THE INTEGRATION OF A HIGH VOLTAGE CABLE FAULT LOCATION INSTRUMENT WITH MODERN INFORMATION TECHNOLOGY

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APPROVED FOR FINAL SUBMISSION

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Chapter 1

Introduction

1.1 Overview

Modern society as a whole seems destined to have an ever-increasing demand for power for both industrial and domestic use, as continued population growth means that cities, suburbs and industrial areas become larger and denser. At the same time the trend toward increased productivity in all segments of industry is influencing the development and techniques employed at locating faults in power cables and networks to ensure only limited downtime and reduced direct and indirect costs associated with the location of faults.

Although telecommunications are moving into the field of microwave and fibre optics, power systems will remain on wire systems. Power distribution systems employ both overhead lines/cables as well as underground cables. In order to keep pace with expectations for increased power and efficient fault location it has been necessary for cables and power transmission equipment, as well as techniques and methodologies for identifying faults, to evolve so as to meet these demands and remain abreast with the overall advancement in technology.

This thesis focuses on power cable fault location with an emphasis on the specific area of cable fault location by the Time Domain Reflection (TDR) method. Derivatives applicable in high voltage applications will also be addressed (Clegg et al. 1975 and Gale 1975). There are several methods of fault location on power cable, as can be found in references such as those by Tanaka et al. (1983), as well as Clegg (1995). These various methods will be explored with the objective of building the case for an integrated cable fault and cable reticulation database system, which will be described in some detail in the body of this thesis.

1.2 Motivation

During a series of interviews and site visits in 1993 repeated complaints were recorded by engineers involved in the location of cable faults as to the difficulties faced in locating pilot cable faults accurately. This difficulty on pilot cables is essentially due to the noisy electrical environment, the length of cables and their joints, which are at times approximately every 500 meters. Coupled to this is the fact that TDR waveforms depicted on cable fault location instruments are often complex and therefore not always straightforward to interpret making the fault location on pilot cables extremely difficult.

As most traditional cable fault location instruments at the time (1993) only captured the current TDR waveforms of the cable being explored, it became apparent that if a method could be derived whereby an instrument could store TDR waveforms captured before the fault, then this could be retrieved at the time a new fault was being investigated, providing a comparison with the original, healthy TDR trace and facilitating in the interpretation as to the location of the fault. Considerations such as aging, temperature etc. would however also need to be considered in this analysis.

By reviewing the literature on signal processing (Van Biesen et al. 1990 and Ho et al 1993), the probability of developing an instrument with these characteristics became increasingly feasible. At the time (1993) fault location instruments did not have very flexible storage functionality and usually made a hard copy of the waveform using a printer or a Polaroid camera. In order to test the signal processing algorithms, a better storage system and a platform, which would provide a lot of flexibility, was needed. The personal computer provided the initial solution as data could be captured via a high-speed data capture unit, saved and the results then processed and analysed. The next steps were therefore to define the goals and limitations and to build the new instrument. This commenced in 1994 with on-going enhancements with each test phase.

While this thesis will focus on the design, principals and methodologies of the original instrument and the results captured, the concluding chapter will highlight the various strengths and weaknesses that have become apparent through its implementation and sets the conclusions/foundations as to the characteristics that will need to be incorporated into a new instrument, considering not only the observed strengths and weaknesses but also the most recent advance in technology, drawing inter alia from the paper "Signature Representation of Underground Cables and its Application to Fault Diagnosis" by Ho et al. 1993, which has provided further validation to the proposed new instrument and its future enhancements.

1.3 Research Goals and Scope

The problem of fault location on wire cable belongs to several broad areas, namely to Radio (Bisset 1988), Telephone, Communication and Power Engineering. The particular section that this research will be aimed at is power cables as covered by Clegg (1995) and McAlister (1982). Power wire networks can again be subdivided into three subgroups namely High Voltage (HV), Low Voltage (LV) and Protection System Networks. Although fault location methods could apply to all three subgroups of networks, the main focus will be biased towards the fault location on protection networks.

In power reticulation systems there are a number of substations feeding energy/power into the network. Separate cables (pilot cables) link substations. These cables carry the interconnected protection system signals. In the event that a fault develops in the reticulation system the substations effected will transmit alarm and protection signals to appropriately isolate them from delivering energy to the fault. Without these protection systems the cables and related equipment would be damaged due to the high levels of fault current. The protection system therefore forms an extremely vital part of the reticulation system as do the pilot cables carrying the alarm control signals for the protection systems.

One of the methods used for cable fault location is known as Time Domain Reflection (TDR). Time Domain Reflection is also known as Pulse Echo (PE) and 'Radar Method' as detailed in Clegg (1995). It is obtained by injecting a narrow pulse signal into the one end of a cable and collecting the signal 'reflected' by the impedance changes along the length of the cable. The cables are however not communication cables and they are not terminated by the characteristic impedance of the cable. A TDR trace therefore has many impedance mismatches caused by the joints along the length of the cable. An occurrence of a fault adds additional 'mismatches' which may indicate the position of the fault. The identification of the fault is therefore difficult due to the abnormalities mentioned above and is compounded by the noise that is usually present on such cables. There is also supporting evidence that a pulse applied to a cable will cause a TDR trace that will be dependent on the cables topology. This trace is repeatable and hence may be characterised as a 'Cable Signature' (Ho et al. 1993). The comparison of the cable's signature and the fault condition signature should enable easier fault location. This is of great significance and supports the justification of a database of 'signatures'. The database of signatures by itself is however not of much use if the information is:-

- not correctly collected
- not always collected
- difficult to use and apply
- costly to apply in terms of additional overheads
- or if the database management is not transparent to the fault location engineer

While today's TDR type instruments are optimised for communication cable type faults (Bisset 1988) they fall short in the number of traces that they can display and information that can be managed for use at a later date. In short, they are good instruments but what is required is an integrated fault system. It is with this in mind and taking into account the significant advances in computer and information technology that it was proposed to combine both these components to form an integrated system placing more emphases on the system to enable rapid and accurate fault location but on power pilot cables.

By actually producing a limited scale system (the Baseline) and evaluating it, will produce evidence of the advantages of the proposed solution and will quantify the benefits of such a systems. The proposed system is seen to considerably improve fault location technology in the field of its application.

The research goals therefore focused on:-

- The development of a fault location instruments which will be controlled by a laptop computer
- The development of a methodology for establishing a system approach to fault location within an electrical distribution/utility company conditions
- Software development for implementation of the control, capture and database program
- The study and evaluation of the practical implementation of the system evaluating the benefits

The challenges of the research can essentially be described as:-

- The development of an effective data capture instrument for capturing the Time Domain Reflection traces (hardware and software)
- The development of a storage/file manipulation system
- The development of a database
- The development of a methodology for a comprehensive fault location system developed for power transmission networks, specifically related to

the pilot cable fault location

The hypothesis around which the high speed cable fault location instrument (Baseline) was developed was that the TDR trace obtained from a cable will indicate the characteristic impedances changes along the cable length. This will characterize the cable condition. By comparing the previous captured trace with that of one captured at the present time on the same cable will indicate changes due to degradation of the cable. A fault condition will be an extreme case and should immediately flag the fault position in most cases.

Chapter 2

Introduction to Cable Fault Location by use of the Time Domain Reflection (TDR) Method

In this chapter the principles of the time domain reflection test methods used to locate faults will be summarised, in particular the faults on power reticulation cable systems and related cables.

2.1 Time Domain Reflection Test Method for Fault Location

The time domain reflection method of locating faults in cables is based on transmission line theory where a narrow pulse is injected into one end of the cable under test. The transmitted pulse and its reflections, due to mismatches (impedance changes) along the cable, are recorded and displayed on a display device such as a crt ,video or lcd display.

Understanding just how the pulse will react with various types of impedance mismatches allows the engineer to determine if a cable fault is either a short, open or a high resistance fault. By knowing the time from the transmitted pulse to the return pulse, as well as the velocity of propagation, the distance to the fault may be derived from :

$$d=\rho c\frac{t}{2} \quad \text{where} \qquad (2.1)$$

t = time to fault and back

c = the speed of light (m/s)

ρ = the velocity factor

While this forms the basis of the method, to obtain a clearer understanding a little more detail needs to be explained.

2.1.1 Cable Characteristic Impedance

In a cable the conductors are separated by an insulation medium such as paper, oil impregnated paper and, in newer cables, polymers as well as various pvc's. A cable has a capacitance between conductors and possesses inductance and resistance. To direct current (DC) the cable will be dominated by resistance. As the frequency is increased the inductance and capacitance become increasingly more significant and an approximation would need to include inductance and capacitance. At very high frequencies the inductance and capacitance tend to be the dominant factors and the cable can be considered as a transmission line. At these frequencies the cable can be considered under transmission line theory. As such the cable will be seen to have an impedance which is termed the Characteristic Impedance (Millman et al. 1965)

which is given by $$Z_0 = \frac{\sqrt{L}}{C} \qquad (2.2)$$

where Z_o = characteristic impedance
L = inductance
C = capacitance

The capacitance and inductance of the cable will be determined by the cable's physical construction. Factors such as conductor spacing and permittivity of the insulating medium, termed cable construction geometry, affect the characteristic impedance. As a result any change in the geometry of construction or change in the insulating medium will result in a change in the characteristic impedance.

From transmission line theory (Millman et al. 1965) a transmission line terminated in its characteristic impedance will not produce any reflections. From this it is inferred that any line not terminated in its characteristic impedance will produce reflections. A fault on a cable would usually alter the geometry of the cable at the point of fault and hence a reflection would take place.

2.1.2 Reflection Factor

The reflection factor is the ratio of signal reflected and is given by:-

$$p=\frac{(Z/Z_0-1)}{(Z/Z_0+1)} \text{ (Millman et al. 1965)} \qquad (2.3)$$

where Z is the termination impedance and Z_0 is the characteristic impedance
p is the reflection factor and has a value in the range - 1 to + 1

In general then if $Z > Z_0$ then p is positive which implies a non inverted reflected waveform and if $Z < Z_0$ then p is negative which implies an inverted reflected waveform.

It can further be inferred that

$p = +1$ => Z is ∞ or an open circuit
$p = -1$ => Z is 0 or a short circuit
$1 > p > 0$ => $Z > Z_0$
$-1 < p < 0$ => $Z < Z_0$
$p = 0$ => $Z = Z_0$

2.1.3 Cable Attenuation/Loss

In addition to the reflection factor, cables do have losses which attenuate the injected pulse. Thus a pulse injected into an open circuit cable is attenuated and reflected. If the pulse is attenuated by 10 dB while traveling to the end then the reflected pulse will be subjected to a 10 dB attenuation. On arrival back at the input end it will be attenuated by 20 dB and as the reflection factor is +1 from above it will not be inverted.

An example of a pulse applied to an open or high resistance fault will produce a waveform or trace as in Figure 2-1, while a pulse applied to a cable terminated in a short will produce a waveform/trace as can be seen in Figure 2-2.

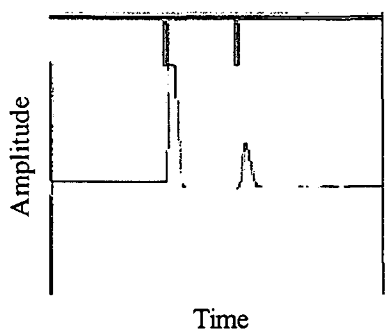


Figure 2-1 Open Circuit

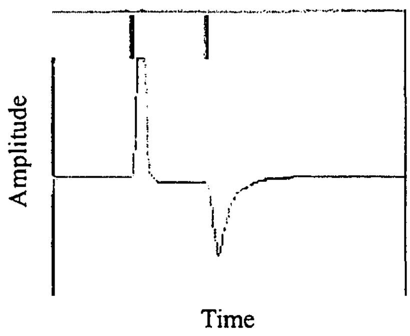


Figure 2-2 Short Circuit

These waveforms, which are typical of this method will in future be referred to as a Time Domain Reflection (TDR) trace or waveform or more often just as a TDR trace.

2.1.4 Velocity Factor

Earlier it was stated that the distance to the fault could be obtained from the expression:-

$$d = \rho c \frac{t}{2} \tag{2.4}$$

Firstly, as the pulse travels to the cable end and back it actually covers twice the distance and thus must be divided by 2. Secondly, the velocity factor needs to be known in order for the distance to be accurately measured.

Once again from transmission theory (Millman et al 1965), for lines that are of uniform cross section and in free space the velocity is given by:--

$$u = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu \epsilon}} \qquad (2.5)$$

where $\mu = \mu_0 \mu_r$ and $\epsilon = \epsilon_0 \epsilon_r$

μ = 4 p x 10 $^{-7}$ which is the permittivity of free space.

ϵ = 1/(36p x 10^9) which is the permeability free space.

For air the expression resolves to 3 x 10^8 m/s or the speed of light (c).

For a dielectric the relative permittivity will be > 1, thus it is clear that the velocity of the pulse in the cable will be traveling slower than the speed of light. The expression (2.5) may be re written to take this into account as:

$$u = \frac{1}{\sqrt{(\mu_0 \epsilon_0 \epsilon_r)}} \qquad (2.6)$$

The velocity factor is given by $r = \frac{u}{c} = \frac{\sqrt{(\mu_0 \epsilon_0)}}{\sqrt{(\mu_0 \epsilon_0 \epsilon_r)}}$

$$\rho = \frac{1}{(\sqrt{\epsilon_r})} \qquad (2.7)$$

also since $\rho = \frac{u}{c}$

it follows that

$$u = \frac{c}{\sqrt{(\epsilon_r)}} \qquad (2.6)$$

The above section provides the background and mechanism of the TDR method. The principles also apply to various derived methods used in fault location on high voltage cables which will be discussed later.

2.2 Applications and High Voltage Derivatives and Methods

While Chapter 2.1 described the principles and formula of the TDR method, this section provides a very brief overview of the application of the principles and methods and its directives as applicable in high voltage fault location. This is not a detailed description but rather gives an appreciation of the methods that are applicable. It is relevant in the design phase of the hardware as well as software of the cable fault location instrument that was developed and is discussed later in this thesis. There are many good references for a more detailed description such Clegg (1995), Millman et al. (1965), Dixon (1993) and William (1993).

2.2.1 TDR Method

This method is also referred to as the "Low Voltage Pulse Radar Method" or "Pulse Echo Method". While in a signal transmission cable every effort is made to match the characteristic impedance of one cable to another at joins so as to minimize reflections this is not the object for power cables and pilot cables. The main objective of power cables is to deliver power at 50 or 60 Hz and as such a good connection and insulation are the prime considerations.

In order to achieve these cable lengths many shorter lengths of cable are joined together. As these cable lengths are usually set at the time that the cable is installed, each section of cable will typically be the length that fits on a cable drum. These lengths naturally vary for the thickness of cable and the drum size. The result of this is that pilot cables might be joined every 500m and 11 kv three phase power cable at 250m. Because the emphasis is on jointing the cable, as opposed to matching, there will be significant reflections from both joints and terminations.

When this method is applied to a pilot cable the complex TDR trace of Figure 2-3 is more likely to be the result than that of the simple cable as shown in Figure 2-1 and Figure 2-2 earlier.

The TDR trace shown in Figure 2-3 is that of a healthy pair in a 14 km cable.

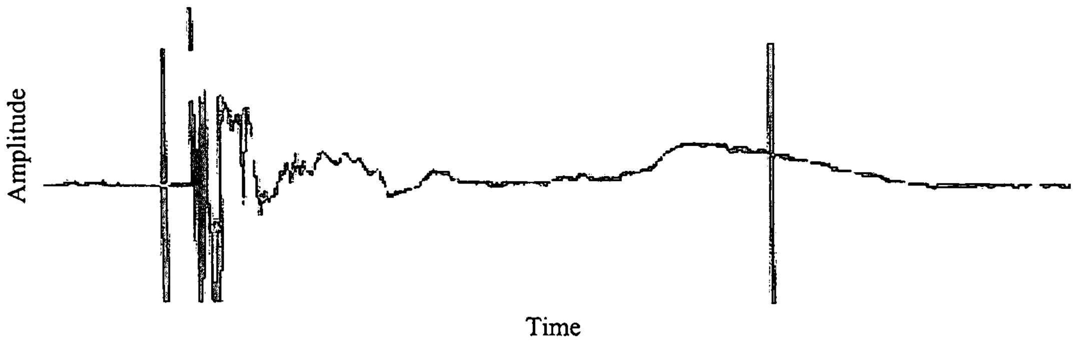


Figure 2-3: Complex TDR Waveform/Trace

From Figure 2-3 it will be seen that there are a vast number of reflections which give rise to huge reflections at the beginning and diminish with cable length. The transmission pulse experiences not only attenuation from the cable but each reflected pulse is subjected to mismatches on the return path. This significantly attenuates the return signal so making faults on long cables even more difficult to diagnose.

The TDR method is often applied to cables that have a main cable into which a tapping is made to supply a user. The cable layout of such a network can be seen in Figure 2-4. The application of a pulse injected into such a network will result in a TDR trace as shown in Figure 2-4. Here again the reflections seen clearly show the joints and terminations at the consumers. On closer inspection it is again noted that without a cable layout drawing it is hard to distinguish which return pulse is the result of a mismatch at the consumer or is due to a 'T' section.

As we are dealing with cable faults on high voltage cables, there are a number of methods that have the same principles of the TDR method but involve high voltage pulses.

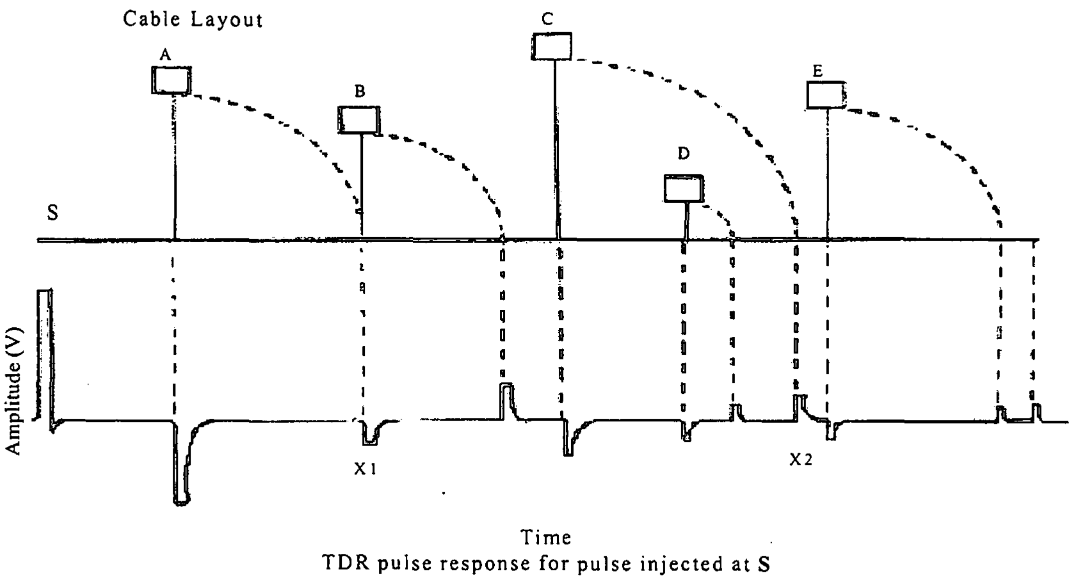


Figure 2-4: Multi "T" Domestic Cable Layout and its TDR pulse Response

2.2.2 High Voltage Reflection Methods

In high voltage networks a fault may flash over at the rated voltage which will cause the network to trip out by blowing a fuse or causing an electrical breaker to open. The flash over may not cause the cable to be blown apart or become welded together. If after a fault and circuit/network being isolated it can happen that the resistance between corresponding phases and earth shows no sign of a fault when tested. On reconnection of the high voltage supply this will however once again result in a fault condition. This is due to the ionization which takes place at the fault point as a result of the high voltage being re-applied. The ionization results in an arc developing and as this arc is a relatively low impedance path, high fault current results. These are termed flashing faults. A low voltage TDR instrument may also not show much as the cables may not be damaged enough to show a massive reflection. Due to this, methods have been developed over the years to apply high voltage pulses to the cable and record the reflections produced as a result. A very brief overview follows

2.2.2.1 High Voltage Surge Method

This method is also referred to as the "High Voltage Pulse Radar Method" (Tanaka 1983). The high voltage developed is rectified and charges up a capacitor to a set voltage. Once this voltage is reached a switch is closed and the high voltage pulse applied to the cable under test is as in Figure 2-5:

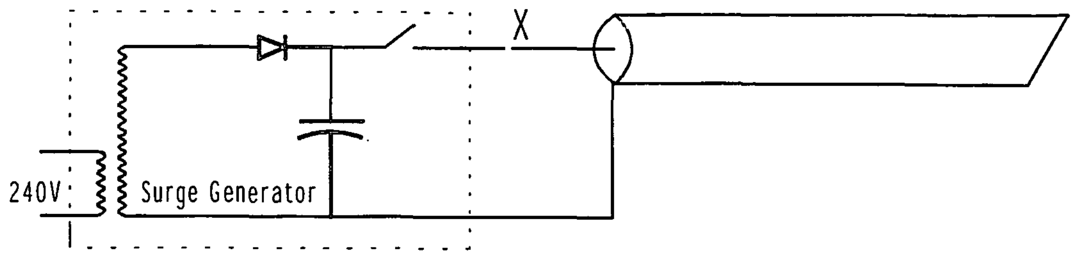


Figure 2-5: High Voltage Storage Test Method

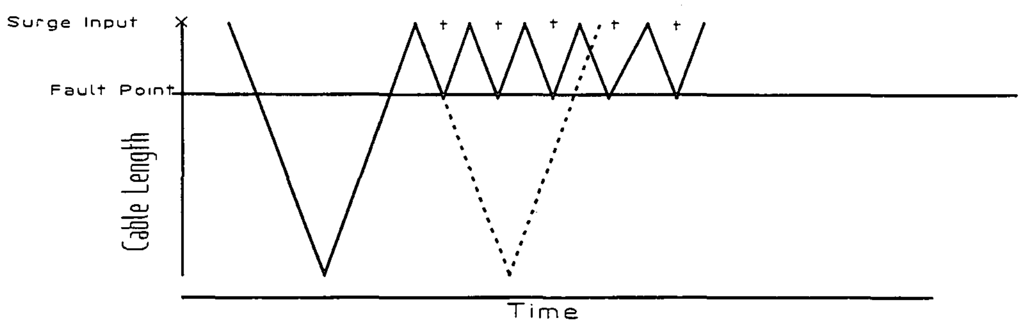


Figure 2-6: Traveling Surge Position Verse Time Diagram

The main difference is that the high voltage pulse behaves in the first instant just like the low voltage TDR, however at some time later ionization takes place and at that instant the impedance at the point of fault drops to a low value. The result is that after ionization the high voltage pulse travels only to the point of fault and back. This oscillation continues until the energy has been dissipated as a result of the cable losses. The main distinction is that there is an ionization time to take into consideration.

2.2.2.2 Discharge Pulse Detection Method

This method is also known as the "Discharge Detection Pulse Radar Method" (Tanaka 1983) as well as the 'Relaxation Test' (Clegg 1995) and is demonstrated in Figure 2-7 below:-

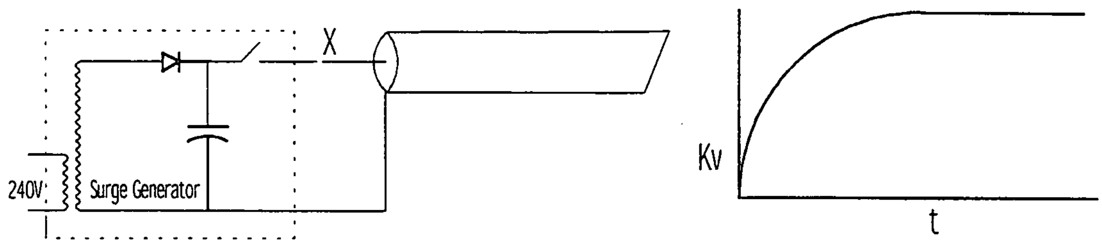
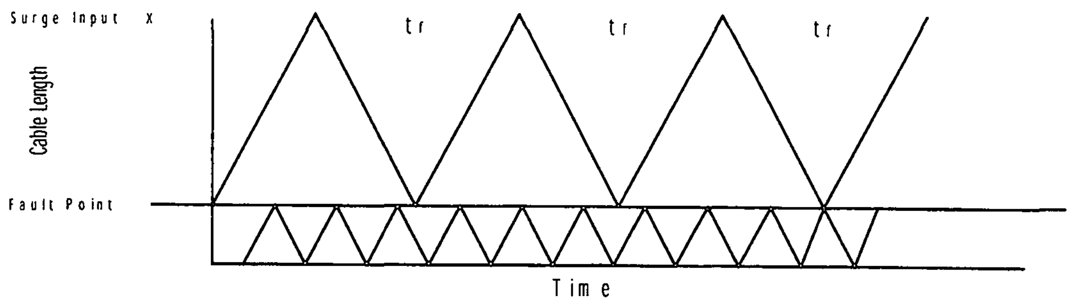


Figure 2-7: Discharge Detection Test Method

If a high voltage pulse is injected into the cable under test and the fault (high impedance) does not ionize then the pulse simply travels to the end and back and continues this oscillation as it is attenuated by the losses in the cable. This does not give a fault position but simply provides the length of the cable.

In order to cause the fault point to ionize and arc/ flash over the cable is charged up to the required test voltage and kept there until ionization takes place so causing a flash over. This flash over produces a low impedance path and the cable is rapidly discharged. This discharging generates a wave traveling in both directions away from the fault and again oscillating until the energy has been dissipated. The wave traveling in the section connected to the fault recorder travels repeatedly between the fault and the recording end. This is depicted in Figure 2-8.

Figure 2-8: Discharge Pulse Position Verse Time Diagram



It can thus be seen that the distance to the fault is given by $l_f = \frac{(\rho c t)}{2}$ xxxx

A combination of the TDR and Discharge Pulse Detection Method or Relaxation Test is termed the "Arc Reflection Method" (Clegg 1995) and the 'Modified Pulse Radar Measurement Method" (Tanaka 1983). This is illustrated in Figure 2-9.

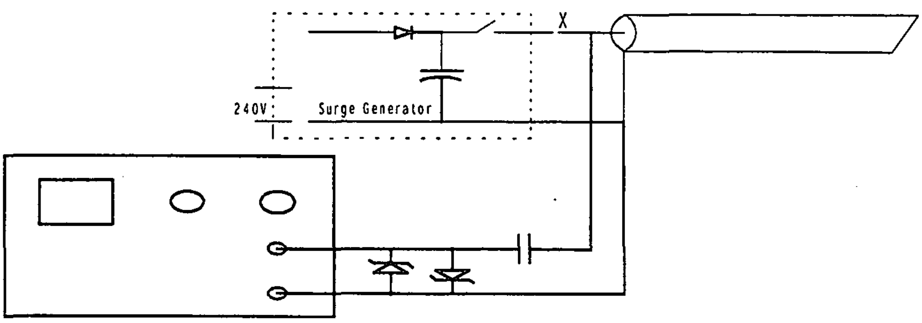


Figure 2-9: The Arc Reflection Test Method

In this method a generator that generates high voltage DC is applied to the cable under test. A TDR instrument is coupled to the cable under test as well via a high pass filter, which is also capable of withstanding the high voltage DC. The TDR captures a trace of the cable before the high voltage is applied. Next the high voltage is applied causing the fault to ionize and an arc to form. Another TDR trace is then captured. The two traces are then superimposed as indicated in Figure 2-10. From the first and second traces the divergence indicates the point of fault. This is found by the equation (2.1).

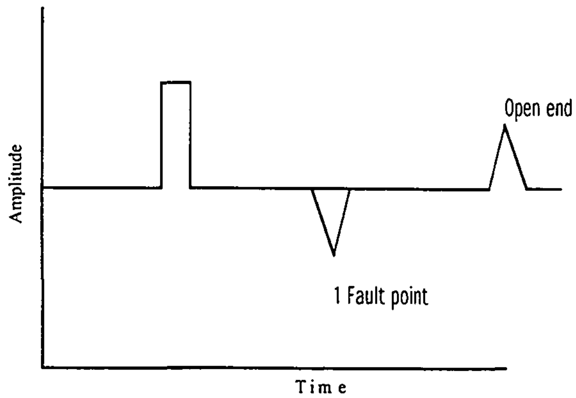


Figure 2-10: Superimposed Traces as seen by the Arc Reflection Method

As illustrated above, there are a number of TDR methods for which the applications and high voltage derivatives share the same principles.

Section 2.1 and 2.2 of this chapter have provided an overview of some of the considerations when designing an instrument for the waveform analysis as applicable in the field of power cable fault location. The next section considers the way in which the coupling is made to cables especially at high voltages and introduces the coupler.

2.2.3 Pulse and High Voltage Generators

It is necessary to include the differences between pulse generators for low voltage and high voltage in order to understand the waveforms that appear later.

The low voltage type pulse generators produce a pulse that is essentially a fixed voltage and usually less than 10v peak. These pulse generators usually have the ability to vary the pulse width from around 10 ns to 200 ns. The pulse is usually of positive polarity and the rise and fall times are usually in the order of 5 ns to 20 ns.

High voltage pulse generators in contrast are usually referred to as surge generators and basically consist of a high voltage transformer, the output of which is rectified and fed to a capacitor or capacitor bank. The capacitor bank is charged negatively and the voltage is usually controlled by varying the primary voltage, either electronically or very often by a variac. The pulse is simply generated by closing a switch which then applies the charge on the capacitor to the cable. Thus on the high voltage traces shown the generator pulse appears as being negative.

2.2.4 Coupling Methods

Applying the TDR signal to the cable is quite simple but at high voltages this poses problems. The method of coupling to a high voltage cable can be done by a divider circuit. This is usually done by making use of capacitor divider's. The difficulty in terms of the high voltage and in achieving a high frequency response is often considerable.

An easier connection was developed by Gale (1975) in which a linear coupler was used in the return or ground path of the surge generator.

2.3 Survey of the classic TDR instruments and the transition to the Baseline approach

As mentioned in section 2.1 of this chapter the instruments that were around when the Baseline cable fault location instrument was conceptualised where relatively unsophisticated and had limited function digital oscilloscopes. The classic instruments that had more than one channel where largely being replaced by the newer digital oscilloscopes. The digital memories could save a waveform but many where not capable of retaining these when switched off. If a waveform was required for storage it had to be either photographed or, on the newer digital scopes, it could be printed.

As mentioned these were oscilloscopes and the most advanced TDR and cable fault transient recorders had just reached the digital stage. The use of digital memories has a major advantage as a TDR trace of a healthy pair can be compared with the faulty one. Comparing the difference will normally indicate the point of fault.

Apart from the pilot cable fault location problems there are many instances where the engineer would like a comparative trace. This led to the idea that in addition to being able to save the data for processing it could also be used as a reference should the same cable develop a fault in the future. A non-damaged saved TDR trace could therefore be considered as a baseline from which to start. A paper published by Ho et al. (1993) "Signature Representation of Underground Cables and its Application to Cable Fault Diagnosis" considers that the TDR trace can be viewed as a signature representation which characterizes the cable length giving further weight to the original idea behind the Baseline instrument, which combines a personal computer and a high speed transient data capture unit.

The next chapter focuses on the bandwidth and analogue amplifier requirements for the Baseline instrument.

Chapter 3

Baseline Approach Design

3.1 Concept

While the concept and theoretical framework for the Baseline instrument have briefly been described in the overview section and in various parts of Chapter 2, this chapter will focus on the various considerations and conclusions reached in the design of the hardware and the software.

3.2 Hardware

The Baseline data capture instrument was designed to perform two types of test functions, namely:-

- Transient capture on power fault locations and
- Time domain reflection waveform capturing

Although there are only two broad categories of tests on the cables as listed above some additional parameters needed to be considered in order to understand/define the constraints of the instrument, while simultaneously delivering meaningful results. These parameters will be described in greater details in the remainder of this chapter. Apart from the physical limitations that exist in the hardware and software, there are also cost/benefit considerations that would influence the design of an instrument. For the purposes of this paper, limited focus will however be placed on these considerations.

3.2.1 Bandwidth and Analogue Amplifier Requirements

One of the first considerations was to understand the impedances that the instrument might have to encounter. It can be seen from Clegg (1995) that for a 0.6/1.0 kV belted cable with 4 cores the characteristic impedance ranges from 12.0 - 18.2 ohms, while 11 kV three core cable ranges from 18 ½ to 27.0 ohms. With a twisted pair cable, as in pilot wires the characteristic impedance is around 90 to 100 ohm. The impedance range spans 12 to 100 ohms.

An additional consideration in the understanding of the required parameters is the bandwidth of the cable. As the two main areas that the instrument was designed to be used in were fault location on power cables and pilot cables a consideration of these frequency responses was also be necessary.

Firstly considering a 25 kV XLPE cable and referring to Figure 3-1 and Figure 3-2 (Bartnikas et al. 2000) it was noted that the characteristic impedance varied enormously from a minimum value of 50 ohms to 250 - a range of 200 ohms. Bartnikas et al. (2000) sited this to be the 'semiconducting shields' which causes the cable to behave as a complex quantity.

Also it can be seen from the attenuation versus frequency plot in Figure 2-14 that the attenuation for this cable was approximately -40 dB and at greater frequencies on average, the attenuation was around this figure.

Included for comparison from the Bartnikas et al. (2000) is the test conducted on a RG 58 communication cable. This shows that the characteristic impedance range is 44 to 55, which is a total deviation of 11 ohms across the test frequency.

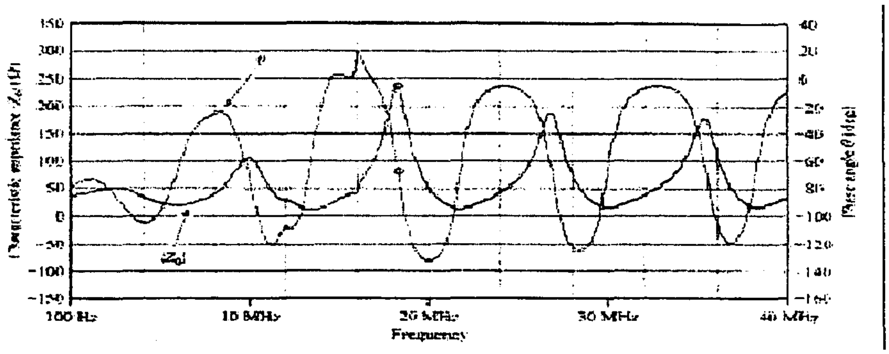


Figure 3-1: Characteristic impedance and phase angle vs frequency of 25 - kV XLPE insulated power cable (Bartnikas et al. 2000)

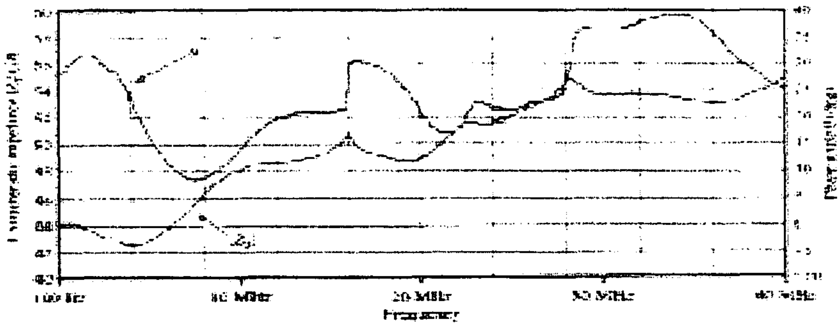


Figure 3-2: Characteristic impedance and phase angle vs frequency of coaxial polyethylene insulated communication cable (Type RG - 58) (Bartnikas et al. 2000)

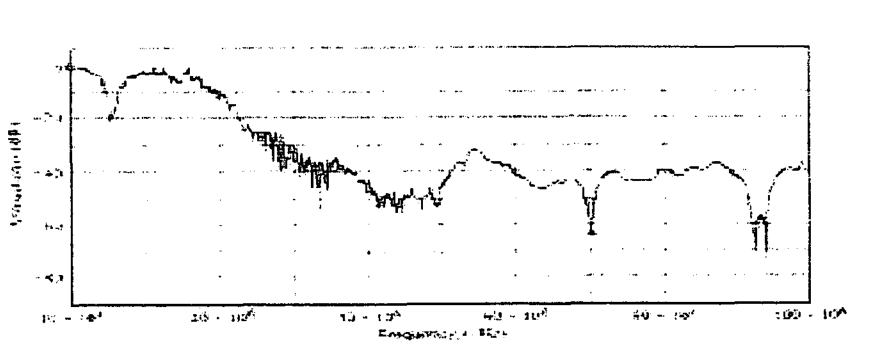


Figure 3-3: Attenuation vs frequency of 800 - ft 25 - kV XLPE power cable terminated with its approximate characteristic impedance of 37 ohms (Bartnikas et al. 2000)

For the twisted pair similar to the pilot cable, a Cat 5 UTP solid cable, which is actually used for LAN applications and is intended to operate at higher frequencies than pilot wires, was used for a upper reference limit. A table of frequency versus attenuation is given below in Table 3-1.

MHz	Attenuation/100m
1	2.1
4	4.3
10	6.6
16	8.2
20	9.2
31.25	11.8
62.25	17.1
100	22

Table 3-1: The attenuation at various frequencies for Cat 5 UTP cables

From the above table it can, for example, be seen that the attenuation that can be expected at a frequency of 100 Mhz would be - 220 dB. For a cable 15 Km in length the attenuation would be 15 x - 220 dB or - 3300 dB. At 20 MHz the figure would be - 90 dB and -1350 db. In the case of the TDR pulse, the distance traveled will be twice. The attenuation for the distances above will correspondingly be double. It should also be pointed out at this point that - 120 dB is 1/1000 0000 . Thus if a 1V pulse is injected into a cable and experiences a - 120 dB loss then the return signal is 1 uV. At - 200 dB the return signal would be 10 nV so any figure smaller than this may be taken as 0 (zero).

As a comparison, the attenuation for a communication cable (i.e.,RG 58) is given at - 2 dB per 100m at 100 Mhz. This RG 58 is the same as a communications cable operating at 100 MHz and having a length of 15 km which would be expected to experience a loss of (2 x 10 x 15) dB or - 300 dB which. Although massive, this is never-the-less far better than that of the Cat 5 UTP cable but may still be regarded as practically zero. As pilot cables vary and are not designed to carry high frequencies of this nature it would be expected to severely attenuate and distort the shape of the injected pulse.

Each of these factors had to be taken into consideration when designing the entire circuitry and demonstrate some of the potential difficulties or constraints.

3.2.1.1 The Amplifier/Attenuator Input Sections

Given the above parameters it was decided to have two amplifier/attenuator sections in the Baseline instrument; one for the transient capture mode to be used in conjunction with the high voltage fault location. The second amplifier would be coupled to the pulse generator for the TDR cable fault location. These separate inputs would be selectable via a selection switch on the instrument's front panel.

Considering the substantial attenuation above 20 Mhz, and that for the XLPE cable at frequencies greater than this the average attenuation appeared to be in the order of - 50 db, a bandwidth of 80 Mhz was deemed to be appropriate. With this, the input section would mean that all frequencies up to 40 Mhz would only be affected by a loss of 1 dB.

3.2.2 High Speed Analogue to Digital Converter

When determining which analogue to digital (A/D) converter to use for the Baseline it was concluded that a flash 8 bit A/D converter with sample and hold and a bandwidth of 30 MHz was the most appropriate. The choice of the appropriate A/D converter was influenced by what components were readily available at the time of design and the various considerations described below.

Firstly, under transient operation the instrument would be in use to locate high-voltage faults. Under these circumstances the pulse or traveling wave oscillates between the pulse injected end of the cable (input) and the end until ionisation takes place, at which point the traveling wave travels between the input and the flashover point, which is the point of fault. The distance to the fault is calculated using the formula : -

$$d_f = \rho c \frac{t}{2} \tag{3.1}$$

40 m samples per second gives a sampling interval of 25 ns. By substituting this value for time gives the resolution that can be expected. For a XLPE power cable the velocity factor would be around 0.65. The resolution could be expressed as:-

$$d_r = \frac{(0.63 x 3 x 10^8 x 25 x 10^{-9})}{2} \tag{3.2}$$

$$=> \quad d_r = 2.36 \quad [m]$$

This implies that in the best case faults can be located to within 2.36 m. The error this represents on a 1 km cable is 0.263% error. It is generally stated that as a rule of thumb a distance of 1% on either side of the fault should be searched (Millman et al.1965) and so the above error due to resolution is deemed to be acceptable.

The second consideration is whether the A/D for the transient capture would be acceptable for the TDR functions. When reviewing TDR reflections with regards to the bandwidth of the A/D converter the limitations set by the cable under test also need to be considered. As already mentioned the pilot wires are only designed to carry signal frequencies in the order of kHz. Frequencies in the MHz range are not considered. Due to this and the fact that there are many various cables used for pilot wires, each with their own bandwidth characteristics, a cable with superior frequency responses was selected for reference comparison. On cables in real-life situations it would be expected that the bandwidth could be worse.

For the data/waveform capture an open circuit or short circuit would be visually detected and the fault point would be resolved within the previous stated 2.36m. Another point to consider was whether information other than an open circuit or short circuit would be detected to enable more subtle influences to be visibly seen. If the amplifier section can be considered a high resistance input section, with some strong capacitance shunting this to ground, followed by an ideal amp, then this input section can be considered an RC circuit and as such will have a rise time associated with the RC time constant.

Applying a pulse to such a circuit results in a rise time which can be expressed in the equation (3.3) below by considering the definition of rise time, as the time taken for a signal to rise from 10% to 90% of its final value.

$$v_o = V(1 - e^{\frac{-t}{RC}}) \tag{3.3}$$

For a RC type circuit this can then be expressed as:-

$$ft = 0.35 \tag{3.4}$$

where f = frequency

t = rise time (10% - 90%)

If the upper frequency f can be considered as the bandwidth frequency the equation can be rewritten as follows:-

$$BW\, t_r = 0.35 \tag{3.5}$$

=> $$t_r = \frac{0.35}{BW}$$

and $$BW = \frac{0.35}{t_r}$$

For the A/D converter a rise time will be seen to be:-

$$t_r = \frac{0.35}{(35\times 10^6)}$$

$$= 10 \text{ ns}$$

Only considering the A/D converter it can be inferred that if the capture signal/waveform rise time is slower than that of the A/D converter then the A/D converter should be able to follow the signal with a limited distortion. If the captured signal has a rise time faster than that of the A/D converter then it can be assumed that there will be a distortion as the A/D converter cannot follow the input waveform response.

Assuming that one might want to inject pulses with a 5 ns rise time into the cable under test there would be both distortion and attenuation. The bandwidth for this rise time would from the previous equations, be calculated as:-

$$BW = \frac{0.35}{5\times 10^{-9}}$$

=> 70 MHz

As this is one octave it would be expected that the attenuation would be -6 dB. However due to the fact that the waveform is decaying exponentially this takes time. For a pulse with a amplitude of V the decay is given by:-

$$v_o = V e^{\frac{-t}{rc}} \qquad (3.6)$$

The waveform is therefore not only attenuated but appears to have a wider pulse width due to the exponential decay.

An application note titled 'High Speed Amplifier Techniques by Williams (1993) gives some clues as to what can be expected. In the section that deals with oscilloscopes and oscilloscope probes a good example of using a lower bandwidth oscilloscope is given. The pulse as shown in Figure 3-4 is 1 ns in pulse width, as well as having a 10 V peak. Of interest is that with a 350 MHz bandwidth oscilloscope the original waveform is attenuated and very slightly distorted but shows a good resemblance to the original pulse.

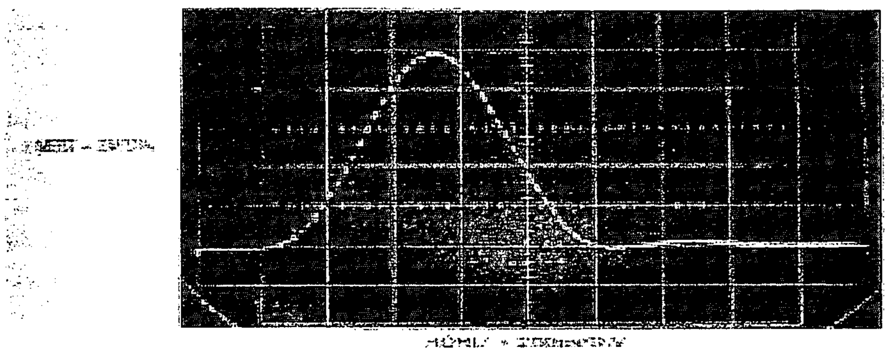


Figure 3-4:A 350 ps Rise/Fall time 10V Pulse monitored on a 1 Ghz Sampling Oscilloscope. Direct 50W input connection is used (William 1993)

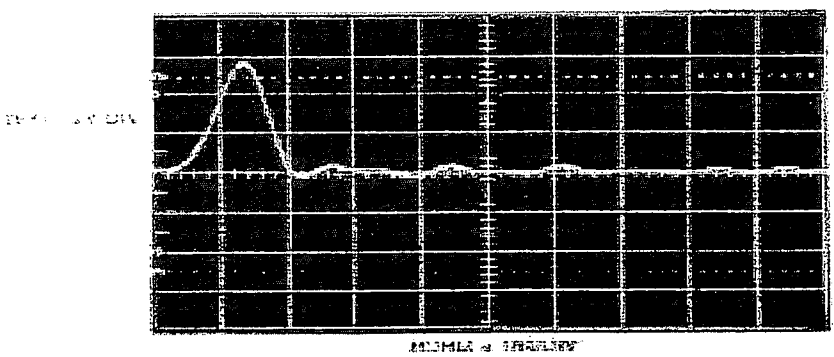


Figure 3-5: The test pulse appears smaller and slower on a 350 Mhz instrument (t_r = 1 ns) (Williams 1993)

From this it can be inferred that signals close to 2.86 times bandwidth can still be readily observed and in the case of the A/D converter's track-and-hold amp should still give a reasonable result if it can be arranged by interleaving. For the 35 MHz bandwidth of the A/D's track-and-hold amp a signal that has a frequency of 35 x 2.86 or 100.1 MHz should be able to be captured, albeit attenuated and slightly distorted. This demonstrates that in examining the waveforms of a TDR trace, the shape of the waveforms is more important than the amplitude. Therefore the use of the 40 mega samples/second A/D converter with a bandwidth [of 35 MHz) would be acceptable if the slight limitations are taken into account.

This A/D converter would have a frequency response that at 70 MHz would be -6 dB. Looking at the Table 3-1 for Cat 5 UTP solid cable it can be seen that at a frequency of 62.25 MHz the attenuation per 100m would be >17.1 db. Thus at these frequencies and as the pulsed travels 2 x length (to end and back) this gives an attenuation > -342 dB /km . Cable lengths of 5 to 10 km are very common so the attenuation for a 5 km cable (> -1710 dB) is far in excess of the 6 dB loss in the A/D and shows that the limitation is cable rather than the instrument let alone the A/D converter.

3.2.3 Data Collection Buffer as a Function of Cable Length and Resolution

In Chapter 3.2.2 it was shown that the resolution that could be expected at a velocity factor of 0.63 would be 2.36 m. Sampling at 40 mega samples per second with a memory depth of 1K bytes (1024) gives a TDR or 'trace distance' of 2.3 x 1024 or 2355 m per Kbytes of memory.

A more general expression can be developed as follows:-

from $d_r = \frac{\rho c t_s}{2}$

$$R_l = \frac{\rho c T_s M_d}{2}$$

where R_l = Recorded trace distance

ρ = velocity factor

c = speed of light

T_s = sampling period

M_d = Memory depth or size

as $T = \frac{1}{f}$ R_e can be expressed in terms of sampling frequency:-

$$R_l = \frac{\rho c M_d}{2 f_s} \qquad (3.7)$$

As a 4 Kbytes (4096) memory was available at the time and addressing could be carried out using 12 bits this conveniently could be done by using 3 cascaded, 4 bit counters. The general arrangement is shown in Figure 3-6 below.

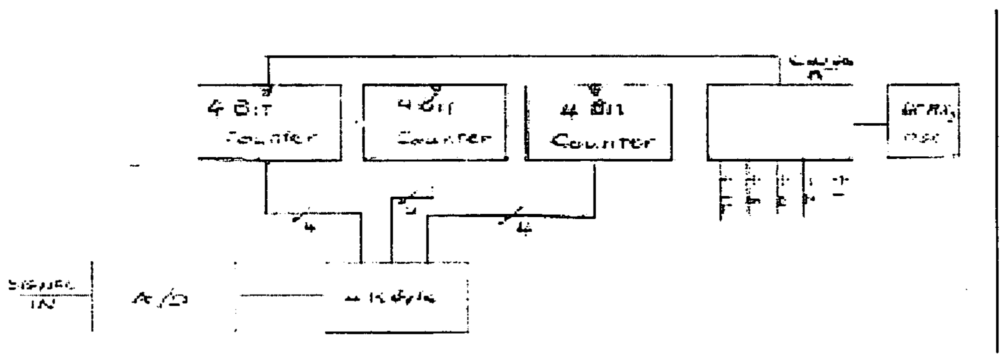


Figure 3-6 General arrangement of counters, A/D converter and memory

Frequency	r_1	Recorded Distance @r_1	r_2	Recorded Distance @r_2
0 MHz	0.63	9674	0.7	10749
20 MHz	0.63	19349	0.7	21499
10 MHz	0.63	38698	0.7	42998
5 MHz	0.63	77398	0.7	85995
2.5 MHz	0.63	154791	0.7	171990

Table 3-2: Recorded length for 4 Kbytes memory at two different velocity factors

For a sampling frequency of 40 Mhz, a velocity factor of 0.63 and with a resolution of 2.3 m the accuracy would be :-

$$\frac{2.3}{9674} \times 100 \ \%$$

=> <u>0.024%</u>

The above results are more than adequate for sampling purposes. There were however two additional reasons for using the 4 Kbytes of memory at the time. These where:-

i. As the data/transient capture unit was to be a separate unit the data would have to be passed to the Personal Computer (PC) where it could be displayed, processed and saved. As the connection would be a RS232 serial type, depending on the data and operation being performed, this would take more time for more data. The latent time from triggering the unit till the data (waveforms) would be displayed was considered and kept to a minimum.

ii. The storage would be on floppy disks and with 4 Kbytes of data per trace this meant that if no other data was to be saved then 64 TDR/transient traces/waveforms could be stored on a disk. If data was also to be saved then at least 40 to 50 traces could be saved.

3.2.4 Function/Pulse Generator and Cable Matching Considerations

As the TDR requires that a pulse is injected into the cable under test and the resulting waveform captured, an appropriate pulse generator needed to be integrated into the unit for the TDR functions of the unit. This was to incorporate a variable pulse width. In addition, due to the attenuation mentioned earlier, as well as the noise from cross talk on the pilot wire cables, it was decided to also include a variable amplitude capability.

3.2.4.1 Function Generator Pulse Width and Amplitude Range

The determination of the function generator range was the next problem that needed to be resolved. Consulting Dixon (1993) provided a good rule of thumb – i.e., 'The resolution obtained along the length (of cable) is approximately one-tenth of the wavelength of the frequency corresponding to the rise time'.

The following expression can then be derived:-

this resolution $\delta_l \approx \frac{\lambda}{10}$ .... A (3.8)

from $f\lambda = c$

=> $\lambda = \frac{c}{f}$ ....B

substituting B into A gives $\delta_l \approx \frac{c}{10f}$ C

As the speed in a cable is slower, the velocity is $v = \rho c$

For a cable the expression C can be written as $\delta_l \approx \frac{\rho c}{10f}$

The resolution can readily be tabulated for various frequencies as follows:

Frequencies Mhz	$\rho = 1$ m	$\rho = 0.83$ m	$\rho = 0.63$ m
20	1.5	0.83	0.63
50	0.9	1.25	0.95
100	0.27	0.75	0.57
200	0.04	0.22	0.17

Table 3-3: Resolution in meters for various pulse widths

The design parameters for the pulse width generator were set as follows :-

Minimum pulse width	-	5 ns
Maximum pulse width	-	10 ms
Min Amplitude	-	3 Volts
Maximum Amplitude	-	25 Volts

Designing the pulse generator in order to obtain a high slew rate, as well as a variable amplitude pulse was not trivial. While compromises had to be made, the required results were achieved as will be seen later in the example TDR traces. Figure 3-7 outlines the general block diagram of the pulse generator configuration.

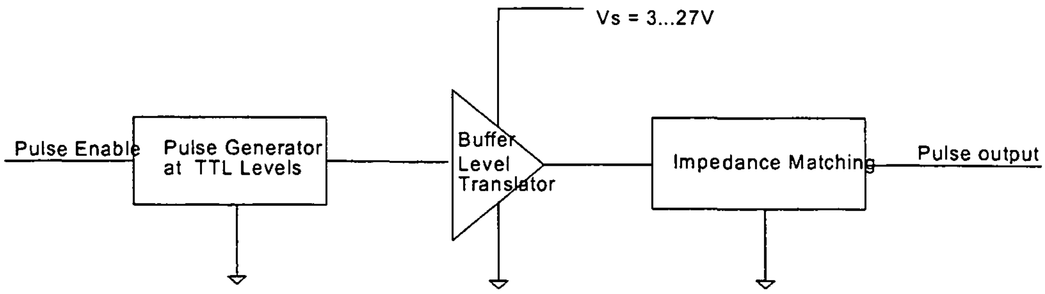


Figure 3-7: The pulse generator block diagram

3.2.5 Triggering Considerations

A method for capturing data in the TDR unit needed to be initiated, recognizing that the method differs for the transient capture and TDR functions. These two methods are outlined below.

3.2.5.1 Triggering Under Transient Capture

Triggering under transient capture is related to the data to be captured during a high voltage fault location using a surge generator. Under these conditions the high voltage pulse is applied to the cable and travels to the cable end and back until ionization takes place, at which point the travel is to the point of fault and back. The time to ionize is the critical element and as this does not occur within a defined time the data capture needs to be initiated at the start of the high voltage pulse injection. The triggering therefore needs to be level and directionally sensitive and as such is asynchronous just as an oscilloscope.

3.2.5.2 Triggering under the TDR Type Cable Fault Location

For the TDR fault location there is no ionization time so the best method is to trigger off the pulse enable signal so making the triggering synchronous. This method allows data to be collected and post processing or signal processing to be easily carried out. One of the major errors to be concerned with is jitter that would be introduced by the high speed data capture itself. As the order of magnitude is in the sub nano second region, whereas the data that is to be captured is of a greater order of magnitude, the effect of the jitter on the final results is deemed not to be material at this data capture rate. Papers such as 'The Effects of Timing Jitter in Sampling Systems' (Souders et al. 1990) and 'Effect of Sampling Jitter on Some Sine Wave Measurements' (Wagdy et al. (1990) considers some of the effects of jitter.

3.2.6 Computing Platform and Data Controller Requirements

As the data/transient and pulse generator was to be a stand alone instrument all communication was to take place with the personal computer via the RS232 serial cable. There also had to be a microprocessor controlling the unit. The type of microprocessor was not of much concern at that time. The main concern was that the microprocessor would act as an instruction processor. This meant that it would have a list of instructions to set up the data capture sections, such as the amplifier gains, trigger settings as well as the trigger direction. The instruction would be issued from the controlling Personal Computer (PC) which would do the signal processing as well as displaying and managing of the data.

In order to ensure potability of the cable fault location instrument, a laptop PC, with an Intel 80286 or 80386 processor was used. Other important features were that the PC had to have a serial RS232 and printer port as well as a floppy disk drive. The initial portable PC or laptop had a monochrome display, although a colour PC's soon became the norm and replaced the monochrome version.

3.3 Software

Chapter 3.2 has dealt with describing the hardware considerations and requirements for a fully integrated cable fault location system. The functionality of such a system is however driven by the appropriate software or application programs. The various components to be considered in the software/application design of the end product are: --

- the application program philosophy of the system
- the operating system
- the display
- the control functions
- data file/storage facility

3.2.1 The Application Program Philosophy of the System

A PC has a number of programs that perform various functions. These programs are called application programs or just applications. The processor is therefore an application that performs the task of writing documents. The personal computer (PC) is normally supplied with a few of these application programs namely notepads, word processors, databases, spreadsheets as well as organisers. In order to be able to collect, save and view the data collected by the high-speed transient recorder it is necessary to have an application program to provide this function. To create a program, a theme or philosophy has to be followed with the objective of reaching the desired goal.

The philosophy or theme that was initially followed for the experimental research instrument was to have a small number of application programs each performing a function. Collectively these application programs would deliver the desired result or objective. This approach benefits from the fact that a small application can easily accept configuration changes. The software for each of these applications therefore needs to be written in a highly modular way thereby facilitating changes. At the system level small stand-alone applications that can be scheduled in and out at will are also beneficial. This arrangement also allows for rapid changes and tests.

For a dedicated instrument to be used by an operator the applications need to be more automated and system details more transparent to the operator. The functions need to be more rigid and integrated into the system.

3.3.2 The Operating System

The main objectives of an operating system, which runs application programs that control the separate high-speed data recorder are:-

- that the system should cater for serial communication ports
- the boot up time should be relatively quick and automatic
- it should be able to recover quickly to major disruptions e.g., as in the event of a power failure
- the system can be multitasking but does not have to be totally deterministic as these functions can be handled by the remote high-speed data recorder
- the system needs to be supported with a good set of tools for development purposes
- documentation of the internal workings should readily be available
- the system should support all the modern storage mediums, such as, floppy disks, CD-ROM's and hard drives
- a support for higher resolution graphic devices is essential
- upgrades to the system must be backward compatible

Originally the operating system was selected on other factors, namely that it was freely available, open and supported IBM compatible PCs. Essentially the operating system (DOS -- by Microsoft) performed most of the functions listed above. There were however a few limitations, such as memory limits that needed to be considered.

Using the DOS operating system applications were relatively easily developed and compatible with the early Windows operating systems. While later upgrades to Windows tended to result in improved graphics, the compatibility with the original operating system became more complex and required consistent enhancements/upgrades to the application software.

While it is not the intention to discuss these compatibility problems in details there are considerable drawbacks in using Windows systems for embedded or stand-alone instruments have become evident. For example, should an operator merely switch the instrument off without shutting down, as required by Windows, there is the risk that the system can be corrupted. This therefore requires a potential change in the behavior of the operator of the instrument as other electronic instruments, such as the oscilloscope are merely switched off, without requiring a lengthy "shutting down" routine. Furthermore, when next operated it would be expected that as the instrument warms up it will be operating on the functions and parameters that were previously selected. Lengthy start times as experienced with Windows operating applications also leave a negative impression as engineers working with the instrument tend to be impatient and wish to get on with the task at hand. The operating system of an instrument should therefore always be transparent to the operator, which is not the case when using a Windows based system.

In a DOS based system if the power was removed at the next start-up of the instrument it would simply go ahead with the application pointed to in the batch files. One may have lost the data collected at the time but the system would largely have remained stable.

3.3.3 The Display

When the first proto-type of the instrument was developed the graphics user interface (GUI) was not available which meant that the graphical displays had to be manually programmed.

When designing a graphical interface it is important to create an effective environment that is intuitive to use. An effective display in a cable fault location instrument is one that focuses the attention on the desired detail results while simultaneously providing a broad overview. This is the philosophy that was applied to the Baseline application software.

One of the main considerations regarding the waveforms was to be able to display all required information on the screen without losing the necessary level of detail. The information that needed to be displayed was:-

- the waveform data for the cable length under view/test.
- a section of detail which could magnify a desired portion of the waveform and
- a section to show the parameters in use such as velocity factor, distance etc

The solution that was developed and is described below is illustrated by snapshots taken from the final screen designs.

Displaying a 13 to 15 TDR trace results in a great variation in the waveforms. In this waveform there is usually a small area of interest. The ability to zoom into a particular section meant that a magnification function was required, bearing in mind that the operator of the instrument should also be able to see the entire waveform displayed. This was achieved by segmenting the screen into three views as shown in Figure 3-8 to Figure 3-14.

- View 1 known as 'the global window' was to hold the entire length of the TDR trace of the cable under test
- View 2 known as 'the zoom or expanded window' enlarged and focused in on the particular section defined by the window cursers set in the global view.
- View 3 known as 'the parameters windows' held the parameters corresponding to the settings of the instrument such as gain, triggering parameters, printer and distance between the measuring cursers, calculated as the velocity factor.

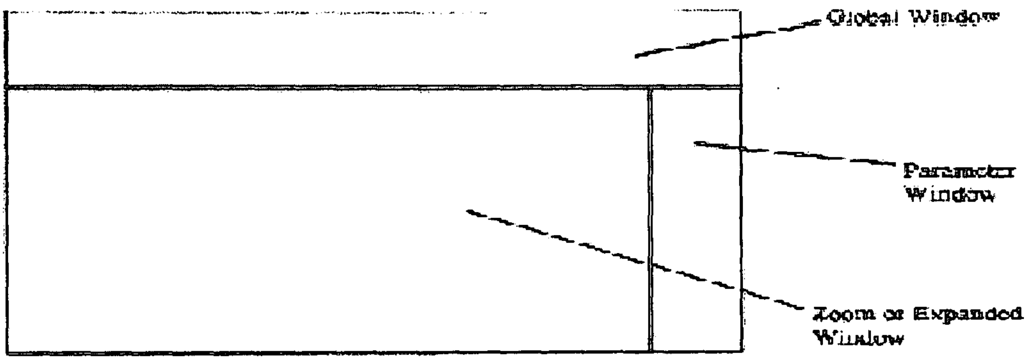


Figure 3-8: The Global Window, Expanded Window and Parameter Window of the Baseline screen

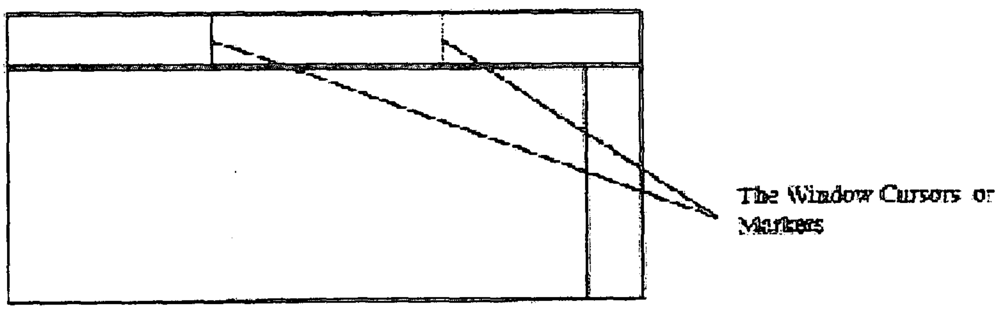


Figure 3-9: The Windows Cursors or Markers on the Baseline Screen

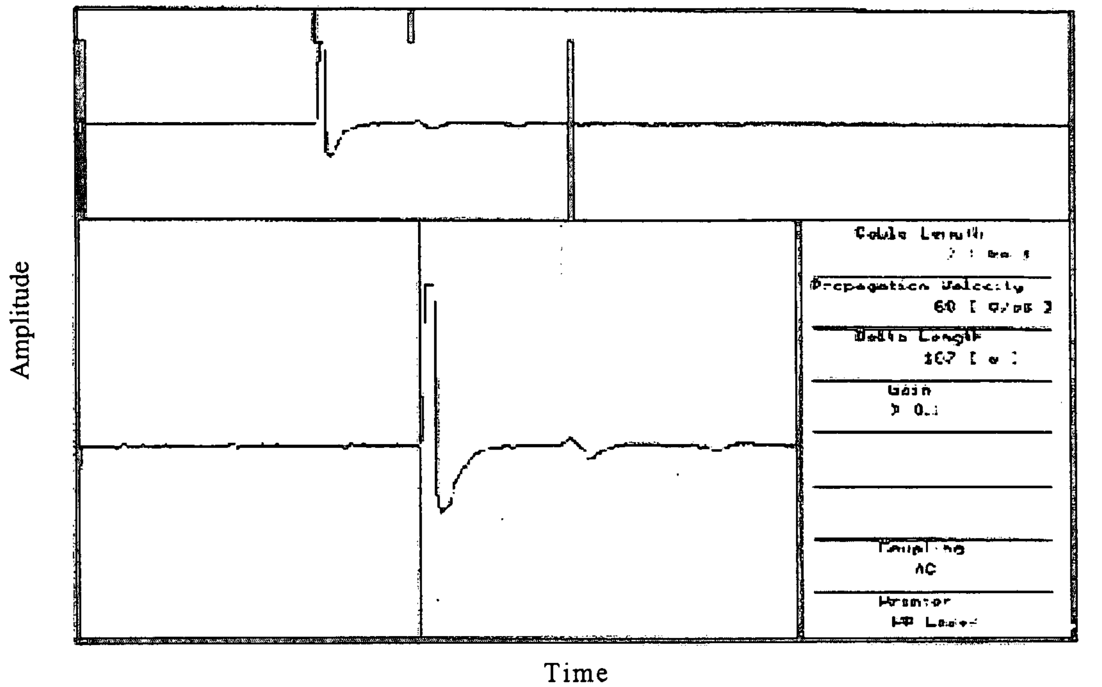


Figure 3-10: A typical Baseline screen, including parameter details

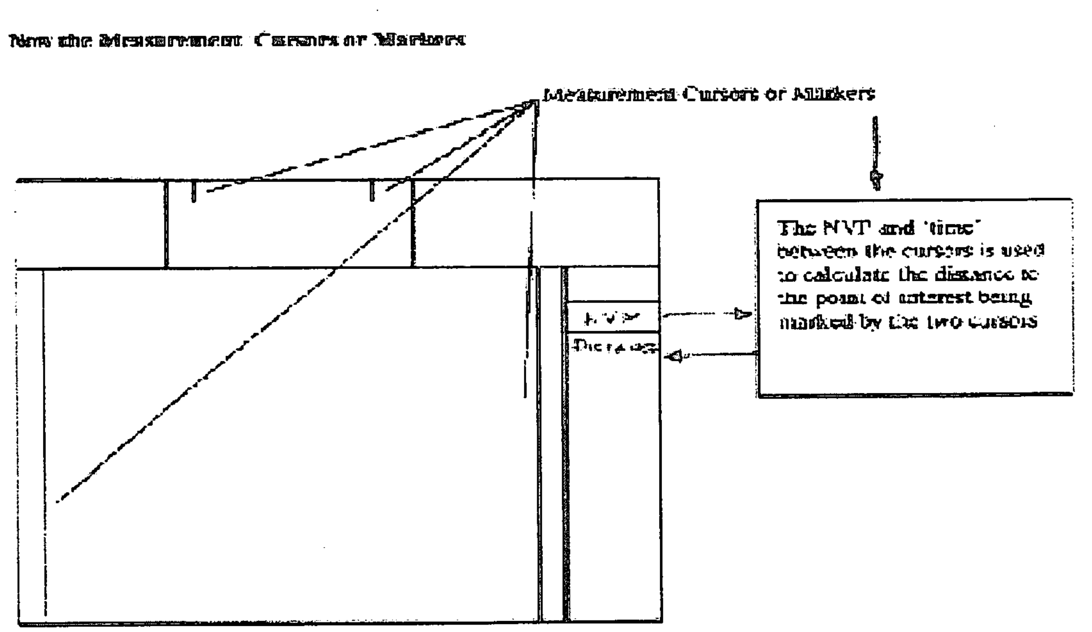


Figure 3-11: Measurement Cursors and Markers

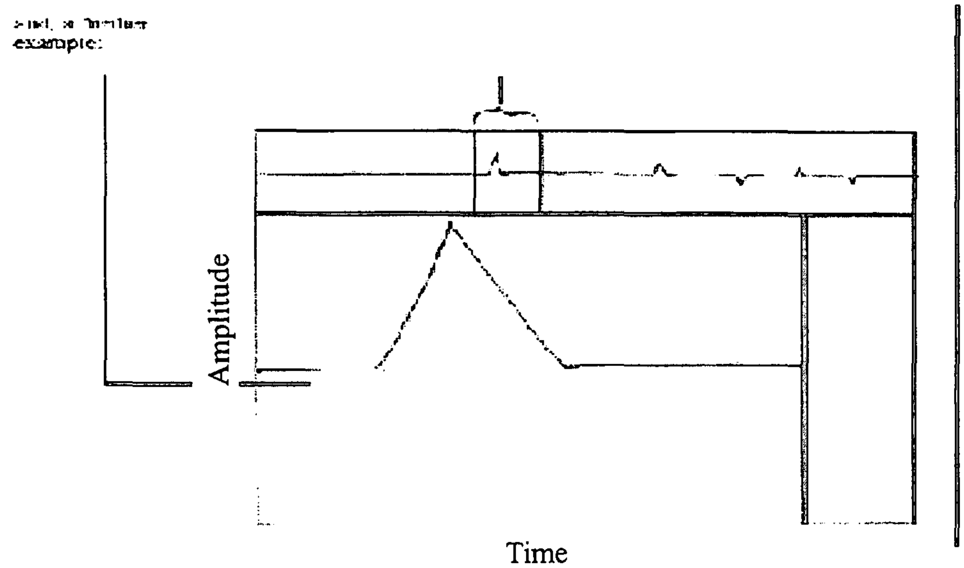


Figure 3-14: An further example of the magnification window

3.3.4 The Control Functions

With any control function the layout should be as simple and intuitive as possible. As the control of the data capture instrument (Baseline) was to be conducted from the laptop computer a few options were available. These included the use of:-

- Keys or keyboard
- Mouse or roller ball.
- Graphics pad or tablet
- Touch screen

As the instrument was designed to be portable and for use in the field to collect data one of the concerns was the operating environment in which the fault location would be conducted. Usually this operation would be from a test van or in a substation. These environments are usually dusty and present a number of problems to the above devices. The keyboard was considered the device least affected under these conditions. On first impression function keys and using keys in general seemed a little awkward. However, tests showed that when the instrument was in constant use – usually daily – it did not take long for the operator to become accustomed to the functions associated with the keys. Once the operator has reached this stage, conducting or performing an operation was rapid and possibly faster than using one of the pointing devices such as a mouse.

One exception to this is in selecting a section of the waveform to be magnified. While this operation is presently done with keys, using one of the more modern pointing devices such as an infrared tracker-ball would possibly improve this greatly in terms of speed. These new infrared track-balls, although not as yet tested would probably also be able to withstand the dusty conditions in which the instrument would be used.

3.3.5 The Data File/Storage Facility

One of the main features that distinguish this instrument/system from the previous generation instruments is the ability to save data and related information in a coherent format. This data can either be saved onto the:-

- internal hard drive or
- a floppy disk drive/CD Rom

Apart from just saving the waveform data, information regarding the saved waveform, as seen in Figure 3-10, can also be stored for later retrieval and post processing, for example:-

- the instrument's operational parameters such as sampling speed and velocity of propagation
- a data file consisting of comments and circuit descriptions relating to the waveform being saved.

The data storage functionalities are the instrument's and in fact the system's biggest advantages as it enables original data to be recalled while examining a new fault. By recalling not only the waveform but also related data and superimposing the new waveform reading on the original trace the fault diagnostic is facilitated. Not only does the waveform provide a reference but the original related notes also provide the necessary background, such as:-

- the cable length
- the propagation velocity
- the cable end would have been established and so that becomes known
- mismatches form a signature which is characteristic of the cable or pilot wire under examination and so the 'historic signature ' is known
- when a comparison of another new trace is made with the historic signature a great difference usually occurs at the fault point

3.3.6 Data Enhancing through Digital Signal Processing

As was seen earlier the longer the cable, the greater the attenuation of the injected signal. The higher the frequency the higher the loss. Therefore for a pulse with a 1 ns rise time injected into a cable, which is terminated in an open circuit there is a reflected pulse which is not only attenuated but will be seen to have a longer rise time.

By fourier analysis a pulse waveform can be shown to consist of a fundamental frequency and harmonics. Any periodic function may be expressed as a fourier series:-

$$f(t)=a_0+\sum_{i=1}^{\infty}(a_i\cos\frac{i2\pi t}{T}+b_i\sin\frac{i2\pi}{T} \qquad (3.9)$$

where

$$a_i = \frac{2}{T} \int f(t) \cos \frac{i 2 \pi t}{T} dt \text{ where } \quad i = 0,1,2,....$$

$$b_i = \frac{2}{T} \int f(t) \sin \frac{i 2 \pi t}{T} dt \quad \text{where} \quad i = 1,2,....$$

and $\quad T = period\, of\, f(t)$ where $\quad T = \frac{1}{f}$

If the injected pulse is repeated then the reflected waveform will be classed as a periodic function. From this it can be seen that the higher frequency components of a injected pulse (into a cable), together with the reflected resultant waveform, are attenuated with the even more attenuated higher harmonics. The result of this is that a pulse injected with a fast rise time returns with a slower rise time and appears rounded. The longer the cable the more the attenuation, the slower rise time and greater 'rounding' of the pulse corners. This phenomenon severely effects the test engineer as will be explained below.

When interpreting the reflected waveform/TDR trace the engineer is looking for reflected pulses. The start of the pulse indicates the location of the feature that caused that disturbance and may well be the fault position. If the cable is long the start of a pulse is however well rounded making the identification of the start point difficult. This problem is known and methods have been developed to try to improve the accuracy. As described later this was addressed by an algorithm which effectively magnified the event and by so doing made the transition more visible. The derived algorithm described below will illustrate this.

One of the major problems which in fact motivated the development of this instrument was the noise encountered on pilot wires. As noise is a random event a process of cumulative averaging can reduce the noise. The first constraint however is that the signal needs to be repetitive and to remove the random data sampling there needs to be a means to synchronise the data capture event. In order to do this the data capture was initiated by using a trigger supplied directly from the pulse generator. To the extent that the waveforms are individual data points, which are summed and then accumulated, while the noise is random and limited to its peak value, then the signal will increase relative to the noise. If expressed in terms of power, as noise generally is, then the expression for Signal to Noise Ratio (SNR) from Horowitz et al (1982) will be given by :-

$$SNR = 10\log\frac{P_s}{p_n} \tag{3.10}$$

where P_s is the signal power

p_n is the noise power

An error that is also cumulative through this method is DC offsets. These are usually are small and can be removed by signal processing. This is very easily accomplished by automatically disconnecting the cable and sampling without generating a pulse, followed by either averaging or filtering. This will ensure that only the DC offset remains and any spurious noise is removed . This can be achieved with either a moving average filter, as described by the expression below (Smith 1997) or by accumulative averaging as expressed in the formula above :-

$$y_{[i]} = \frac{1}{M}\sum_{j=0}^{M-1} x_{[i+j]} \tag{3-11}$$

The DC offset is then subtracted from each individual point. This can be expressed as:-

$$y_i = x_i - e_{dc} \quad \text{for i = 1 to n} \quad (n = 4096) \qquad (3\text{-}12)$$

where n = the number of data points collected (in this case 4096)

y_i is the sample without DC offset

x_i is the sample including the DC offset

e_{dc} is the DC offset

Once the DC offset has been removed the noise can be reduced by cumulative averaging.

The specific method that was implemented in the Baseline instrument was a derivative of the method described above as it was decided, as far as possible, to work with integer math in both calculations and display functions.

Firstly a waveform/trace was captured and saved in an array. This was repeated several time and added to the array. Next the resultant accumulative data was divided by the number of waveforms captured, which gave the average. The result was saved to another array termed the Accumulated Array. As the above process was repeated, subsequent results were summed. At the end the Summed Array was averaged by dividing by the number of iterations performed. This was followed by subtracting the DC offset multiplied by the number of secondary iterations. The result of this was firstly noise reduction by averaging in the first stage and then accumulative averaging in the second stage, as well as any DC offset removal.

Putting this in mathematical terms is done as follows:-

Let the array of sampled data for the waveform of 4096 points be considered as an Array of 1x4096 or a simply a vector $\bar{S}$ and considering that the DC offset can be considered as an array filled with the DC offset error $\bar{E}_{dc}$

Therefore if three waveforms $\bar{S}_1, \bar{S}_2, \bar{S}_3$,were taken then averaged this can be

written as a resultant vector $\bar{S}_r = \dfrac{\bar{S}_1 + \bar{S}_2 + \bar{S}_3}{3}$ (3.13)

Now assuming that the above entire process is repeated 4 times and added, then the DC error subtracted, the result can be expressed as:-

$$\bar{S}_A = (\bar{S}_{r1} + \bar{S}_{r2} + \bar{S}_{r3} + \bar{S}_{r4})/4 - \bar{E}_{\iota} \quad (3\text{-}14)$$

where $\bar{S}_A$ would be the resultant vector.

A more general mathematical description for (3-13) and (3-14) above would be as follows:-

$$\bar{S}_m = \frac{1}{n}\sum_{r=1}^{n} \bar{S}_r \quad (3\text{-}15)$$

$$\bar{S}_A = \frac{1}{p}\sum_{m=1}^{m} \bar{S}_m - \bar{E}_{dc} \quad (3\text{-}16)$$

As memory was however to be conserved in the Baseline, arrays were not implemented in line with the described equations but rather followed the detailed description above.

However as the number of iterations completed by the first general equation (3-14) is 'n' and by the second 'm' it can be seen that for the above where n = 3 and m = 4 would mean that 12 TDR traces would be captured and processed. Making n = 10 and m = 10 then 100 TDR traces would be processed. By making these factors adjustable in the Baseline application process the test engineer could change these factors until the desired averaging and cumulative sum was achieved. This method was used very successfully with positive results.

In general the approach has been to only implement algorithms that give exceptional results for all data collected and processed in commercial systems. The experimental machine (Baseline for development purposes) has other signal processing algorithms that are undergoing a refinement process. One of the advantages of having the PC and operating system is that the process of experimenting with, and including, new algorithms is greatly facilitated.

3.3.7 Database Fundamentals, Concepts and Programs

When data, in this case cable traces and related data, is being collected on a regular basis at some point trying to keep all the information obtained and being able to reference back to a particular trace becomes difficult. Of benefit to the user would therefore be a database/library where data can be 'looked up' and subsequently loaded into the memory for use and analytics. The ideal system for such purposes would be a relational database which stores not only cable traces but all related information required by the test engineer for easy access. This would, for example include, the substation location and equipment as well as cables and their routing maps/charts. Building such a database is no small feat. A scaled-down version was therefore designed with the main objective being able to see if there was a 'baseline' trace for a particular cable and if so to display this historic information. As it was envisaged that changes would initially be made frequently to the system, the concept was to separate the database function from the application program.

Using the high-speed data capture unit (Baseline), cable traces and information collected during the location of cable faults was initially saved and filed on disc. Once the fault location process was completed then the files would be edited and any additional comments made in a standard template, using a file browse and edit application program. The next stage was to run the database application program and load these new traces and data into the database as records. As the data for the individual fields within a record were a function of the high-speed data application program all the corresponding fields would be updated. The database fields that were included are: --

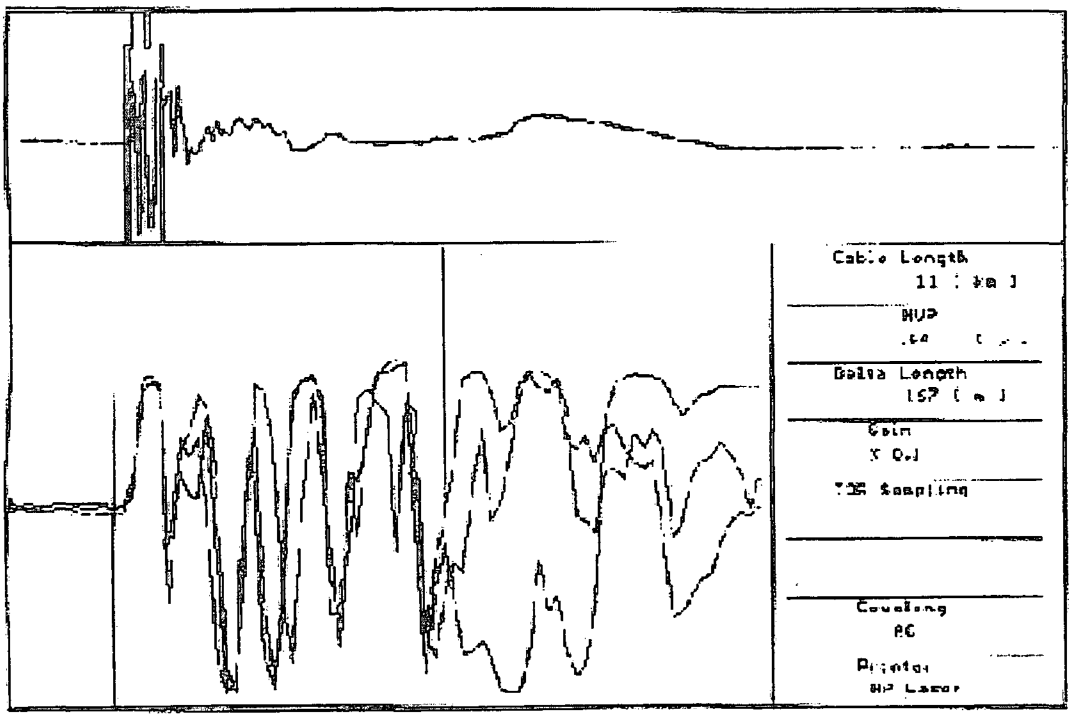
- Date
- Time
- Substation ID
- Cable ID
- Engineer ID
- Contractor ID
- Jointer ID
- Trace Data
- Notes
- File Name

The primary key was chosen to be a combination of the date, time, substation ID, as well as the cable ID which would make the record unique. This would allow one record per second to be saved. It could have been arranged that each of the ID fields such as 'Engineers ID' were foreign keys so making a relational database. This is reserved for future enhancements. As such the 'Engineer ID' could have been linked to engineers database which would have fields such as : --

- Engineers ID
- Surname
- First name
- Address

An example of the data stored in the database is illustrated in Figure 3-15 below.

K&S Engineering and Scientific Ltd



Date	:	
Specialist Name	:	
Location, Address	:	Birimingham
Circuit ID	:	Pilot 0073a
Sub Station	:	
Transformer ID	:	
Switch	:	
Cable	:	
Contractor	:	
Jointer	:	
Note 1	:	A trace of all three traces marking the first
Note 2	:	noticeable discrepancy
Note 3	:	A further zoom in of the first section

Figure 3-15: A typical database record

While the initial foundations of a database were developed and supplied as a standard application with the Baseline instrument the concept and functionalities were not fully developed given the considerable scope of such a project. As an interim step, data was stored as a flat file for pure reference purposes without providing the benefits to be had from a fully integrated relational database.

Unfortunately as the maintenance of the data records was viewed as an extra 'housekeeping' function, test engineers did not use this feature to its full extent. Future developments will therefore need to not only focus on developing a more fully integrated database but also ensure that the completion of all related data is easily integrated into the test engineer's fault location processes.

Chapter 4

Baseline Implementation

4.1 Test Cases/Examples

The previous chapters have dealt with the issues in the design of an instrument that could be capable of high-speed data capture, as well as the data processing and filing. This section will provide a few examples of the various uses and also discusses some of the changes and improvements to the system. Examples of traces used are an exact replica of a trace on the screen of the PC or laptop at the time of the test. While on the screen these traces were in colour, thereby facilitating the analysis, the copies used in this paper are black and white, which may therefore make the illustration less effective.

Examples of tests described below can be divided into the High Voltage and Transient method followed by the TDR and related low voltage methods.

4.1.1 High Voltage and Transient Operations

A few examples of various high voltage tests using a linear coupler and a test method referred to as the ICE (Gale 1975, Clegg 1995) method, as described in Chapter 2.2.4, are illustrated below.

In recalling an historic ICE trace the instrument would be set up according to previously filed/stored traces and data. On observing the trace in Figure 4-1 together with notes that may have been made at the time makes the test engineer more aware of what to expect. Although the new trace will not be the same, unless the fault is exactly in the same place and ionisation takes place at precisely the same time, to the trained eye a lot of information is already present. The distance/length will be valid, as well as the first excursion time of the pulse to the cable end and back as ionisation has not yet taken place. The above example would therefore be the starting point for the location of a new fault on the same cable.

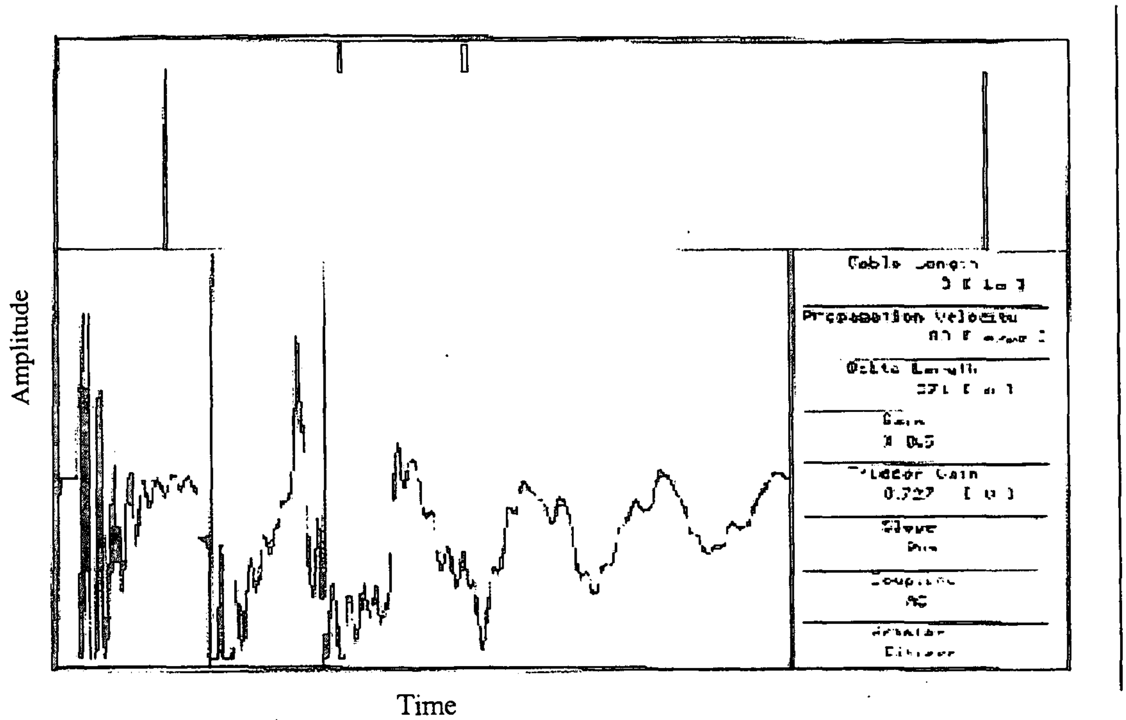


Figure 4-1: A recall of a historic ICE trace

Another example is given in Figure 4-2. This is the typical display seen after capturing an 'ICE' trace and shows the global window together with the magnified window and parameters.

Figure 4-3 demonstrates another method namely the 'loop on loop off' method, used in conjunction with the 'ICE' test method. While this test was conducted on a short test cable, it clearly demonstrates the results. Once again this method can be found in various references such as that by Clegg (1995).

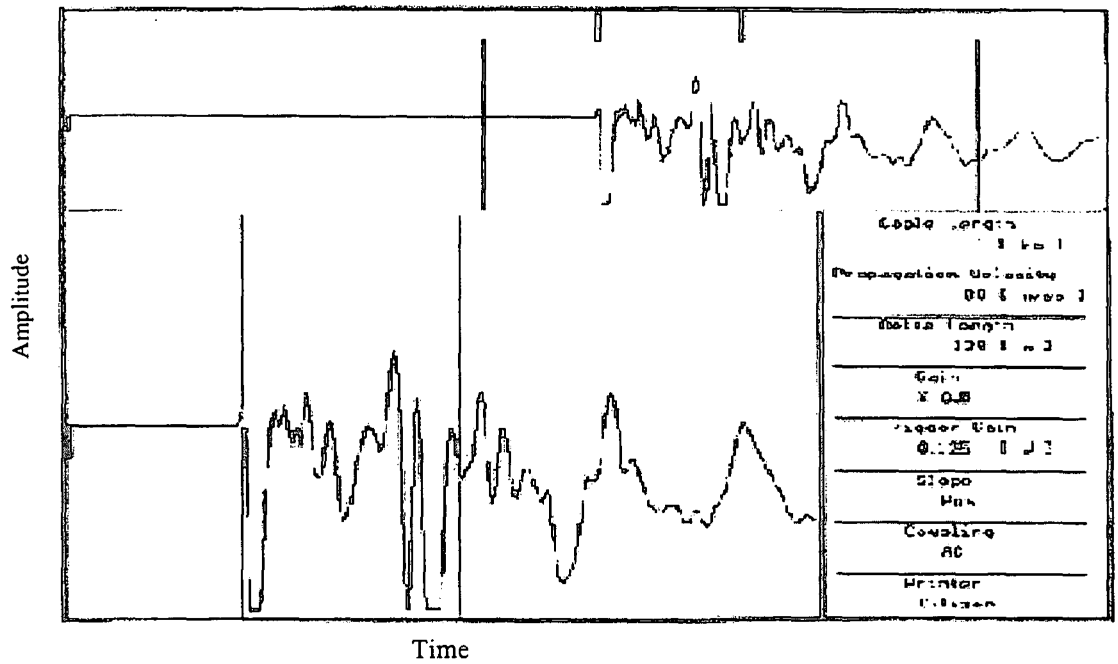


Figure 4-2: A typical ICE trace/waveform as viewed on the screen

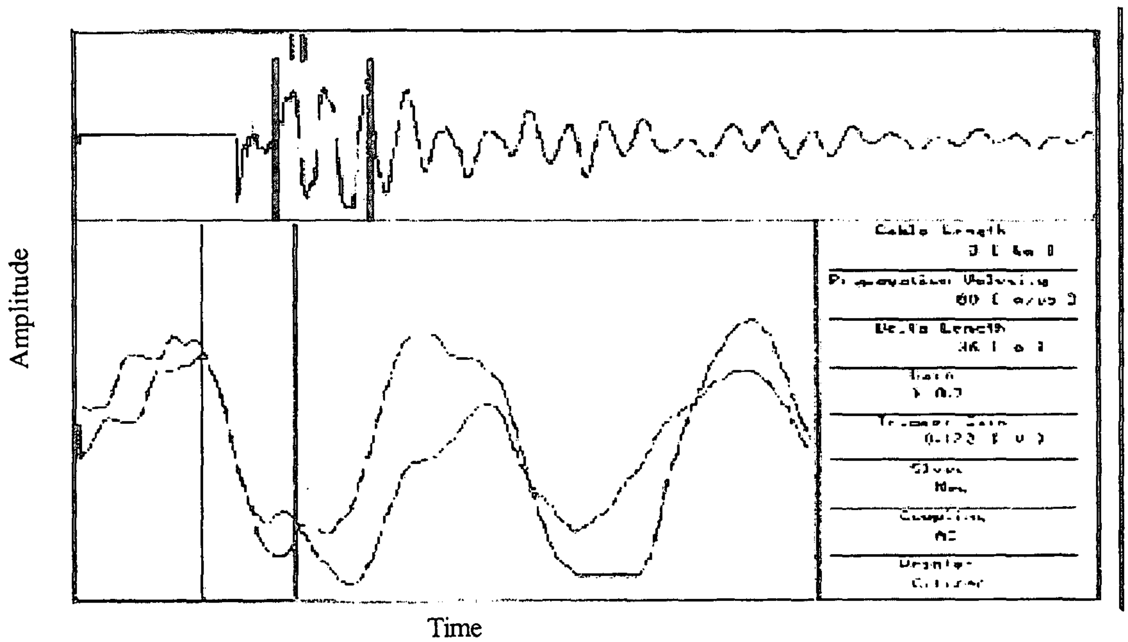


Figure 4-3: Demonstration of the 'loop on loop off ' method as used on a short test cable

4.1.2 TDR and Related Low Voltage Methods

The TDR implementation function is illustrated in Figure 4-4 below. As demonstrated this did not incorporate data processing such as cumulative averaging hence the noise is present on the TDR trace. In a power environment this noise is ever present especially when power consumption levels are high and as a result large currents are involved. Cables are usually laid in ducts and trunks and therefore suffer noise from cross talk. The method used to 'smooth out' this noise is cumulative averaging.

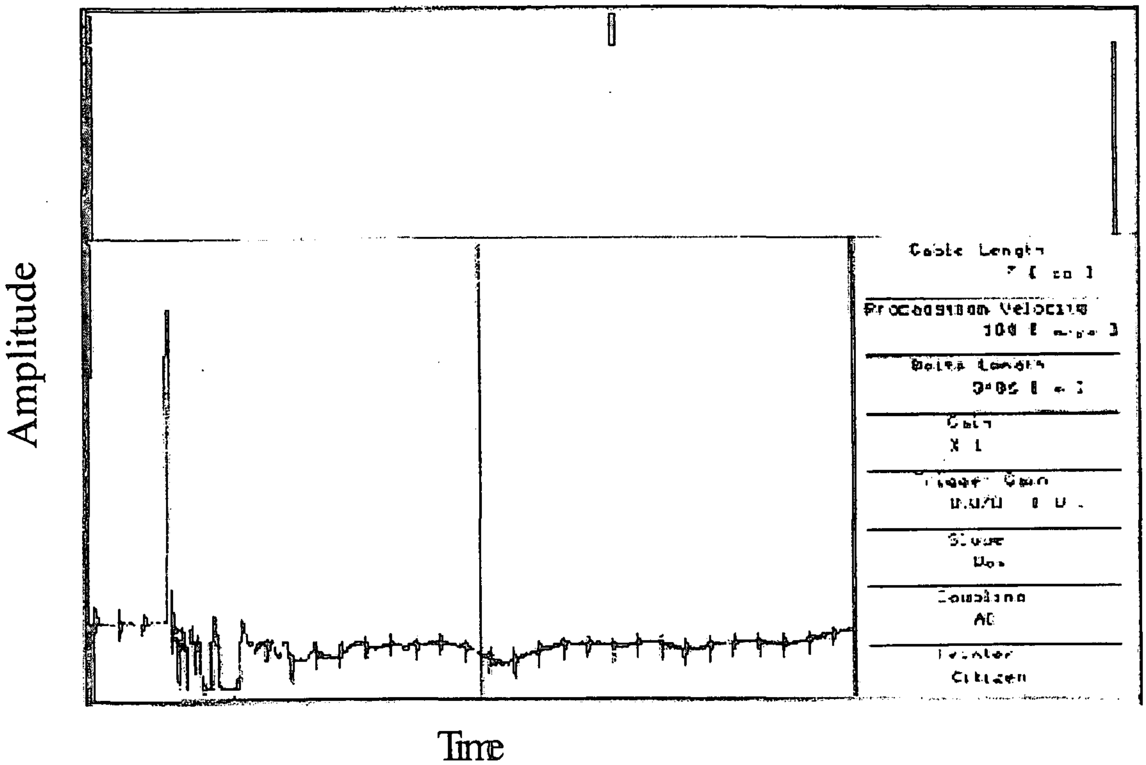


Figure 4-4: A TDR trace without signal processing and correction.

With cumulative averaging the noise is vastly reduced. Various algorithms were tested and then given further field trials before they were incorporated in a function which made the application (Baseline) runtime easy and intuitive, while the details and complexity remained transparent to the operator.

4.1.3 Refinements to the Input Amplifier

Tests on short and medium length cables (3 Km) showed that the TDR was more than acceptable for this range however on testing longer cables and again long pilot cables the results were not acceptable. Beyond 5 km the details were not clear. Increasing the pulse width and amplitude compounded the problem as it resulted in 'swamping' the input amplifier while still being unable to deal with the small return signals in the order of the millivolt range.

On examination of the problem it became clear that no digital processing would be able to improve the situation. When the amplifier reaches its limits:-

- any signal beyond the limit is irrelevant
- the amplifier is no longer operating in the linear region but is rather operating in the saturated or swamped region
- the saturation region leads to the amplifier needing a recovery time. Even though the signal amplitude may be within the amplifier range it is not following and lags behind adding more waveform distortion.

The problem was tackled by reevaluating the specifications with the conclusion that the new limit requirements should be:

Max. Pulse Amplitude	: 25V
Min Pulse Amplitude	: mV

The voltage range was therefore 25,000 millivolts.

This represents a range of 87.96 dB. An 8 bit A/D converter can resolve 1 part in 256 also :-

$$2^{14}=16384$$

$$2^{15}=32768$$

By observation of the above at least a 15 bit A/D was required. As an 8 bit A/D was built into the instrument some type of compression needed to be incorporated. This function could be accomplished by:-

- varying the attenuation or gain proportional to time
- using a limiting amplifier with a logarithmic function

By limiting the input signal at the start to +/- 1 V greatly improves the situation especially if there is a logarithmic function involved.

Another factor that was considered was the fact that as a section of the cable was being examined the pulse amplitude, as well as the pulse width, had to be set so as to optimise the reflected pulse and waveform. The limiting amplifier was constructed and bench tests were then conducted which showed that the amplifier was functioning as expected. The block diagram in Figure 4-5 shows where the limiting amplifier was introduced into the high speed data acquisition/capture instrument (Baseline). Field tests were scheduled on a 15 km pilot cable and the results were very positive.

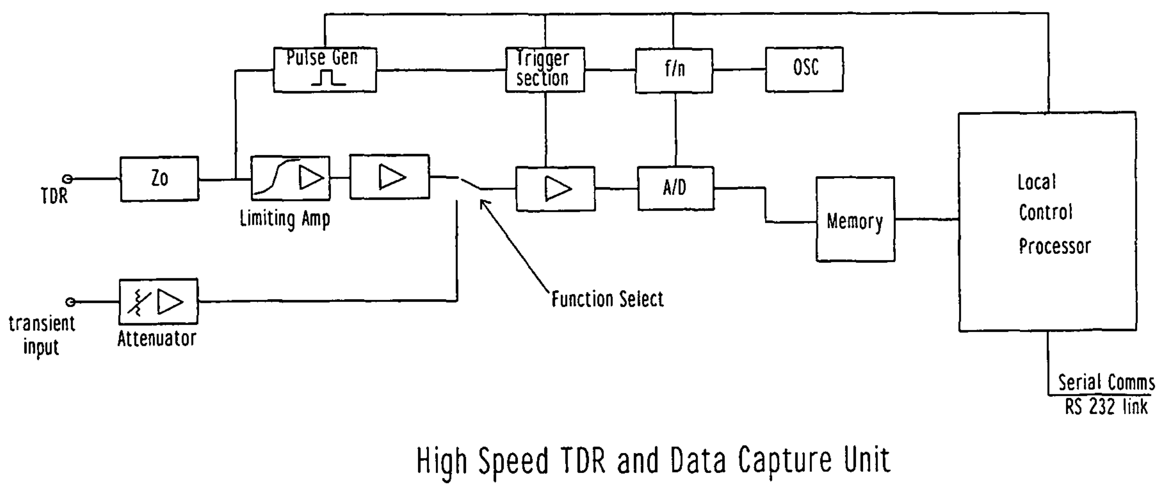


Figure 4-5: High speed TDR and data capture unit

By adding further digital signal processing algorithms which could now deal with the signal range a further enhancement was achieved. An example of the results with an amplifier can be seen in Chapter 4.1.4 under examples of locating complex faults.

While the system was operating well in the field trials it became apparent that other areas could be explored. What follows is a very brief discussion of each of these together with relevant data and captured waveforms.

4.1.4 Examples of Locating Complex Faults

As in the case of pilot cable faults mentioned in the introductory section in Chapter 2.2.1, comparative methods provide a significant aid in the location of faults on these cables. The progress in colour display also meant that the system could be further enhanced to take advantage of the additional features and a multiple trace facility was added. A total of 4 traces could be viewed simultaneously by this method. The ability to display multiple traces each in a different colour facilitated the process of identifying major differences, which would correspondingly be the probable point of fault. An example of this are shown in Figure 4-6 and Figure 4-7.

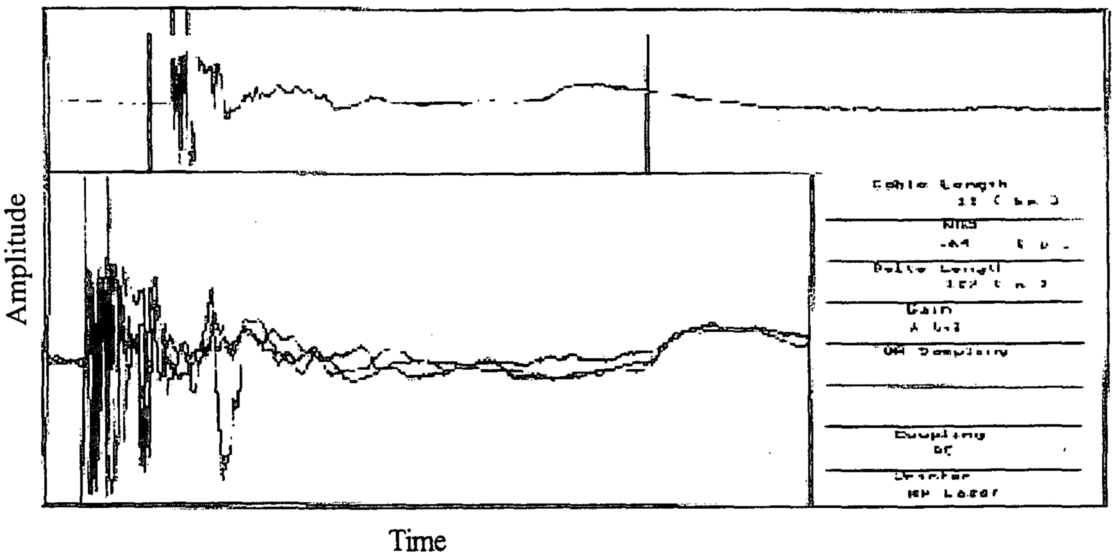


Figure 4-6: Example of a complex fault

Figure 4-6 illustrates a typical TDR waveform/trace taken on a pilot cable. The global window is set up to show an 11 km cable length at a velocity factor of 0.64c (the speed of light). As this velocity factor is adjusted to give the correct length of the cable it is an average value and as such is a nominally set factor. This is referred to as a nominally velocity of propagation factor or NVP in the parameter window.

In the zoomed or expanded window the trace from the global screen, as well as a previously saved trace, which was stored in one of the memories, can be displayed. This is illustrated in Figure 4-7 below.

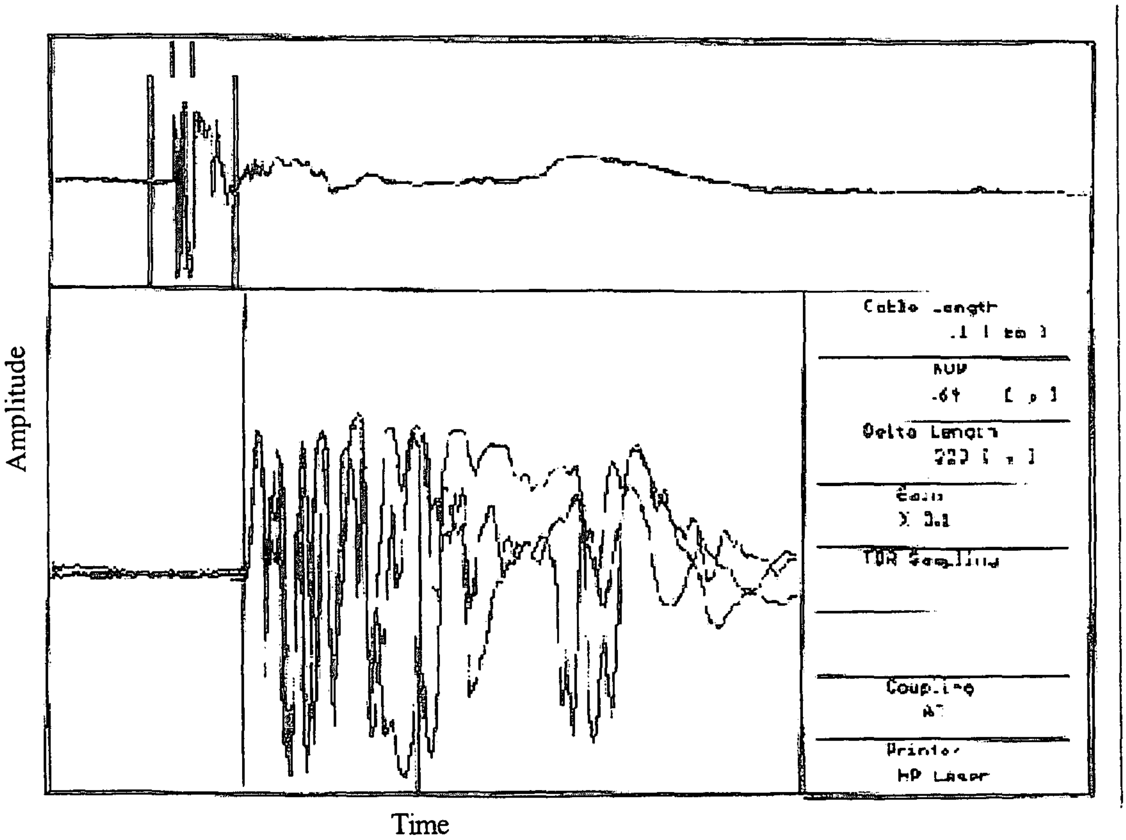


Figure 4-7: The expanded close-in range TDR trace of a cable

Any memory can be viewed or hidden at will allowing details to be removed or added as required.

As was seen and discussed earlier (Chapter 3) a drop off in signal amplitude with distance/time was experienced. This is due to the attenuation discussed. The higher attenuation or roll-off higher frequencies can also be easily depicted. The noise due to cross talk was also severely reduced by signal processing, such that the noise was no longer an issue.

When viewing Figure 4-6 and Figure 4-7 above it becomes apparent that the entire cable would have to be examined to achieve effective results. This is done by zooming into sections of the cable utilising the 'window cursor ' control functions. It is also clear that with complex waveforms, as shown, the comparative method facilitates the process of locating cable faults. With only one TDR trace the task would be almost impossible. A future development could make use of an algorithm to aid in the location process purely on comparative bases on multiple traces.

4.2. Various Additional Applications and Refinements

4.2.1 Live Cables and Blocking Filters

With power reticulation systems much of the distributed power is transformed down from the kilovolt range into the 240 V to 380 V (UK) range for domestic and industrial use.

Locating faults in the domestic and industrial voltage range usually involve the TDR type tests. It is not always possible to isolate consumers and so high-voltage pulses cannot be applied to the cable under diagnosis or test. Precautions are taken which assume any cable to be worked on as live. If a TDR type instrument is attached to these low voltage cables (low tension cables or LV cables) and the cable is energised, apart from the engineer being hurt or potentially electrocuted, the instrument would also be destroyed. In order to facilitate this a blocking filter has to be inserted between the instrument and the cable under investigation. The function of this blocking filter is to allow the narrow pulses to still be injected into the cable, while simultaneously blocking or isolating the 50 Hz mains. The blocking filter has to be fail-safe and, in the event of catastrophic failure of the filter components, both the operator and instrument must be totally safe.

As the emphasis is on safety while simultaneously delivering the pulses, a few compromises had to be made in the design of the blocking filter. Figure 4-8 outlines the basic concept of the blocking filter.

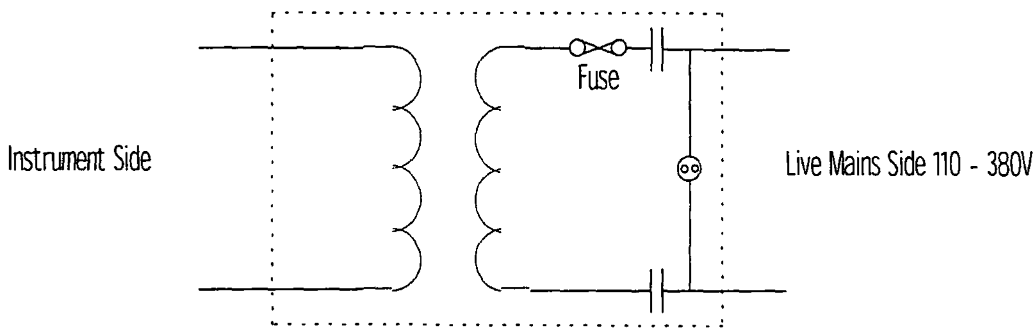


Figure 4-8: Blocking filter schematic

It must be noted that because of the high frequency nature of the pulses, the design of the blocking filter needs to be suitable for frequencies in the 10 MHz to 200 MHz range. The layout and components, including wound components, therefore need to be considered and constructed for the rf. frequency spectrum. This means the inductor needs to be a broad band bifilar winding, and core and capacitors need careful consideration.

As mentioned earlier stray inductance and parasitic capacitance will introduce distortion. If a blocking filter is used on very long LV cables then, due to the increased pulse amplitude and pulse width, these small parasitic parameters start to become significant, with the result that they tend to become visible on the TDR trace. An example of this can be seen in Figure 4-9.

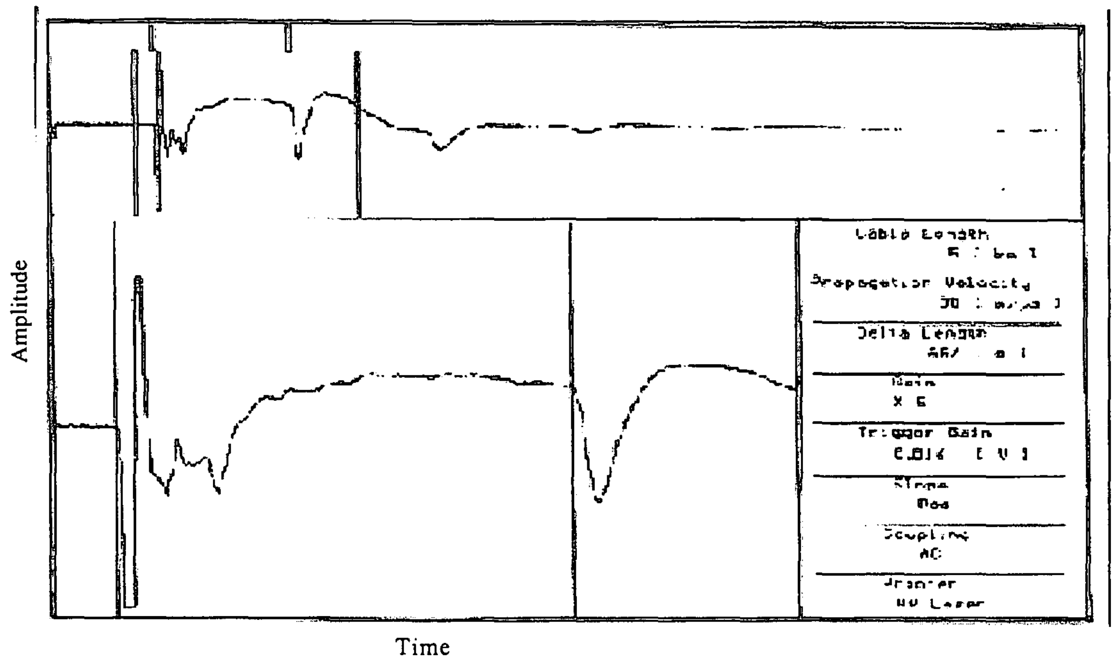


Figure 4-9: Effects of a blocking filter on a TDR trace

As many residential networks are not very long this usually poses minor visible errors. While the blocking filter was being developed the effects of various cable lengths were recorded and improvements were noted and incorporated in the development of the desired final filter. As LV networks continue to develop it is appropriate to mention these effects and the measures used to reduce them as these will need to be incorporated in future enhancements.

4.2.2 Spin-off Applications

Very shortly after the system was developed there where many occasions that arose where data/TDR traces captured in the field/on site needed to be reviewed in the office. This entailed having to couple the instrument to the laptop or PC. By removing the initialising, control and data capturing routines from the initial application software a virtual instrument was developed - termed the Baseline browser. This proved to be a valuable additional functionality of the instrument, opening up more applications for off-site viewing, even enabling traces to be e-mailed, viewed and printed remotely.

4.2.2.1 Remote Testing via Modem

As the instrument is controlled via the serial port this means that introducing a modem at either end allows the instrument section to be controlled over the phone line. This feature has been tested between London and Edinburgh in Scotland (UK). From this it is possible to infer that as long as the phone link is good this feature of remote operation will be possible. With this facility it is conceivable that a specialist engineer could have subordinate junior test engineers take permits and couple the instrument and surge generators to the cable to be tested. Once each engineer had ‘coupled up’ the specialist engineer could then take over and perform all the diagnosis and fault location from a remote head office. Facilitating such a structure or hierarchy could have significant cost and productivity benefits.

4.2.2.2 Training Facilities

As the Baseline browser allows waveforms and data files to be saved and retrieved, waveforms captured during a large number of cable fault location exercises can be saved and then used at a later date for teaching purposes.

4.2.2.3 Databases of Cables and Historic Databases

In addition to storing individual traces in designated memories and files for future retrieval, one of the key future enhancements of the Baseline system, as described in Chapter 3.3.7 will be the development of database facilities which will, for example, enable utility companies to create a full and complete database of all cables in the areas for which they have responsibility. The task of capturing and storing cable traces for existing cables is vast although it could be envisaged that in newly developed areas this is undertaken as a matter of routine. For existing cables the database could be built over time in that each time a fault is located the cable concerned would automatically be stored in the database.

Chapter 5

Results of the Implementation

The best way to analyse the results of the original objectives in the design of the Baseline instrument can be summed up in terms of advantages and achievements, as well as any disadvantages and shortfalls.

5.1 Advantages

When comparing the Baseline instrument with existing instruments, as well as viewing the particular functionalities of the Baseline the advantages can be summarised as follows:-

- The storage of waveforms and data has worked well
- The location of complex faults is greatly facilitated through colour screens and the features that enable the comparison with previously stored traces. This is particularly effective on pilot wire faults
- Signal processing has minimised the noise problem and with simultaneous multi-trace viewing has made fault location easier
- Remote testing has become a possibility
- A virtual instrument means the training with real examples can be undertaken
- Historical data filed can be retrieved
- Analysis and comparison can be undertaken off-site in a quiet un-pressurised environment
- Application software can readily be upgraded
- Algorithms can be amended and directly incorporated into the application

software

- From a development perspective, the instrument can act as a research instrument in that it can be used to collect data to test new:-
  - ➢ algorithms for future use, including neural network algorithms
  - ➢ hardware designs and configurations so that new test results can be compared with previous ones by observing the resulting waveforms

5.2 Disadvantages /Shortfalls

As the Baseline database was not embedded in the system, the instrument has not had a great take-up rate. This will therefore be an area for future development by having a database that is an integral part of the data capture and control application.

Chapter 6

Conclusions and Area for Improvement and Refinement

What this thesis has attempted to do is to not only provide the theoretical background as to the various methods applied in the location of faults on underground cable but also to describe how these methods and principles were applied to the design and development of a high speed cable fault location instrument referred to as the Baseline. Through the development of this instrument a review was undertaken of similar competitor instruments that existed at the time and while integrating most of the features available in these instruments, the Baseline also introduce some new concepts, such as PC based control, multi-trace visualisation, multi-colour traces, remote operation and filing which facilitates historic data recall with automatic instrument set-up.

As demonstrated with selected screen prints, considerable testing of the instrument was undertaken prior to its finalization. The results of this testing, as well as input from test engineers were incorporated into the final product which was sold to a number of utility companies, notably two of the largest in the UK.

As discussed at various stages of the paper, while the instruments continues to achieve its core objectives and remains in use, there are a number of areas that still require enhancements based on ongoing feedback received from its users, notably with regard to the database and the operating system.

A critical feature of any operating system which is integrated into an instrument such as the Baseline is that it must be stable and obtainable throughout the life cycle of the instrument. This could typically be a minimum of seven to ten years. If this is not the case then many upgrades and reprogramming would be required with every new version of the operating system used in the PC of the user's choice. This adds time and reprogramming effort, thereby reducing the efficiency of production and hence eventual profitability. There are a number of operating systems available today which are free and open and these would need to be examined. The advantage of these systems is that upgrades can be driven when required and not driven by the commercial market

In addition to the required review of the core operating system, an alternative system with a fully integrated PC, as opposed to a portable version of the PC may also have wider commercial demand and would be able to withstand a more rugged environment.

Whatever operating system and final housing is adopted, the database filing feature will need to be merged and incorporated into the new application program. This will make the operation transparent and automatic to the test engineer thereby reducing "housekeeping" time and simultaneously automatically creating an historic database.

For the transient TDR data capture instrument, enhancements will also be made in order to cater for the future. The A/D converter will be increased to at least 100 MHz and most probably 220 MHz. As the sample and hold incorporated into these A/D's nowadays usually have much higher bandwidth the input and limiting amplifier section will also have to be revamped to make the most of the bandwidth.

With regard to the TDR it is envisaged that a Digital Signal Processor (DSP) or fuse programmable gate array would be incorporated with the objective of being able to undertake real-time pre-processing quicker and more efficiently. By handling more data and conducting a more complex signal processing set of algorithms better results would be achieved.

While the above additional enhancements will be incorporated in to any new instrument the basic principles described will continue to apply.

Chapter 7

Bibliography

Amsel G, Bosshard R, Rausch R, C Zajde, (1971), Time Domain Compensation of Cable Induced Distortions Using Passive Filters for the Transmission of Fast Pulses, *The Review of Scientific Instruments,* Volume 42, Number 8

Anderson S.J, (1990). Use of Power Cables in Commerce and Industry. Modern Power Cable Tracing and Fault Location Techniques, *Conference Proceedings (ERA 90-0145)* ERA Technol, UK

Anderson, J.M., (1971), Wide Frequency Range Current Transformers, *The Review of Scientific Instruments,* Volume 42, Number 7, July 1971

Aubanel, E.E. and Oldham, K.B., (1985), Fourier Smoothing without the Fast Fourier Transform, *Byte,* February 1985

Bartnikas, R. and Srivastava, K., (2000), Power and Communication Cables Theory and Applications, IEEE Press

Barwicz, A., Bellemere, D. and Morawski, R.Z. (1990), Digital Correction of A/D Conversion Error Due to Multiplexing Delay, *IEEE Transaction on Instrument and Measurement,* Vol. 39, No 1, February 1990

BICC (1957), BICC Electrical Conductors, British Insulated Calendar's Cables Limited, London

Bisset J.P., (1988), New Pulse Reflectometer Overcomes Field Problems:, *Broad Cast Technology*, Vol 14 Iss 2, October 1988

Burgess, D.A. And Kwei, G.H. (1971), A Variable Delay Gate Generator for Two-Channel Counting Systems, *Department of Chemistry, State University of New York,* 1 March 1971

Clegg B. (1995). Underground Cable Fault Location, ISBN 0-07-707804-7

Clegg, B and Lord , N.G : Modern (1975), Cable Fault Location Methods, *Proc, IEE*, vol 122, No. 4, 1975

Firth, J.M. (1971), A Generator for Nanosecond Charge Pulses, *The Review of Scientific Instruments,* Volume 42, Number 8, August 1971

Dixon, M.W., (1993), A Microwave Handbook, Volume 1, Royal Society of Great Britain

Gale, P.F., (1975), Cable Fault Location by Impulse Current Method, *Proc. IEEE,* 122 (4)

Goen, T (1987). Electrical Power Distribution System Engineering, McGraw-Hill, Singapore

Gyles, C. (1990), 800 Ms/s Arbitrary Function Generator, *IEEE Transactions on Instruments and Measurement,* Vol. 39. No. 1, February 1990

Ho, C.M.; Lee, W.K; Hung, Y.S; (1993). Signature Representation of Underground Cables and its Application to Fault Diagnosis, *IEEE 2nd International Conference on Advances in Power System Control, Operation and Management*, December 1993, Hong Kong

Horowitz and Hill (1982), The Art of Electronics, Cambridge University Press, Cambridge

Houtman H. (2000) I-Ghz Sampling Oscilloscope Front End Id Easily Modified, *Electronic Design,* September 18, 2000

Imamura, M., (1990), A 1-Ms/s 16-Bit Analog-to-Digital Converter, *IEEE Transactions on Instrumentation and Measurement,* Vol. 39, No 1, February 1990

Kuo,F., (1962), Network Analysis and Synthesis, Wiley International Edition

Kurtz E.B. and Shoemaker, T.M., (1986), The Lineman's and Cableman's Handbook, McGraw-Hill, New York

Lee, W.K; Hung, Y.S May (1991). Cable Fault Diagnosis Using Signal Processing Techniques. *Insulated Line and Cable Systems, International Conference and Workshop,* Vol 2.

McAllister, D., (1982), Electric Cables Handbook – Chapter 28, Granada, London

Millman and Taub (1965) Pulse Digital and Switching Waveforms, McGraw-Hill, International Student's Edition

Morton A.H, (1966), Advanced Electrical Engineering, Pitman Publishing Ltd

Padmanabhiah, M.A (1989). Cable Handling, Laying, Storage, Routine Maintenance, Layout Drawings, Cable Faults, Fault Location and Analysis, *Electric India*, Vol 29 Iss:3, Date 15 Feb.

Shepherd, J., Morton, A.H. And Spence, L.F. (1975), Higher Electrical Engineering, Pitman Publishing Ltd

Siew W.H .; Lee, P.C (1989). An Intelligent Cable Fault Locator, *Proceedings of the 1989 IEEE Instrumentation and Measurement Technology, Seventh Conference on Electric Power Supply Industry,* 15-22 Oct 1988.

Smith S.W., (1997) The Scientists and Engineers Guide to Digital Signal Processing, California Technical Publishing

Souders M., Flach D.R., Hagwood C., Yang G.L. (1990) The Effects of Timing Jitter in Sampling Systems, *IEEE Truncations on Instrumentation and Measurement vol. 39 No 1 February 1990 (5)*

Tanaka, T., and Greenwood, A. (1983), Advanced Power Cable Technology, Volume 1 Basic Concepts and Testing, CRC Press Inc., Florida

Trigger, J.P. and Appleby, S. (1989), Advanced Techniques for Customer Line Fault Location, *Br Telecom Technol J,* Vol 7, No 2, April 1989

Van Biesen, L.P.; Renneboog, J.; Barel, A.R.F. (1990). High Accuracy Location of Faults on Electrical Lines using Digital Signal Processing, *IEEE Transactions on Instrumentation and Measurement*, Vol: 39 No 1, ! February 1990,

Wagdy M.F., and Award S.S.(1990), Effects of Sampling Jitter on Some Sine Wave Measurements, *IEEE Truncations on Instrumentation and Measurement vol. 39 No 1 February 1990 (6)*

Williams J. (1993) Linear Applications Handbook Volume ii. ' A Guide to Linear Circuit Design' Application note 47 ' High Speed Amplifier Techniques'