures, such as automatic data retrieval and analysis, so that the full benefits of on-line LV cable fault location can be realized.

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