TECHNIQUES FOR CABLE FAULT LOCATING

Radiodetection Ltd

ABSTRACT

Cables do fail and for a variety of reasons. Manufacturing errors, installation errors, ground conditions and even rodents all play a part in the lifespan of a cable. When these cables fail they usually cause disruption to the people relying on them and can cause a decrease in both internal and external customers' confidence. This paper will introduce the basics of cable fault locating and the tools to accomplish it in use today.

Keywords: locator, electric, cable, fault, TDR, thumper, bridge, a-frame

INTRODUCTION

As you imagine, all these buildings, plants, and systems don't do a thing without some wires tying them all together. Being able to locate the cables and in downtimes, locate the problems with these cables is very important. In cases where there is no suitable redundancy, a substantial portion of the operation of an enterprise could rest on getting these cables identified and repaired.

When people talk about locating, often it is thought of as being related to metal detectors. It is an understatement to say locating is poorly understood. Some types of cable fault location are related to the basic theories of cable location. Light, gas, water, power and communications are the lifeblood of the community and buried pipes and cables are the arteries that supply these necessities for life to the community, business, and industry. No one can afford the cost of utility failure or the danger a poor locate can pose.

There are many types of problems that are all lumped together under the heading of 'Faults'

- Resistance from one conductor to another hot conductor, to a ground or neutral conductor, or to earth. Low resistance problems are easy to find but high resistance can be more difficult, sometimes requiring a resistance bridge to locate them.

- Series resistance along a cable, nearly any is too much. It often accompanies a fault to ground when the insulation has failed and the wire corroded. This results in low to zero voltage at the far end. I have heard these described as "letting 50 volts through" where in fact, they act as a current limiter and the voltage at the far end is dependent on the load there.

- High voltage (HV) faults. Some faults show fine with low voltage test methods, only causing problems at high voltages. Even then, they can work correctly until the right set of circumstances occurs. A test voltage higher than normal operation often will aid in the detection of these faults at the expense of cable stress.

- Intermittent Faults. Sometimes similar to the flashing faults above, they can be very difficult to find. For example, a splice or fixture can gradually fill with moisture until it is enough to cause a fault. When the moisture conducts, it can vaporize the moisture and clear the fault. This leaves the technologist nothing to detect when they come out to fix the problem.

We will be covering in more detail the techniques and equipment used to detect and locate all of these types of faults.

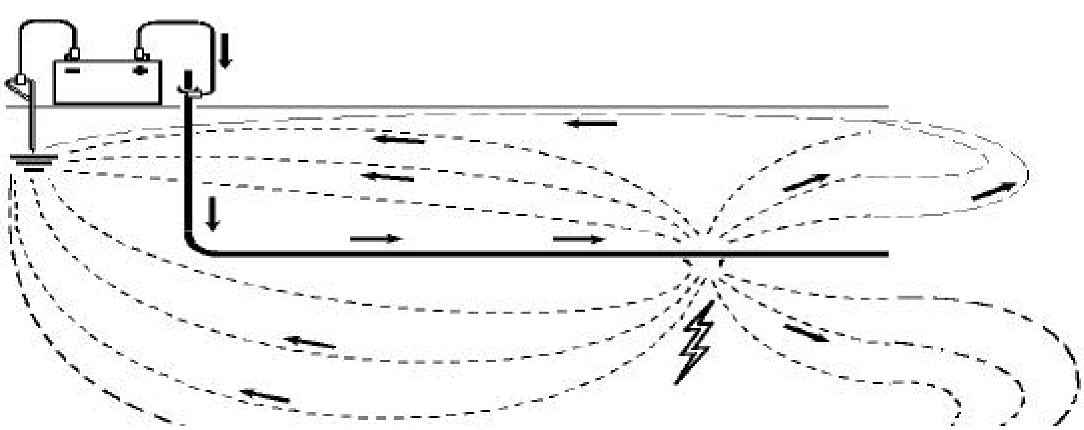
The three main tools for these are the method usually called 'earth fault locator' or 'a-frame', Time Domain Reflectometers or TDRs, and Surge Generators or Thumpers. One other device that is sometimes called upon is the good-old bridge.

A-FRAME / EARTH FAULT DETECTION

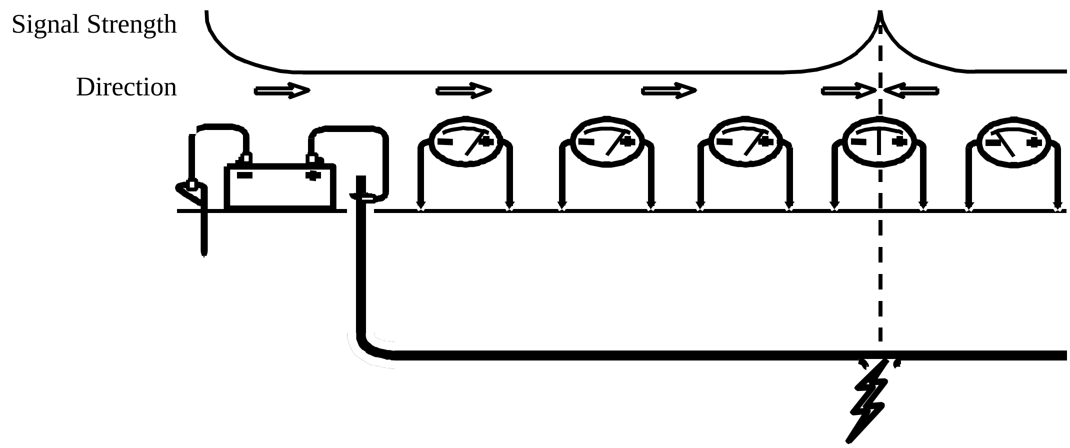
The type of fault should be determined, as different faults require different approaches. A persistent fault to earth (a ground fault) is usually most accurately and most easily found with an A-frame. Open and short circuits are best found with a TDR, and a 'flashing' fault that only happens at high voltages usually requires a high voltage surge generator or 'thumper'. Most transmitters in a fault-finding system will have some way to indicate if there is a path to ground such as an ammeter or ohmmeter and some have both. If there is a path to earth, the a-frame is still one of the most popular and most recommended methods when the conductor is not enclosed in duct.

The A-frame method is well known especially from telecom and low voltage cabling. It is based around a transmitter and a receiver, often part of the same system used for cable locating. The theory of its use is signal from the transmitter is applied to the faulted cable.

We know that cable locating is achieved by creating an alternating current (AC) on a cable and tracing the resulting AC electromagnetic (EM) field with a tuned receiver. A-frame systems differ in that in addition to the locate signal, we add a pulsed DC current



(for ground fault locating) to the cable under test. The use of DC allows the detection of current direction and will lead the user towards a fault. Where there is contact with the earth, this current will flow out of the CUT at the fault and back to the ground stake of the transmitter. The current will be concentrated near the fault(s) and the ground stake but from those points will travel very wide and deep in search of the path of least resistance. Current through a resistance makes a voltage. The flow of the pulsed DC through the impedance of the earth will create a slight DC voltage and that is how we find faults. The addition of an A-frame to a locator turns the locator into a very sensitive voltmeter and following the pulsing DC through the earth with the A-frame gives a direction to and magnitude of the fault(s).



To eliminate the signal 'bleeding off' the cable by the inherent capacitive coupling to earth, the transmitter uses a very low frequency, usually around 8 Hz. (not kHz, Hz.)

For best results when using an a-frame:

- A very low resistance ground for the transmitter is necessary. Place the ground stake in wet soil; extend it out as far as possible, at least 15'. Use a ground extension lead if required to get to a better ground.

- Disconnect all other conductors in the cable **at both ends**, including grounds and neutrals. This forces the FF signal to get to the ground stake through the fault and into the earth where the a-frame can detect it.

- If possible, perform the test on a day where the soil / pavement is wet. There will be more current available near the surface with wet ground.

- Since we need contact with the earth, locating through concrete, rock or ballast will reduce the connection to earth. Especially with rock, scrape it aside so the points on the a-frame get good earth contact.

- Test the a-frame close to the ground stake. Make sure there is sufficient signal strength and the arrows point away from the ground stake (towards the fault)

- Don't touch the a-frame with weaker signals; allow the readings to stabilize.

- Use a Time Domain Reflectometer (see next section) to reduce walking time.

- If the cable is under concrete but there is a parallel strip of grass or dirt, a-frame along the soil until the arrows reverse then locate the point on the cable that is 90 degrees perpendicular to that.

- 'Megger' all of the conductors in a cable to find the wire with least resistance to earth. This will typically be the easiest fault to find. Most complete FF systems will include a digital ohmmeter / Megger for this purpose.

- Re-Megger the system after fixing to insure there are no other faults.

- Finally and most importantly **trust the equipment**. It is very common on long locates for the signal to have spread out so far that the a-frame system can not see it in the middle. If you are confident you haven't walked over it, keep walking. As you approach the fault, the signal strength and arrows will begin to find the signal again. It is common to see the signal for the first 100m out from the stating point and then walk hundreds of meters without an indication before we begin to find it again.

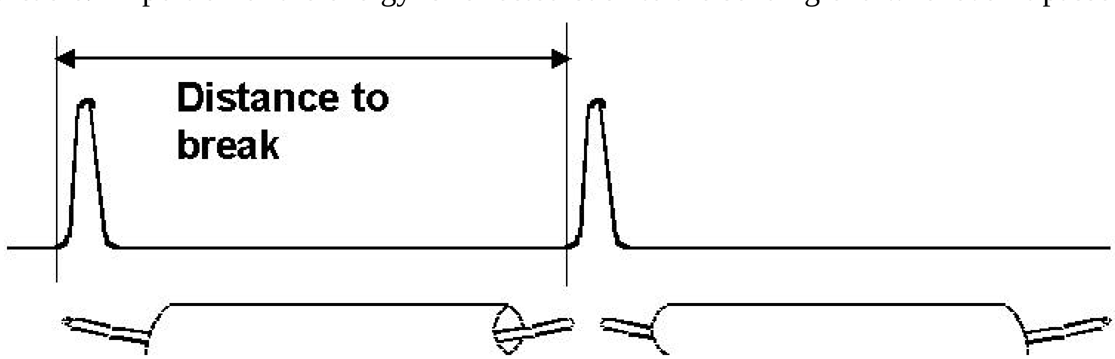
An a-frame based system is relatively inexpensive, usually costing around C$7,000 for modern, quality equipment.

TIME DOMAIN REFLECTOMETERS (TDRs)

A TDR is the most convenient method to find shorts and opens in cables where there is no associated path to ground that can be used for 'A-frame' type locating. A TDR may also be more accurate for cables in duct where the path to ground may not be at the point of the fault but rather at an unrelated duct damage (crack, joint, etc.).

A basic TDR consists of a pulse generator circuit connected to a display similar to an oscilloscope and both of these are connected to an external connection to test leads. Most TDRs include circuitry to adjust the amplification of the outgoing and returning pulses; cursors to measure pulse timing with, internal batteries and other controls.

The theory of a TDR is that it transmits a pulse of energy that travels or propagates along a cable. A portion of the energy is reflected back to the sending end whenever it passes a



large change in the impedance of the cable. The time the reflections take to return is proportional to the distance. If we know the approximate speed of the pulse in the cable and multiply it by the time the reflection takes to return, the distance to the anomaly is easily calculated. Most TDR instruments automatically do all the math, displaying the distance in feet or meters.

The speed of the pulse in the cable is not at the speed of light as we might expect but typically closer to half that value. The impedance of a cable limits the speed so we should review this topic. Cable impedance is different from resistance; it includes the sum of all of the reactive resistance we encounter in a cable. The source of this reactance is from four sources: the DC resistance of the wire; the resistance between the conductors through the insulation; the capacitance created by the insulated conductors; and the inductance of the cable. The single biggest factor affecting the impedance, and hence speed, is insulation material. For example, signals in coaxial cable propagate at close to 85% of the speed of light, polyethylene (PE) results in a speed of around 65%, and cross-linked PE (XLPE) is a little slower yet at around 54%.

A TDR does require that there are at least two individual conductors in the cable under test, insulated from each other. Multiple single conductors, not in a common jacket can often not be tested, as there is too many impedance changes due to changes in the spacing. This can be overcome by capturing a copy of the traces when the system is new and comparing it to future results after the cable has failed.

TDRs do have a couple of drawbacks. The impedance of the fault must be quite different from the normal impedance. Series faults have to be close to an open circuit; a 'green' high-resistance area is often missed. Similarly, a fault to earth or another conductor must be below approximately 300 ohms. Another is that the accuracy of the distance is very dependent on the accuracy of the VOP selected. 1% inaccuracy means potentially digging up to 5' if the fault is 500' away. We can get around this requirement by taking measurements from both ends and using a little additional math. Treat the two distances reported as a ratio to get accurate distance without knowing the VOP. Another consideration is that a TDR gives a distance to the fault but it does not locate the cable. For this reason, they are often used in conjunction with a cable locator and a measuring wheel to find the true path of the cable. Any cable in slack loops and pole bases, including the 1 meter of depth, must also be accounted for. Finally, the fault must be 'persistent', that is the fault must be there at low voltages. Arcing faults that short only when high voltage is applied require the use of a high voltage surge generator also known as a 'thumper'. Some modern thumpers have the equivalent of a TDR built into them to reduce the number of surges required and thus reduce the electrical over-voltage stress on the cables.

TDRs can also be used in conjunction with a-frames for increased efficiency. One example is a cable with an earth fault that we know we can find with the a-frame. Since faults often happen at splices, operators can use a TDR to find the position of splices, drive to them and check them first with the a-frame. This can reduce the walking from hundreds or thousands of meters to tens of meters. Even if there isn't a splice, series resistance will show up and again reduce the amount of time required to locate the fault.

Advanced control of a TDR usually includes several functions.

Pulse Width is usually adjustable for a couple of reasons. A wider pulse will have more energy and be able to test longer distances and show up smaller faults. The trade-off is that faults can be difficult to detect if they are close to the normally occurring reflection caused by the test lead to cable connection or close behind a splice or another fault. Narrow pulses give more useable resolution but no more accuracy.

Another advanced control is amplification. Control over the vertical amplification of the displayed trace allows smaller faults with weak reflections to still be detected. Faults can be as small as a pinched coax and still show up.

A screen zoom function is desirable to allow more accurate placement of a cursor when measuring distances. The resolution of the LCD screen will affect the accuracy of cursor placement and the ability to zoom in to improve the resolution will give greater accuracy.

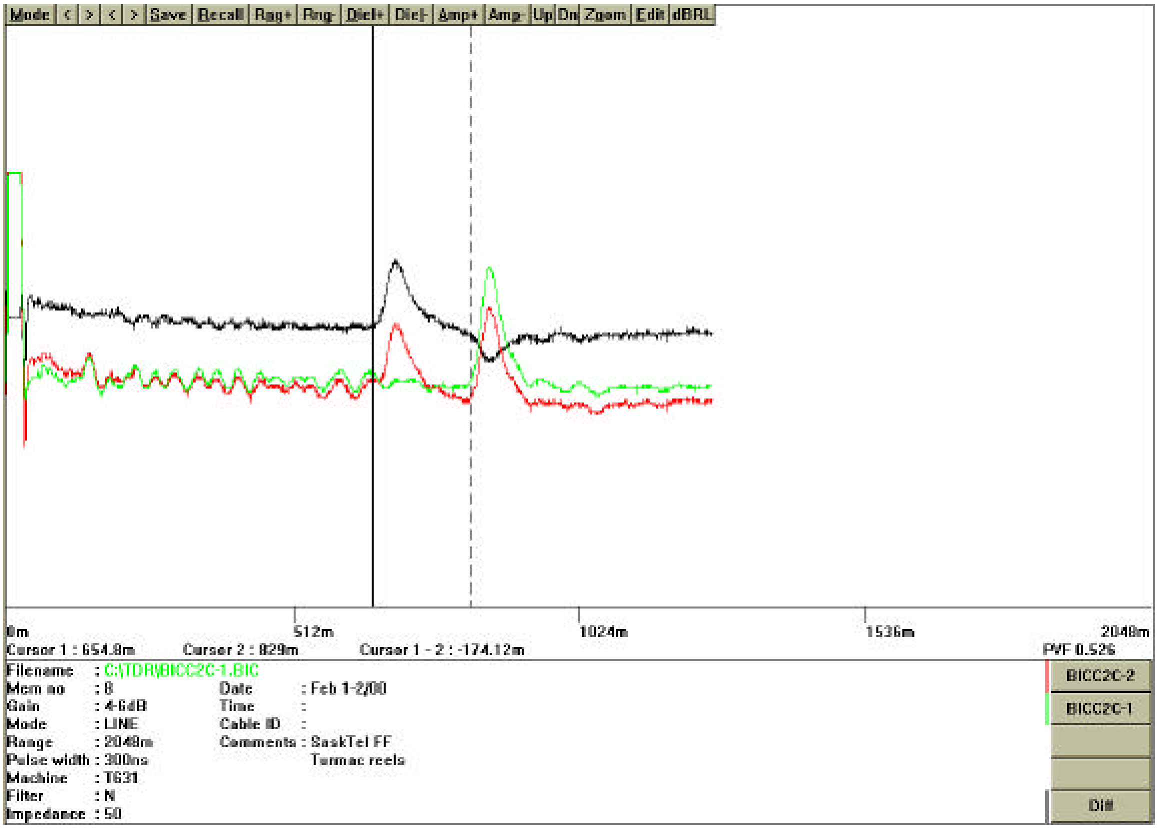
Two channels and/or memory settings give additional trouble-shooting ability. Due to their design, or environment (wetness for example), some cables may show a 'noisy' trace that is difficult to interpret. Comparing a trace on a bad phase to the equally difficult trace on a phase known to be operational will often allow the fault to be detected. TDRs that can show both traces at the same time or even better, mathematically subtracting one trace from the other make many faults show up very well.

The uses of a TDR are just about limitless. Technicians and engineers in any industry that has cable problems can usually find ways of detecting and locating their problems. This includes fire suppression and detection systems; aircraft, shipboard power and communications cables, electrical contractors, linemen, underground primary and secondary cable, street lighting, mine cables, heat tracing cable and more. Cable inventory is also a popular use of TDRs.

Training. The best equipment manufactured can still not give the needed information if the operators don't understand how to effectively use it. Make sure training and applications support is available, included, and utilized when purchasing test equipment.

A typical TDR application can be to locate an open circuit in a streetlight cable in duct. Because of the duct, there is no path to ground to use an a-frame. The following TDR display easily show the end of a good pair of wires (BICC2C-1) ending at 829 meters and the other wire with an open circuit fault 174 meters before that point.

Some software allows adding a difference waveform, that of the good pair minus the bad pair. This has the benefit of removing much of the noise and natural reflections. The top trace in the following display is a difference that shows no significant reflections until the 654 meter point and clearly shows where the fault is.



For best results when using a TDR:

- Use with a cable locator and measuring wheel to determine path and length. Set full scale so that you see the entire cable.
- Test from both ends, sometimes what you think is the far end isn't.
- Test a length of similar cable if the VOP isn't known.
- Test when repaired and optionally keep a copy for archival purposes.

HIGH-VOLTAGE SURGE GENERATORS / THUMPERS

In older times, surge generation equipment simply subjected the cable to a high voltage pulse controlled by a simple timed relay closing. The linemen would walk along the length of the cable listening for the muffled 'thump' coming from underground caused by the electrical arc.

As technology advanced, use of a mechanical microphone, or geophone, gave the operator better ears. Placing this microphone on, or even better, pressed into the ground allowed fainter sound to be detected.

Listening devices also began to have an electromagnetic detection system in them that would detect the current flow and cause a meter reflection. The theory here is that there is current flow up to the fault and this current flow causes an electromagnetic pulse that we can detect. As we walk past the fault there is no response and as such gives a faster method of getting to the general area of the fault.

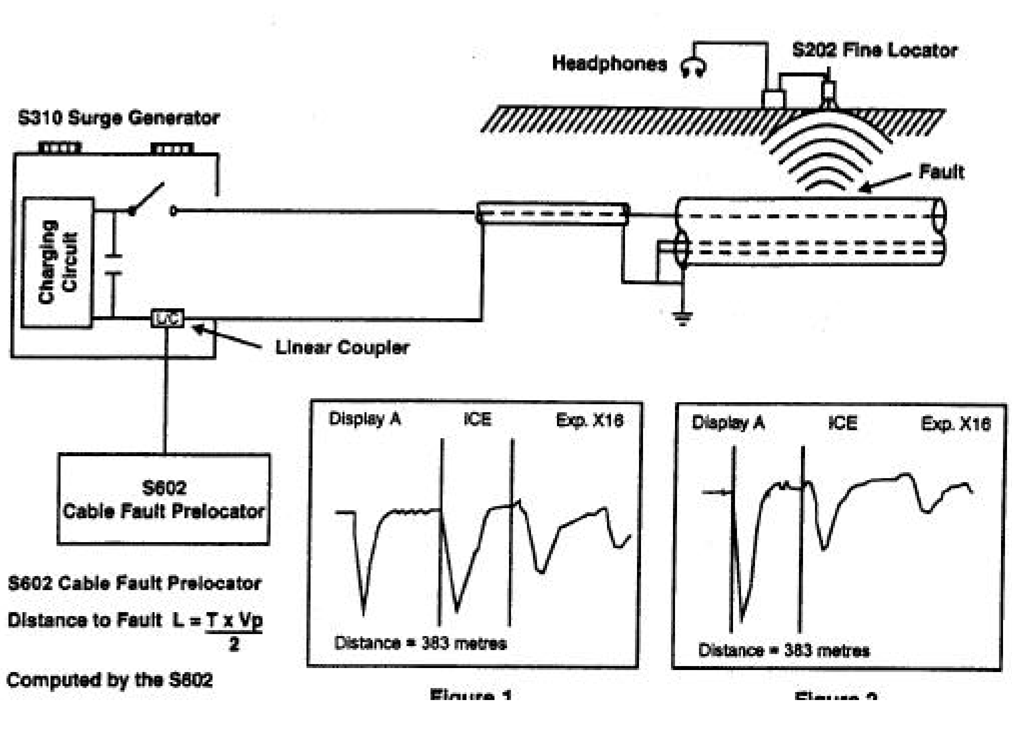
The problem is that this subjected the cable to many surges, often over the rated voltage of the cable. Although we found the fault today, oddly enough more faults came along relatively quickly.

It was also often slow, especially on long cable runs where the technician had to walk along listening very carefully. In industrial areas, this often had to be done at night to reduce the background noise to acceptable levels.

Modern surge generators feature a visual display at the console. This display is similar to a HV TDR. More modern and efficient methods have been developed to prelocate the fault within a few percent of the distance with as few as two HV surges.

Impulse Current Equipment (ICE method) monitors the current transients that occur either when a surge generator is discharged into a faulty cable, or when a cable breaks don upon the application of HV DC. The above current transients are detected by an inductive pick-up, known as a linear coupler, and transferred to the display unit where

FAULT LOCATION SCHEMATIC



they are recorded and displayed for analysis.

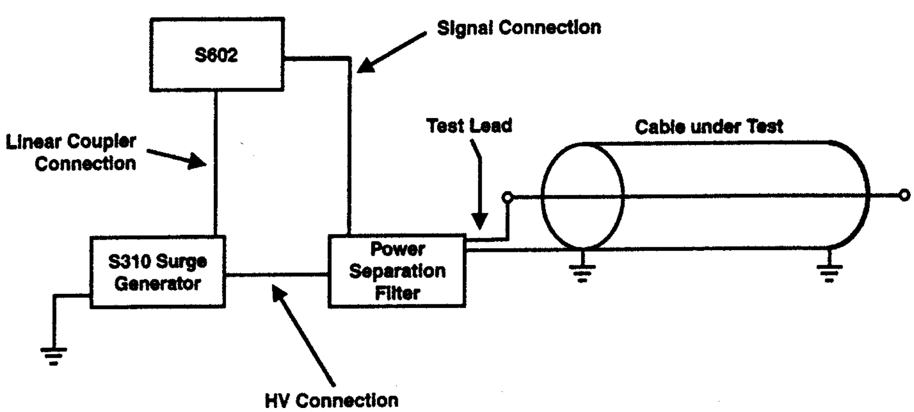
With a high resistance fault (fault resistance is greater than cable surge impedance Z_o) the voltage wave travels along the cable and passes some distance past the fault before it breaks down. Break down does not happen at the instant it passes the fault due to the phenomenon know as ionization delay. When the fault breaks down, however, it generates a new wavefront. This wavefront is reflected back and forth between the surge generator and the fault while the fault is in a low impedance state. Use of the cursors and zoom function on the display screen allow the user to pick out the coarse position of the fault.

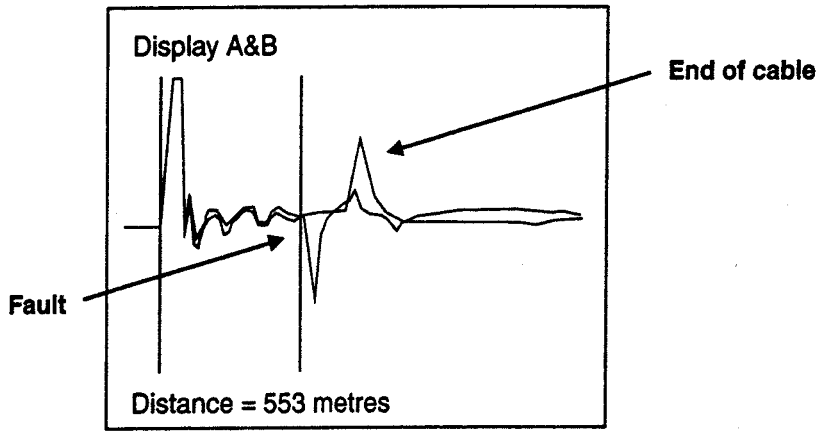
In the case of a low resistance or short circuit fault there is no ionization delay time. When the wavefront reaches the fault it is immediately reflected back to the generator. In this case the time may be measured from the first impulse leaving the generator to its first arrival back from the fault.

In the case of an open conductor fault there is also no ionization delay time. When the wavefront reaches the fault it is immediately reflected back to the generator. Again, the time may be measured from the first impulse leaving the generator to its first arrival back from the fault.

Intermittent or flashing fault is one where the fault is not usually apparent to insulation resistance measuring instruments (a-frame or megger). It may not break down on the application of a surge generator, but will break down under application of HV DC. In this case the breakdown 'triggers' the display so it appears at the start of the waveform. The measurement is made from the breakdown to its first reflection.

The Secondary Impulse Method (SIM) is intended to give a greater flexibility in HV cable fault location by adding a pulse echo (TDR) capability to the Impulse Current Method.





When a cable fault flashed over, (this is usually caused by a high voltage impulse from the Surge Generator, but will sometimes be achieved by the application of high voltage DC), a low impedance exists at the fault point. This low impedance can be detected by low voltage pulse echo (TDR) techniques. The Power Separation Filter is required to isolate the high voltage energy from the low voltage signals. The filter also extends the time for which the low impedance exists, thereby making it easier to detect.

By comparing a trace before the HV is applied with one whilst the fault is broken down, the fault position can be clearly identified.

When choosing and using surge generators a few of the more important specifications are the energy available in the surge, usually expressed in Joules, and the maximum voltage. Since the Joules are a function of voltage and capacitance, some units do not deliver the same energy at all voltage ranges leaving the user with insufficient power to find all faults without resorting to higher voltages. By starting at a low setting and working up through the range, the operator does not risk changing the character of the fault - which can make the job much more difficult.

Proper safety procedures, controls and lockouts are imperative when working at these voltages. **Make Sure** everyone is well informed and accounted for. Training on the equipment, the theory of its use and the design and construction of the cable under test is mandatory.

WHEATSTONE BRIDGE

Variations of the Wheatstone Bride are still required today for some high resistance faults. The Wheatstone bridge is basically an analog comparison of two voltages, one along a good conductor and the other along the faulted conductor. By comparing the percentage of difference between them, the distance to the fault is shown as a percentage of the distance of the complete cable. An external DC supply of 12 to 24 volts is often required to drive enough current through high resistance faults.

INTERMITTENT FAULT DETECTION

Intermittent faults can be a lineman's and his customers worst nightmare. Methods of detecting them all basically involve data acquisition.

Some advanced TDRs include a mode such as Intermittent Fault Detection. This, when coupled with mains blocking filters that allow connection to a live low voltage (<600v) cable allow the TDR to sit on the live line indefinitely. A trace showing the normal 'baseline' is displayed on the TDR, any deviation from this display is laid on top of the display allowing the operator to easily see where the fault occurred.

Other products are more specific fault data loggers that basically work on the same premise with a simpler setup requirement.

Intermittent faults on high voltage cables are more difficult to find and the typical method is to keep increasing the surge voltage until a flashing fault is forced. This has the unfortunate side-effect of possibly subjecting the cable to higher than rated voltages.

DUCTS

Cable in duct adds several new considerations, especially with an a-frame. Because we are following the path of current through the earth, cables in duct cause us problems. Even if we have fault find signal flow, it doesn't necessarily lead us to the fault. If the cable problem happens to be at the point of duct damage, we may have sufficient current flow through the earth from that location. Quite possible though is that there is moisture inside the duct and we are getting some current flow through that path as well, limiting our signal that leads us to the fault. If the cable problem is entirely within a good duct (such as happens when a jacket gets skinned while pulling it into the duct) all of our current flow can be inside the duct until a path to ground is reached, (such as at a defective duct joint) and we can't find the fault. At best we can find where the moisture inside the duct is coming into contact with the earth such as at a bad joint.

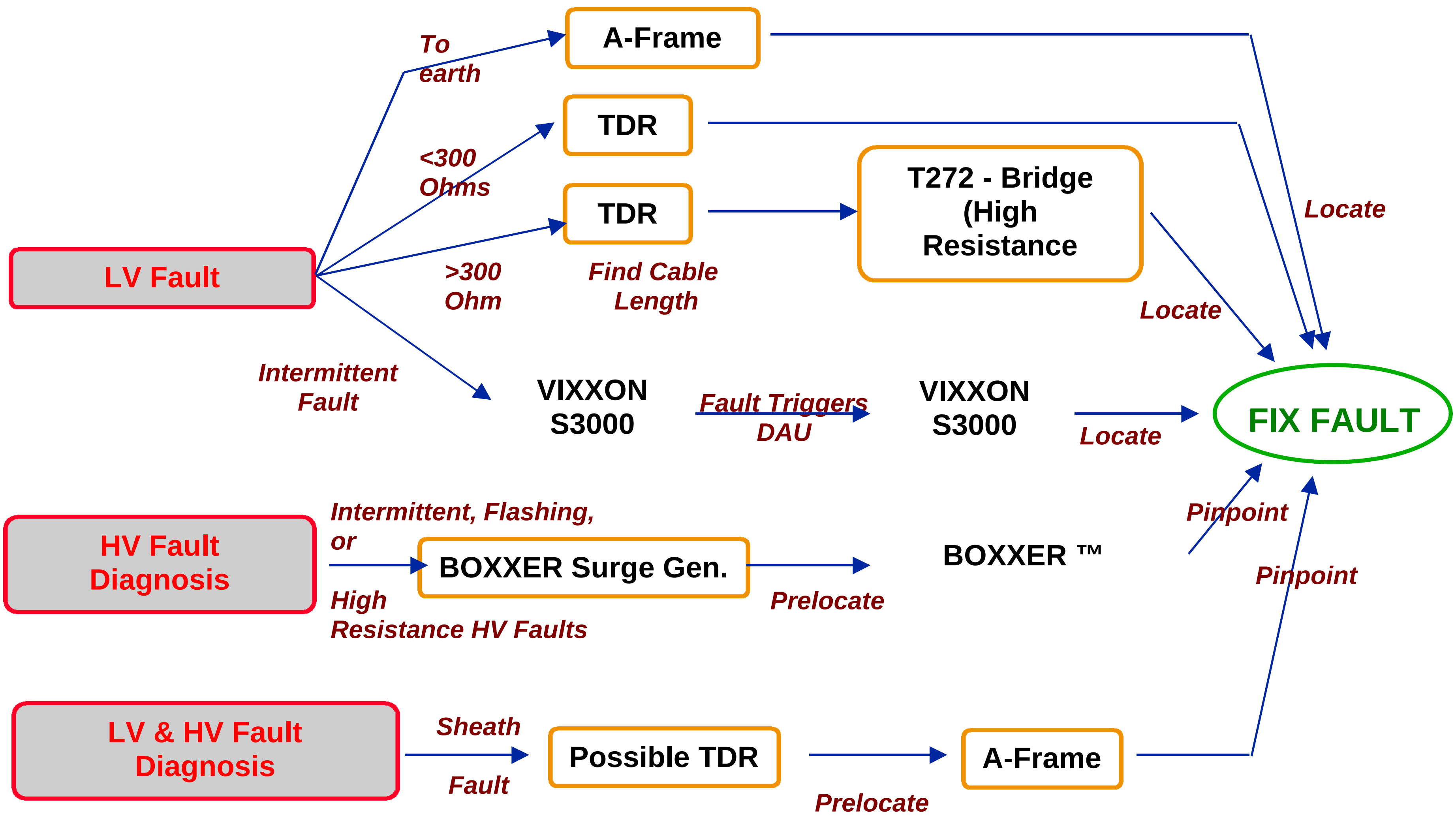
There are small camera systems available to inspect nearly any size of duct. Smaller systems are available as manual feed, push in units saving the cost of electrical drives. For smaller ducts or tighter budgets, a transmitting sonde can be inserted into a duct and pushed along with a standard fiberglass utility 'rodder'. When the sonde reaches duct damage and won't move any further, the positions is easily found with a cable locator. Direct buried cables sometimes go into duct for road and runway crossings. Finding where the duct ends can be difficult without some sort of marker. Products such as

Industrial Technology's OmniMarker will make it very easy to find that position anytime in the future.

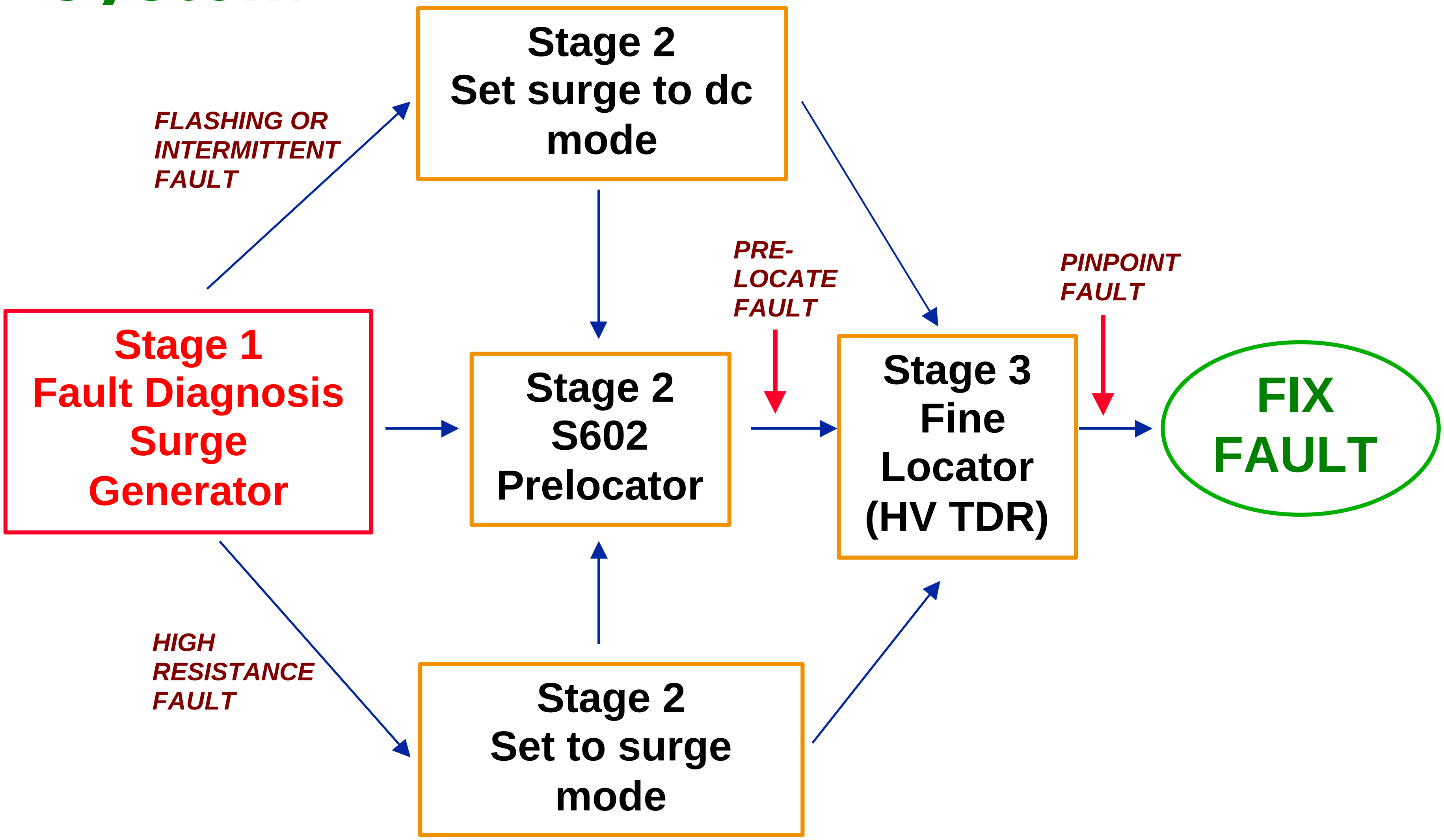
An interesting note about ducts and cold weather. Ducting often fills with water and when the ground gets cold enough the water will obviously freeze. In plastic duct this will cause the duct to burst and reduce the usefulness of the duct (i.e. unable to pull new cable through it easily). In metal duct it can cause more serious problems and cable damage. In fact an owner of a fiber-optic cable had a 'black-out' due to the pressure of the ice exerting enough force to cause a micro-bend and unacceptable loss in the cable. One relatively inexpensive method to limit the damage is to install foam tubes or lengths of ABS pipe with the ends glued and capped. These will crush before the cable and reduce the likelihood of problems.

This has been only an basic introduction to the tools and techniques that are available for fault locating. Some types of faults can be very difficult and time consuming to locate but there is a method for finding every type of fault, some just take more time and preparation than others. We manufacturers have been working on a magic wand but it still eludes us. In the meantime we have to apply current technology and logic in equal parts for success.

Comprehensive HV and LV Fault Location Process



BOXXER™ S4000 SURGE GENERATOR system



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