UNIVERSITY OF SOUTHAMPTON

ON-LINE DETECTION OF PARTIAL DISCHARGE ACTIVITY IN HV CABLES AND ACCESSORIES USING DIRECTIONAL COUPLING TECHNIQUES

BY

GRAEME WILLIAMS MEng MIEE

A THESIS SUBMITTED FOR THE DEGREE

OF MASTER OF PHILOSOPHY

IN

THE SCHOOL OF ELECTRONICS AND COMPUTER SCIENCE

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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Master of Philosophy

On-Line Detection of Partial Discharge Activity in HV Cables And Accessories Using Directional Coupling Techniques

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This thesis is concerned with the development of new reliable methods of pd detection and the possible use of directional couplers as the sensing element. Directional couplers are used in commercial on-line systems to detect pd sources within XLPE cables. It is important to monitor the cable on-line, as conventional testing requires the cable to be taken out of service causing a disruption to the power supply. A directional coupler uses both a capacitive and inductive effect to induce two different output signals from the same sensor. Directional couplers have the advantage over other detection methods as the two output signals can be used to discriminate a pd signal from noise.

Current on-line pd detection methods have been evaluated and their response under screened laboratory conditions compared with conventional detection methods. The operational conditions likely to be encountered by an on-line measurement system have been established through field measurements at a National Grid Transco substation. Commercially available pd detection systems have also been assessed for performance and suitability for on-line applications.

The directional coupler characteristics have been examined and the response of the coupler to alterations in design parameters established. Finally the possible methods of signal acquisition and transmission from multiple sensors have been considered.

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Acknowledgements

I would like to express my thanks to my supervisor, Dr Paul Lewin, for his guidance and support throughout this research project. My gratitude must also go to Professor Tony Davies, for providing me with the opportunity to conduct research in the High Voltage Laboratory. He is fondly remembered by all.

I would also like to thank all of my colleagues during my time in the high voltage lab, as they have all at one time or another been of some assistance, especially Dr David Swaffield and Dr Adrian Robinson with their valuable and frequent discussions. In particular my thanks go to the technical staff, Mr Roland Caldecutt, Mr Neil Palmer, Mr Brian Rogers, Mr Mike Smith and Mr Richard Howell for all of their invaluable help. Roland's energy and humour are sorely missed by all within the lab.

My gratitude must also be extended to National Grid Transco, for the funding the company provided for this project, and in particular Dr Simon Sutton, Professor Steve Swingler and Dr Graham Hathaway.

My final and greatest thanks go to my family, especially my parents, for their love, and encouragement throughout this project and everything leading up to it. Your support will always be remembered.

1. Introduction

As defined by IEC 270 a partial discharge (pd) is a localised discharge that only partially bridges the insulation between conductors, i.e. the main conductor and ground, and may occur adjacent to the conductor [1]. A partial discharge will not result in discharge directly between the two electrodes due to being confined, and thus will not result in a failure of the system.

Partial discharges can be caused by many different factors, the most common being voids or impurities within the insulation. An impurity will introduce a differing dielectric constant to that of the surrounding dielectric insulation, so when an alternating electric field is applied the electrical stress surrounding the impurity will differ from that of the rest of the dielectric material. If the breakdown strength of the impurity is lower than that of the surrounding dielectric, as in the case of a void, a breakdown will occur across the void, and hence a partial discharge. If a conductive impurity, i.e. higher electric constant, is introduced to the dielectric material the electrical field around the impurity will be greatly concentrated and hence lead to partial discharges.

Corona discharge can occur around a conductor surrounded by gas, i.e. at the high voltage terminals, if the electrical strength around the conductor is above the breakdown strength of the gas. Corona can also be caused by any part of the surrounding electrical equipment not being properly grounded resulting in floating potentials.

If left unchecked the discharges across these impurities will grow until they span the dielectric material between the conductors. While partial discharge activity may not compromise the electrical equipment directly it will eventually lead to a full discharge across the dielectric material and a system failure. Thus partial discharge detection and monitoring is an important factor in ensuring continuous high voltage power transmission.

Thorough electrical insulation quality tests are undertaken on all power cables before they leave the factory, and on passing these tests are considered discharge free [2,3]. These type of tests have been performed for over 50 years, however they require that the cable be within an electrically noise free environment and that the cable be off-line.

However, these types of tests are extremely difficult to implement on a cable that has already been installed into a system. In this case it is a lot more useful to first of all detect the on-set of a partial discharge while the cable is in normal use and then monitor the magnitude of it. If the magnitude of the pd within the dielectric should pass a certain cut off then the cable would be taken out of service before a full discharge can occur. However, there are several problems associated with on-line monitoring. Electrical interference can be very bad due to the high voltage signal of the conductor, so any monitoring technique must be able to distinguish between pd and any interference signals that would be experienced under screened conditions.

It is not usually expected to detect partial discharges at first inception as they may be exceptionally small, however a sensitivity limit may be set so that any defect within the dielectric that will endanger the continuous operation of the cable can be identified and located. An upper level of partial discharge magnitude may also be set so that between these two limits the discharge magnitude may be monitored, to prevent a full breakdown.

The principle objective of this thesis is to investigate the application of directional coupler techniques to partial discharge detection and the data transmission of the monitored events. Chapter 2 will introduce partial discharge theory and fundamentals.

Chapter 3 will compare different methods of partial discharge detection and evaluate their suitability for pd detection within hv cables. In Chapter 4 a commercially available direction coupler pd detection system will be reviewed. Chapter 5 will assess pd detection techniques in the field in the presence of high levels of electrical noise. Chapter 6 will investigate directional coupler theory and partial discharge detection using directional couplers, including experimental results. Partial discharge acquisition and transmission techniques will be reviewed and a design for the most suitable system will be proposed in Chapter 7. Finally Chapter 8 will discuss the overall conclusions drawn from this project.

2. Partial Discharge Fundamentals

2.1 History

The subject of pd and corona discharges, constitutes a field of endeavour which can be traced back to the beginning of the twentieth century. While the study of pd may thus be considered as a well developed field, its pre-eminent importance as a tool for assessing the quality and performance characteristics of HV equipment has been responsible for sustaining a high level of activity in investigations related to its mechanisms, physical and chemical effects, and detection and measurement techniques [4,5]. Over the years, the level of investigative effort in the pd field has varied considerably both as regards to the type of electrical apparatus under consideration as well as the type of discharge behavioural aspect being examined, e.g. nature and form of the discharge, detection sensitivity, degradation of insulation exposed to the pd, discharge pulse quantities recorded such as the apparent charge transfer, pulse repetition rate, energy loss, distributions of pulse heights, discharge phase and pulse separation time intervals, as well as pulse pattern recognition in terms of the sources causing the discharge.

Perhaps nowhere are the different tendencies in pd studies and testing procedures easier to follow and evaluate in their chronological development over the last five decades than those applicable to solid extruded dielectric insulated power distribution cables. This is attributable to a large extent to the relatively simple geometry of cables and their transmission line behaviour, which greatly facilitate the interpretation of the pd measurements. While few interpretational difficulties arise in low capacitance lumped hv components such as bushings and capacitors, the detection of pd in capacitors of high capacitance poses substantial difficulties. Discharge detection and its accurate measurement in transformer specimens becomes appreciably more complicated as a result of a more complex transmission line behaviour of the coils as well as coupling and resonance effects between the windings. Similar interpretational and calibration difficulties are encountered also with rotating machines, where, in addition to the difficulties inherent with transformer specimens, the magnitudes of the detected pulses may vary appreciably, ranging from low levels generally intrinsic to internal discharges within stator bar insulation to extremely high levels ordinarily associated with slot discharges. Also the question of calibration has not been resolved and there is indeed considerable controversy as to whether or not calibration should be a prerequisite for specimens. Within this chapter pd mechanisms and their behavioural characteristics will be examined and will be compared to the pd detection and measurement procedures that have evolved over the past five decades, which are currently utilized on different hv electrical apparatus and cables.

2.2 Preliminary Considerations

Oscilloscope methods have been employed in the detection of pd in electrical apparatus and cables, following the work reported by Tykociner et al in 1933 [6]. These techniques respond principally to pulse type discharges; while pulse-less glow and pseudo-glow discharges can readily occur, their appearance is generally accompanied by the occurrence of pulsed type discharges that can be readily detected so that in the vast majority of cases conventional pd pulse detectors are effective indicators of the presence of pd. However, it should be borne in mind that pulsed pd detectors may not always indicate the full extent or intensity of the pd present. There are bridge type pd detectors available that respond to both pulse and pulse-less discharges, but their intrinsically lower sensitivity has tended to impede their large scale implementation in the pd area.

Although the fastest rise time limit of pulse type discharges at the pd site of origin may be established theoretically, historically the fastest measurable rise times, claimed to be recorded experimentally, tended to suggest a monotonically decreasing relationship with the bandwidth capability of the oscilloscopes used. With the availability of GHz bandwidth oscilloscopes, it is now generally agreed that pd pulses may have rise times as short as 1 or 2ns, which should however not infer that most discharges do exhibit these rapid rise times. Thus detection of pd pulses at frequencies at bandwidths up to 1GHz are suitable, but awareness should be made of the fact that the energy content of pd pulses is a decreasing function of frequency. Most commercially available conventional pd detectors for routine use on cables, capacitors and transformers are of the narrow band type and are designed to operate within the band of ~30 to 400kHz; they are charge integrating devices and may be calibrated directly to provide the charge transfers associated with detected discharge pulses. Higher bandwidths are used in research related work, where faithful reproduction of the pd pulse shapes is of paramount importance. Also, for improved pulse resolution, wider bandwidths are employed on work involving discharge site location in cables (~20MHz), rotating machines (800kHz to 1GHz) and bus ducts as well as compressed gas cables (~1GHz).

Early pd detection systems employed analogue instrumentation. This instrumentation performed adequately well for discharge inception and extinction voltage measurements, with the pd pulse displayed on an oscilloscope with a power frequency time base and calibrated ordinate scale. The charge transfers associated with the discrete discharge pulses could be estimated visually and the approximate phase relationship between the pulses and the applied voltage noted by the observer performing the tests. The availability of crystal controlled pulse counters in the 1950s, allowed the counting of pd pulses per unit time and thus the determination of the pulse density of discharge patterns [7,8], and permitted as well the development of differential pulse height analysers and single channel pulse-height analysers. The availability of low cost analogue to digital converters led to the commercial introduction of multi channelled analysers in the 1960s suitable for pd pulse height distribution analysis. The area of discharge pulse interval and discharge pulse phase distribution measurements developed rapidly thereafter in the 1970s and was extended into the practical area with application to rotating machines [9]. This was shortly followed by the introduction of computerised techniques for the measurement of pd pulse distributions [10-12].

The advent of pc computers in the 1980s and their extensive use in the 1990s rapidly altered the approach in the pd pulse distribution analysis area in that the measurement systems shifted away from the hardware based instrumentation to software dominated techniques [13-15]. This study area eventually led to investigations on discharge pattern recognition and classification, involving the use of neural networks [16,17] and fuzzy logic. Early studies indicated that the magnitude of a discharge pulse and its phase is strongly influenced by the occurrence of a preceding pulse or pulses. This process was rigorously analysed using a stochastic approach by van Brunt [18] in order to explain the conditional statistical nature of the discharge mechanism. The obtained results posed some serious questions concerning the effectiveness of pd pattern classification and recognition as well as any statistical treatment of such data in order to render it more amenable to interpretation. Yet it must be observed that the statistical treatment of pd patterns whether of the pulse-height or phase distribution [19] or pulse shape [16,20] type have yielded some interesting practical results.

The 1990s saw the introduction of rapid response digital circuits for pd measurement applications [21]. While the use of digital techniques in pd pulse detection, measurement and acquisition has been growing markedly, commercially available pd detectors have retained their separate analogue and digital measurement options. In this respect it should be emphasized that the peak pd pulse magnitude determined by the digital system will not generally be the same as the true magnitude determined in real time by the analogue circuit because of its dependence upon sampling rate, bandwidth and storage capacity of the digital system. It should also be pointed out that normally the analogue circuitry precedes the digital acquisition system for the purpose of pd signal amplification and shaping [22]. Also, often the pd sensing circuit may be of an analogue-digital hybrid configuration. The variety of digital circuits, available and in use for pd measurements over the last decade has evoked the publication of a of a position paper by the IEEE Committee on Digital Measurement Techniques [23] and a subsequent paper with invited discussions by experts in the field. Some effort will be put towards a critical examination of the various analogue and digital techniques either currently in use or with possible future application to pd measurements on hv power apparatus and cables.

2.3 PD Mechanisms

Proper design, application and development of pd sensing and measurement circuits entail a certain degree of awareness and understanding of the pd process. It is important to use proper and correct terminology in reference to different forms of pd to maintain clarity in the subject. For example, it is one matter to refer to certain types of pd as 'streamer-like' discharges and another matter to refer to the same form of discharge as a 'streamer discharge'. The streamer discharge theory, considers large gaps in which the relatively short times of gap breakdown are accounted for by the occurrence of streamer discharges, which propagate rapidly across long gaps due to ionising photon radiation at the streamer heads or tails. Thus, the use of the term 'streamer' by itself, when applied to pd in relatively short gaps or small cavity diameters, introduces an unnecessarily misleading term in the pd lexicon.

PD, when occurring in short gaps, may assume different forms: rapid and slow rise time spark type pulses, true pulse-less glows or pseudo-glow discharges [24-26]. All these forms of discharges are cathode emission-sustained discharges i.e. they are essentially Townsend discharges in contradiction to streamer discharges whose distinguishing features are their independence on cathode emission and their dependence upon photo-ionisation in the gas volume. The classical Townsend discharges are characterised by weakly ionised plasma having a small space charge producing field, which is negligible compared to the externally applied field. Its electron temperature is approximately 10^4K and the dominant ionisation process is by direct ionisation.

The true glow or pulse-less discharge consists of weakly ionising diffused plasma generally occupying all available inter-electrode space. Appreciable space charge formation occurs in both the proximity of the anode and cathode and the discharge process as in the case of the classical Townsend discharge is maintained through cathode emission. A glow discharge is not in local thermal equilibrium and the electron temperature ranges from 10^4 to $2x10^4$K. Direct ionisation plays a significant role and step wise ionisation, while negligible at low currents, may become appreciable at currents in the range of 100mA. The pseudo-glow discharge is similar to the pulse-less glow in the degree of ionisation, electron temperature and particle densities, but exhibits at the same time the presence of minute discharge pulses having features characteristic of spark type discharges. The presence of the minute pulses is readily detected electronically [24] or optically by means of a photo-multiplier.

The presence of oxygen within a discharging cavity tends to inhibit the occurrence of pseudo-glow and pulse-less glow discharges because of the electro–negativity of the oxygen gas, which reduces the availability of free electrons necessary for discharge initiation and limits the expansion of the discharge channel necessary for the formation of glow discharges. This is evident from the very regular pulse-type discharge behaviour observed with oxygen [27] as compared to the predisposition of other gases to support atmospheric pressure glow discharges under certain conditions [24]. It also accounts for the predominance of spark or pulse type discharges in air and the transition from a glow discharge process to pulse discharge type behaviour in other gases upon the addition of small trace amounts of oxygen [28]. It is also observed that in cavities containing air-like atmospheres, depletion of oxygen from the atmosphere and the surrounding surfaces coupled with increases in the conductivity of the walls due to deposition of acidic reaction products created by the discharge, will also cause a transition from spark (pulse) to pseudo-glow and pulse-less glow discharges to take place.

A gap space under going pseudo-glow or pulse-less glow discharge can superficially exhibit a uniform glow over its surface, which may not always be uniform in a strict sense, but consists of a multiplicity of light emitting dots that are caused by micro-avalanches. The arrangement or array of the micro-avalanche sites, constituting the overall dot pattern, is a function of their density, which in turn is a function of the applied voltage [29]. The micro-avalanche dot patterns may be readily observed via a light transparent indium tin oxide ground electrode deposited upon a glass surface, which acts as dielectric barrier to the discharge in the metallic/dielectric electrode gap.

The short gap pulse or spark pd is similar to the pulse-less glow and pseudo-glow discharges in that it is also a Townsend type discharge, although its underlying distinguishing attribute being that it is characterised by a higher degree of ionisation and conductivity; but the discharge is still far removed from having achieved local thermodynamic equilibration. It occurs within a brightly luminous narrowly constricted channel as opposed to the relatively faint emitted diffused glow of a pulse-less or pseudo-glow discharge; yet it is also sustained by cathode emission. Spark type pd are commonly classified as rapidly and slowly developing sparks or pulses, which are detected by the external pd sensing circuits as high amplitude fast rise time and low amplitude low rise time pulses respectively [26]. The former are also frequently referred to as streamer or streamer-like discharges, and the latter as Townsend-type discharges [30-32]. The term streamer-like has been applied to rapid rise time short duration pulses, because of its similarity in form to the rapid streamer pulses in long gaps [30]. However, there is an important and subtle difference in the mechanisms of these two forms of discharge. Since the mechanisms of development for streamer related pulses in long gaps involves ionisation wave propagation in a very high field region where the ionisation and influx of electrons at the discharge head are produced by a space charge field due to separation of positive and negative charges, the use of the term 'streamer' to denote a rapidly developing discharge pulse in a short gap is misleading. Both rapidly and slowly developing sparks or discharge pulses involve the cathode feedback mechanism of the Townsend type, albeit that in the rapidly developing pulse discharge, the classical ion induced cathode emission process plays a very minor role because of the predominance of the space charge mechanism in the vicinity of the cathode which gives rise to very intense photo-emission at the cathode.

In the field of pd measurement there has been relatively little attention paid to the detection or measurement of pulse-less glow and pseudo glow discharges [4]. Traditionally, since the early introduction of oscilloscopic techniques to pd studies, pd in electrical apparatus have, in the most part, been predominately detected and measured on electrical apparatus and cables in terms of pulse-type discharges. In retrospect much of this tendency must be attributed to the ease with which pulse-type measurement techniques may be deployed and utilized, particularly more recently with increased usage of signal processing procedures. This preoccupied tendency with only pulse discharges has resulted in relegating the existence of pulse-less glow and pseudo glow discharges to be conveniently forgotten.

Nevertheless, it must be also emphasised that the form of discharge in physical cavities is rarely, if ever, of the pulse-less or pseudo-glow type; most frequently, it is found that all these types of discharge may occur simultaneously over each applied voltage cycle. This then is the redeeming feature of pd pulse detection methods; they are sufficient enough to indicate the presence of pd, the pd inception voltage and the pd pulse intensity, even though they may not always indicate the full extent of the overall discharge process that may comprise the occurrence of pulse-less glow and pseudo-glow discharges to which they fail to respond. A case in point is the dissipation factor (tanδ) measurement, which is normally performed on stator bar instrumentation and oil/paper insulated cables to assess their quality. Frequently, it may be found that the increase in tip-up of the tanδ value with voltage may not be fully accountable by the sum of the pd pulse type losses and the dielectric losses, conceivably indicating significant pulse-less discharge loss contribution to the overall tanδ value.

Attempts have been made to ascertain theoretically the conditions that favour discharge channel expansion i.e. transition from a spark to a glow discharge. Numerical studies have been carried out on the short gap breakdown to examine the theoretical aspect of discharge channel constriction and expansion in helium, hydrogen and air at atmospheric pressure. [25,26, 33-35]. Discharges were found to exhibit an increased tendency towards discharge channel broadening when dielectric surfaces are involved. Experimental data has also demonstrated that accumulation of surface discharge products and the associated changes of surface conductivity (which affect the surface charge distribution) favour the occurrence of glow and pseudo-glow discharges.

In view of the current emphasis on pd pulse detection techniques as concerned with electrical power apparatus and cables, no further discussion shall be made on pulse-less and pseudo-glow discharges and devote the remainder of this chapter to an in-depth discussion on the subject related to pd pulse characteristics and associated test methods.

If idealised cavities within an insulating system are subjected to a sinusoidally varying applied voltage and assuming that the cavity undergoes only pulse or spark type discharge, then the cavity will discharge when the voltage across the cavity attains its breakdown value. At this point in time or phase the voltage across the cavity will collapse abruptly either to zero or some finite value normally named the 'residual voltage'. The resultant generated voltage step will excite the pd pulse detection circuit and the spark-type generated event will be detected as a discrete pd pulse. Further pulses will be generated along the ascending and descending portions of the sinusoidal voltage wave each time the applied voltage exceeds an integer value of the breakdown voltage value in the two polarities. If the breakdown and residual voltages in the two polarities are equal and constant, all detected pd pulses will be of equal magnitude. However, this is not a common occurrence in practice.

The response of pd pulse detectors decreases with the increasing rise time of the detected pd pulses. The rise time of the incident pd pulse front at the pd detector input is determined by the initial pd pulse front rise time at the discharge site and any subsequent degradation of the pd pulse rise time along its transmission path from its site of origin to the pd detector end. The latter effect is of particular importance in specimens which exhibit transmission line behaviour e.g. cables, transformers and rotating machines. However, there are also some important variations within the spark discharge mechanism, which may affect significantly the rise time of the discharge pulse formed at the site of its origin as the cavity undergoes successive discharges.

When the pd pulse discharge pattern is viewed superimposed upon the power frequency sinusoidal wave, it is observed to exhibit appreciable instability. The amplitudes of the discrete pulses are perceived to undergo substantial fluctuations accompanied by significant displacements of the associated discharge phases themselves. The phase variations of the pd pulse positions with respect to the applied sinusoidal voltage wave have been referred to as the precession of discharge. This precession of discharge phases may be explained in terms of changes in the breakdown voltage and hence, the resultant pd pulse magnitudes, which are caused by variations in the statistical time lag i.e. the time required for a free electron to appear in the cavity volume where it is necessary to initiate the electron avalanche required to produce voltage breakdown across the cavity. This means essentially that the discharge phase of a preceding discharge pulse will influence the discharge phase with respect to the applied voltage wave at which the subsequent discharge will occur. However, in addition the position of the discharge phase of each subsequent discharge will in turn also be affected by the time of appearance of the initiating electron in its own environment. The overall result of the precession of discharge phases is that each discrete pulse discharge event in a given cavity is controlled to some extent by the time occurrence of its preceding discharge. This stochastic discharge behaviour, which has been more recently examined to a considerable depth [21], poses some important ramifications as to the degree of accuracy with which pd patterns may be recognised and related to cavity size and its location in different types of power apparatus and cables.

The retarded appearance of the initiating electron in a given cavity means that in the absence of the electron at the point on time when the applied voltage becomes just equal to the breakdown voltage of the cavity, breakdown will not occur and the applied voltage will continue rising until such time that an initiating electron becomes available. The consequence will be that the breakdown of the cavity will take place at a higher voltage, thereby generating a greater magnitude of pd pulse. To illustrate the effect of a protracted statistical time lag upon the magnitude and rise time of the ensuing pd pulse, one must consider the manner in which the pd pulse shape is altered as a function of the over-voltage across a cavity or short gap.

Figure 2.1 portrays the shapes of calculated breakdown current pulses obtained with a 0.5 mm gap in air under atmospheric pressure at low values of over-voltage in ascending order of magnitude. At low over voltages, the peak breakdown current is seen to decrease very substantially with falling over-voltage; accompanied by a pronounced increase in the rise time of the pulse. The slow low amplitude current pulses are essentially pulses formed by the movement of ions across the gap, since the electrons, released from the cathode due to the ion impact necessary to sustain the Townsend type discharge, are more rapidly swept out of the gap than the slow moving ions.

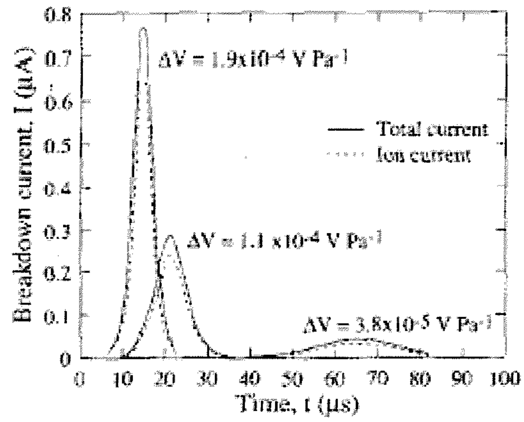

Figure 2.1 – Calculated Breakdown Current Pulse Forms of a 0.5mm Gap, With Over-Voltage ΔV as a Parameter [35]

Hence the contribution of electrons to the breakdown current pulse is relatively small. It is palpably evident that at extremely low over-voltages across a cavity undergoing Townsend type pulse discharge, the generated pulse magnitudes with inherently long rise times, may render their detection difficult with conventional pd pulse detectors having high lower cut off frequencies. At higher over-voltages, increasingly more electrons are emitted from the cathode leaving behind the slower moving ions of polarities, causing the accumulated space charge due to the positive ions to augment the ionisation rate at the proximity of the cathode. As the positive ion space charge effects become more predominant in relation to the classical Townsend process of electron emission resulting principally from positive ion impact at the cathode, the pulse form of the current is perceptibly altered.

2.4 Cable Specimens

The introduction of cross linked polyethylene (xlpe) extruded cables into the power distribution sector in the early 1950s required a rapid development of pd detection techniques and testing standards to assess the reliability of these cables. Much development work went into characterising the pd behaviour in these cables as well as determining their resistance to pd induced degradation. Figure 2.2 is a schematic connection diagram of an early arrangement used in the late 1950s and early 1960s for the measurement of the pd discharge rate and differential pulse height distribution on cables [7,8]. Short cables lengths (shown as C_p), which acted as lumped capacitance specimens at the frequencies of measurement, were used for the investigations.

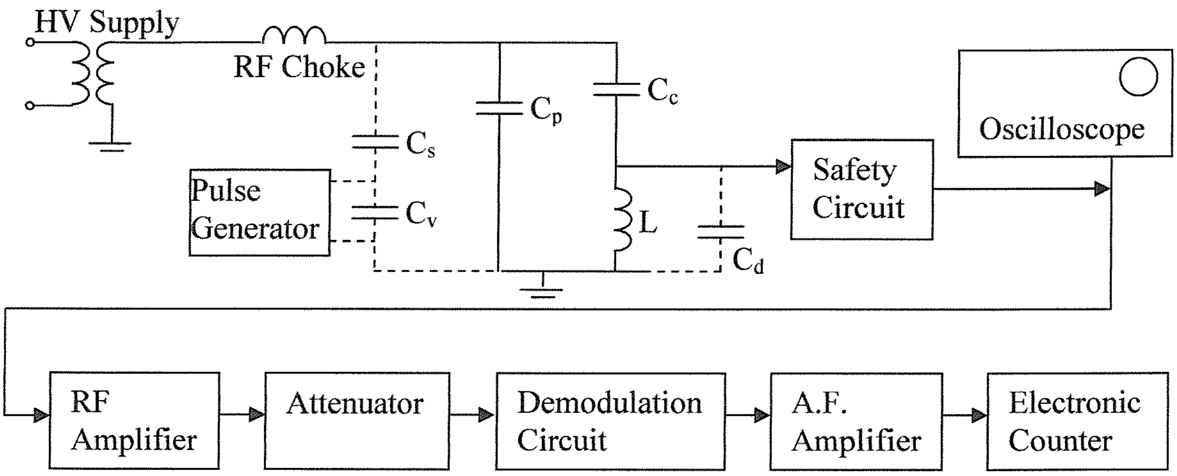

Figure 2.2 – Early Schematic Circuit Arrangement for the Measurement of Pulse Discharge Rate and Differential pd Pulse Height Analysis [7]

There was general consensus that pd originated from cavities from within the extruded insulation or at the interfaces between the insulation and the semi-conducting conductor and insulation shields. It became apparent that, in contrast to paper/oil insulated cables, polymeric cables were highly susceptible to pd induced degradation and could not operate in the presence of pd without undergoing eventual failure. Accordingly, pd test standards were devised, which required the polymeric cables to be free of discharges at operating voltage, when tested at a detection sensitivity of 5pC. With the improvement in the extrusion process of solid polymeric dielectrics and smooth, low contaminant containing extruded semi-conducting and insulation shields, the pd test standards became proportionately more stringent, necessitating the polymeric extruded cables to meet the 5pC sensitivity requirements at voltages substantially above the operating voltage level. With this added requirement an additional safety factor was introduced with the consequence that newly produced polymeric cables leaving the manufacturing facility are now free of discharges not only at the operating voltage level but also at voltages above those levels which can be envisaged to be imposed upon the cables under surge voltage conditions.

In view of the foregoing discharge operating constraints, pd tests on newly manufactured polymeric cables are essentially go/no-go type tests in that the cable specimens are rejected if they exhibit the presence of discharges at the prescribed sensitivity and voltage test level or accepted in their absence [36]. Long power cable specimens behave as transmission lines and must, therefore, be terminated in their characteristic impedance, if measurement errors due to pd pulse reflection effects are to be obviated. Since routine pd measurements are carried out on newly manufactured cables with the specimens invariably unterminated, pulse reflection errors occur but these are minimised by specifying the so called α pulse shape response of the detection circuit, whereby the integration errors due to pulse overlap are additive, resulting in increased rather than decreased detection sensitivity. The α response simply refers to a highly damped pulse in which the first peak of oscillation represents the maximum amplitude of the pd pulse. Additional sensitivity is achieved with suitably designed noise filtering circuits to reduce extraneous interference.

With the stringent pd specifications in place to eliminate cables at the production site, which are subject to pd, the current effort and activity in the cable area has shifted to elaborate pd measurement schemes to locate discharges and assess their severity in cables in the field that may either be introduced in the course of mishandling during their installation or through aging developed discharge activity. If identification of the type of discharge sites is attempted in terms of the pd pulse-height and discharge phase distribution patterns, then, in order to eliminate pattern errors due to reflections from the far end, the cable specimen under test must be terminated by its characteristic impedance, utilising a hv termination arrangement.

Unlike coaxial communication cables, polymeric power cables are lossy systems at elevated frequencies so that their characteristic impedance is a complex quantity and differs in magnitude from that of a loss-less transmission line where L and C denote respectively the incremental inductance and capacitance parameters of the cable.

When new cable designs are evaluated in terms of their pd pulse height and discharge phase distribution characteristics for which precise measurements of the discharge pulse amplitude and the actual number of discharge pulses are necessary, it is expedient to use short cable specimen lengths. With sufficiently short lengths of cable, pulse reflection effects from the far end of the cable do not cause problems when conventional low frequency narrow band detectors are employed.

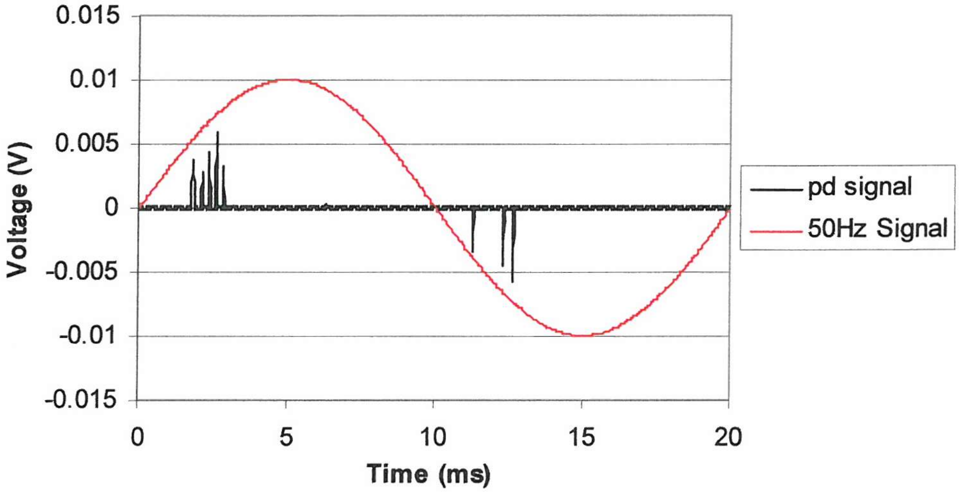

Figure 2.3 – Example of pd Pattern

The widespread usage of computer-based techniques in the measurement of pd has provided added flexibility in the treatment of pd test data and associated signal processing techniques. With computer assisted techniques, it is readily possible to display simultaneously three dimensional plots of pd pulse charge transfer, discharge rate or pulse number at the discharge phase of occurrence of the individual pulse with applied voltage or testing time as a parameter. A convenient display of pd pulse data consists of simultaneously obtained plots of the number of pd pulses and pd pulse amplitudes as a function of the discharge phase, obtained over a given applied voltage. Such pd patterns obtained on a xlpe cable permit not only the determination of energy dissipated by the positive and negative pd pulses but may in some cases provide a possible means for identifying the defects responsible for the observed pd behaviour [7].

Over the last decade or so there has been a considerable increase in pd measurement activities related to pd discharge site location on both distribution and power transmission polymeric type cables in the field, some of the same type of work has also involved oil/paper insulated cables. The objective is to remove cables or sections of cable circuits as well as cable joints, which exhibit various degrees of pd activity and are judged to be in imminent danger of undergoing failure. The portable pd locating techniques available for solid and solid-liquid type cables can essentially be categorised into probe and non-probe test methods. There are a number of non-probe pd site location methods, most notably the pd polarity correlator [37] and a number of variations of the time domain reflectometry (tdr) procedures [38]. The advantage of the tdr technique is that the measurements may be carried out in-situ on directly buried cables or cables installed in ducts. There are disadvantages though, in that tdr methods require temporary interruption of service and a portable power supply to energise the disconnected cables. In contrast, while the probe methods may be directly applied on cables under operating conditions, they are by their very nature scanning devices and require accessibility to the cable exterior surfaces. The latter disadvantage may in part be circumvented in the case of splice or joint tests, where it is becoming common practice (particularly in the case of extra high voltage polymeric transmission cables) to install permanent pd detection probes to monitor any possible development of pd in the joints.

TDR methods employed for the location of pd discharge sites in polymeric cables utilise either low frequency 0.1Hz voltage sources, which permit the testing of longer cable lengths [39], or the usual power frequency 50Hz voltage sources, which produce a larger number of pd pulses per unit time and thus facilitate electronically the pd site detection procedure [40-42]. Current tdr methods have been greatly improved by the use of digital techniques and are capable of locating pd discharge sites with acceptable precision. Since discharge site location is determined in terms of the incident pd pulses and the time delay between their multiple reflections, the accuracy and the precision of the discharge site location is a function of the rise time and pulse width of the discharge pulses, their distortion and broadening as they propagate along the cable as well as the signal to noise ratio characteristics of the detection circuit.

In discharge site location tests on in-service cables, it is desirable to utilise detector sensitivity levels of 5pC, since newly manufactured cables are rejected with discharges at and above this specified level. As the extraneous noise levels in service environments generally exceed this level, suitable noise rejection filters must be incorporated in the test circuitry. Communications related electromagnetic interference occurs at fixed frequencies and is, therefore, most simply removed by band rejection or notch filters. Another simple noise elimination procedure is available for the rejection of interference pulses that are generated from switching events which bear a definite phase relationship to the applied sinusoidal voltage wave, such that blanking circuitry may be employed to eliminate all pulses within the applied phase segments over which the interference pulses appear. When direct operator intervention in the noise filtering approach is not feasible, adaptive digital filtering techniques can be used [41,43]. If the pulse response of a full cable specimen length as well as its attenuation and phase constants are known, the response due to a discharge at any point on the cable may be derived in terms of its transfer function [41]. Consequently, the pulse response associated with a discharge at any point along the cable specimen may be correlated with the measured noise i.e., the location of the pd site corresponds to that value, which yields the maximum cross-correlation coefficient.

As has been mentioned already, the alternative procedure for the location of pd sites in solid polymeric and oil impregnated paper cables involves the use of scanning couplers, which may be of the capacitive or inductive type. Capacitive couplers function well only on unshielded cables sections or cable ends, however, capacitive couplers may also be installed permanently under shield in joints to monitor or detect newly initiated discharge activity. It should also pointed out that acoustical probes which function well with compressed gas cable or buss sections, do not perform particularly well on polymeric cables that are characterised by high acoustical impedances although having the advantage of being electrically noise free.

Since the presence of pd in polymeric cable under operating conditions cannot be tolerated due to the high susceptibility of the polymeric dielectrics to pd induced degradation, discharge on-set monitoring of on-line hv power transmission cables is of paramount importance [44,45]. The appearance of pd may necessitate immediate removal of the accessory of the polymeric cable segment in which the pd source is located in order to avert service interruption due to a high probability of imminent failure at elevated voltages.

While acoustical methods are relatively ineffective for pd tests on polymeric cables, they are better suited for pd site location on compressed gas cables. This can be readily achieved using conventional commercially available ultrasonic detection circuitry. Acoustical methods may achieve sensitivity levels of 20 to 25pC, which is substantially less sensitive than those of electrical pd detectors, which can detect pulses down to levels of 1pC. It should also be added, that while acoustical methods can readily detect discharges due to the movement of particles, they are quite ineffective in detecting low level pd pulses which occur within the occluded cavities of the spacer insulators.

In closing the discussion on pd measurements on cable specimens some remarks ought to be made in regard to pd site location tests at cable manufacturing facilities. PD site location tests were frequently and in some cases routinely carried out on polymeric cables until the early 1970s. As solid dielectric extrusion techniques improved along with the introduction of extruded semi-conducting shields that replaced the antecedent carbon-tape shields, the occurrence of pd in newly manufactured cables diminished markedly. The most effective technique for locating pd sites in polymeric extruded insulation and cavities at interfaces between the conductor/semi-conducting shield and the extruded insulation, involved the use of the so-called Gooding train [46] whereby a polymeric cable without the outside insulation semi-conducting shield was passed over through a hollow cylindrical hv electrode situated at the centre of a long pipe, containing high resistivity de-ionised water. The water column at the end was grounded via two grounded tanks, thereby causing the cavities to undergo maximum discharge intensity at the centre of the tube. Since the Gooding train technique could not be applied directly to finished cables with insulation semi-conducting shields in place, x-ray techniques were utilised to scan voltage-energised cables. X-ray irradiation of cavities provided the free electrons to initiate and maintain the pd in the cavities, which normally could not have undergone discharge.

3. Comparison of On-Line Partial Discharge Detection Methods for XLPE Cable Joints

3.1 Introduction

Various methods of on-line partial discharge detection are currently being investigated within the University of Southampton High Voltage Laboratory in collaboration with National Grid Transco and Pirelli Cables. The aim of this chapter is to assess a selection of these methods to determine whether they provide both the reliability and sensitivity required for use in on-line partial discharge detection applications. Radio frequency current transformers (rfcts), Rogowski coil and capacitive coupling techniques were assessed.

3.2 Methodology

For the purposes of these tests a 10m length of 132kV cable including a joint with a known partial discharge site was used. The lead sheath around the joint and cable 1m each side of the joint were removed, so the sensors could be placed on the outer semi-con layer, with copper mesh wrapped around the rest of the exposed semi-con. The copper mesh was extended to form a loop at the joint, so the RFCTs and Rogowski coil could be attached for measurement purposes. The experimental arrangement can be seen in Figure 3.1.

Sensors were placed at the sheath break on the joint, similar to placing sensors at a junction box for cross-bonded cables, and secondly at the termination of the cable on the earth strap. However it is impossible to implement a capacitive coupler on an earth strap, as it isn't a coaxial arrangement. A conventional Robinson detector was connected to the loop at the termination so the input waveform of the calibrator could compare the sensor responses.

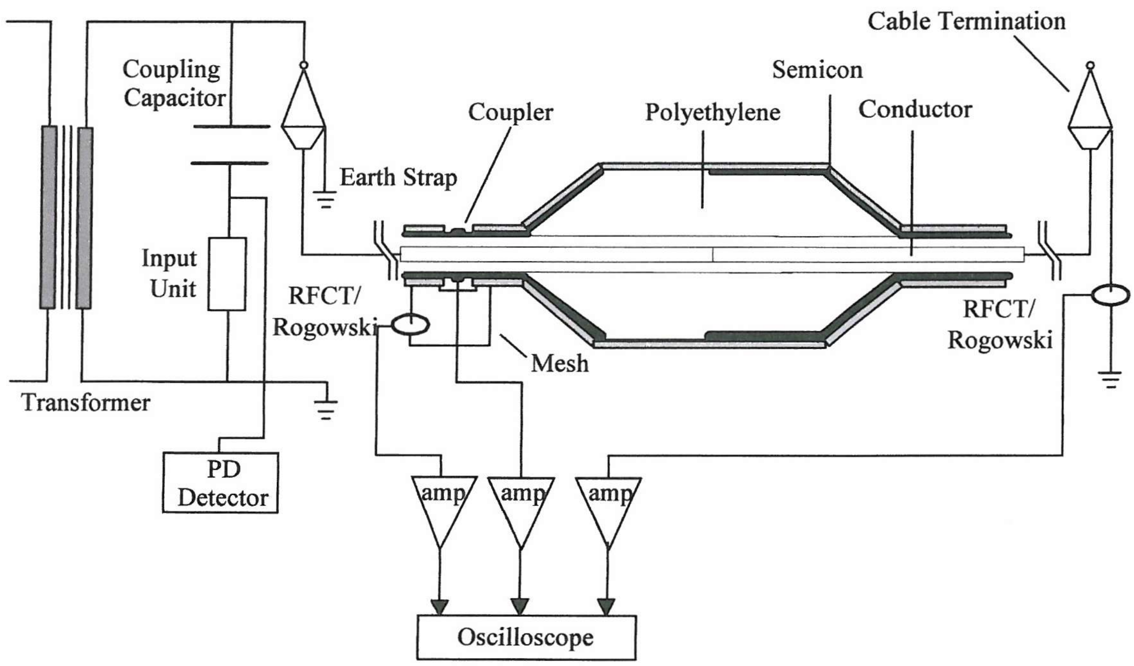

Figure 3.1 – Experimental Arrangement

To determine the on-line suitability for each detection method two different approaches were investigated. Firstly partial discharge calibrators were used to inject pulses of known magnitude into the termination and the responses of the sensors were recorded. Secondly voltage was applied to the hv loop to achieve real partial discharges and simulated corona discharge.

Two different types of pulse calibrator were used, the first was a low frequency Robinson calibrator and the second was a high frequency Lemke Diagnostics calibrator. The low frequency Robinson calibrator was used to inject pulses into the termination and the responses of the rfcts and Rogowski coils recorded. The same tests were repeated with the addition of a 50Ω in-line rf pre-amplifier, with a 20dB gain, to determine if they improved the sensitivity of the sensors.

The Robinson calibrator was then replaced with a Lemke calibrator so that the calibration pulse could now be varied to any specified magnitude between 0 - 500pC. The magnitude of the pulse was varied so that the minimum detectable level of discharge could be determined for each of the sensors. The minimum level of detection was defined as the lowest magnitude of input pulse that the sensor could clearly distinguish between noise and the injected pulse. The lowest detectable level of discharge was measured for each sensor type both with and without the rf pre-amplifiers.

3.3 Results

Table 3.1 shows the results for the Robinson Calibrator.

	Pulse Detected?							
	Without Amp				With Amp			
	50pC		500pC		50pC		500pC	
	Joint	Termin.	Joint	Termin.	Joint	Termin.	Joint	Termin.
rfct	x	x	✓	✓	x	x	✓	✓
Rogowski coil	x	x	x	x	x	x	✓	✓
Capacitive Coupler	x	-	✓	-	x	-	✓	-

Table 3.1 – Results for Robinson Calibrator

Table 3.2 shows the minimum detectable pulses injected with the Lemke calibrator

	Without Amp		With Amp	
	Joint	Termination	Joint	Termination
rfct	150pC	60pC	30pC	15pC
Rogowski coil	150pC	60pC	60pC	30pC
Capacitive coupler	15pC	-	5pC	-

Table 3.2 – Minimum Detectable Pulses using Lemke Calibrator

Table 3.3 shows the results of the sensors when detecting real PD (typically 20pC in each case) and corona (typically 60pC). All results were taken using pre-amplification.

	PD Detected? (~20pC)		Corona Detected? (~60pC)	
	Joint	Termination	Joint	Termination
rfct	✓	x	✓	✓
Rogowski coil	x	x	✓	✓
Capacitive coupler	✓	-	✓	-

Table3.3 – Results for PD/Corona

3.3.1 Robinson Calibrator Results

Initially the Robinson calibrator was used to inject a 50pC pulse into the system at the termination and the responses of the rfcts, Rogowski coil and capacitive coupler were measured at both the joint and the termination. However none of the sensors could detect a signal above that of noise, so the injected pulse was increased to 500pC.

At 500pC the rfct at the termination (Figure 3.3) gave a better response, by roughly 50%, compared to the rfct on the joint (Figure 3.2). This is due to attenuation within the cable, as the pulse was injected at the termination

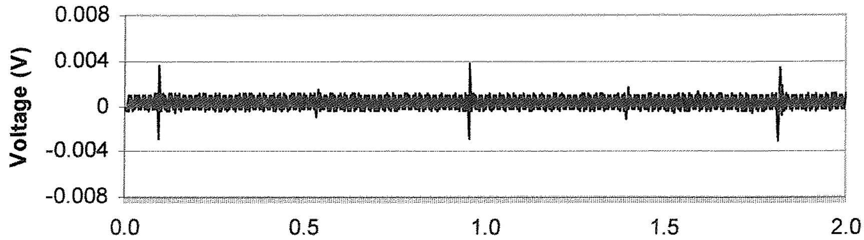

Figure 3.2 – rfct at Joint Response to 500pC Pulse

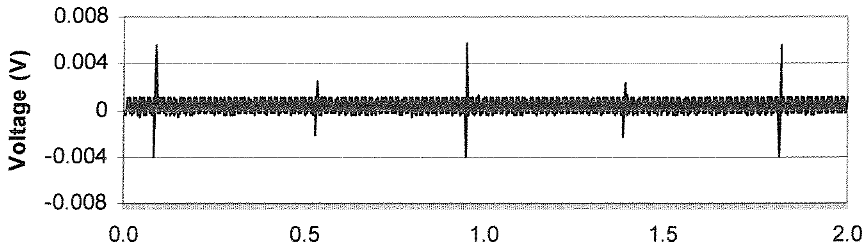

Figure 3.3 – rfct at Termination Response to 500pC

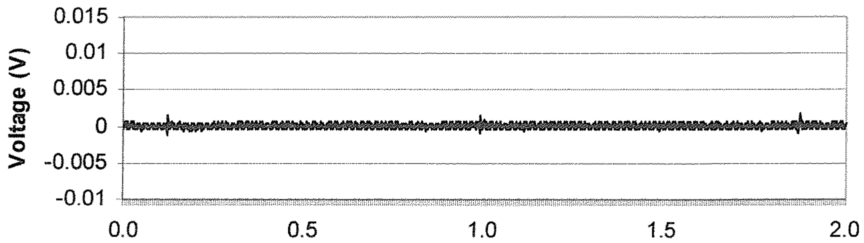

Figure 3.4 – Capacitive Coupler Response to 500pC

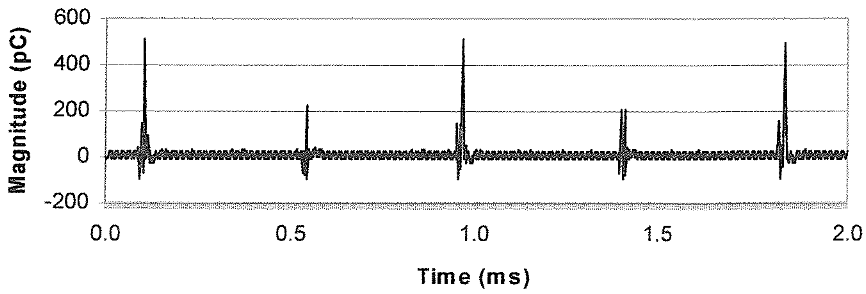

Figure 3.5 – Robinson Detector Response to 500pC

At 500pC it was still not possible for the Rogowski coil to distinguish the input pulse from noise at either the termination or the joint. With the addition of a pre-amplifier the Rogowski coil was able to detect the 500pC pulse at both the termination and the joint (Figures 3.6 and 3.7 respectively), again the coil at the termination giving a better response due to signal attenuation within the cable.

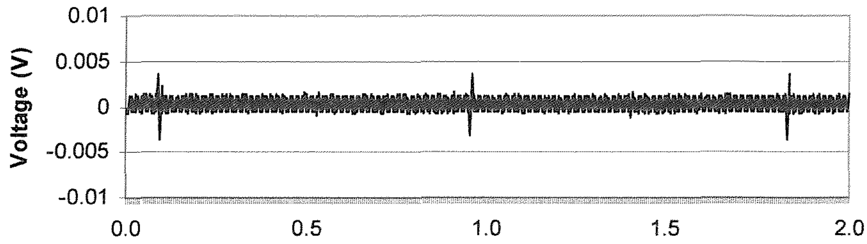

Figure 3.6 – Rogowski Coil at Joint With Amp Response to 500pC

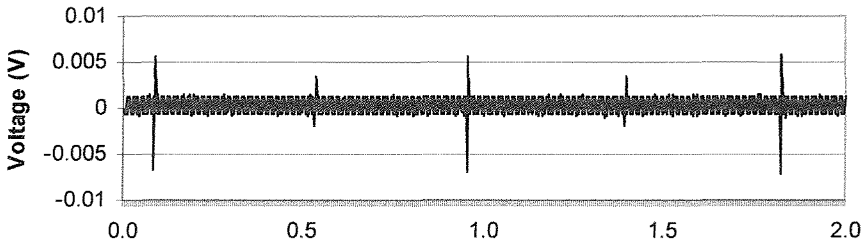

Figure 3.7 – Rogowski Coil at Termination With Amp Response to 500pC

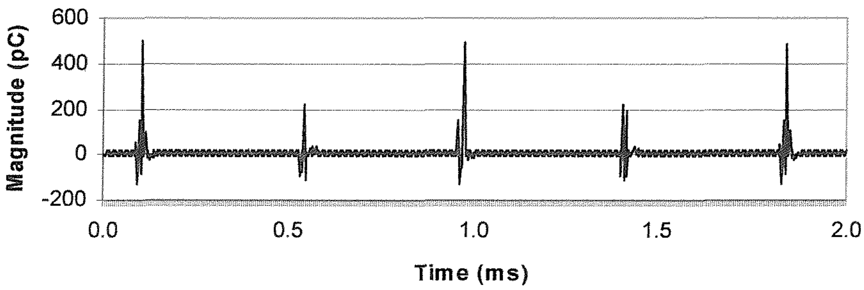

Figure 3.8 – Robinson Detector Response to 500pC

The Rogowski coil was unable to detect a 50pC pulse above noise with the pre-amplifier. The rfct and capacitive coupler could not detect the 50pC pulse with the addition on the pre-amp either but were still able to detect the 500pC pulse with amplification.

3.3.2 Lemke Diagnostics Calibrator Results

Without any pre-amplification both rfcts and Rogowski coils could detect a minimum of around 150pC, with the exception of the RFCT at the termination, which could go as low as 60pC. The capacitive coupler was able to detect 15pC.

However with the addition of the pre-amplifier the rfcts could detect discharges of 15pC at the termination and 30pC at the joint (Figures 3.9 and 3.10 respectively), and the Rogowski coil was able to detect pulses of around 20pC at both locations (Figures 3.11 and 3.12), whereas the capacitive coupler was able to detect as low as 5pC (Figure 3.13). The pre-amps did however amplify the communications and background noise also as can be seen in the figures.

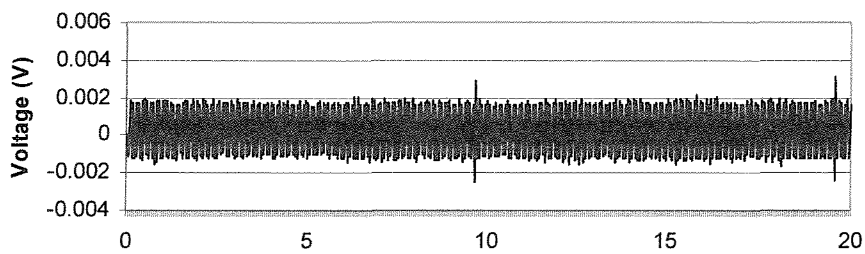

Figure 3.9 – rfct at Joint With Amp Min Detect 30pC

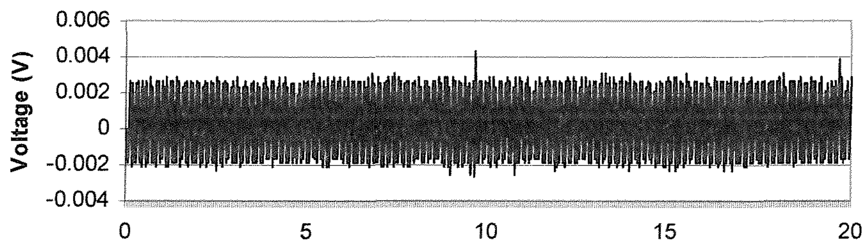

Figure 3.10 – rfct at Termination With Amp Min Detect 15pC

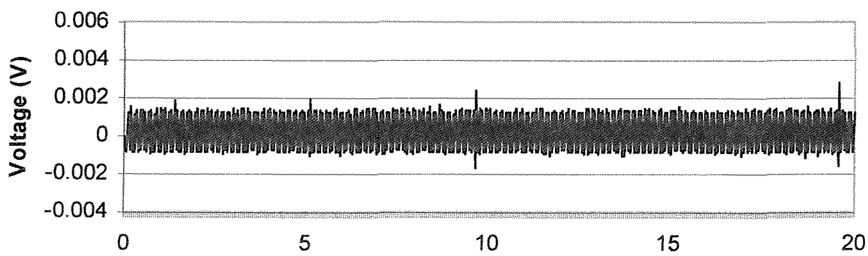

Figure 3.11 – Rogowski Coil at Joint With Amp Min Detect 30pC

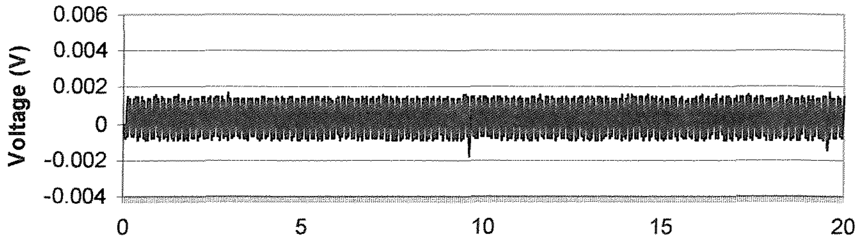

Figure 3.12 – Rogowski Coil at Termination With Amp Min Detect 30pC

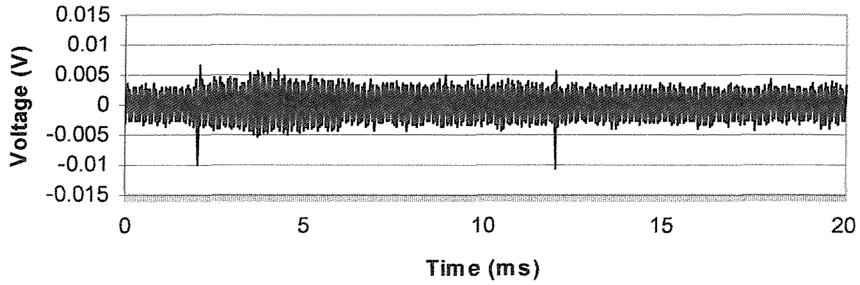

Figure 3.13 – Capacitive Coupler With Amp Min Detect

3.3.3 Applied Voltage

High voltage was applied to the cable to determine the response of the sensors to both partial discharges and corona. The inception voltage for partial discharges and corona was typically 42kV and 22kV respectively. These voltages were applied for all measurements taken, typically inducing partial discharges of 20pC and corona of 60pC.

However, as the discharges were now in the joint itself it was found that the sensors on the joint were more sensitive as they were now closer to the discharge site, so the pulses attenuated as they travelled towards the terminations. All readings were taken using the pre-amplifier to increase sensitivity.

The internal discharge of the Robinson detector was calibrated to 50pC during these readings so the magnitude of the discharges from the joint could be scaled and to provide a trigger signal for the oscillope. These signals can be seen on Figures 3.15 at 9 and 19ms, and on Figure 3.17 at 8 and 18ms.

3.3.4 Partial Discharge Results

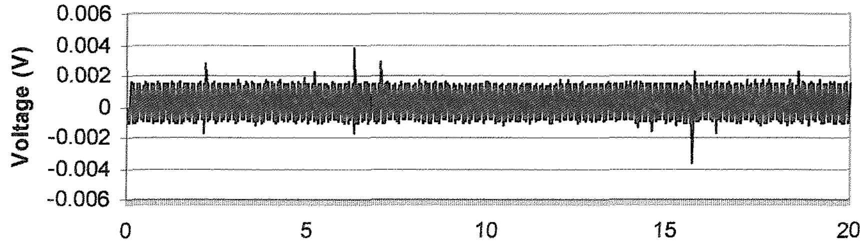

Figure 3.14 – rfct at Joint With Amp Response to pd

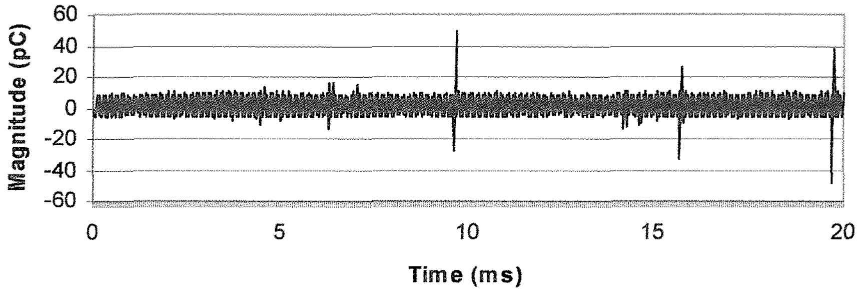

Figure 3.15 – Robinson Detector Response to pd

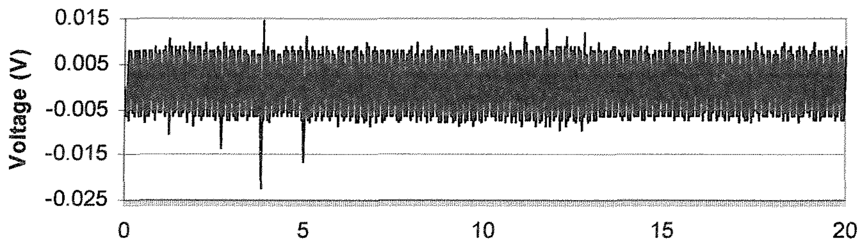

Figure 3.16 – Capacitive Coupler With Amp Response to pd

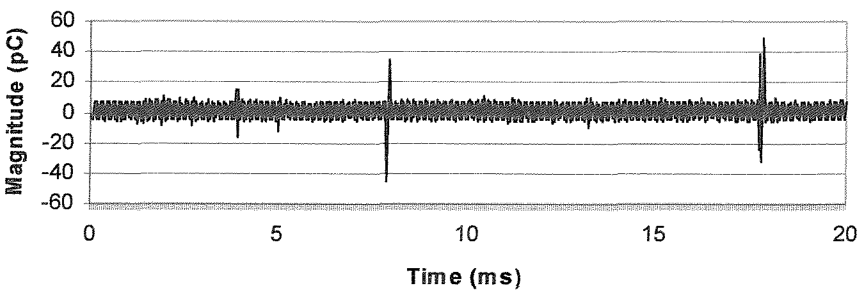

Figure 3.17 – Robinson Detector Response to pd

Neither the rfct at the termination or the Rogowski coils at the termination or joint were able to detect partial discharge signals above that of noise, at the specified voltage.

3.3.5 Corona Results

Finally a thin wire was connected to the terminals of the transformer to simulate corona discharge. Again as this discharge was on the termination, the response of the sensors at the termination was better than those at the joint due to attenuation. The internal Robinson Pulse can be seen in Figure 3.19, 3.21, 3.23, 3.25 and 3.27 at 7 and 17ms

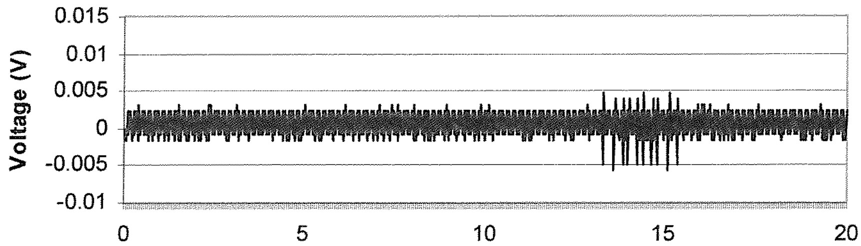

Figure 3.18 – rfct at Joint With Amp Response to Corona

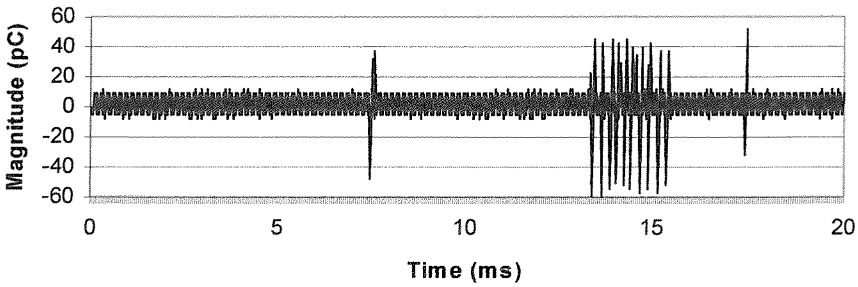

Figure 3.19 – Robinson Detector Response to Corona

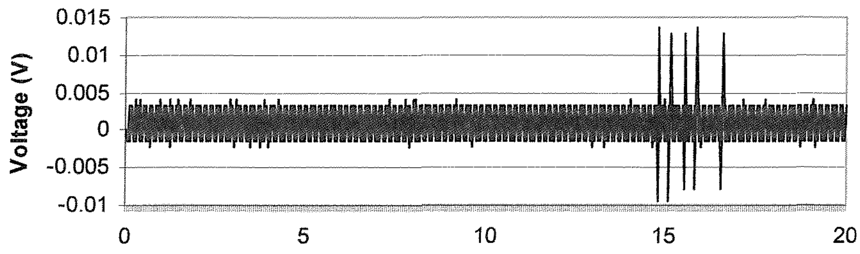

Figure 3.20 – rfct at Termination With Amp Response to Corona

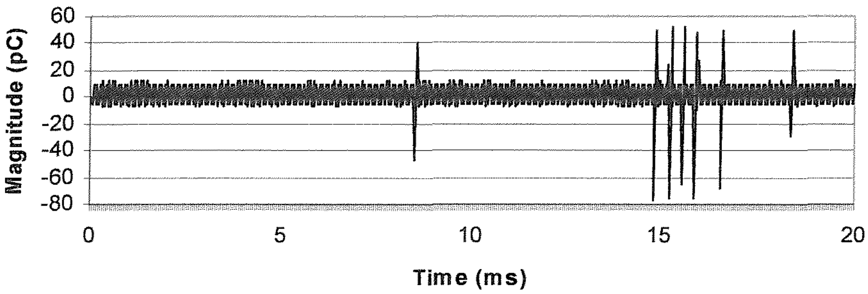

Figure 3.21 – Robinson Detector Response to Corona

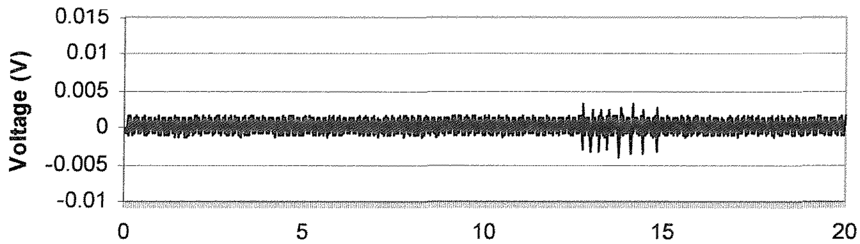

Figure 3.22 - Rogowski Coil at Joint With Amp Response to Corona

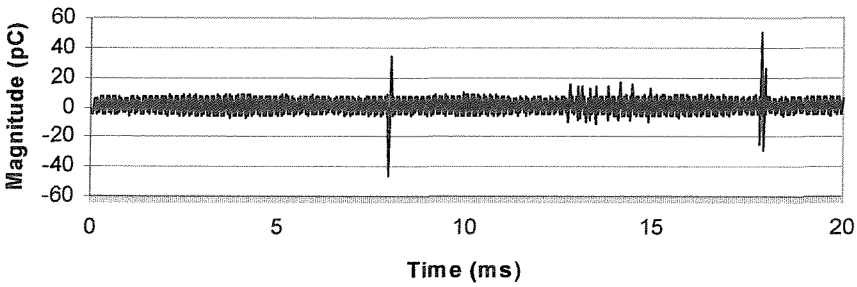

Figure 3.23 – Robinson Detector Response to Corona

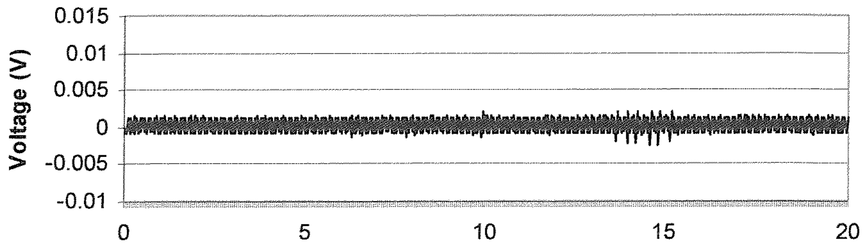

Figure 3.24 – Rogowski Coil at Termination With Amp Response to Corona

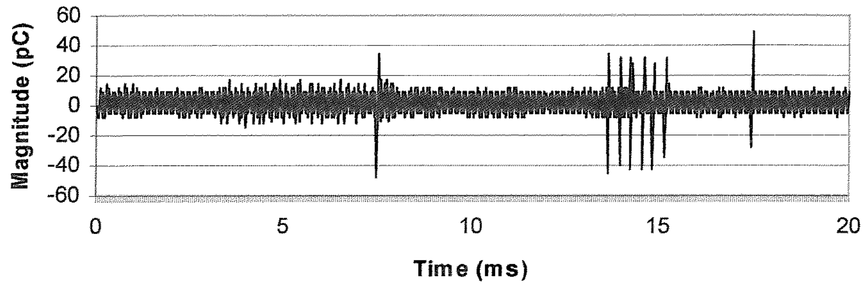

Figure 3.25 – Robinson Detector Response to Corona

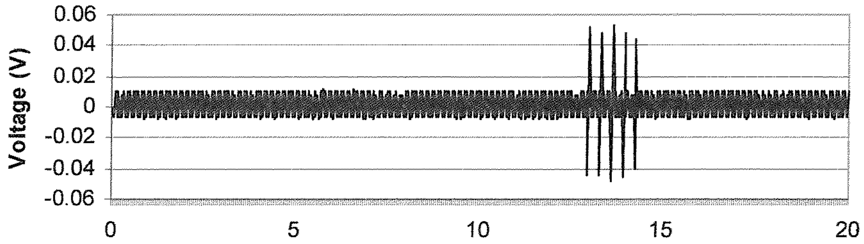

Figure 3.26 – Capacitive Coupler With Amp Response to Corona

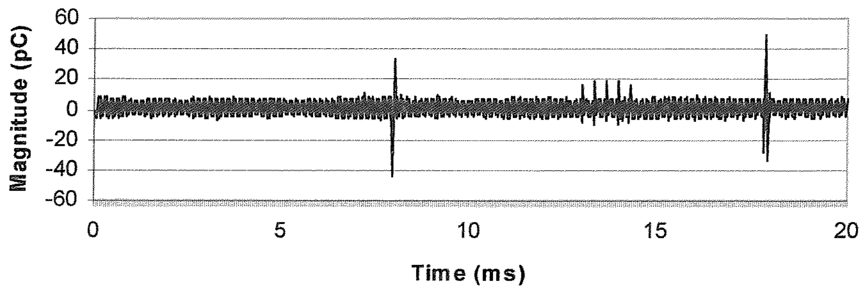

Figure 3.27 – Robinson Detector Response to Corona

3.4. Conclusions

It is important to remember that the calibrator pulses were injected at the termination and real pd occurs within the joint. Therefore due to attenuation the sensors at the terminations will have a better response to injected pulses than the sensors at the joint, and vice versa for pd.

Comparing the results obtained from the Robinson calibrator and the Lemke Diagnostics calibrator it can be seen that the sensors have a better response to the Lemke calibrator. Further investigation of the calibrator pulses (Figures 3.28 and 3.29) shows that not only does the Lemke calibrator have a rise time one order of magnitude faster than the Robinson calibrator but it also generates a pulse one order of magnitude greater in volts for a pulse of equal charge.

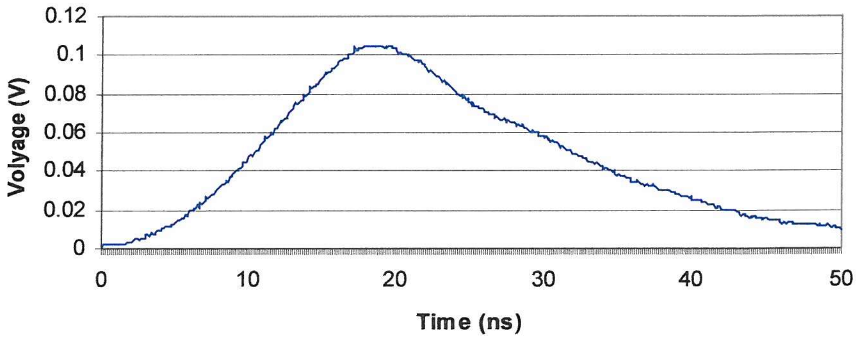

Figure 3.28 - Robinson Calibrator Expanded Pulse

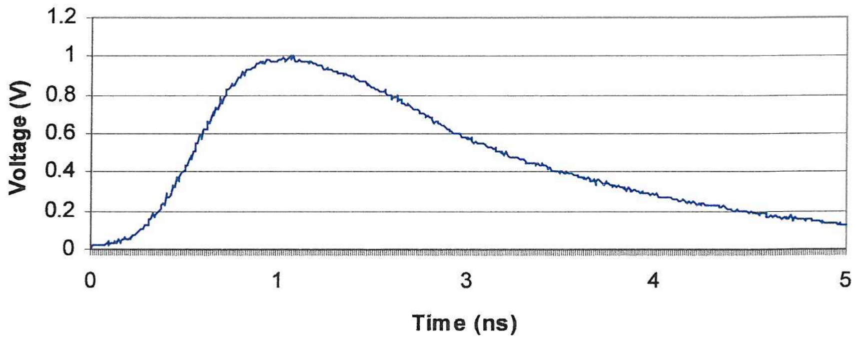

Figure 3.29 – Lemke Calibrator Expanded Pulse

With both the rise time and magnitude of the pulse being greater on the Lemke calibrator in comparison to the Robinson calibrator the sensors see a larger pulse with a much greater rate of change of flux.

Due to the method in which a capacitive coupler is implemented it has much better electrical and magnetic coupling than either the rfct or the Rogowski coil. The capacitive coupler directly couples the signal within the sheath, whereas the rfct and Rogowski coil couple the signal that has been coupled onto the sheath.

The different bandwidths of the sensors affect measurement sensitivity. The rfct and capacitive coupler have larger bandwidths (typically 10kHZ – 250MHz) than the Rogowski coil (typically 100kHz – 100MHz). The frequency of the injected pulses was within the bandwidth of all three sensors, however the gain of both the rfct and Rogowski coil is lower than that of the capacitive coupler. The frequency of pd was higher than the injected pulses and exceeded the bandwidth of the Rogowski coil limiting its performance. However, the presence of high frequency components improved the detection sensitivity of the rfct and capacitive coupler.

The capacitive coupler response is noisier than the rfct or Rogowski coil, but has a greater sensitivity and hence detects pd at lower levels. However a capacitive coupler is not easily implemented in the field as it requires the removal of the sheath, unlike rfct and Rogowski coils which can be readily implemented on the cross bonding leads.

4. Review of Commercially Available Systems: LDIC LDY724 Directional Coupler PD Monitoring System

4.1 Introduction

The directional coupling measuring system LDY-724 manufactured by LEMKE Diagnostics GmbH is designed for sensitive, location of pd faults in high and extra high voltage cables and accessories. The fault location is determined by the propagation direction of the pd signal detected by directional coupling sensors. The system is designed to have high noise suppression so that pd signals can be discriminated from noise at the site location.

The LDY-724 main application is for the monitoring of cables and their accessories in unscreened environments, displaying the results as a Windows front end format. It should be noted that due to problems with this system no useful results were obtained.

4.1.1 System Architecture

The LDY-724 consists of three main elements:

- A computer based user interface
- Two signal processors
- Two directional couplers

The system is designed to implement all functions in a digital format. The directional couplers are placed on a cable, with one each side of the potential discharge site, e.g. either side of a cable joint, and each end of these is connected via a coaxial cable to a pre-processor, which are in turn connected via an optical link to the user interface. A discharge within the cable will induce a signal within the directional coupler, which will give two different output magnitudes dependant on the direction of propagation of the signal. The pre-processor runs as a peak detector and as a variable attenuator, the level for both can be varied dependant on signal strength and noise. The signal is then converted into a digital optical signal, and fed to the main computer where the information is displayed and is recorded for interpretation either by the computer or the operator.

4.2. Basic Principles

4.2.1 Directional Coupler Principle

Consider a coaxial system shown in Figure 4.1:

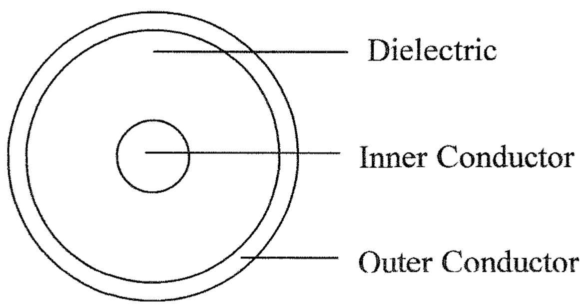

Figure 4.1 – Cross Section of a Coaxial System

The basic principle of directional coupler theory is that when a pulse is injected into the inner conductor there is both a current pulse with an associated magnetic field and a voltage pulse with an associated electromagnetic field.

Any current flowing in a conductor will set up a magnetic field that is inversely square to the distance from the conductor, and conversely a magnetic field moving through a conductor will induce an electric current. When a current pulse is injected into the inner conductor a magnetic field is created, which will pass through the outer conductor and hence induce an emf in it.

Similarly if the potential on one plate of a capacitor is raised a current flows through the capacitor until the maximum charge capacity of it is reached. When a voltage pulse travels along the inner conductor, if an elemental cross section is considered, it will see a sharp rise then fall in voltage resulting in a current flow across the two.

A directional coupler is simply a conductor placed around the outer semi-con layer of an HV cable, where the outer conductor has been removed as illustrated in Figure 4.2. However, in addition to this connecting leads are taken off the sensor at each end.

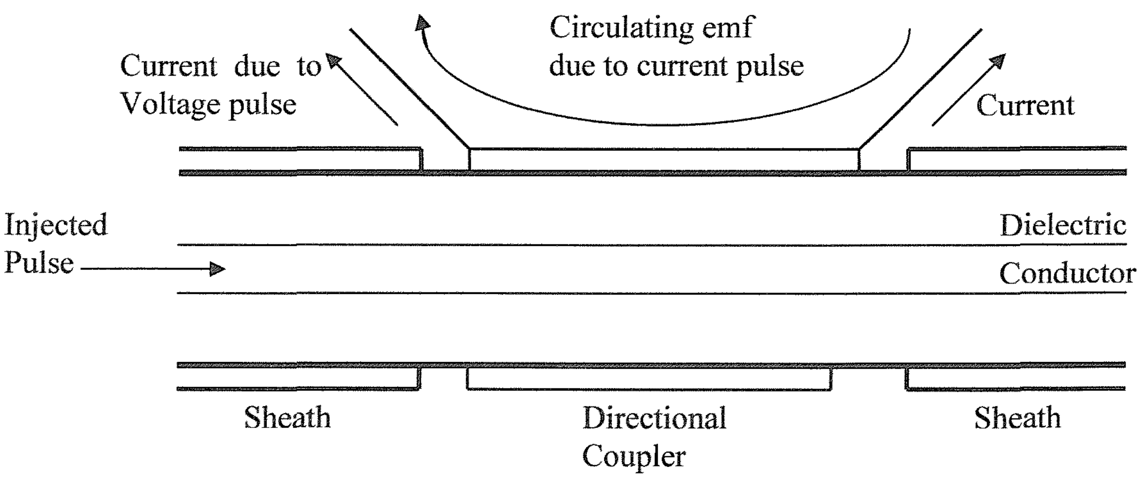

Figure 4.2 – Directional Coupler Implementation

When a pulse is injected into the conductor the sensor outputs are dependant on magnetic and electromagnetic responses. With reference to Figure 4.2 when the pulse is injected from the left the current due to the electromagnetic field of the voltage pulse is superimposed on the emf of the magnetic field on the left hand side of the sensor [47]. However the circulating emf is opposing the current on the right side of the sensor, which in the ideal case cancels the electromagnetic current effect.

Hence the direction of propagation of the pulse can be determined, as the signal on the left hand side of the sensor will be larger than that on the right.

The LDY-724 uses this principal to determine the direction of propagation of a partial discharge signal, and by using another identical sensor placed the other side of a cable joint it can determine whether the discharge was within the joint or external to it. Typically the discharge site is within the joint as it is assumed that cables are manufactured discharge free.

4.2.2 Noise Discrimination and PD Location

To distinguish them from noise the pd signals are evaluated within the signal processors, or directional coupler detectors (dcd). Using peak detectors the four signals from the two couplers are time gated so that only impulses during the first 40ns after the trigger event are measured. This time is large enough to capture the pulse information on both sides of the joint but short enough to avoid measuring any reflected pulses from terminations.

The dcds assign each pulse a source, i.e. if the pulse came from the right of the joint, the left of the joint or from within the joint. Consider the system shown in Figure 4.3:

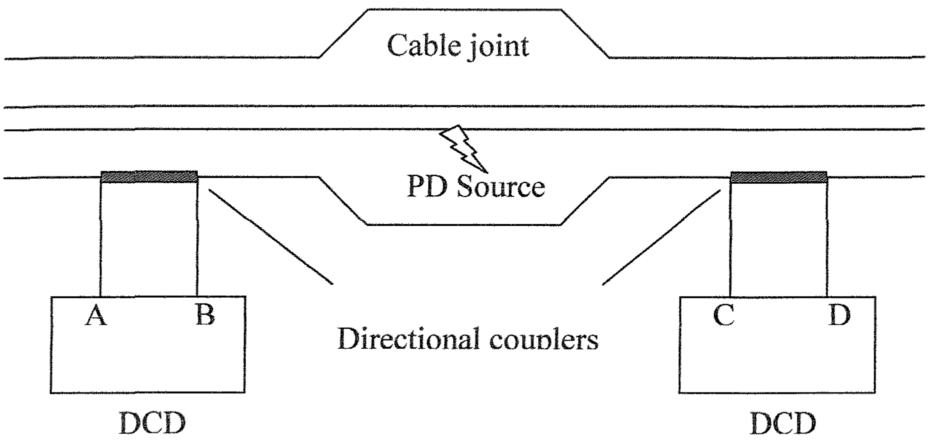

Figure 4.3 – PD Detection in a Joint Using Directional Couplers

If there is a partial discharge within the joint then, due to the nature of directional couplers the signals on B and C will be greater than those on A and D, however noise signals will be even across all channels. Discharge signals are assigned as those that have a ratio of 1:2 between the two outputs on the same coupler. Therefore, signals that cannot be assigned to a source by a 1:2 margin are regarded as noise [49]. The LDY-724 will discriminate a discharge within the joint from noise if the following conditions are realised:

$$B \geq 2A$$

$$C \geq 2D$$

A similar set of relationships have to be realised for discharges either side of the joint, i.e. discharges from the left of the joint will couple with A and C, and discharges from the right of the joint will couple with B and D. Table 4.1 shows how the coupling of outputs gives the direction of the discharge site.

	A	B	C	D
Discharge from left	X		X	
Discharge within joint		X	X	
Discharge from right		X		X

Table 4.1 – Directional Detection

The pd signals are then digitised and transmitted via the fibre optic link to the main computer. The fibre optic link assures a high immunity to noise and offers additional safety to the operating personnel and equipment [47].

4.3 Installation of Directional Couplers

4.3.1 Directional Couplers

The LDY-724 is supplied with two directional coupler sensors (dcs), in one of two forms. For permanent installation on a cable the dcs are supplied with rigid coaxial cables, however for experimental laboratory work where the sensors are to be moved frequently the dcs are better fitted with normal flexible coaxial cables.

The dcs are in simple terms two copper plates separated by polyethylene, the conductor of the coax is connected to the lower plate and the coax sheath connected to the upper-earthed plate. The response, i.e. inductance and capacitance of the dcs can be varied by altering the distance between the plates, which is achieved by increasing or decreasing the amount of polyethylene between them. The amount of polyethylene required between the plates will vary depending on the diameter of the cable being monitored.

4.3.2 Set Up

Before the dcs is installed onto the cable, the cable sheath must be removed from the cable either side of the joint to allow enough space for the dcs. The dcs should be placed on top of the outer layer of semi-con, preferably by means of an adjustable strap, i.e. cable ties, and with only enough pressure applied to hold them in place.

Before the dcd or the computer is connected it is essential to measure the responses of the dcs with an oscilloscope and a calibrator. The calibrator should be connected to port B of the dcs. Port A should be connected to the trigger channel of the oscilloscope, but it is not necessary to display this signal. Finally ports C and D should be connected to the scope and displayed, and ensure all channels are set to 50Ω input impedance.

The calibrator level should be adjusted until a signal is seen on channel C, 100pC for example, and the scope setting adjusted so the complete pulse can be clearly seen, ensuring both channels C and D are set to the same levels. While observing the response on the scope if the pressure on the dcs is varied it is possible to see if it's necessary to add or remove some of the polyethylene sheets (5 sheets is normal). When the response of channel C is 5 times that of channel D the dcs will achieve directivity, ideally channel D with show no response at all. Typically the response should be similar to that shown in Figure 4.4.

In this case channel 4 (injected signal into B) was used as the trigger channel and channels 1 and 2 correspond to C and D respectively. Also the scale for C is set to 10mV/div and D to 2mV/div, so that when the two traces are lined up on top of each other if the signals are of the same height a ratio of 1:5 has been achieved, however in this case there is a much greater ratio, therefore higher directivity.

This process should be repeated, injecting into C and measuring the response of A and B, this time the response of B should be 5 times greater than A.

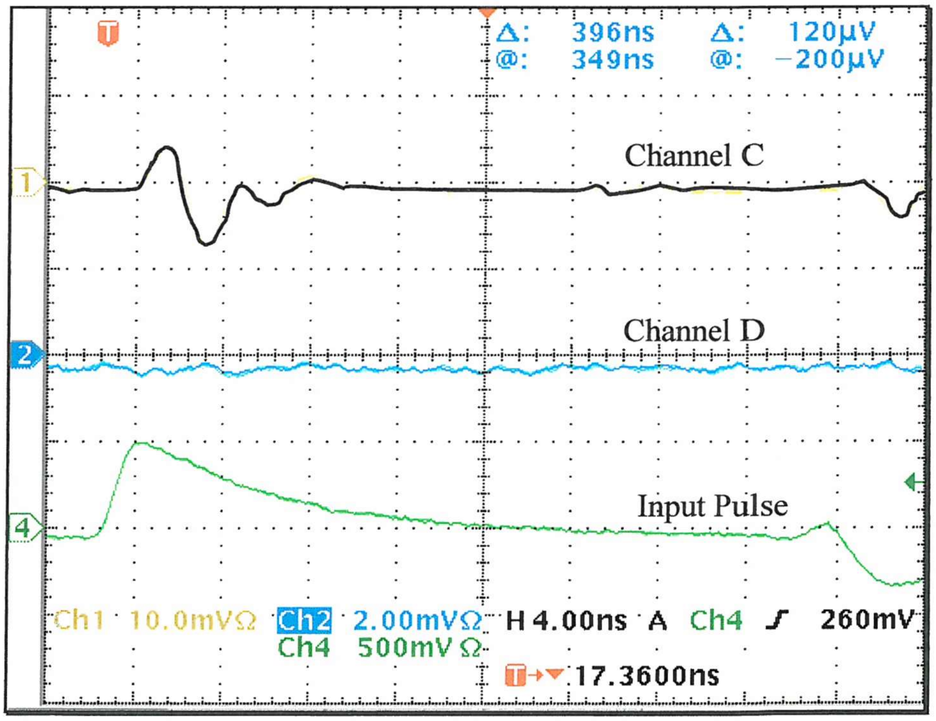

Figure 4.4 – Calibration Measurements

4.4 Results

Due to a major fault within the apparatus it was not possible to record any meaningful results. A fully operational system was not available from Pirelli Cables and the funds for a repair unavailable, so no meaningful results could be taken.

4.5 Conclusions

The LDIC LDY-724 has been partially practically assessed within an hv laboratory. It is possible to calibrate and tune the sensors to achieve directivity and a measure of apparent charge. At the time of use, this equipment was on loan from Pirelli Cables, who had four of these systems throughout Europe. The system was sent back to the manufacturers once for recalibration as one of the channels was not working properly, however it came back in an even worse condition and was totally un-useable this has led to the conclusion therefore that the equipment is not industrially robust and has not been found reliable enough to obtain any practical pd measurement data.

5. Field Measurements: Fawley Substation

5.1 Introduction

A series of electrical measurements were taken at the National Grid Transco substation at Fawley to determine the minimum detectable pd level within an idle cable in an electrically noisy environment. These measurements were taken to establish the frequency ranges and magnitude of airborne background noise. This was achieved by conducting a series of experiments adjacent to an operational 400/132kV super-grid transformer.

5.2 Measurements

The measurements taken were on signals induced in a 1m length of 33kV Isle of Man cable that was placed on the perimeter wall of the transformer, 5m away from the transformer itself (Figure 5.1).

Figure 5.1 – Experimental Arrangement

Figure 5.2 – 33kV Cable With BNC Connector

The cable consisted of a 21mm diameter stranded copper conductor and bulk insulation of diameter 54.9mm with two semi-conductive layers between the conductor and insulation and on the outer of the insulation (Figure 5.2). A tin foil screen was wrapped around the outer layer of the semi-con to simulate a sheath and to screen the inner conductor. BNC bulkhead terminals were connected at either end of the cable to the inner conductor and the foil sheath.

The measuring equipment was housed in an earthed Faraday box to ensure total screening of the system (Figure 5.3), i.e. all measured signals were those induced on the cable and not in the measuring equipment. All connections from the cable were connected to the measuring equipment through a special panel at the back of the Faraday box that incorporated surge protection equipment (Figure 5.4).

Figure 5.3 – Measurement Apparatus Set-Up

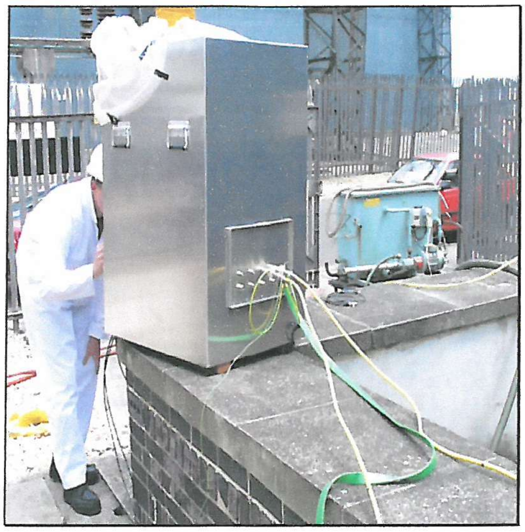

Figure 5.4 – Faraday Box Connections

The measurements taken were:

5.2.1 Signal on a Screened Cable

The cable was fully screened to minimise noise penetration and an oscilloscope was connected to one end of the cable (Figure 5.5). The signals on the cable were measured on the oscilloscope to assess the effectiveness of foil for screening.

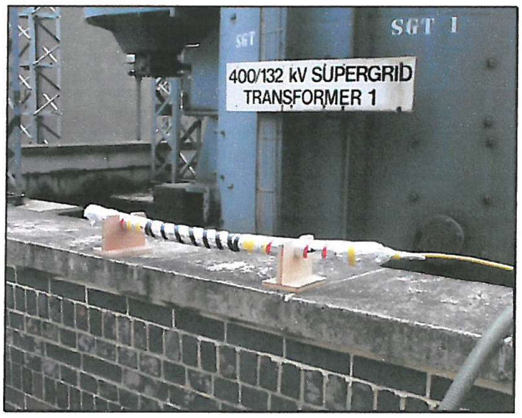

Figure 5.5 – Screened Cable Connected to Oscilloscope

5.2.2 Signal on a Cable With an Aerial

A 5m copper annealed wire was connected to the inner conductor to act as an aerial and introduce noise onto the cable. The oscilloscope was connected to the opposite end of the cable and the magnitude of the noise signal was measured.

5.2.3 Signal on a Cable With an Aerial and an Injected Pulse

The pulse generator was connected to the aerial (Figure 5.6) and the oscilloscope to the opposite end of the cable. The magnitude of the pulse was varied to measure the minimum detectable pulse on the noisy cable. This minimum detectable pulse was compared to the magnitude of noise that was recorded in the previous experiment.

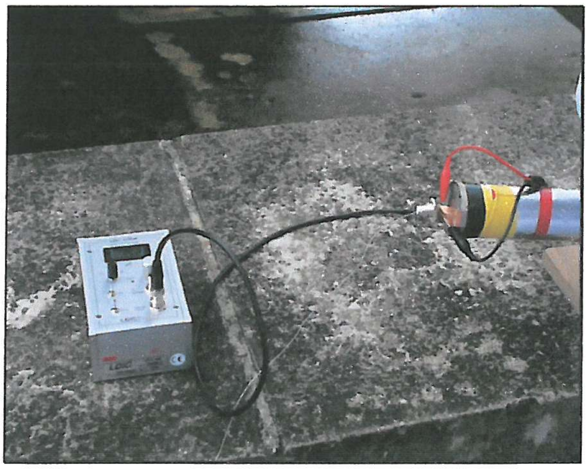

Figure 5.6 – Pulse Generator and Aerial Connected to Inner Conductor

5.2.4 Capacitive Coupler Signal on a Screened Cable and Injected Pulse

The aerial was removed and a section of the foil sheath was removed. A simple capacitive coupler was implemented on the cable (Figure 5.7) and the whole cable was again screened. The capacitive coupler differs from the directional coupler in that it has a single connection to the insulated conductor placed on the exposed outer semi-con layer of the cable under test. The oscilloscope was connected directly to the coupler. The pulse generator was connected to the cable at one of the terminations and again the pulse magnitude was varied until the minimum detectable pulse was recorded.

Figure 5.7 – Unscreened Capacitive Coupler with BNC Connector Output

5.2.5 Capacitive Coupler Signal on a Cable With Aerial and Injected Pulse

The aerial was again connected to the inner conductor of the cable and the pulse generator was connected to the aerial. The oscilloscope was connected to the capacitive coupler, and the pulse magnitude was then varied to find the minimum detectable pulse for the coupler on a noisy cable. All readings were taken using a 20dB gain pre-amplifier with a bandwidth of 10kHz – 1100MHz.

A series of spectrum analyser and frequency response readings were taken for all the above cases. However, the spectrum analyser requires a continuous signal to detect a specific frequency, but the pulse generator only gave one 4ns pulse every 20ms, hence the analyser could not detect the frequency spectra for the pulse generator. The signals detected were fm radio (88-108MHz) and mobile telephony (~470MHz) and have not been included in this chapter.

5.3 Results

Note that the scales used on the following graphs may vary as the signal to noise ratio was in some cases 1:100, hence it is not practical to display these on the same scale.

5.3.1 Signal on a Screened Cable

When the oscilloscope was connected directly to the screened cable the level of noise was low hence proving the screening was sound (typical case shown in Figure 5.8).

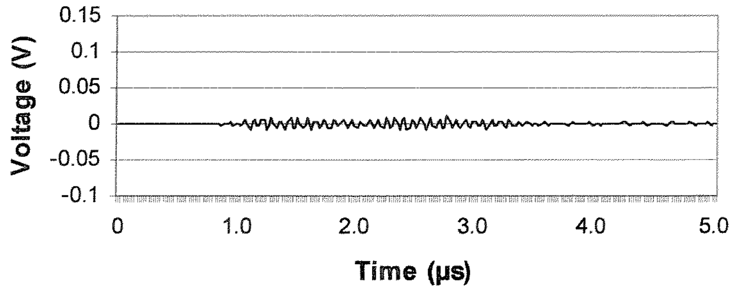

Figure 5.8 – Response of Oscilloscope Connected Directly to the Cable

5.3.2 Signal on a Cable With an Aerial

When the aerial was connected to the inner conductor the noise level measured on the oscilloscope increased by more than two orders of magnitude (Figure 5.9).

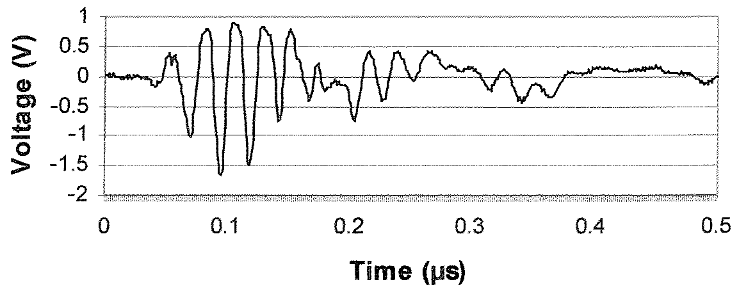

Figure 5.9 – Noise Levels Measured on the Cable With Aerial Connected

5.3.3 Signal on a Cable With an Aerial and an Injected Pulse

When a pulse was injected onto the aerial it was possible to trigger the oscilloscope on pulses as low as 15pC reliably (Figure 5.10). The noise level was typically equivalent to 10pC.

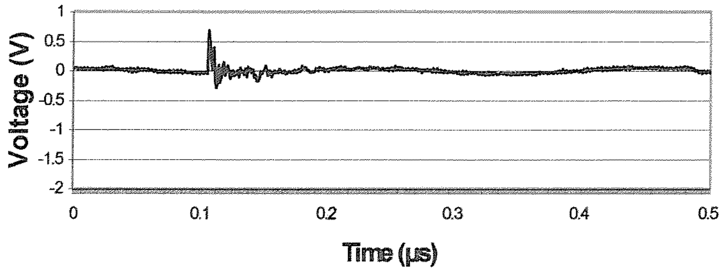

Figure 5.10 – Response of Oscilloscope to 15pC Pulse Injected onto Aerial

5.3.4 Capacitive Coupler Signal on a Screened Cable and Injected Pulse

With a capacitive coupler it was possible to trigger the oscilloscope on pulses injected onto the inner conductor as low as 4pC (Figure 5.11). Signal to noise ratio of 1:1 was at 2pC

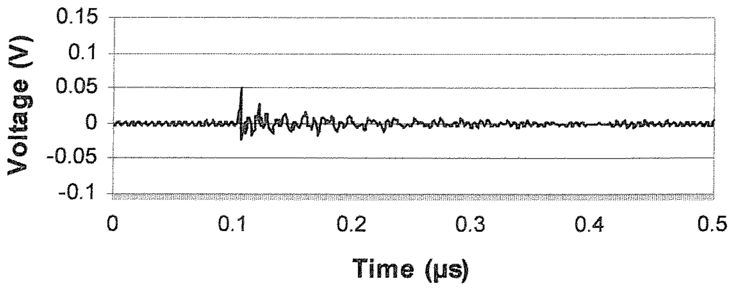

Figure 5.11 – Response of Capacitive Coupler to 4pC Pulse on a Screened Cable

5.3.5 Capacitive Coupler Signal on a Cable With Aerial and Injected Pulse

The oscilloscope was able to trigger on signals as low as 15pC from the capacitive coupler, when the aerial was connected to the inner conductor and pulses injected onto the aerial (Figure 5.12). Signal to noise ratio of 1:1 was at 8pC

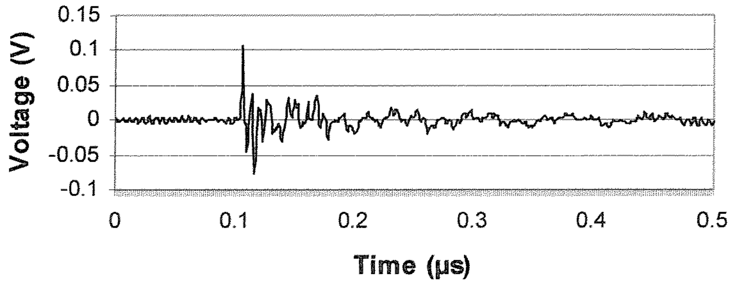

Figure 5.12 – Response of Capacitive Coupler to 15pC Pulse on Unscreened Cable

5.4 Conclusions

The results show that it was possible to detect a 15pC pulse on an unscreened cable using a capacitive coupler in the presence of a background noise level 100 times that of the pulse, and that adequate screening greatly reduce the noise level. The scope could detect the injected pulse amongst a noise signal that was measured to be 100 times greater than the injected pulse. The capacitive coupler was able to detect pulses of equal magnitude to the oscilloscope connected directly to the cable, and could detect pulses as low as 2pC if there was adequate screening.

6. Directional Coupler Design Characteristics

6.1 Introduction

Conventional directional coupler theory states that certain design parameters of the coupler will greatly effect its response while others will have no effect at all [48]. Conventional theory states that the output voltage response of the coupler in real time is proportional to the characteristic impedance of the coupler, i.e. the inductance and capacitance per unit length. As the diameter varies so does the capacitance and inductance and therefore the response of the coupler should vary also. Although, as the length of the coupler varies the response of the coupler should remain constant as the characteristic impedance is proportional to the inductance per unit length divided by the capacitance per unit length. Directional coupler theory states that an optimised directional coupler response to a pd signal would give a signal of positive magnitude on the coupler output nearest the pd source and a negligible signal on the coupler output furthest away from the source [48].

However, this theory only considers two parallel conductors separated by an insulation gap, where the conductor sizes and spacings are negligible compared to the wavelength, and all currents are confined to the conductor surfaces. In the case of a directional coupler placed on the outer layer of semi-con of a cable there will be current flow from the cable sheath to the coupler across the semi-con.

This chapter examines the response of a simple directional coupler by varying the dimensions and construction of the coupler.

6.2 Methodology

For the purposes of these experiments a 1.3meter length of 33kV cable, with a characteristic impedance of 38Ω (from manufacturer's specifications) was used. The cable consisted of a 21mm diameter stranded copper conductor and bulk insulation of diameter 54.9mm with semi-conductive layers between the conductor and insulation and on the outer of the insulation. A tin foil screen was wrapped around the outer layer of the semi-con to simulate a sheath and to screen the inner conductor. BNC bulkhead terminals were connected at either end of the cable to the inner conductor and the foil sheath.

The measurement circuit for the experiments was constructed using standard 50Ω leads and connectors and an oscilloscope, so the circuit had to be matched to the cable to prevent reflections. This was achieved using a series of in-line variable resistors. The characteristic impedance of the cable had to be found so that the cable could be terminated in its matching impedance. Using the cable dimensions, the inductance and capacitance were calculated by standard formulas and hence the impedance was calculated to be 35.86Ω. This value was then verified experimentally by varying the terminating resistor of the cable until reflections were minimised, giving a value of 35.65Ω. The reflections were measured using a directional coupler implemented on the cable. The circuit arrangement for the reflection test is shown in Figure 6.1.

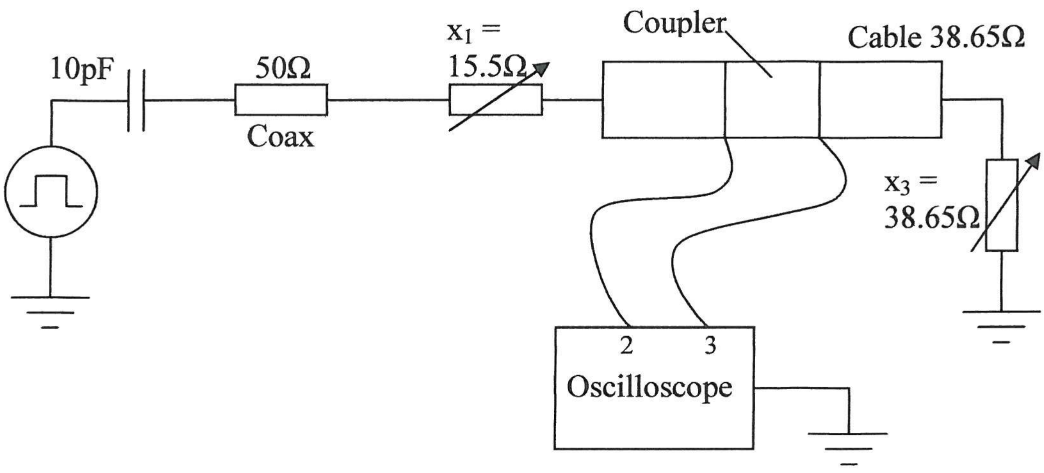

Figure 6.1 – Reflection Test Arrangement

The terminating resistor was varied to reduce reflections at the termination of the cable while a resistor between the coaxial cable from the pulse generator and the cable was used to cancel any mismatch between the two. The final values of the variable resistors x_1 and x_3 for a matched system are as shown in Figure 6.1. We can surmise that the characteristic impedance of the cable is 38.65Ω from the value of x_3, therefore x_1 should match the cable to the 50Ω of the coax. The combined value of $x_1 + x_3$ is 54.15Ω, giving an error of 8.3% between theoretical and measured values.

Figures 6.2 and 6.3 show the measured values on Channel 2 and 3 of the oscilloscope respectively, for the terminating resistor x_3 matched, open and short-circuited. These figures show that although reflection has not been totally eliminated it has been significantly reduced. The remaining reflections are a result of connecting devices.

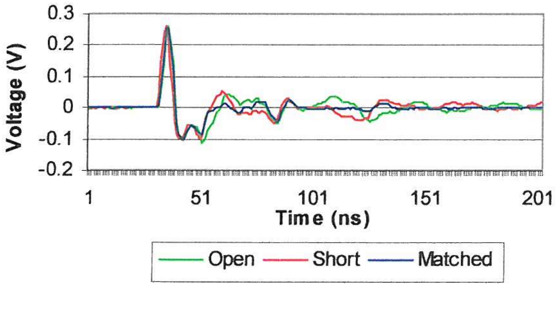

Figure 6.2 – Channel 2 Response

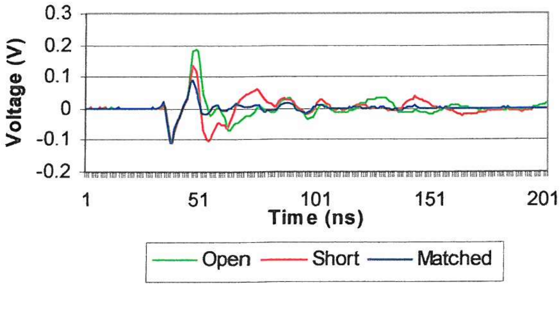

Figure 6.3 – Channel 3 Response

Once the characteristic impedance of the cable had been determined it was possible to connect an additional circuit so the pulse injected into the cable could be recorded as well as the response of the coupler. The additional circuit had to be matched to the system so that reflections were minimised and the pulse seen at the oscilloscope was of the same magnitude as that injected into the cable. The matching values of the additional variable resistors were calculated mathematically using the conditions stated above and implemented into the circuit.

Figure 6.4 and 6.5 shows the final experimental circuit used to measure the response of the couplers.

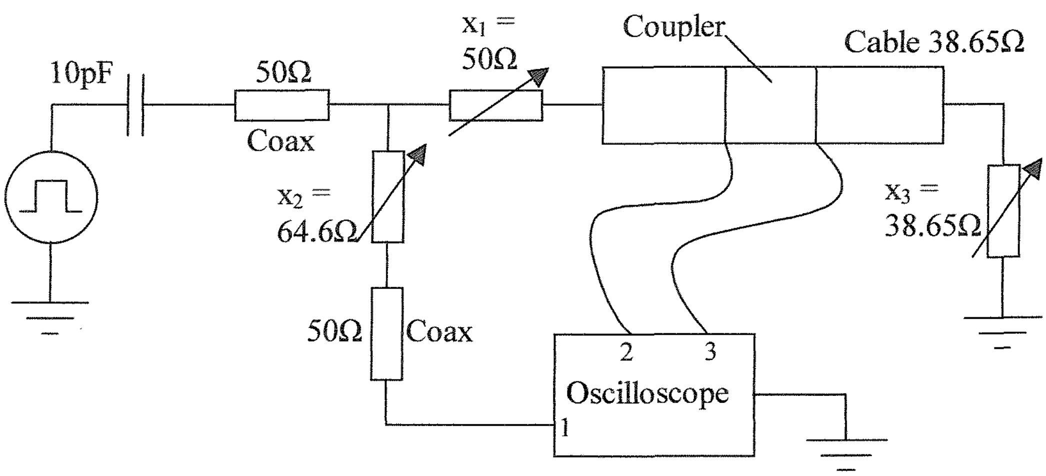

Figure 6.4 – Experimental Circuit Arrangement

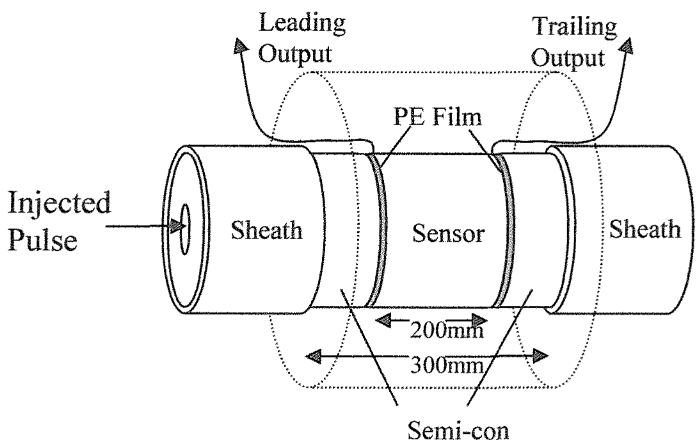

Figure 6.5 – Experimental Circuit Arrangement

Channel 1 of the oscilloscope was now used as the trigger and the response of the coupler was recorded on channels 2 and 3. A 10pF capacitor in series with a square wave oscillator, with a 5V pulse height, was used to generate a 50pC pulse that was injected into the circuit. Therefore under matched conditions a 25pC was injected into the cable and the same was seen on channel 1 of the oscilloscope.

6.3 Coupler Response to Diameter Variation

Directional coupler theory suggests that the length of the coupler should not affect the response of the coupler, however, it is proportional to the ratio of the inner diameter of the coupler to the outer diameter. Therefore the first experiment was to vary the outer diameter of the coupler while keeping the inner diameter and length constant.

A simple coupler was implemented on the outer semi-con of the cable of arbitrary length 200mm, with an insulation gap between the coupler and earth sheath of 50mm at each end. Figure 6.6 shows the coupler on the cable.

Figure 6.6 – Directional Coupler

Bubble wrap was then used as the dielectric to insulate the coupler from its outer earth, as seen in Figure 6.7.

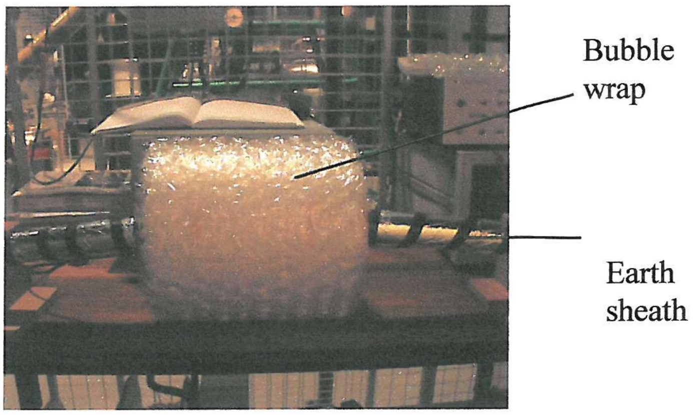

Figure 6.7 – Directional Coupler Construction

For the purposes of measuring the diameter of the coupler a wire mesh was then secured around the bubble wrap. After each response measurement the length of the wire mesh, and hence the circumference of coupler, was measured thus giving the diameter of the coupler. The mesh also ensured a constant diameter was maintained around the coupler. Figure 6.8 shows the wire mesh around the bubble wrap.

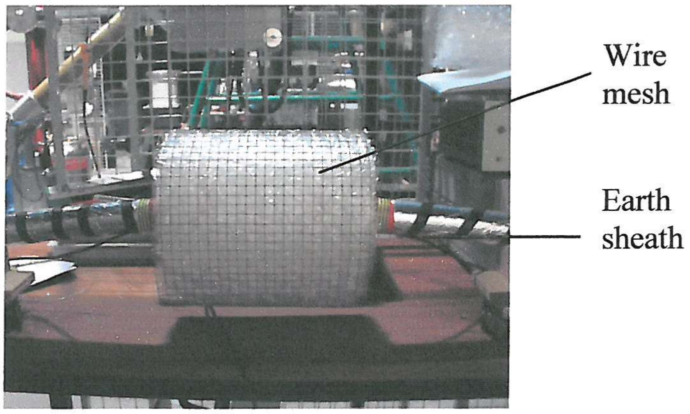

Figure 6.8 – Directional Coupler Construction

Finally foil was implemented around the wire, providing the earth screen for coupler and an electrical connection between the earth sheath at either end of the cable, as seen in Figure 6.9.

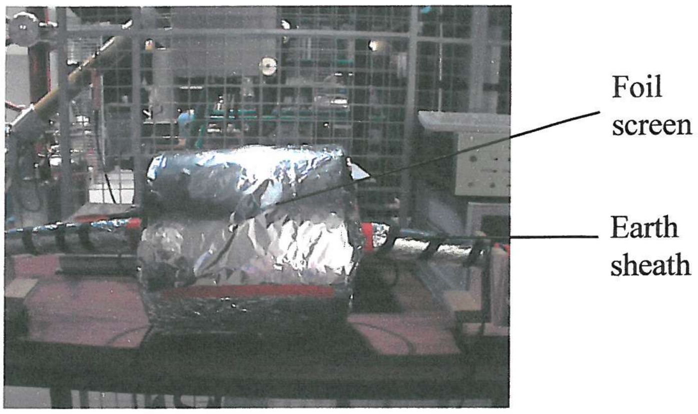

Figure 6.9 – Directional Coupler Construction

The response of the coupler against the diameter of the foil screen was measured for the 25pC injected pulse.

6.4 Response of Insulated Coupler to Diameter Variation

Directional coupler theory is based on two parallel lines insulated from each other. However in Section 6.3 the coupler was implemented directly onto the semi con of the cable, thus providing a conduction path between the earth sheath and the coupler. To insulate the coupler from the semi con a layer of polyethylene was first wrapped around the cable and the coupler then placed on top of this. The response of the coupler was then measured in the same way as in Section 6.3.

6.5 Response of Coupler to Length

Theory states that the response of a directional coupler is proportional to its characteristic impedance, which in the case of a coaxial system is proportional to the inductance per unit length divided by the capacitance per unit length. Thus the characteristic impedance of the coupler should be independent of length. In order to verify theory the diameter of the coupler was fixed and the length varied from 600mm to 50mm in 50mm steps, as seen in Figure 6.10.

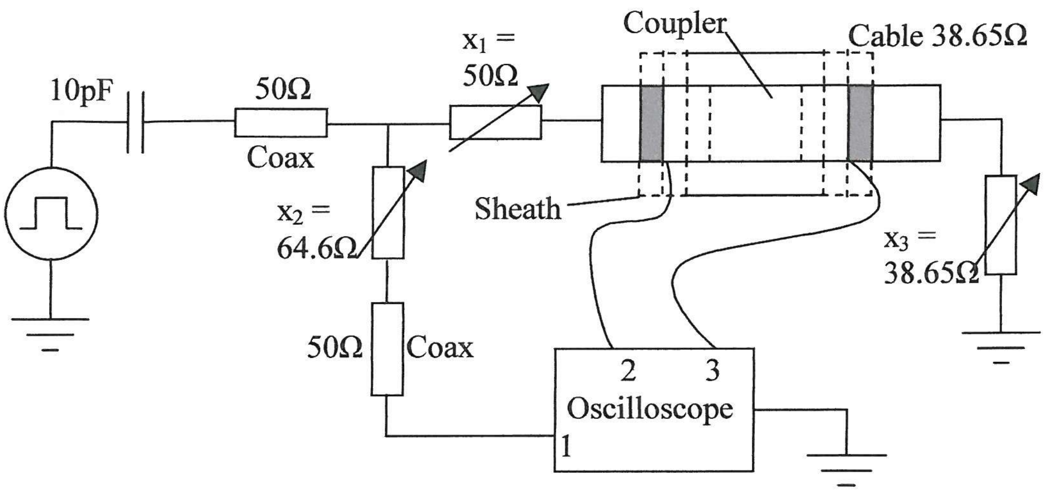

Figure 6.10 – Experimental Set-Up Varying Coupler Length

6.6 Coupler Response to Different Materials

If the response of a directional coupler is proportional to its characteristic impedance and hence its capacitance then the materials used in the construction of the coupler should affect the response. The couplers implemented in the previous experiments have been simple couplers using aluminium foil for the coupler and bubble wrap for the insulation (i.e. air). Constructing the coupler using a material of higher permeability than aluminium foil will change the inductance of the coupler and using a material of higher permittivity for the insulation than air will change the capacitance of the coupler.

Therefore by altering the characteristic impedance of the coupler the response of the coupler can be altered.

6.7 Varying Sensor Diameter and Keeping Sheath Diameter Constant

While keeping the diameter of the outer sheath constant the diameter of the sensor was varied from 5cm to 15cm between the cable and the sheath, as shown in Figure 6.11.

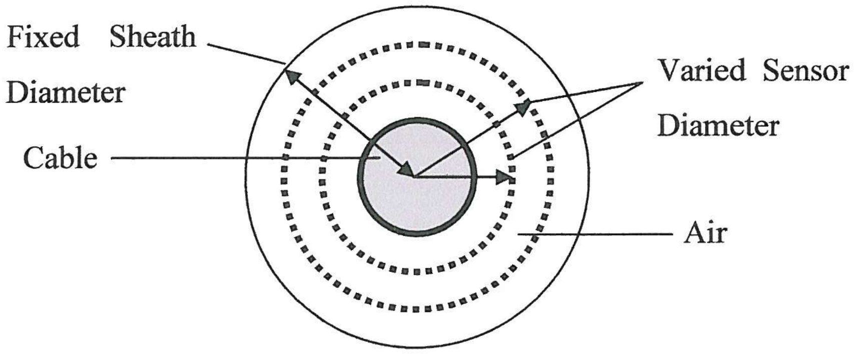

Figure 6.11 – Cross Sectional View of Cable and Sensor

6.8 Varying Sheath and Sensor Diameter and Keeping the Distance Between Both Constant

The distance between the sensor and the outer sheath was kept constant and the diameter of both varied with respect to the diameter of the cable, as shown in Figure 6.12.

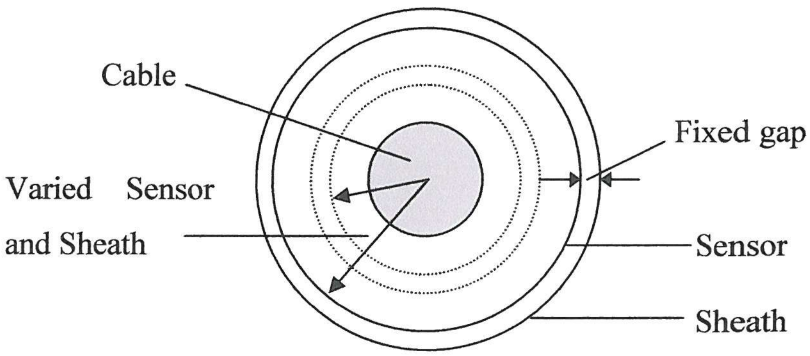

Figure 6.12 – Varied Sheath and Sensor Diameter With a Fixed Gap Between Both

6.9 Patch Couplers

Instead of using a coupler that completely encircled the cable, patches that only partly encircle the cable were investigated to see what if any effect it had on the response of the coupler. A patch consisting of a square of foil attached to the cable were connected in the same way as all other couplers and the response measured over a range of different sheath diameters, so comparisons could be made to results obtained in the previous sections. The patch only encircled half of the cable, as shown in Figure 6.13.

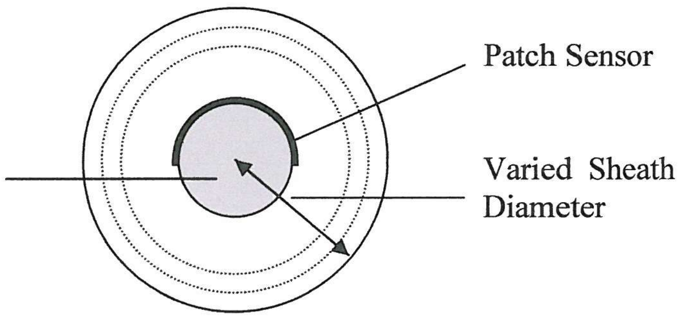

Figure 6.13 – Patch Sensor With Varied Sheath Diameter

6.9.1 Patch Couplers Using Different Materials

The sensor part of the coupler was constructed as above, but using the same variation of materials that were used in section 6.9

6.10 Results

The response of a coupler was measured as the magnitude of the first peak of the signal detected. i.e. considering the wave form in Figure 6.14:

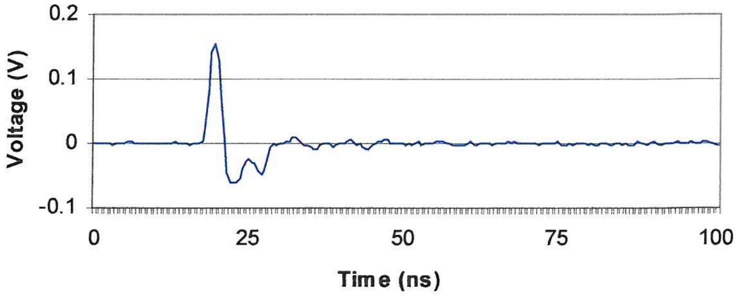

Figure 6.14 – Typical Coupler Response

6.10.1 Coupler Response to Diameter

As the diameter of the sheath was increased the response of the coupler increased. It was found that as the diameter increased the first pulse seen on the leading output of the coupler increased. However, the first pulse seen on the trailing output of the coupler decreased, and at the larger diameters disappeared, as in the ideal case. As the diameter of the sheath was increased the capacitance between the sensor and sheath should decrease exponentially and the inductance increase exponentially. Results are shown in Figures 6.15 and 6.16.

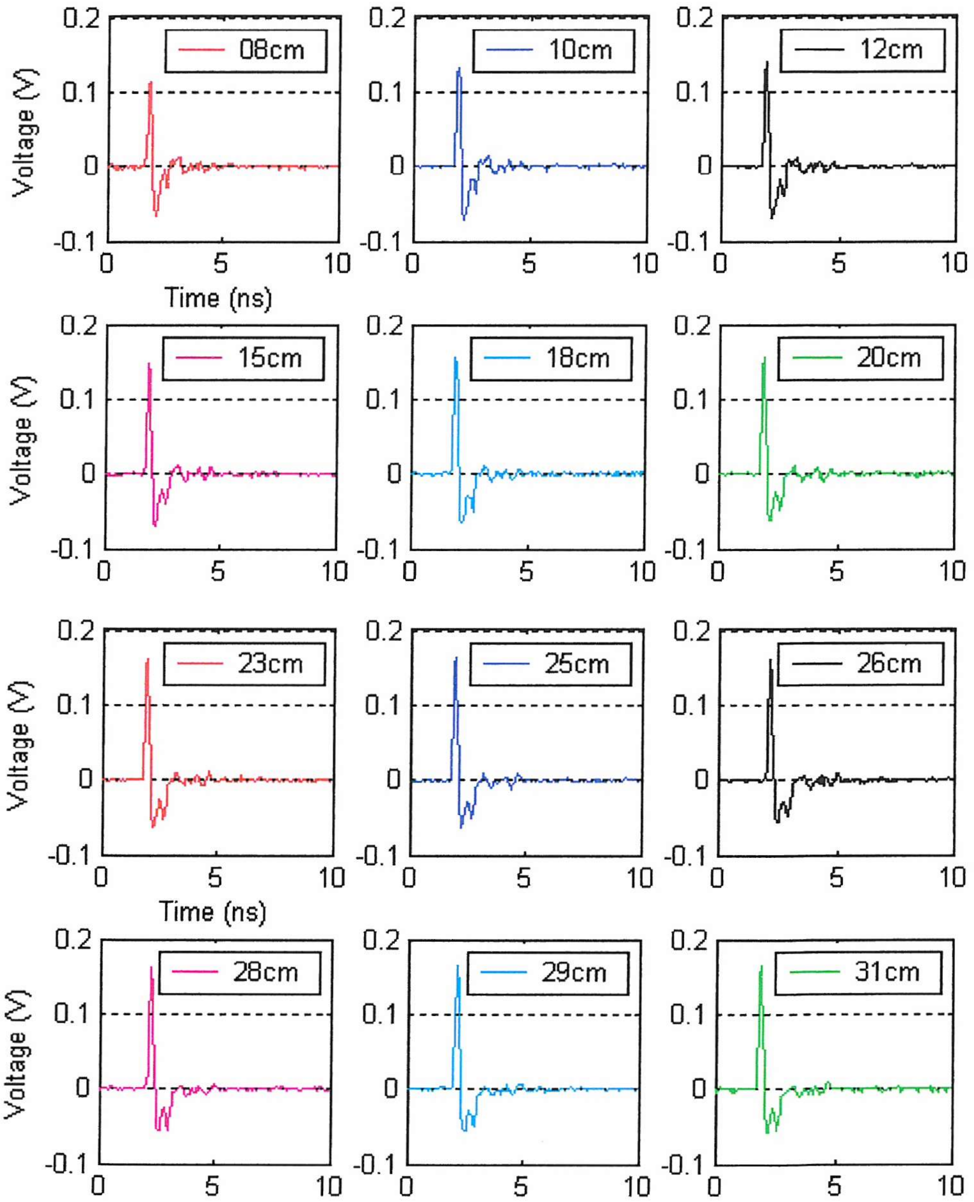

Figure 6.15 – Coupler Response to Sheath Diameter – Leading Output

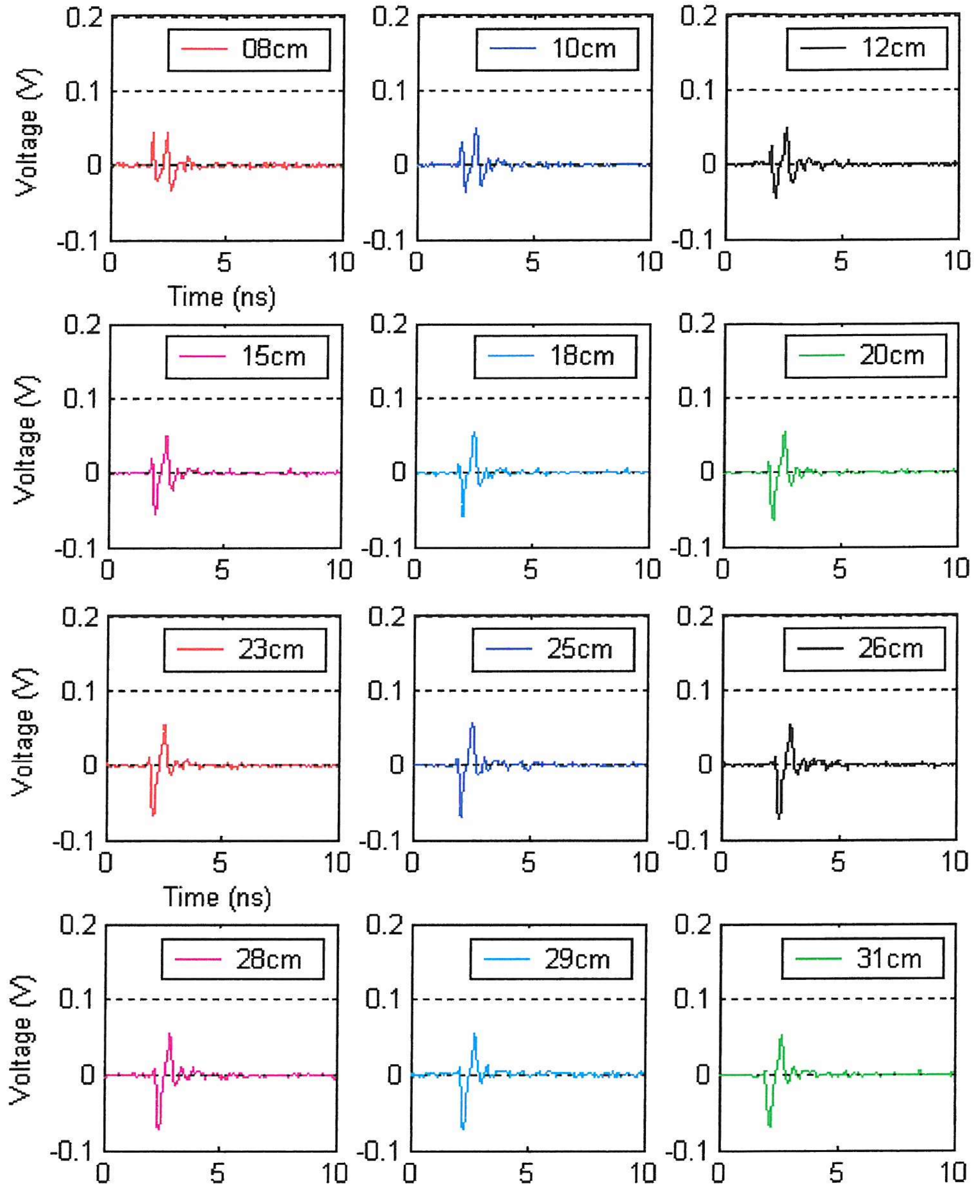

Figure 6.16 – Coupler Response to Sheath Diameter – Trailing Output

6.10.2 Response of Insulated Coupler to Diameter

Having the sensor insulated from the semi-con of the cable didn't have any significant effect on the response of the coupler when injecting pulses into the cable, however, under live line conditions when there is high voltage on the cable a significantly larger current could flow between the sensor and the sheath across the semi-con. The results for this experiment are shown in Figures 6.17 and 6.18.

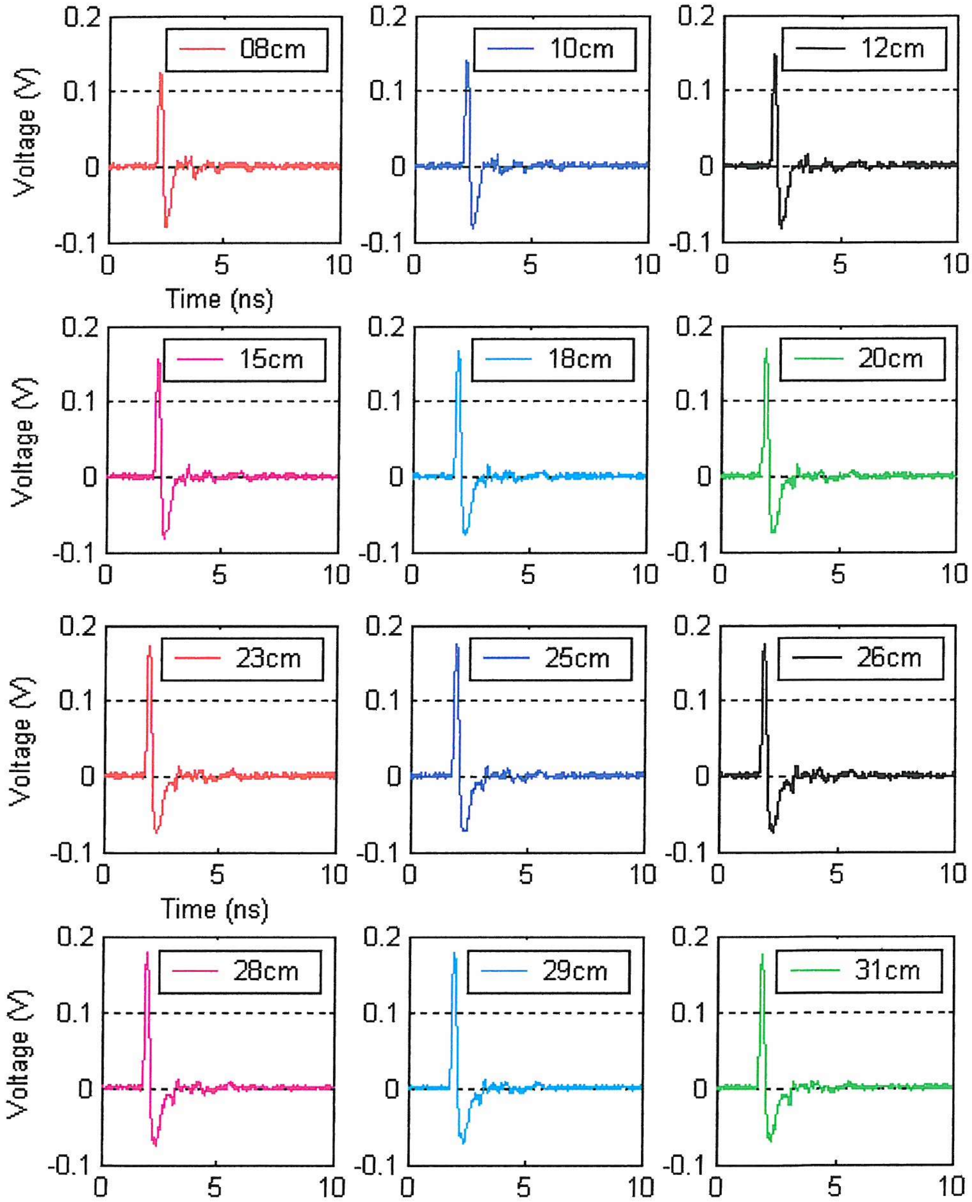

Figure 6.17 – Insulated Coupler Response to Sheath Diameter – Leading Output

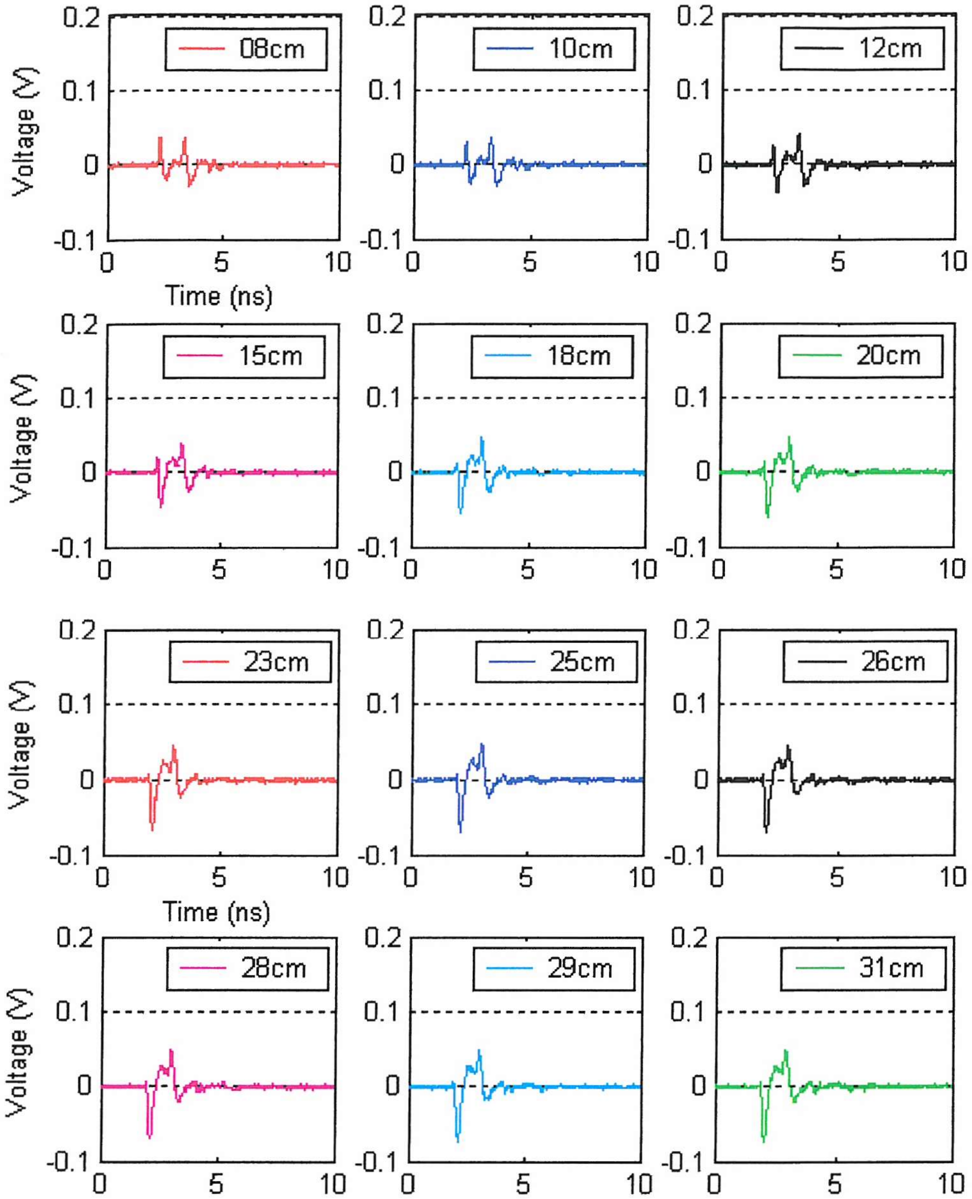

Figure 6.18 – Insulated Coupler Response to Sheath Diameter – Trailing Output

6.10.3 Response of Coupler to Length

In contrary to theory it was found that the length of the coupler did change the response of the coupler, because in short transients as were used in these experiments dimensions are still significant and internal reflections will occur. The response of the coupler increased the shorter the length became. The results are shown in Figures 6.19 and 6.20. Although the response of the leading output didn't vary much over the range of coupler lengths, the response of the trailing output increased significantly, and hence the ratio of the two signals was smaller the greater the length of the coupler.

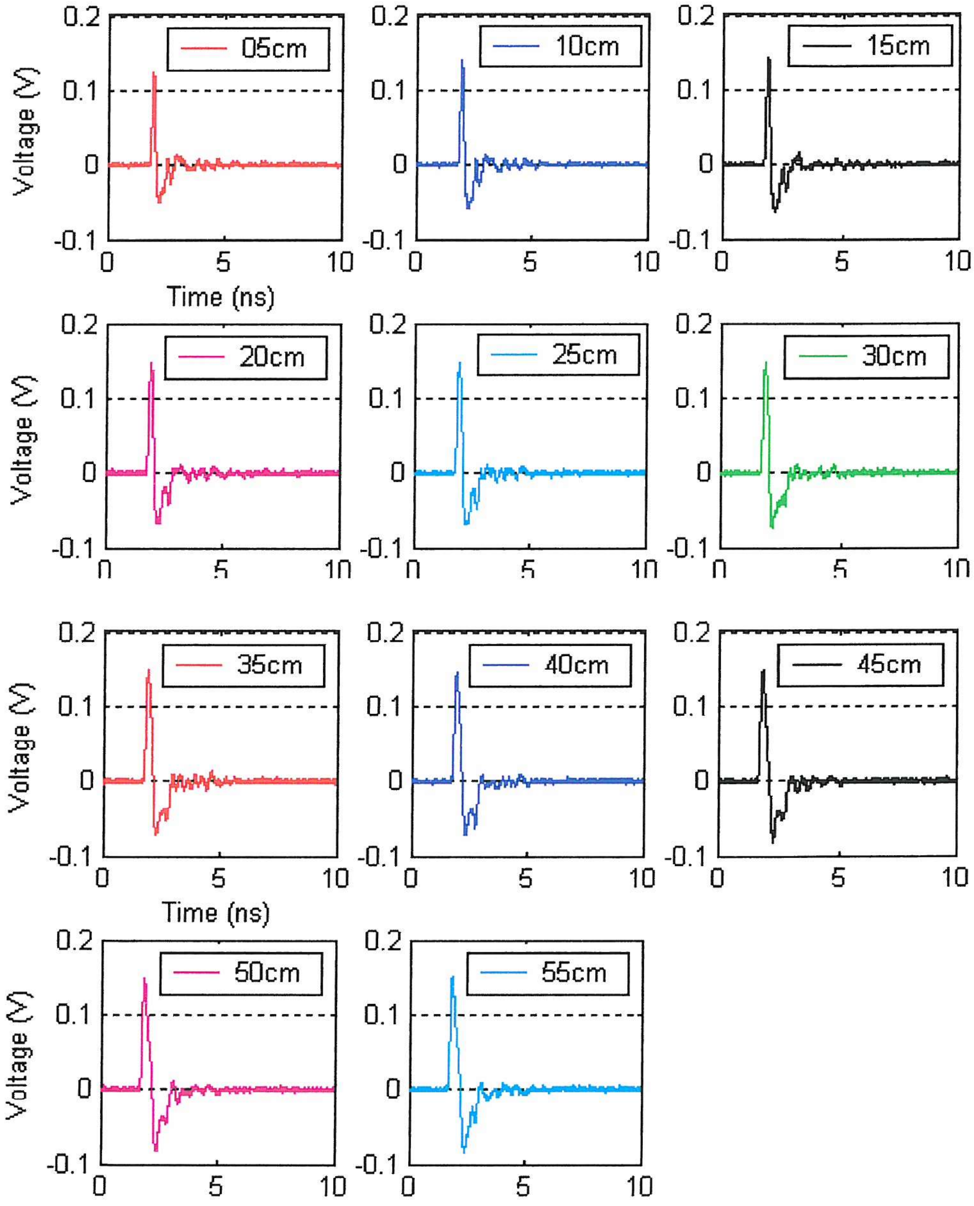

Figure 6.19 – Coupler Response to Length – Leading Output

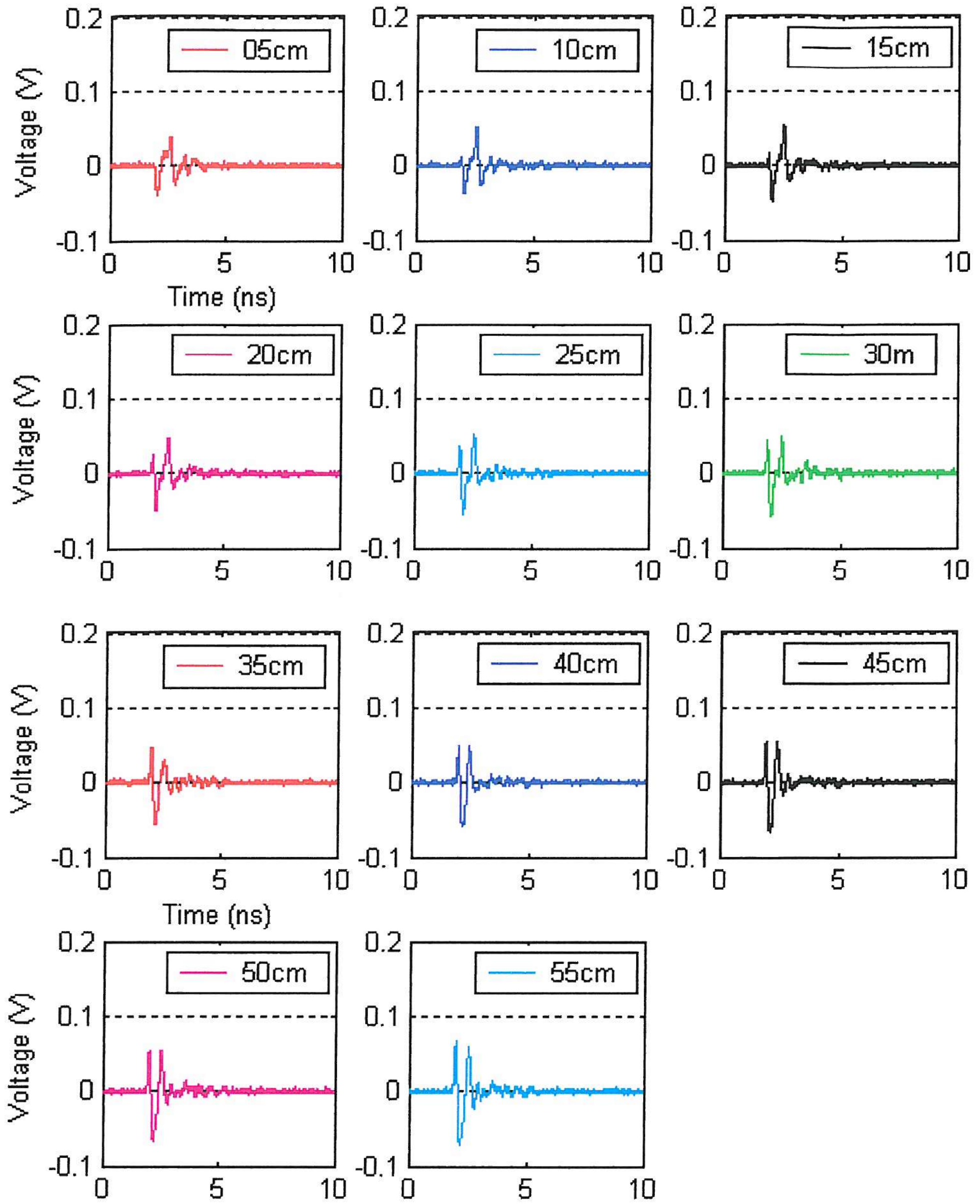

Figure 6.20 – Coupler Response to Length – Trailing Output

6.10.4 Coupler Response to Different Materials

The materials chosen instead of foil and bubble wrap were mu metal, which has a very high permeability and polyethylene, which has a permittivity just over double that of bubble wrap (air). Due to the constraints of how thick the polyethylene insulation could be made couplers of sheath diameter 10cm were used for each arrangement and the responses measured. Firstly a standard foil and bubble wrap coupler was implemented, followed by a mu metal and bubble wrap coupler, a foil and PE coupler and finally a mu metal and polyethylene coupler. However it was found that these materials had little effect on the response, but if anything they actually decreased the response of the couplers and the foil and bubble wrap coupler had the best response as seen in Figures 6.21 and 6.22.

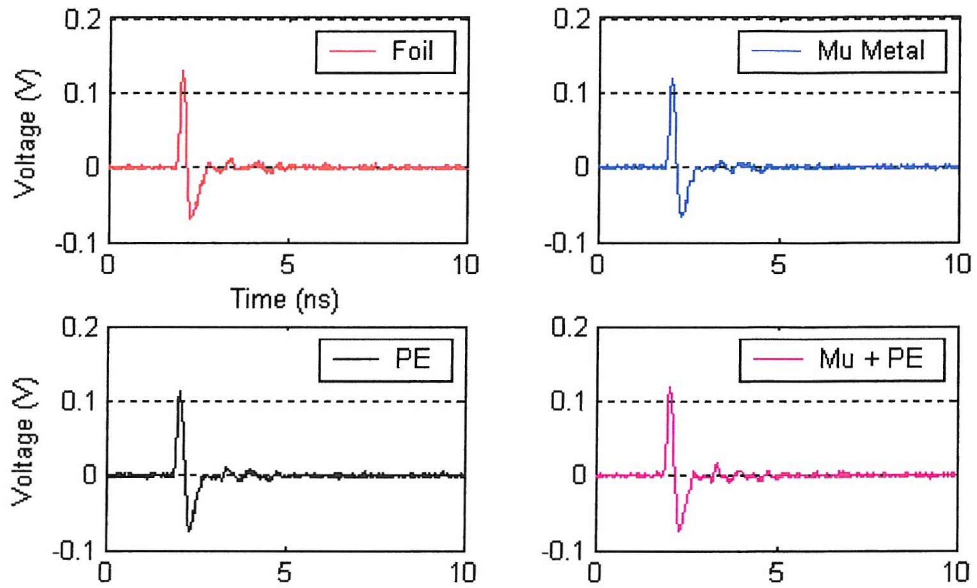

Figure 6.21 - Coupler Response to Different Materials – Leading Output

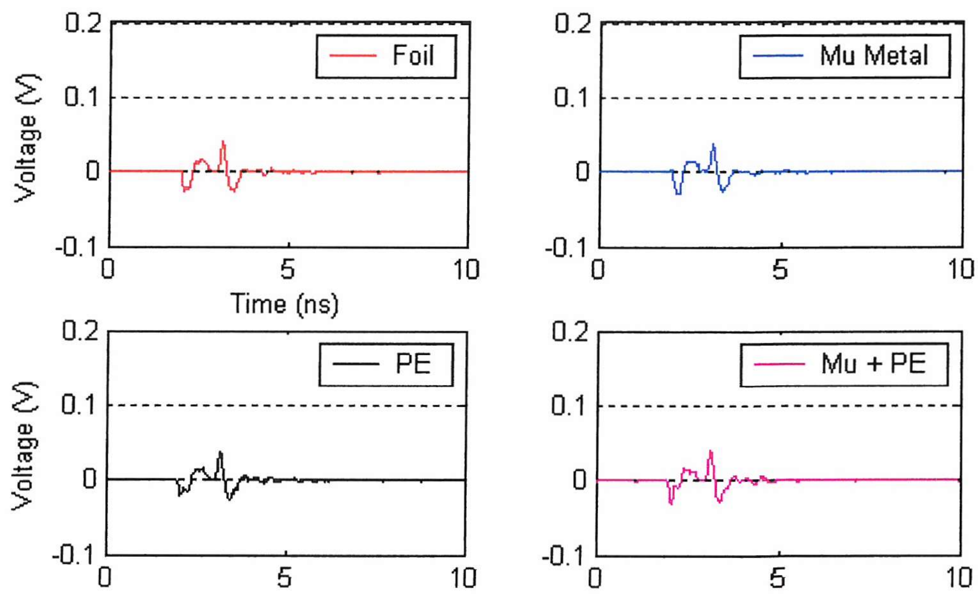

Figure 6.22 – Coupler Response to Different Materials – Trailing Output

6.10.5 Varying Sensor Diameter and Keeping Sheath Diameter Constant

By keeping the sheath diameter constant and varying the sensor diameter from the cable to the sheath it was found that the leading output response rapidly deteriorated, however, the trailing output response improved. The response of the coupler decreased though the nearer the sensor was to the sheath, as seen in Figure 6.23, as the leading response is much larger at 5cm diameter than at 15cm.

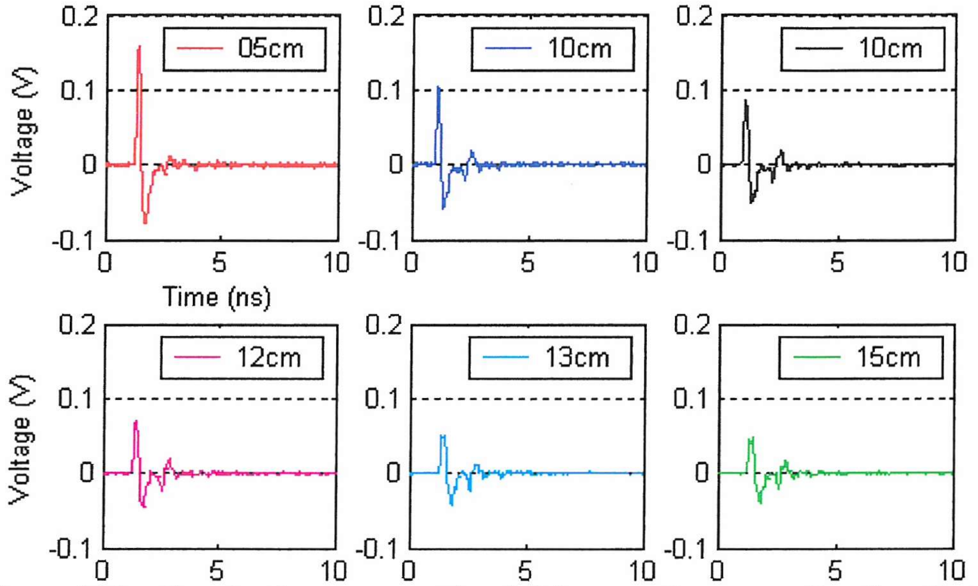

Figure 6.23 – Coupler Response to Sheath Diameter Constant – Leading Output

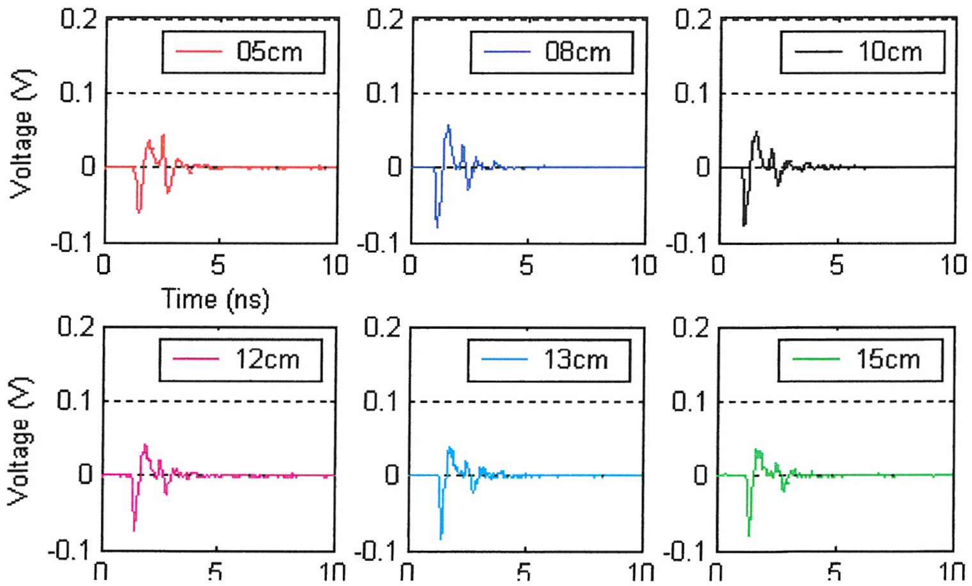

Figure 6.24 – Coupler Response to Sheath Diameter Constant – Trailing Output

6.10.6 Varying Sheath and Sensor Diameter and Keeping the Distance Between Both Constant

By keeping the distance between the sensor and sheath constant and varying the diameter of both with respect to the cable, it was found that the response of the leading output decreased rapidly with distance from the cable, and the response of the trailing output increased. The response of the leading coupler output decreased the further the sensor and sheath were from the cable, as shown in Figure 6.25.

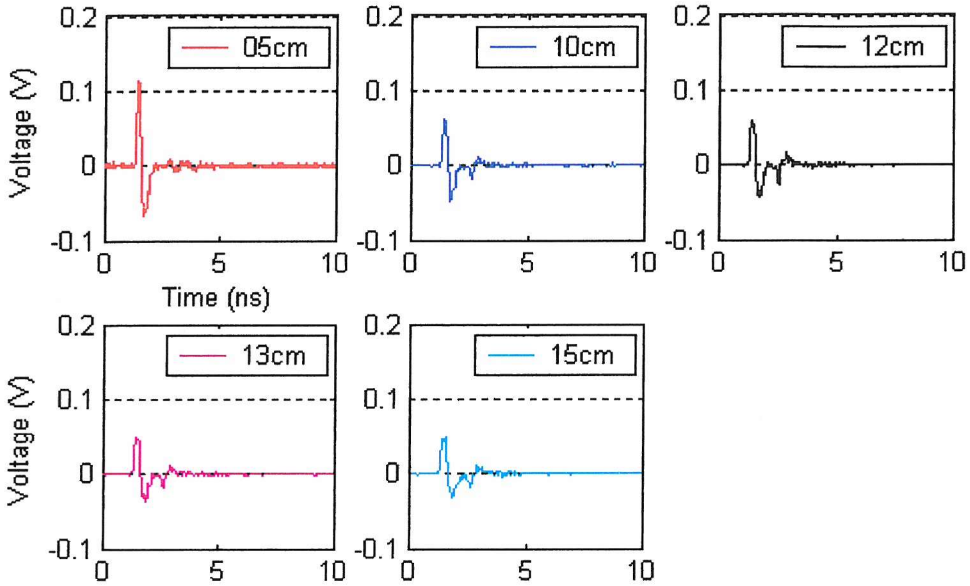

Figure 6.25 – Coupler Response to Sheath and Sensor Varied Equally – Leading Output

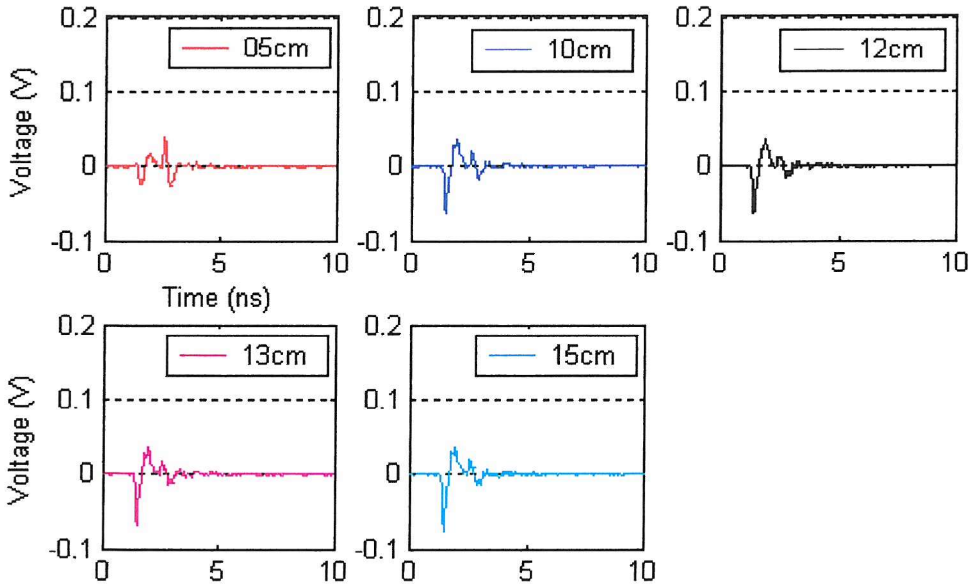

Figure 6.26 – Coupler Response to Sheath and Sensor Varied Equally – Trailing Output

6.10.7 Patch Couplers

A patch coupler where the sensor encircled only half the diameter of the cable was found to have a response similar to that of a coupler with a sensor that encircles the whole cable. The diameter of the sheath was only varied over a small range, however it can be seen that the responses of the coupler are almost identical to those in section 6.10.1 and 6.10.2. The results are shown in Figures 6.27 and 6.28.

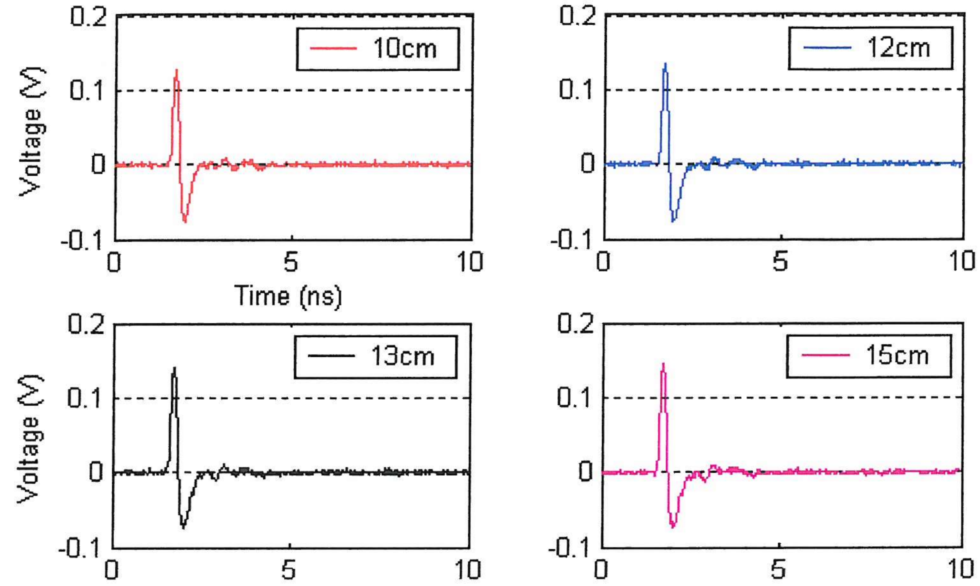

Figure 6.27 – Patch Coupler Response to Diameter – Leading Output

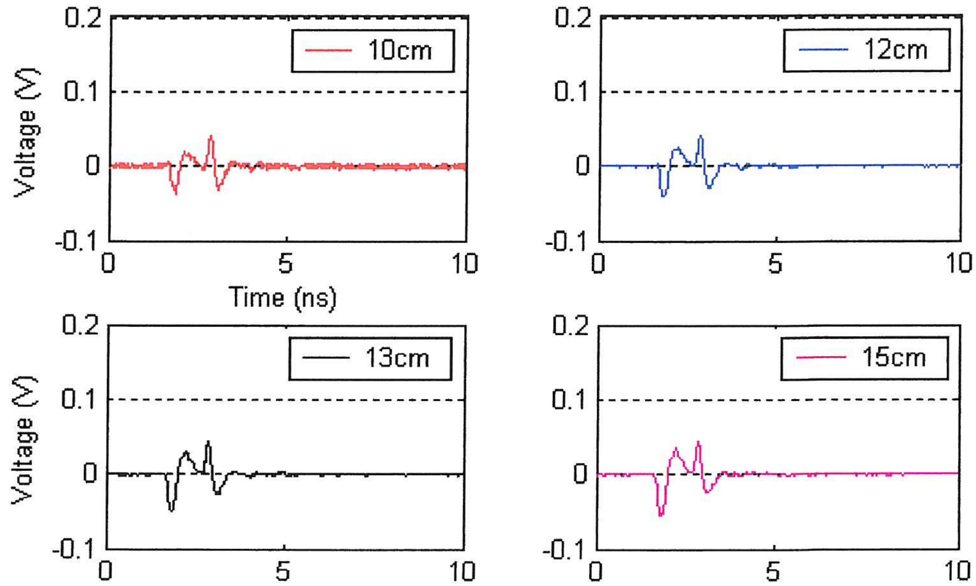

Figure 6.28 – Patch Coupler Response to Diameter – Trailing Output

6.10.8 Patch Couplers Using Different Materials

As with section 6.10.4 it was found that using Mu metal instead of foil didn't have a great effect on the response of the coupler and if anything slightly decreased the response, as seen in Figure 6.29 and 6.30.

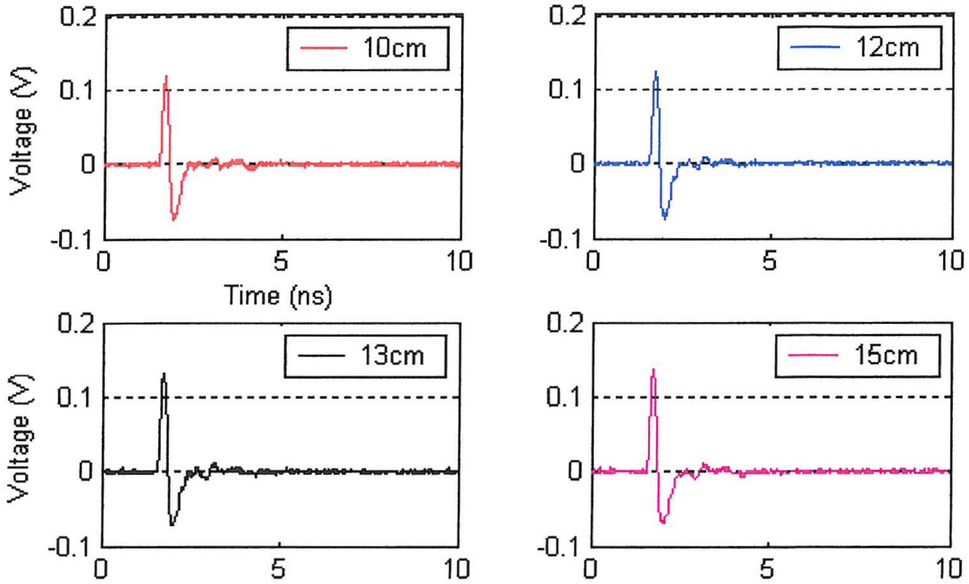

Figure 6.29 – Mu Metal Patch Response to Sheath Diameter – Leading Output

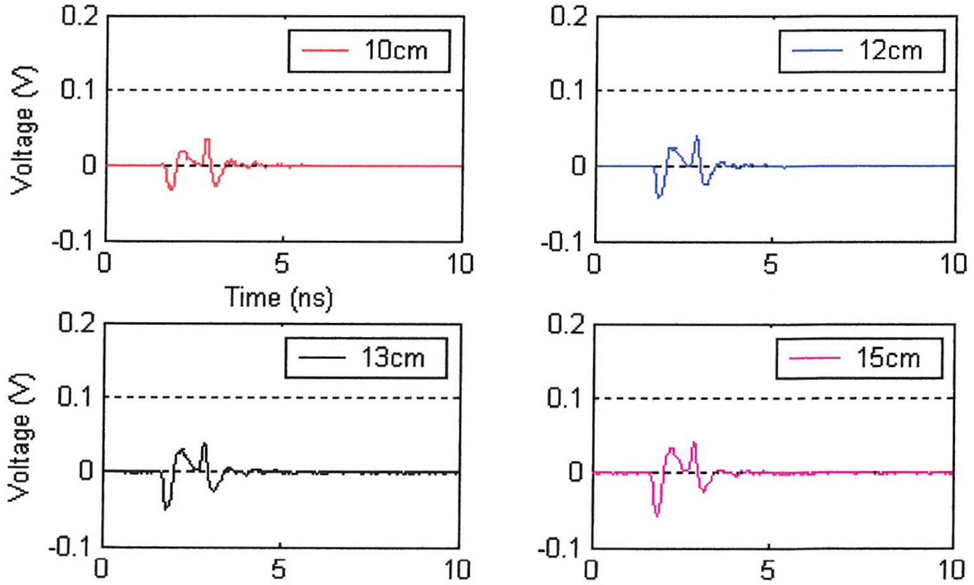

Figure 6.30 – Mu Metal Patch Response to Sheath Diameter – Trailing Output

6.11 Simulation

Software based circuit modelling was used to simulate the experimental circuit and coupler. The variations in coupler design parameters were simulated by varying the model circuit's component values and the results were recorded. The model coupler's component values were calculated using finite element modelling for the values of capacitance and inductance.

Using conventional theory the simulation circuit adopted is shown in Figure 6.31, where C_2 and C_3 represent the capacitance between the cable and the sensor, C_4 and C_5 represent the capacitance between the sensor and the earth sheath and M_1 represents the mutual inductance between the cable and the sensor.

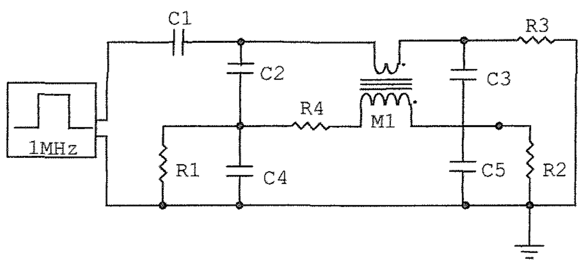

Figure 6.31 - Simulation Circuit Model

Using this circuit and finite element analysis to derive the component values within the circuit, a square wave generator and capacitor were used to simulate a fast rise time pulse being injected into the circuit, as had been done experimentally. The voltage wave form across R_1 and R_2 was then recorded, simulating the waveform that would be seen on an oscilloscope. Using this circuit and a least mean squares approach to alter the values of the component parts, it was not possible to satisfactorily simulate the recorded experimental waveforms, suggesting that the model is incorrect and that conventional directional coupler theory does not apply to the co-axial system that is used for pd detection within an xlpe cable.

However from experimentation it was found that directional couplers are predominantly capacitive, as the responses of an output remain almost unchanged if the other output connected to the same coupler is disconnected. Conventional directional coupler theory is based on two parallel lines, where a capacitive current and an inductive voltage are set up in the second line. If one of the outputs of the second line is removed then no inductive voltage can be set up, as there will be no return path. Also, in case of partial discharge detection in xlpe cables a directional coupler is used in a coaxial system as opposed to the conventional parallel line theory.

From experimentation on patch couplers it has been shown that the conduction path between the two output leads of the coupler is relatively small, i.e. only a small part of the coupler plays a role in the coupling process, as when patches that encircled less of the cable were used there was little change in the response of the coupler. Finite element analysis has shown that the mutual inductance term for a strip coupler is comparatively small and when used in the simulation circuit the capacitive effects dominate the response.

If the response is not directly related to conventional directional coupler theory, i.e. the characteristic capacitance and inductance, then coupler response will not be independent of length. Therefore as the length of the coupler is varied so the response will change also, as found experimentally.

If the inductive effect of a directional coupler is almost negligible then altering the permeability of the sensor will have little effect on the response of the coupler. Whereas, replacing bubble wrap with polyethylene as the insulator between the sensor and the earth sheath will make the response of the coupler worse. Polyethylene has a higher permittivity than air and hence by using polyethylene the values of C_4 and C_5 will increase, thus decreasing the response of the coupler.

6.12 Conclusions

Directional couplers when used in a coaxial system as with partial discharge detection in xlpe cables do not behave the way conventional directional coupler theory states. Conventional theory is based on two parallel lines, whereas in a coaxial system there are three parallel conductors: the cable core, the sensor and the earth sheath. In addition, the whole of the sensor is not conducting and, the inductive effect of the coupler is almost negligible, thus the capacitive effects dominate the response.

For the best response from a directional coupler the following should be implemented:

- a short sensor
- large sheath diameter
- materials appear to make no difference
- a strip/patch sensor is as effective as a full sensor.

It should also be borne in mind that while a large sheath diameter will give a better response, it is only necessary to make it large enough so that reliable discrimination between the two outputs can be made.

For the cable used in these experiments it was found that a short coupler (5cm length) and a diameter of around 15cm was the best compromise, providing a good response to distinguish between noise and pd signals without being too bulky. It was also found that the materials did not make much difference and that a standard coupler using foil and air gives a good enough response. It should be noted that these dimensions only apply to the cable used in these experiments as other cables will have different geometries, hence different characteristic capacitances and inductances that would affect the response of the coupler.

7. Partial Discharge Signal Acquisition and Transmission

7.1 Introduction

On-line monitoring of partial discharges within solid dielectric cables involves the constant monitoring a large number of possible pd sites. Even if it is assumed that pd will only occur within the joints of the cable neglecting the possibility of pd occurring within the cable itself, the number of sites to be monitored mount up rapidly, e.g. if a 20km three phase cable with joints every 1km is to be monitored for pd activity then there will be 19 joints to monitor on each phase, resulting in 57 joints in total, and that's assuming there's only one pd sensor per phase per joint bay. If the high sampling frequency required for accurate pd monitoring is then taken into account, there is a vast amount of data to be collected, transmitted and then finally analysed.

Added to these considerations are other factors not relating to simply the amount of data such a system will produce. Ideally such a system will require no additional power sources for the pd sensors or for electrical to optical transducers, i.e. be a passive system, thus reducing the amount of additional cable that would have to be laid in order to just sense pd signals. The aim of this chapter is to assess a variety of different possible design solutions to this problem.

Electrical, mechanical, thermal and chemical processes indicate aging and failure of insulating systems. During manufacture and operation, these create defects reducing the dielectric strength of the insulation locally. At such defects partial discharges can occur, which cause further degradation of the insulation and limit the lifetime of the equipment. Hence, the quality of an electrical insulation system can be characterised by pd measurements which serve to identify type and status of a defect. To correctly acquire partial discharge signals and interpret the measurements, the partial discharge physics (pd signal generation) and the pd signal transmission need to be understood.

Partial discharges generate locally confined impulses in the nano to microsecond range (wide-band), usually of low magnitude. Depending on the local electromagnetic environment, they are also often hidden in noise. In addition, the transfer function of the network formed by the equipment is extremely complex and acts to distort the shape of the current pulses on their way from the partial discharge source to the measurement device.

For quality assurance purposes in a laboratory setting there are well-defined procedures to reduce noise and signal distortion, these include comprehensive shielding and limitation of the acquisition frequency band (filtering). Such methods make possible very high frequency measurement sensitivity with calibration down to less than 1pC [50-55]. However, for on site diagnosis and on-line monitoring, emphasis is on noise reduction and detectability and not necessarily on calibration. Various modern processing techniques and non-conventional coupling circuits or sensors can be applied to these special problems.

The above challenges, detailed in Figure 7.1, show that a variety of information has to be compiled to correctly interpret partial discharge measurements. Three types of information have to be distinguished:

- Physical defect models which relate the measured apparent charges to the defect physics, associated damage and failure risks
- The characteristics of the pd signals e.g. their polarity, amplitudes, frequency of occurrence, their relation to the phase of the applied voltage, etc.
- Knowledge about the structure of the insulation system such as maximum local fields, internal signal propagation, etc.

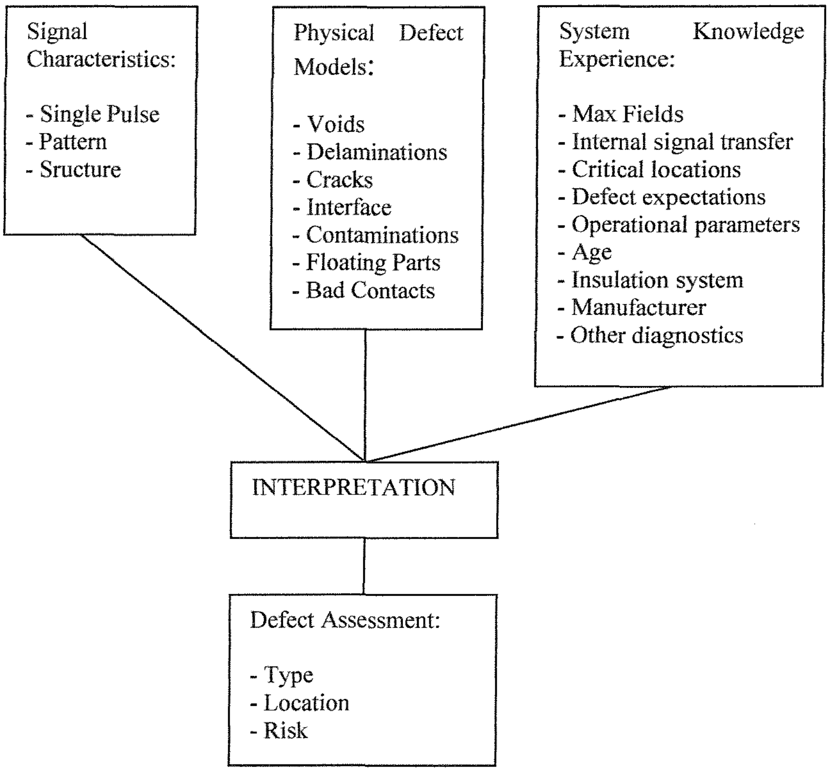

Figure 7.1 – Information Required for the Interpretation of pd Measurements [54]

Partial discharge measurement is an effective and universally applicable technique for condition monitoring. As pd is involved in the aging and deterioration process of high voltage insulation, on-line monitoring of pd provides an effective way of avoiding interruptions and failures due to slowly progressing electrical deterioration of insulation. Traditionally pd measurements have been carried out off-line during an interruption in the normal operation and with special equipment [56]. In addition, an experienced specialist has usually been needed to interpret the results. In order to fully utilise pd measurements for condition monitoring purposes pd measuring systems meeting the requirements for on-line measurements in a noisy environment must be available. Numerous pilot systems for measuring pd for instance in cables, transformers and rotating machines or gas insulated switchgears have been developed and reported in literature [57-59].

In high voltage networks wide application of on-line pd measurement as a condition monitoring technique has not been practically or economically provided. This is partly because of the high costs of the equipment and resources needed compared to the cost of the components to be monitored. One way of reducing the costs of implementing an on-line pd measuring system is to keep sensors as simple as possible.

The aim of this chapter is to investigate some of the possibilities of utilising condition monitoring based on pd measurements in industrial networks. The main objective was to suggest a pd measurement system applicable to an industrial cable network, where interruptions must be avoided.

When designing an on-line pd measurement system one major problem to be solved is the method for noise suppression. The system must be able to detect the actual pd pulses originating from a defect from the measured signal which includes also all the noise caused for example by radio transmissions. From the pd pulses the system must also be able to pick out the harmful pulses and ignore the others. With simple sensors and automatic methods for noise suppression and analysis the measuring system may not be as accurate as a dedicated pd measuring unit used with an experienced specialist. On the other hand, due to the simple design it is economical to distribute the measurement units into a network and the automatic analysis functions make the system suitable for on-line condition monitoring.

The main areas that this chapter will focus on are noise suppression, signal multiplexing, optical modulation, peak detection, data logging techniques and isolation devices.

7.2 Noise Suppression

The utilisation of pd measurements in industrial networks have so far been limited, partly due to the lack of efficient and cost effective methods for noise suppression [50,52]. PD initiates very fast travelling pulses in the high frequency (>MHz) range. Especially outside screened laboratory environments there are a lot of additional high frequency signals disturbing the measurement. There are also corona discharges and sparks present in the network in addition to the internal pd that is degrading the insulation structures. In on-line pd measurements the pd deteriorating the insulation structures must be identified and distinguished from the noise and harmless pulses.

In general, noise sources can be divided into four main groups; broadband (white) noise (arises in amplifiers etc.), narrow band interference (caused by radio broadcasts and communication networks), periodical pulse shaped signals (caused by power electronics and machine control) and stochastic pulse shaped signals (caused by lightning or switching operations). The broadband noise level is typically low and the narrow band noise problems can usually be avoided by selecting a proper frequency window in which to operate. In an industrial environment the noise caused by power-electronic devices such as three-phase bridges and inverters is the most problematic type of noise.

7.2.1 Intuitive Removal of Noise

The innate human ability in pattern recognition generally allows the skilled operator to immediately determine when a pattern is superimposed by noise. At this time suitable image processing software to achieve this automatically is not commercially available.

7.2.2 Signal Propagation and Coupler Design

A pd test detects the fast transients generated at one or several discharge sites and test results are based on the number and magnitude of pulses measured [61]. Since the discharge may occur anywhere along a considerable length of cable, pulse propagation characteristics determine the bandwidth of the pulse detectors, and ultimately the maximum length of the cable that may be tested. A xlpe cable can be considered as an rf transmission line [62]. The line's loss factor is derived from the real part of its propagation constant, which has two components: series and parallel. For an operating coaxial line, series components describe the resistivity and inductance of the conductor, and the parallel components describe the capacitance and conductivity of the dielectric, including the semi-conducting layers. Since copper is a good conductor and xlpe a good insulator, the semi-conductive layers are responsible for most of the loss and dispersion.

It can be shown that an effective sensor must have a wide enough bandwidth to accommodate the fast edge of a pd pulse that occurs nearby and the longer rise times of pulses that travel greater distances. In addition, a detector must have good rejection at power frequency and a strong, flat response to the pd signal.

Most partial discharge sensors connect in parallel with the device under test and filter out the high voltage, usually power frequency, component of the signal. With this arrangement the detecting filter must support the high voltage, but the ground connection offers a path for noise to enter the system and interfere with the pd signals.

7.2.3 Suppression of Narrow Band Periodical Noise

Since periodical noises have a narrow bandwidth, an analogue filter with suitable band stop can be used to effectively suppress these noises. Unfortunately, the centre frequency and bandwidth of the periodical noises are usually unknown and may differ from site to site, and furthermore, vary with time at the same site. So it is difficult to suppress all periodical noise using an analogue filter with fixed band stop.

Compared to an analogue filter, a digital filter can automatically determine the frequency of periodical noise and adaptively adjust the stop band of the filter. In fact, a digital filter works as a multi band stop filter. There are many ways of realising a digital filter.

Popular filtering methods are based on the fact that a pd pulse has a nearly flat frequency spectrum over the whole frequency range of the detector, whereas, theoretically periodical noise has large spectral value only in a narrow frequency range [63]. The detected signal is first transformed to the frequency domain by a fast fourier transform (fft). The noise frequency is determined by comparing all spectral values to a preset threshold. If the spectral value at a discrete frequency is larger than the threshold, this frequency is considered disturbed. All disturbed frequencies are then set to zero, thus suppressing the noise. Finally, the signal is transformed back to the time domain.

An adaptive digital filter can be developed to suppress narrow band periodical noise [64]. The filter consists of two parts; one part is a programmable filter, the other is the adaptation algorithm which modifies the weights of the filter according to the error between the expected output and the real output. The adaptive filter works on the principle that only the stationary part of the input signal, i.e. the periodical narrow band noises can be predicted, whereas, the non-stationary part, i.e. all pulses cannot be predetermined and remain in the output signal after the subtraction of the predicted value from the actual input signal. There are different types of programmable filters, among which finite impulse response (FIR) and infinite impulse response (IIR) are widely used. Recursive Least Squares (RLS) and Least Mean Square (LMS) algorithms are extensively used for adapting the parameters of the filter.

7.3 Isolation devices

There are many situations where low-level signals must be detected and amplified in the presence of potentially dangerous voltages. Examples can be found in remote sensing, motor control, data acquisition, and medical monitoring. An isolation device acts as an interface between external devices and data acquisition systems. It provides galvanic isolation between the input and output. It also rejects large common-mode signals appearing at the input and avoids ground loops since the input and output are floating relative to each other.

In industrial control, a common method of determining current is to measure the voltage drop across a known resistance. In this case, there is a small voltage riding on top of a much larger common-mode voltage. An isolation amplifier rejects the common-mode voltage and allows the signal of interest to be accurately measured.

7.3.1 Basic Concepts

An isolation device passes a signal, either analogue or digital, from input to output across an isolation barrier. This barrier ensures that there is no ohmic connection between input and output. To be effective, the isolation barrier must have high breakdown voltage, low dc leakage (high barrier resistance), and low ac leakage (low barrier capacitance). An ideal isolation device would transmit the input signal across the barrier and reproduce it perfectly at the output, as seen in Figure 7.2.

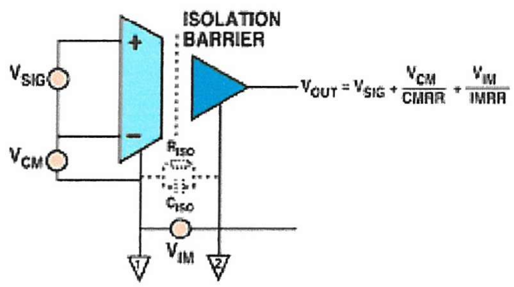

Figure 7.2 – An Ideal Isolation Device [65]

7.3.2 Isolation Voltage

Also known as dielectric withstand voltage, isolation voltage is a measure of the device's ability to protect itself and the surrounding circuitry against physical damage resulting from different voltage potentials. The insulating material between input and output, as well as the packaging technology, are the primary determinants of withstand voltage capability. The specification of this parameter varies by manufacturer. V_{ISO} is selected according to the requirements of the application

7.3.3 Isolation Capacitance

The parasitic capacitance of the isolation device should be as low as possible because it forms an ac connection across the barrier. Although R_{ISO} is usually in the ranges of several thousand MΩ and C_{ISO} is typically <10pF, the impedance observed at high frequencies is much lower. At 10MHz, a barrier capacitance of 10pF has an equivalent resistance of:

$$X_C = \frac{1}{2\pi f C_{ISO}} = \frac{1}{2\pi(10^7 Hz)(10pF)} \approx 1.6k\Omega \qquad (7.1)$$

The 10MHz signal could have several origins such as fast edges in digital systems of switching power supplies. Even if the barrier capacitance is small, stray capacitance on the circuit board can couple noise across the barrier. There are several other key parameters that define the performance of an isolation device, such as switching transients and lightening strikes in power systems.

7.3.4 Isolation-Mode Rejection

The IMR is a measure of how well the isolation device rejects isolation-mode voltage, shown in Figure 7.2 as V_{IM}. The isolation-mode voltage causes a spurious signal to appear in the output V_{OUT}, which behaves like an input-referred error signal with a magnitude of V_{IM} / IMRR

7.3.5 Common-Mode Rejection Ratio

The CMMR measures how well the device rejects common-mode signals. It defines the relationship of differential signal gain (signal applied between the input and input ground pins) to the common-mode gain (input pins tied together and the signal applied to both inputs simultaneously). Referring to Figure 7.2, a common-mode voltage V_{CM} at the input causes an output-referred error of $K \bullet V_{CM} / CMRR$, where K is the isolation amplifier input stage gain.

7.3.6 Isolation Device Technology

A number of barrier arrangements and signal modulation schemes are available. The barrier can be optical, magnetic transformer, capacitive, or even heat transfer. Modulation methods include amplitude, voltage-to-frequency, duty cycle, pulse width, and so on. The modulation ripple voltage can be removed by adding a filter in series with the output. The three techniques in common use are optical isolation, inductive isolation, and capacitive isolation.

7.3.7 Optical Isolation

The analogue optical isolation barrier consists of an LED made of gallium-arsenide-phosphide (GaAsP) or aluminum-gallium-arsenide (AlGaAs), and a photodetector. The input signal modulates the LED and the photodetector converts the light back into current. The LED's output tends to decrease over time; increasing the operating temperature or operating current hastens the deterioration, and device failure may eventually result. Various techniques are used to compensate for this phenomenon.

In digital applications the LED driver must have a built-in overdrive capability, which increases power consumption. In analogue applications, where preserving the original signal amplitude is important, there are two common techniques. If the signal is passed across the barrier in its analogue form, a more complicated approach is required that uses a second matched photodiode to provide feedback compensation. This approach offers real-time continuous analogue signal transmission and is relatively immune to interference. Another advantage is that no modulation or demodulation ripple voltage is generated in the output.

Alternatively, the signal can be digitised, passed across the barrier, then converted back to an analogue signal with a D/A converter, see Figure 7.3.

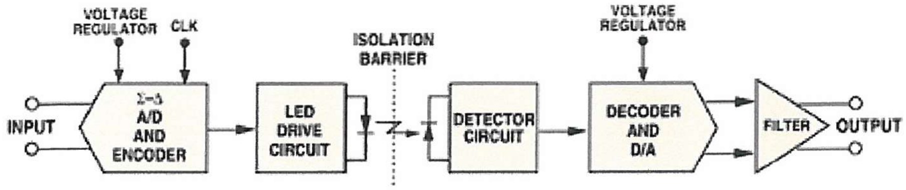

Figure 7.3 – Optical Isolation Device [65]

This avoids the use of a second expensive photodiode but increases the complexity of the surrounding circuitry, and the A/D,D/A conversion stages introduce additional errors.

7.3.8 Inductive Isolation

The signal modulates a high-frequency carrier and is transformer-coupled from input to output. Transformer-coupled devices are the most effective at transmitting power in a given volume and are invariably used in dc/dc converters. Disadvantages include lower transient immunity due to inter-winding capacitance and electromagnetic radiation and susceptibility. In addition, it may be difficult to package the transformer in a form suitable for high-volume manufacturing.

7.3.9 Capacitive Isolation

The signal modulates a high-frequency carrier and is capacitively coupled from input to output. Either duty-cycle or frequency modulation techniques are used, and the signal is passed differentially across the barrier. Capacitive devices have lower transient immunity performance since some fast transient common-mode pulses pass across the coupling capacitor and are not filtered out.

7.3.10 System Architecture Considerations

Once it has been determined if isolation is required in a particular application, there are several tradeoffs to be made when deciding where in the signal chain the isolation takes place. The typical multi-channel isolated data acquisition signal chain shown in Figure 7.4 consists of a multiplexed front end feeding into a programmable gain stage, followed by an A/D converter.

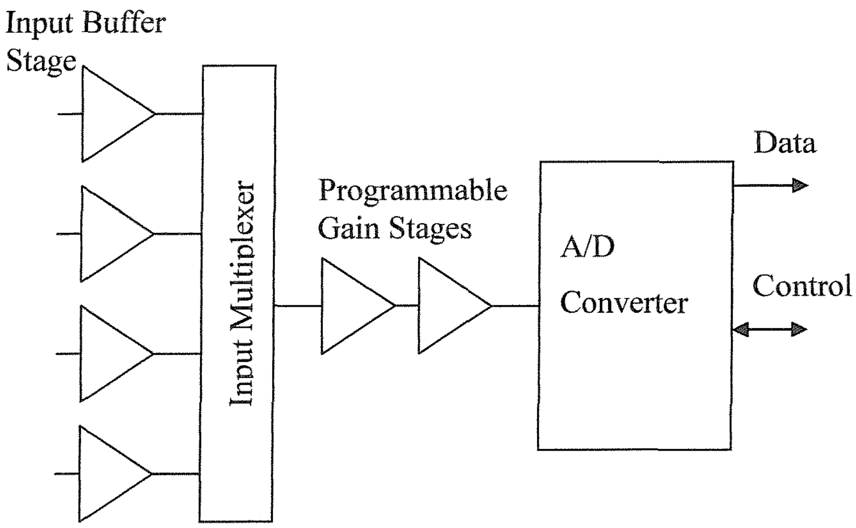

Figure 7.4 – Typical Multi-Channel Isolated Data Acquisition Signal Chain

The isolation devices can be placed in at least three points in this chain, in between each of the satges; the choice depends on the precise requirements of the application.

7.3.11 Summary

A wide variety of isolation devices is available to help the system designer solve tricky applications issues in fields ranging from industrial process control to medical pc-based data acquisition systems. Effective use of these devices requires an understanding of the technologies involved and their attendant trade-offs.

7.4 Peak Detection

Any continuous periodic waveform can contain a variety of desirable information, such as the beginning and end points of a cycle, the minimum, maximum, or mean signal values within the cycle, and the rate at which the cycle repeats. This information is obtained, in many cases, from a quick glance at the waveform and a simple calculation. The problem is not one of procedure, but time. Consider a more typical application involving not one, but several hundred cycles and the need to calculate with reasonable accuracy the parameters mentioned above on a cycle-by-cycle basis, i.e. partial discharge monitoring, the task becomes overwhelming. Without question, the process may be simplified by looking at large groups of waveforms for average maximum, minimum, mean, and rate values.

The obvious solution is to use a computer. Although it is true that for any number of samples a computer can be programmed to report the highest and lowest values, it fails to duplicate the ability of an experienced technician to intuitively identify the beginning and end points of a cycle. Since the accurate determination of minimum, maximum, mean, and rate information depends on an equally accurate determination of cycle beginning and end points, the computer-based solution fails.

There have been developments of algorithms focused on solving the beginning and end point determination problem, since this is the only barrier preventing a computer from automating the labour-intensive process described above. Through innovative software design, and by making the technician or researcher part of the evaluation process, a peak capture algorithm represents a computer-based solution to the automatic detection of peak, valley, mean, and period information. In addition to the peak capture algorithm, the advanced packages can also include a report generator utility and software routines for waveform integration, differentiation, moving averages, rectification, and arithmetic operations.

7.4.1 Peak Detection Theory

Peak detection algorithms allow the cycle-by-cycle extraction of peak, valley, or peak and valley data points from a periodic waveform. Any sampled waveform can be thought of as a long string or collection of data values. Aside from the peak and/or valley data value, the rest of these values are many times of little or no interest to the technician or researcher. The peak capture algorithm can be applied to virtually any waveform with the purpose of reducing this large number of waveform data values to several meaningful values per waveform cycle, representing the maximum, minimum, or maximum and minimum signal excursion within the cycle [66,67].

The procedure used by the algorithm to determine cyclic peak and valley waveform values involves the use of a sensitivity setting. This sensitivity level, controlled by the user through the software, can be increased or decreased to mask or allow minor changes in waveform, resulting in a valid peak and/or valley detection. The software then automatically tags these waveform data values with a positive and/or negative going event marker to indicate cyclic peak and valley points respectively. These tagged points can be reviewed to verify the results and even edited if desired. Once tagged, these values can be sent to a utility called a report generator to further aid analysis and interpretation of the acquired.

7.4.2 The Peak Capture Algorithm and Base Line Shift

A salient feature of a peak detection algorithm is its ability to capture peak and/or valley data on a waveform containing large baseline variations. Waveforms containing a large amount of varying offset voltage on which the desired peaks and valleys ride pose no problem for the standard peak detection algorithm. Neither do pd-type waveforms that feature peaks and valleys on a trend that shifts dramatically from the baseline in both positive and negative directions. The peak detection algorithm is still able to peak and/or valley capture these types of waveforms because of the unique design of the algorithm.

Less sophisticated analysis software can interpret minor changes in waveform inflection as a valid inflection point, resulting in erroneous data. Peak detection algorithms, however, can be adjusted to this variation in the waveform. By decreasing the sensitivity of the algorithm, the minor inflections of the waveform will be masked, leaving only true cyclic peaks detected, just as if a skilled technician had analysed the waveform.

The first step in deriving relevant information from the raw waveform is to peak and valley capture the waveform with a peak detection algorithm. The peak and/or valley markers can be written to a channel that contains a different waveform or to the same channel that contains the original waveform. The mode of capture defines whether the peak detection algorithm will mark peaks, valleys, or peaks and valleys. The sensitivity level determines how sensitive the algorithm will be to inflections in the waveform. The sensitivity level has a default setting that provides perfect results for most applications, but if the application deals with an unusual waveform, the sensitivity can be adjusted over a wide range to respond properly.

The next step is to pass the peak and valley captured waveform through a report generator. The report generator extracts the peak and valley markers placed on the waveform by the peak detection algorithm as point values. Using these point values, the report generator will create a report (in the form of a new file) of the minimum, maximum, mean, and time values per cycle. This report can be created in one of two user selectable data file storage formats: spreadsheet/ASCII compatible or Excel compatible. The spreadsheet compatible format can be imported directly into spreadsheet software (e.g. Excel, etc.) for further analysis and plotting. The Excel compatible format can be imported directly by a variety of standard analysis packages.

The mean value reported by the report generator is not an approximation, which would be expected from less sophisticated analysis software, but rather a true cyclic mean value. Using integration, the mean value of a waveform with respect to time from the beginning to the end of the cycle is calculated by:

$$mean_{cycle} = \frac{\int_{0}^{t_1} f(t)dt}{t_1 - t_0} \qquad (7.2)$$

Where:

t_o = Time at the beginning of the cycle

t_l = Time at the end of the cycle

A waveform cycle can be reported as an interval (in seconds) or as a rate in either cycles per second (Hz) or cycles per minute. The waveform cycle interval is reported by taking the difference between the cycle beginning and end points (t_l - t_0), which were previously defined for the mean value calculation. The waveform cycle rate in cycles per second (Hz) is reported by taking the reciprocal of the interval, and the waveform cycle rate in cycles per minute is reported by multiplying the reciprocal of the interval by 60.

7.5 Data Loggers

A data logger is an instrument used to record values from various predefined instruments (sensors) at predefined intervals and to display or print the results when prompted to do so. By recording data over a period of time, it is possible to gain important insights into trends and therefore to check on the way equipment is performing [68, 69].

Each logger is capable of recording the parameters detected by one or more sensors designed especially for the purpose. A single channel logger will record from only one sensor, while a multi-channel logger can record from two or more sensors simultaneously. It is possible to produce a logging system with over one hundred sensors.

7.5.1 Simple Data Loggers

A very simple logger will record a single parameter, and record a measurement at predetermined intervals of perhaps a minute. More complex single channel loggers can have the logging interval pre-programmed into them and the best can have the logging interval changed by the user simply by connecting them to a personal computer and running a simple program.

At the end of the logging period the data must be extracted from the logger and presented to the user in an appropriate form such as a printed list (showing date, and recorded information) or a graphical display. The main disadvantage with simple data loggers is that they must be visited in order to download the data before it can be used. Another problem is that some data loggers rely on batteries which need changing after a year or so - if they go flat the system will stop working and a vital alarm condition may be missed.

7.5.2 Alarms

Sometimes simply logging pd activity is not sufficient, the user needs to know if the parameter being measured goes over preset levels at any time. To fulfil this need the logger needs to be programmed with the level at which to trigger the alarm and also needs to communicate this to an alarm system in some way.

7.5.3 The Ideal Data Logger

Having considered the above an ideal data logger can be defined:

- No need to visit it to access the readings
- Start with a few sensors and grow as required
- Provide alarms
- Be easy to install
- Not require periodic battery changes

Data loggers are available as a small single channel device containing a battery and tiny radio transmitter, the battery can be designed to last for ten years and is sealed inside the unit. Twice a minute the sensor reads the specified parameter and sends it by radio to a central collection and display unit that can handle up to 32 sensors.

The collect unit is preset with channel (sensor) identifiers, logging intervals and alarm levels for each sensor in the system. It is this collect unit that detects when an alarm condition occurs and as soon as it does a warning signal can be sent, i.e. a red light on the unit is illuminated, or a buzzer can sound. Using additional equipment the alarm can also be sent to a pager, mobile phone or fax machine.

7.5.4 Data Logging in Real Time Process Systems

Real time monitoring and control applications such as manufacturing automation, distributed process control and network management need to access the data sampled from plants and maintain the log of the data in disk files. The data log is a history of the system's state, and can be used for analysing the trend of certain subsystems, controlling the activities of the systems, generating reports, etc. [68]. The overall architecture of a real time monitoring and control system is shown in Figure 7.5.

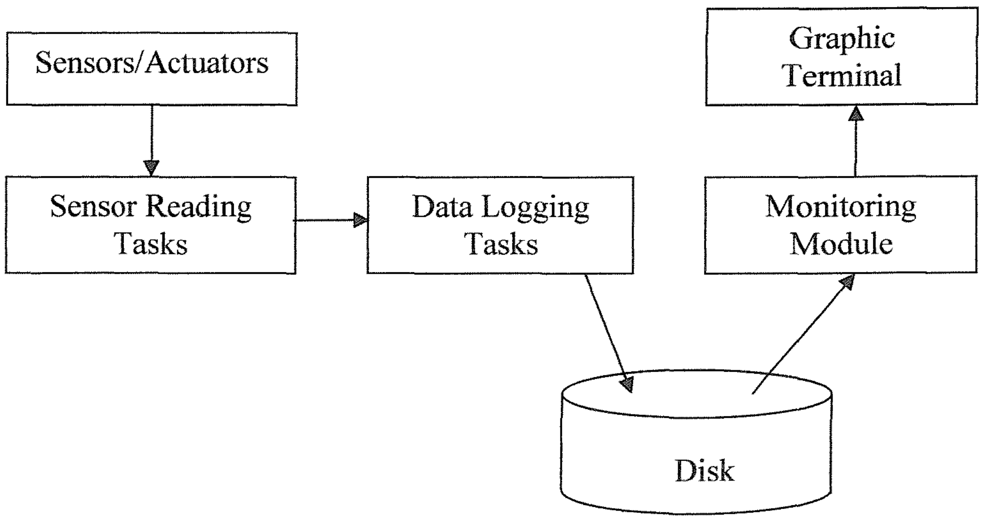

Figure 7.5 – Overall Architecture of Monitoring and Control Systems [70]

As shown in Figure 7.5, real time monitoring and control systems have three major types of tasks: sensor reading, data logging, and monitoring. Sensor reading tasks acquire the current state of the equipment or sensors at fixed intervals and store them in their own main-memory buffers. In order to monitor and control the system effectively, these functions have to obtain the system's status within their sampling interval. The sampled data will be sent to data logging functions and monitoring functions.

Data logging functions store the data acquired by sensor reading tasks in disk files, which maintain the entire history of the data. These functions must save all of the sampled data in disk files before the buffer of sensor reading functions runs out. Therefore, data logging must meet the hard deadline imposed by the buffer size and the sampling rate of each sensor reading task.

Monitoring functions receive the current state of the system from sensor reading functions and display it on a graphical terminal. They also access some of the logged data stored in disk files and will present their statistical trend or generate reports. The statistics and reports will be used to analyse and control the system activities. The monitoring functions will be invoked by system operators

Several approaches to scheduling both periodic real time functions and soft aperiodic real time functions have been proposed in literature [68-71]. Based on a rate monotonic scheduling algorithm, deferrable server, priority exchange [68] and slack stealing [69] algorithms have been proposed to schedule aperiodic functions while meeting the deadline of all periodic functions. All of these algorithms require an assumed knowledge of the worst-case execution time of each functions. However, this knowledge is difficult to obtain in practice, because it is difficult determine the worst-case response time of each disk input/output request. When a functions requests to write to a disk block it sends a disk I/O request to the disk controller.

At first glance data loggers would seem a very good way to record the pd activity at cable joints, as they would require little extra wiring to install them and the data could be collected as required. However, to effectively monitor pd in cable joints a very high sample rate is required, to capture pulses that can have durations of down to a few nanoseconds, thus a large amount of data would have to be stored. Data loggers have not yet been used in any major commercial partial discharge monitoring systems as there are not any data loggers available that have either the high frequency sampling rate needed or the amount of memory required to accurately measure pd activity.

7.6 Optical Multiplexing

Despite the success of fibre optic technology, it has so far been used primarily as a low loss, high bandwidth and electrical interference free replacement to electrical cable in point to point transmission links [72-75]. In most systems, optical signals are converted to electrical domain at intermediate nodes in order to perform switching. For example, in the internet, electronic switches are used to route packets to their destinations. However, in this approach, the maximum serial line rate will always be limited by the bandwidth of electronics, which is considerably less than the tens of TeraHertz bandwidth available in optical fibre. In effect, a bottleneck is created in the system.

By applying optical multiplexing techniques, the bandwidth of fibre optics can be utilized more efficiently. There are three primary optical multiplexing techniques. The most basic technique, space division multiplexing (sdm), is a brute force approach that simply uses separate optical fibres for each channel. Of course, this approach starts to become unwieldy as the number of channels and connections increases in a fully connected network.

A second approach, by using separate optical wavelength division multiplexing (wdm) technology, a single transmission fibre can be used instead of separate fibres for each channel. The multiplexing and demultiplexing of the signals can be accomplished using passive optical components, since this is a relatively low cost technology, wdm had a great deal of success in the past. However, wdm is still primarily used as a way if increasing the transport capacity over a given link, and the optical paths are relatively static. Functionally, the wdm system is very similar to the sdm technique. Fast optical switching is not performed with the network. If any switching is required, it is accomplished by separating the wavelengths of each fibre into different space switches such as micro-mechanical optical switches. The switching times of such switches are limited to milliseconds.

To actually perform fast switching in the optical domain, active optical techniques must be employed. One such approach is optical time division multiplexing (otdm). It is based on the use of very short optical pulses that are used to interleave a number of channels in the time domain. Since the aggregated data rates can easily exceed 100Gb/s, active optical switching techniques must be used to recover the signals at their destination.

7.6.1 Optical Time Division Multiplexing

Time-division multiplexing (tdm) is a method of putting multiple data streams in a single signal by separating the signal into many segments, each having a very short duration. Each individual data stream is reassembled at the receiving end based on the timing.

The circuit that combines signals at the transmitting end of a communications link is known as a multiplexer. It accepts the input from each individual end user, breaks each signal into segments, and assigns the segments to the composite signal in a rotating, repeating sequence. The composite signal thus contains data from multiple senders. At the other end of the long-distance cable, the individual signals are separated out by means of a circuit called a demultiplexer, and routed to the proper end users. A two-way communications circuit requires a multiplexer/demultiplexer at each end of the long-distance, high-bandwidth cable.

If many signals must be sent along a single long-distance line, careful engineering is required to ensure that the system will perform properly. An asset of tdm is its flexibility. The scheme allows for variation in the number of signals being sent along the line, and constantly adjusts the time intervals to make optimum use of the available bandwidth. The internet is a classic example of a communications network in which the volume of traffic can change drastically from hour to hour.

7.6.2 Optical Frequency Division Multiplexing

Frequency-division multiplexing (fdm) is a scheme in which numerous signals are combined for transmission on a single communications line or channel. Each signal is assigned a different frequency (sub-channel) within the main channel.

A typical analogue internet connection via a twisted pair telephone line is limited to approximately three kilohertz (3kHz) of bandwidth for accurate and reliable data transfer. Twisted-pair lines are common in households and small businesses. But major telephone cables, operating between large businesses, government agencies, and municipalities, are capable of much larger bandwidths.

Suppose a long-distance cable is available with a bandwidth allotment of three megahertz (3MHz). This is 3,000kHz, so in theory, it is possible to place 1,000 signals, each 3kHz wide, into the long-distance channel. The circuit that does this is the multiplexer. It accepts the input from each individual end user, and generates a signal on a different carrier frequency for each of the inputs. This results in a high-bandwidth, complex signal containing data from all the end users. At the other end of the long-distance cable, the individual signals are separated out by means of a demultiplexer, and routed to the proper end users. A two-way communications circuit requires a multiplexer/demultiplexer at each end of the long-distance, high-bandwidth cable.

When fdm is used in a communications network, each input signal is sent and received at maximum speed at all times. This is its chief asset. However, if many signals must be sent along a single long-distance line, the necessary bandwidth is large, and careful engineering is required to ensure that the system will perform properly.

7.6.3 Phase Modulation

Phase modulation (pm) is a method of impressing data onto an alternating-current waveform by varying the instantaneous phase of the wave. This scheme can be used with analogue or digital data.

In analogue pm, the phase of the ac signal wave, also called the carrier, varies in a continuous manner. Thus, there are infinitely many possible carrier phase states. When the instantaneous data input waveform has positive polarity, the carrier phase shifts in one direction; when the instantaneous data input waveform has negative polarity, the carrier phase shifts in the opposite direction. At every instant in time, the extent of carrier-phase shift (the phase angle) is directly proportional to the extent to which the signal amplitude is positive or negative.

In digital pm, the carrier phase shifts abruptly, rather than continuously back and forth. The number of possible carrier phase states is usually a power of 2. If there are only two possible phase states, the mode is called bi-phase modulation. In more complex modes, there can be four, eight, or more different phase states. Each phase angle (that is, each shift from one phase state to another) represents a specific digital input data state. Phase modulation is similar in practice to frequency modulation (fm) but the relationship between phase and frequency variations is not linear; that is, phase and frequency do not vary in direct proportion.

7.7 Conclusions

This chapter has considered just some of the possible solutions to the problem of collecting transmitting and analysing the large amount of data generated by partial discharge monitoring within long lengths of high voltage solid dielectric cables. Methods of noise suppression have been discussed in order to improve the sensitivity of a chosen monitoring device, from intuitive methods to banded filters, to reduce noise signals such as communications signals. Isolation devices were introduced as a method of protecting sensitive monitoring devices from the high voltages that they would be subjected to and also provide filtering in the form of common mode rejection. Data loggers were also discussed as a method of monitoring and storing pd activity within cable joints, although presently they do not seem to have the required specifications to perform at the levels required for pd monitoring.

Having reviewed the more suitable solutions it is considered that the most likely solution to meet the requirements of on-line monitoring would be a combination of the following:

- Optical phase modulators connected to the sensors to convert the pd impulses from electrical to optical signals that can then be transmitted over long distances with virtually no loss.
- Time division multiplexing and switching at a collector/analyser, where a single optical signal is sent down several separate optical fibres each connected in turn to a separate optical phase modulator at each cable joint, which then feeds back to a de-multiplexer and opto-electrical converter.

This way all the data from each joint can be stored and analysed at a single location at one end of the cable. By using optical fibre as a means of transmitting the data no electrical interference will be picked up and virtually none of the signal will be lost in transmitting the signal over the distances. Also this way only one laser source is required, but switched through several fibre optics, which will have a suitably high sampling frequency for pd monitoring.

8. Conclusions

One of the main contributions this thesis has been the comparison of on-line detection methods for pd within xlpe cables. It has been shown that the capacitive coupler has a much better response to pd signals than other methods, such as rogowski coils and rfcts, when used for pd detection in xlpe cable joints. This is due to the higher operating bandwidth of the capacitive coupler. However, it should be noted that capacitive couplers are not always the best type of sensor, as they require a section of the shielding to be removed from the cable, so unless prefabricated into the cable joint they are not easy to implement. It is often easier to place an rfct around a cross bonding lead than to implement a capacitive coupler onto a cable joint.

It has also been shown in practical experiments that capacitive couplers have a low susceptibility to low frequency noise associated with substations compared to other methods of pd detection, thus making them a very good method for detection with on-line cables as well as under laboratory conditions.

A commercially available pd detection system using directional couplers was obtained from Lemke Diagnostics and tested under laboratory conditions for its suitability to the detection of pd within hv cable joints. Some initial results were promising and were in close agreement with a Robinson Detector that was used in parallel with the Lemke system, however, upon being advised to have the Lemke unit re-calibrated the system was returned in a far worse condition than it left. Thus, it was concluded that system was far too fragile for use with on-line systems in the field. The Lemke system also had a number of flaws that made it unsuitable for on line monitoring. For example, the system as a whole was very bulky due to the large batteries required for it to run in the field, and thus could not be easily transported to a cable joint site. Also, the system lacked the versatility to be able to monitor multiple joints simultaneously. The documentation that was provided with the system detailing how it should be implemented and operated was also very poor and did not detail a lot of the finer points on how to install the directional coupler for optimum results.

Detailed experimentation was undertaken in order to better understand how the directional coupler operates. These experiments led to some guidelines on how best to implement a coupler on a cable, however, attempts to simulate the processes occurring within a directional coupler did not succeed and no relationship between the results measured and the variables altered could be drawn. Using various methods of to try to model the couplers, i.e. transfer functions, circuit modelling software and finite element packages, an accurate model of a directional coupler was not determined. It appears that the internal workings of a coaxial directional coupler are more complex than first thought and could not be accurately determined within the time scale of this project. The simulation model was based on accepted theory of how a directional coupler operates, i.e. two parallel transmission lines, however, the inductance of a coaxial directional coupler is extremely small compared to its capacitance. Therefore, transmission line based theory is not appropriate for explaining directional coupler behaviour for pd detection on hv coaxial cables.

Due to the rapid attenuation of high frequency signals, such as those excited by pd, along a length of xlpe cable it is unrealistic to monitor the full length of a cable, thus certain simplifications need to be made. If the assumption that cables are totally pd free and that all pd signals come from within the joint is used, directional couplers possess no advantage over capacitive couplers but possess a number of disadvantages in comparison. If it is assumed the only pd sites will come from within the joint then it is already known which direction the signal came from, thus using a directional coupler an extra redundant signal is produced which will need to be monitored as well. The output of a capacitive coupler is also comparable to the leading output of a directional coupler, thus there is no advantage in using directional coupler from a sensitivity point of view. Capacitive couplers are also less complex to implement and thus can be installed a lot quicker upon a cable than a directional coupler.

Finally an investigation was undertaken to assess the best ways of acquiring, collecting and analysing the data from a monitored cable circuit. A design with which a full underground cable circuit comprising multiple cable joints could be monitored was proposed, in contrast to the Lemke system which could only monitor a single joint at a time. The main design problem was the huge amount of data that would be generated while monitoring multiple joints at high frequency. It was proposed that a passive system would be best for transmitting the data from the sensor, as this would not require the additional use of power sources such as battery packs. Optical modulators proved ideal in this situation as they are passive devices and would convert the electrical signals from the sensors into an optical signal that can be transmitted over large distances without loss and are free from additional electrical interference. Using optical modulators in conjunction with time division multiplexers means that each joint can be monitored in turn, and a warning flagged up on any cable joint that displays pd activity above a certain level.

9. References

[1] "Partial Discharge Measurements", IEC Publication 270, 1981

[2] T Heizmann, T Aschwanden, H Hahn, M Laurent, L Ritter, "On Site Partial Discharge Measurements on Premolded Cross Bonding Joints of 170kV EPR Cables", IEEE Transactions on Power Delivery, pp330-335, April 1998

[3] U Schichler, "A Sensitive Method for on-Site Partial Discharge Detection on XLPE Cable Joints", Proceedings of the 5th International Conference on Properties and Applications of Dielectric Materials, pp. 1099-1102, 1997

[4] R Bartnikas, "A commentary on PD measurement and detection", IEEE Trans. On Electrical Insulation, pp 629-655, 1987

[5] R Bartnikas "Detection of pd in electrical apparatus" IEEE Trans. On Electrical Insulation, pp 111-124, 1990

[6] G E Quinn "Detection of the ionisation point in electrical apparatus" AIEE Trans., pp709-714, 1940

[7] G L d'Ombrain, R Bartnikas "A method for determining the dissipation factor value from corona intensity and pulse count" IEEE Trans. on Power Apparatus and Systems, pp 366-375, 1963

[8] R Bartnikas, G L d'Ombrain "A study of the corona discharge rate and energy loss in spark gaps" IEEE Trans. on Power Apparatus and Systems, pp 770-779, 1965

[9] A Kelen, "The functional testing of hv generator stator insulation" Proc. CIGR, Paris 1976

[10] J Austin, R James, "On-line digital computer systems for measurement of pd on insulation structures" IEEE Trans. on Electrical Insulation, pp 129-139, 1976

[11] R Morin, R Bartnikas "Corona pulse charge transfer at elevated frequencies", IEEE Trans on Electrical Insulation, pp458-461, 1983

[12] T Okamoto, T Tanaka, "Novel pd measurement computer aided measurement systems" IEEE Trans. on Electrical Insulation, pp1015-1019, 1986

[13] B Fruth, L Niemeyer, M Haessig, J Fuhr, T Dunz, " Phase resolved pd measurements and computer aided pd analysis performed on different HV apparatus" 6th International Symposium on HV Engineering, pp 15.03-15.06, 1989

[14] E Gulski, F H Kreuger, "Computer aided recognition of discharge patterns" IEEE Trans on Electrical Insulation, pp 82-92, 1992

[15] E Gulski, "Computer aided measurement of pd in HV equipment" IEEE Trans on Electrical Insulation, pp 969-983, 1993

[16] A A Mazroua, M M Salama, R Bartnikas, "PD pattern recognition with neural networks using the multiplayer perception technique" IEEE Trans on Electrical Insulation, pp 1082-1089, 1993

[17] E Gulski, A Krivda, "Neural networks as a tool for recognition of pd" IEEE Trans on Electrical Insulation, pp984-1001, 1993

[18] R I van Brunt, "Stochastic properties of pd phenomena" IEEE Trans on Electrical Insulation, pp 902-948, 1991

[19] J P Zondervan, E Gulski, J J Swit, "Fundamental aspects of pd patterns of on-line measurements on turbo generators" IEEE Trans on Dielectrcis and Electrical Insulation, pp 59-70, 2000

[20] G C Montanari, A Contin, A Cavalini, "Random sampling and data processing for pd pulse height and shape analysis" IEEE Trans on Electrical Insulation, pp 905-916, 2000

[21] P von Glahn, R I van Brunt, "Continuous recording and stochastic analysis of pd" IEEE Trans on dielectrics and Electrical Insulation, pp 590-601, 1995

[22] T Ficker, J Macur, L Pazdera, M Klimnet, S Filip, "Simplified digital acquisition of microcharge pulses" IEEE Trans on Dielectrics and Electrical Insulation, pp 220-227, 2001

[23] B H Ward, "Digital techniques for pd Measurements" IEEE Trans on Power Delivery, pp 469-479, 1992

[24] R Bartnikas, "Some observations on the character of corona discharges in short gaps" IEEE Trans on Electrical Insulation, pp 63-75, 1971

[25] J P Novak, "Early stages of channel formation in a short gap breakdown" Journal of applied Physics, pp 1767-1774, 1988

[26] J P Novak, R Bartnikas, " On the character of different forms of pd and their related terminologies" IEEE Trans on Electrical Insulation, pp 956-968, 1993

[27] I Radu, G Czeremuskin, M R Wertheimer, R Bartnikas, "Diagnostics of dielectric barrier discharges at atmospheric pressure in noble gases" Proceedings of the International Conference on High Pressure Low Temperature Plasma Chemistry, 21-26 July 2002

[28] W Breazeal, K M Flynn, E G Gwinn, "Static and dynamic two dimensional patterns in self extinguishing discharge avalanches" Physics Review, pp 1503-1515, 1995

[29] J C Devins, "The physics of pd in solid dielectrics" IEEE Trans on Electrical Insulation, pp 475-495, 1984

[30] P H Morshuis, F H Krueger, "Transmission from streamer to Townsend mechanisms in dieletric voids" Journal of Physics and Applied Physics, pp 1562-1568, 1990

[31] J P Novak, "Density profiles, electric field and energy dissipation in a short gap breakdown; a two dimensional model" Journal of Physics, pp 896-903, 1988

[32] J P Novak, R Bartnikas, "Collinsional phenomena and current in the electrical breakdown of hydrogen" IEEE Trans on Plasma Science, pp 775-783, 1990

[33] J P Novak, R Bartnikas, "Effect of dielectric surfaces on the nature of pd" IEEE Trans on Dielectrcis and Electrical Insulation, pp 146-151, 2000

[34] V Nikonov, R Bartnikas, M R Wertheimer, "The influence of dielectric surface charge distribution upon thepd behaviour in short gaps" IEEE Trans on Plasma Science, pp 866-874, 2001

[35] R Bartnikas, J P Novak, " Effect of over-voltage on the rise time and amplitude of pd pulses" IEEE Trans on Dielectrics and Electrical Insulation, pp 557-566, 1995

[36] G S Eager, G Bahder, D A Silver, " Corona detection experience in commercial production of power cables with extruded insulation" IEEE Trans on Power Apparatus and Systems, pp 342-364, 1969

[37] W L Weeks, J P Steiner, "Instrumentation for the detection and location of incipient faults in power cables" IEEE Trans on Power Apparatus and Systems, pp 2328-2335, 1982

[38] M Beyer, W Kamm, H Bosi, K Feser, "A new method for detection and location of distributed pd cable faults in HV cables under external interference" IEEE Trans on Power Apparatus and Systems, pp 3438-3451, 1982

[39] E F Steenis, "Diagnostic testing of distribution cable systems" Minutes of the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society, 1996

[40] C H Knapp, R Bausal, M S Mashikian, R B Northrup, "Signal processing techniques for pd site location in cables" IEEE Trans on Power Delivery, pp 859-865, 1990

[41] M S Mashikian, F Palmieri, R Bansal, R B Northrup, " Location of pd in the presence of high noise" IEEE Trans on Electrical Insulation, pp37-43, 1992

[42] M S Mashikian, R Luther, J C McIver, J Jurcision, P W Spencer, "Evaluation of field aged crosslinked PE cables by pd location" IEEE Trans on Power Delivery, pp 620-628, 1994

[43] J R Steiner, P H Reynolds, W L Weeks, "Estimating the location of pd in cables" IEEE Trans on Electrical Insulation, pp 44-59, 1992

[44] G Katsuka, A Toya, K Muraoka, T Endoh, Y Sekii, C Ikeda, "Development of a method of partial discharge detection in extra HV cross-linked PE insulated cable lines" IEEE Trans on Power delivery, pp 1068-1079, 1992

[45] C G Henningsen, K Polster, B A Fruth, D W Cross, "Experience with an on-line monitoring system for 400kV XLPE cables" IEEE Transmission and Distribution Conference, 1996

[46] F H Gooding, H B Slade, "Corona level scanning of HV cables" AIEE Trans on Power Apparatus and Systems, pp 999-1009, 1957

[47] "LDIC LDY-724 Operating Manual"

[48] B. M. Oliver "Directional Electromagnetic Couplers" *Proceedings of the IRE* November 1954

[49] D. Pommerenke, T. Strehl and W. Kalkner "Directional Coupler Sensor for Partial Discharge Recognition on High Voltage Cable Systems" *10th International symposium on High Voltage Engineering* August 1997

[50] R. Whodek, Z. Florkowski, P. Zydron, "Improvement of Signal to Noise Ratio in Partial Discharge Measurements" Proceedings of the 4th International Conference on Properties and Applications of Dielectric Materials, July 3-8 1994

[51] D. Pommerenke, T. Strehl, W. Kalkner, "Directional Coupler Sensor for Partial Discharge Recognition on High Voltage Cable Systems" 10th International Symposium on high Voltage Engineering, August 25-29 Canada 1997

[52] Xiongwei Jiang, Xiaohong Zhang, Zhidong Jia, Hengkun Xie, "Noise Rejection Techniques Used for On-Line Monitoring of Partial Discharges in Large Turbine Generators" Proceedings of the 6th international Conference on Properties and Applications of Dielectric Materials, June 21-26 2000

[53] G.C. Stone "Partial Discharge – Part VII: Practical Techniques for Measuring PD in Operating Equipment" IEEE Electrical Insulation Magazine, July/August 1991 Vol.7, No. 4

[54] B.A. Fruth, D.W. Gross "Partial Discharge Signal Generation, Transmission and Acquisition" Proceeding on Science and Measuring Technology, January 1995, Vol. 142, No. 1

[55] T. Strehl, R. Heinrich, W. Kalkner "Discrimination Between Internal PD and Other Pulses Using Directional Coupling Sensors on HV Cable Systems" IEEE Transactions on Dielectrics and Electrical Insulation December 1999 Vol.6 No. 6

[56] Kane, B. Lease, A. Golbev "Practical Experiences of On-line Partial Discharge Measurements on a Variety of Medium Voltage Electrical Equipment" Petroleum and Chemical Industry Conference, 1998

[57] J.P. Steiner "Partial Discharge – Part IV: Commercial PD Testing" IEEE Electrical Insulation Magazine 1991, Jan/Feb 1991

[58] K. Fukunaga, M. Tan, H. Takehana, T. Yoshida "New Partial Discharge Detection Method for Live Power Cable Systems" Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, July 8-12 1991

[59] H. Maekawa, T. Ito, E. Yajima "GIS Monitoring Sensors" Proceedings of the 4th International Conference on Advances in Power System Control, Operation and Management November 1997

[60] G.C. Stone "The use of Partial Discharge Measurements to Assess the Condition of Rotating Machine Insulation" IEEE Electrical Insulation Magazine, July/August 1996

[61] S.A. Boggs "Partial Discharge: Overview and Signal Generation" IEEE Electrical Insulation Magazine, July August 1990 Vol. 6, No.4

[62] J.M. Braun, D.J. Horrocks, J.P. Levine and H.G. Sedding "Development of On-Site Partial Discharge Testing For Transmission Class Cables" Power Cables and Accessories 10kV-500kV, 23-25 November 1993

[63] G. Konig, K. Feser "A New Digital Filter to Reduce Periodical Noise in Partial Discharge Measurements" 6th International Symposium on HV Engineering, 1989

[64] Hengkun Xie, Xiongwei Jiang "The Study on On-Line Monitoring of Fault Discharge in Large Turbine Generators" Proceedings of AICDEI 1996 and 4th JCCEID

[65] Paul Pickering, "A System Designer's Guide to Isolation Devices" Sensors Magazine, January 1999

[66] Melissa R. Weimer "A Closer Look at the Advanced CODAS Peak Capture Algorithm" DataQ Instruments Operational Guide

[67] S. Carrato, A. Contin "Application of a Peak Detection algorithm For The Shape Analysis of Partial Discharge Amplitude Distributions" IEEE International Symposium on electrical Insulation, 5-8 June 1994

[68] H. Shimakawa "Acquisition and Service of Temporal Data for Real-Time Plant Monitoring" Proceedings of the Real Time Systems Symposium, 1993

[69] J. P. Lehoczky, S.R. Thuel "An Optimal Algorithm for Scheduling Soft Aperiodic Tasks in Fixed Priority Pre-emptive Systems" Proceedings of the Real Time Systems Symposium, 1992

[70] Jinho Kim, Kang G. Shin "On Data Logging in Real Time Process Control Systems" Third International Workshop on Real-Time Computing Systems and Applications, Oct 30th – Nov 1st 1996

[71] Lee Tat Man "Recording Power Demand Characteristics and Harmonic Pollution by a General Purpose Data Logger" IEE International Conference on Advances in Power System Control, Operation and Management, November 1991

[72] A. Zargari, T.R. Blackburn "Application of Optical Fibre Sensor for Partial Discharge Detection in High Voltage Power Equipment" IEEE Annual Report – Conference on Electrical Insulation and Dielectric Phenomena, October 20-23 1996

[73] A. Lord, L.C. Blank, J.M Boggis, W.A. Stallard, E. Bryant "Submerged Optical Multiplexing Techniques for Future Transmission Networks" IEE Colloquium on Submarine Optical Transmission Systems, 24 March 1998

[74] P.R. Prucnal, B.C. Wang, I. Glesk "System Perspective on Optical Processing/Packet Networks" IEEE/LEOS Summer Topi, 15-17 July 2002

[75] R.J. Landman, B. Louie "A Multi-Drop Fibre Optic Communications System For Supervisory Control and Data Acquisition in Underground Networks" IEEE Power and Engineering Society Transmission and Distribution Conference, 22-27 September 1991

Appendix 1 – Publications

Comparison of On-Line Partial Discharge Detection Methods for XLPE Cable Joints

G M Williams, P L Lewin, A E Davies, S J Sutton* and S G Swingler*
Electrical Power Engineering Group, Department of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ
* National Grid, Surrey, KT22 7ST

ABSTRACT

There is no standard technique for on-line detection of partial discharge (pd) activity within high voltage cable circuits and consequently there are several different on-line pd detection methods. There is a standard method for electrical detection of pd within the laboratory using commercially available pd detectors, but this approach is difficult to implement on a cable in service. A comparison of three different methods has been studied to determine which approach is best suited for detecting sources of pd activity within cross-linked polyethylene (XLPE) high voltage cable joints.
(**Keywords:** Partial discharge, on-line monitoring)

INTRODUCTION

The term "partial discharge" (pd) is defined by the standard IEC 270 as a localised electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor [1]. A pd is confined to the insulation of the cable, preventing a full discharge between the conductor and outer metallic screen that would cause the system to fail.

Partial discharge can be caused by the existence of a void within or on the surface of the insulation. The dielectric constant of the gas within the void is lower than that of the solid insulation and therefore the electric stress of the void will be higher than the surrounding dielectric. Under certain conditions, usually due to rapid change in the applied voltage a discharge will occur across the void. Continual pd activity causes deterioration of the dielectric and may eventually lead to breakdown of the insulation. Therefore, on-line pd detection is important in order to prevent system outages. Partial discharge tests have been used for over 50 years within the laboratory to measure the quality of electrical insulation [2]. Such tests are performed off-line within a well-screened environment, using voltages higher than the normal operational voltage. The test circuit should be able to detect the permissible discharge quantity regulated for the test object. However, more recently the goal of pd measurement has been to detect possible deterioration while the high voltage cable circuit is in normal use in the field. External interference from the 50Hz signal, fm radio and corona may be severe under on-line conditions, if the pd test is to be carried out at the normal operating voltage. Therefore, pd on-line monitoring is very different from conventional electrical detection as defined in IEC 270 [1]. On-line monitoring may not be able to detect small discharges during the initiation of insulation deterioration, but it must be able to detect discharges that will endanger operational safety. Ideally it should warn the user when the deterioration has reached a certain defined level, in order to prevent the occurrence of breakdown and allow maintenance/repair to be planned, scheduled and undertaken.

This paper describes three different sensing methods of on-line pd detection which have been investigated and assessed to determine whether they provide the reliability and sensitivity required for use on high voltage XLPE cable joints. The three different sensors studied were the radio frequency current transformer (rfct), the rogowski coil and the capacitive coupler. In practice rfcts and rogowski coils can be placed around the cross bonding leads at junction boxes [3] and capacitive couplers implemented on a section of the cable that has had a small section of the metallic earth sheath removed close to the joint under test [4].

To determine the on-line suitability for each detection method two different experiments were undertaken. Firstly a high frequency pulse generator was used to inject calibrated pulses into the cable conductor in order to determine a minimum detectable level of apparent pd activity for each sensor. Secondly a cable joint containing a known pd site was energised and the responses of the sensors recorded. In both cases results were compared with values obtained using the standard electrical detection method [5].

METHODOLOGY

A 132kV cable used for the experiment was 10m long and included a joint containing a known partial discharge site. The lead sheath around the cable and joint was removed 0.5m either side of the joint so that capacitive couplers could be placed on the outer semi-conducting screen. A copper mesh lead was extended to form a loop at the joint in order to simulate a cross bonding lead so that the rfcts and rogowski coil could be attached.

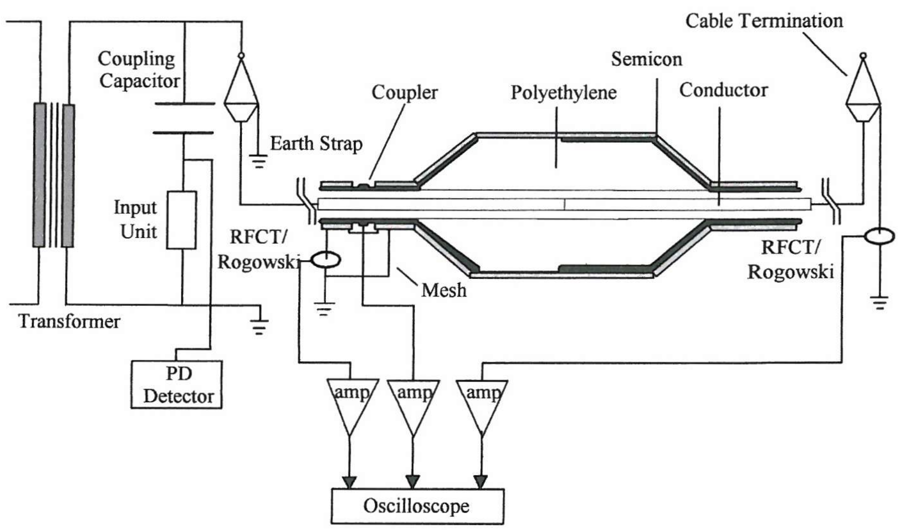

Figure 1 – Experimental arrangement

Standard electrical pd detection was achieved using a conventional detector [5] connected to the cable loop at one of the terminations. The detector provided an apparent value of charge, expressed in coulombs for any pd activity and the measured responses of the sensors were compared to these values.

Injected pulses

A high frequency pd calibrator (a square wave generator in series with a capacitor, charge = voltage x capacitance) was used to inject pulses into the termination of the cable and the responses of the sensors were recorded with and without amplification. The amplifier used had a gain of 20dB. The calibrator was used to determine the lowest charge pulse detectable for each sensor. The minimum level of detection was defined as the lowest possible magnitude of input pulse that the sensor could clearly distinguish above the background noise.

Applied voltage

High voltage was applied to the cable above the pd inception voltage in order to evaluate the response of the sensors to real pd activity, i.e. a voltage of 42kV, typically producing a detected pd of 20pC. Amplification of 20dB for each sensor was used during this experiment.

RESULTS

The results from the sensors for both the injected pulses and partial discharge and shown in table 1. Typical responses of the rfct and capacitive coupler are shown in Figure 2.

	Minimum Detectable Pulse (pC)		PD Detected? (typically 20pC)
	No Amp	With Amp	
RFCT	150	30	Yes
Rogowski Coil	150	30	No
Capacitive Coupler	15	5	Yes

Table 1 – Sensor performance

The pulses were injected at the termination, so it is possible that the high frequency components were significantly attenuated before reaching the sensors. When the cable was energised the sensors were significantly closer to the source of pd activity, consequently the rfct and capacitive coupler achieved a much improved response.

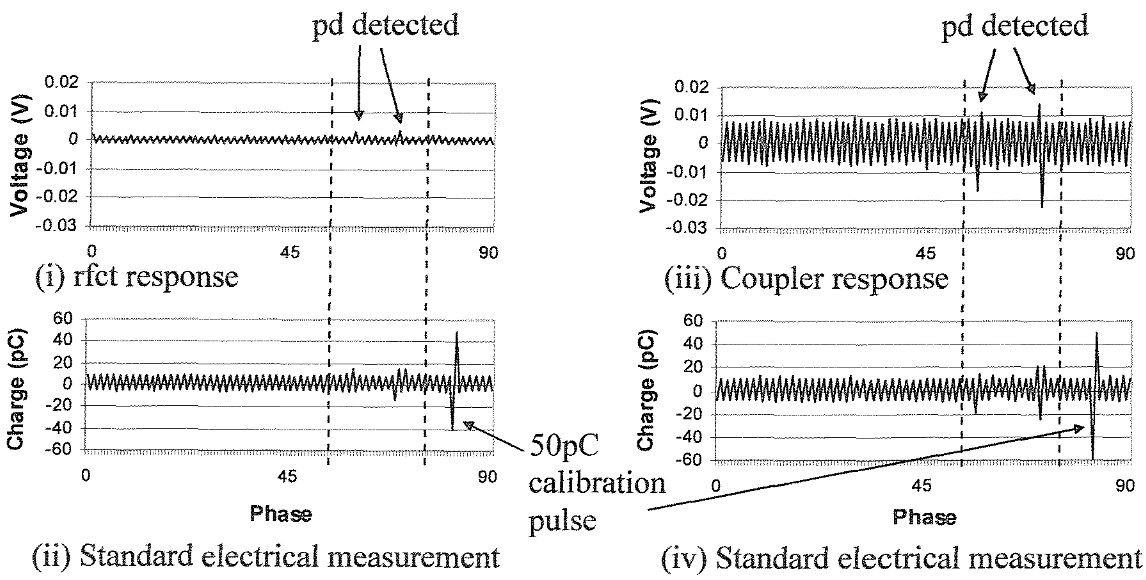

Figure 2 – Typical sensor responses to real pd

CONCLUSION

The results show that the sensitivity of both the RFCTs and Rogowski coil are the same for injected pulses. However, the capacitive coupler was 6 times more sensitive than both rfct and rogowski coil. When the sensors were implemented to detect real pd the rogowski coil was unable to detect any signal, whereas both the rfct and capacitive coupler detected pd, again the capacitive coupler was more sensitive than the rfct.

The different bandwidths of the sensors affect measurement sensitivity. The rfct and capacitive coupler have larger bandwidths (typically 10kHz – 250MHz) than the rogowski coil (typically 100kHz – 100MHz). The frequency spectra of the injected pulses was within the bandwidth of all three sensors. However, the gain of both the rfct and rogowski coil was lower than that of the capacitive coupler. The frequency spectra of real pd is higher than those for injected pulses and exceeded the bandwidth of the rogowski coil limiting its performance. The detection sensitivity of the rfct and capacitive coupler however, were improved by the presence of the higher frequency components of real pd.

Due to the method in which a capacitive sensor is implemented it has much better electrical and magnetic coupling than either the rfct or rogowski coil. The capacitive coupler directly couples the signal within the cable, whereas the rfct and rogowski coil couple the signal travelling along the earthed sheath. The capacitive coupler response is noisier than the rfct or rogowski coil, but has a greater sensitivity and hence detects pd at lower levels. However a capacitive coupler is not easily implemented in the field as it requires the removal of the sheath, unlike rfcts and rogowski coils which can be readily implemented on the cross bonding leads.

ACKNOWLEDGEMENTS

The financial support from National Grid for this work is gratefully acknowledged.

REFERENCES

[1] "Partial Discharge Measurements", *IEC Publication 270*, 1981

[2] C. Qiu and N. Wang, "Techniques for Measuring Partial Discharges in Electrical Apparatus", *Mechanical Industry Press*, China, 1994

[3] R. J. Jackson, A. Wilson, and D.B. Giesner, "Partial discharges in power cable Joints: their propagation along a cross bonded circuit and methods for their detection", *IEE Proc.* Vol. 127, Pt. C, No. 6, pp. 420-429, November 1980

[4] E Pultrum, M Van Riet, "HF partial discharge detection of HV extruded cable accessories", *JICABLE*, pp. 662-665, 1995

[5] Technical Operation Manual of Discharge Detector (model 5 type 700), *Robinson Instruments Company*

DIRECTIONAL COUPLER DESIGN FOR PARTIAL DISCHARGE DETECTION IN XLPE CABLE

G. M. Williams, P. L. Lewin, Y. F. F. Ho, Y Tian, S. J. Sutton* and S. G. Swingler*
Electrical Power Engineering Group, Department of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK
*The National Grid Company Plc, Surrey, KT22 7ST

ABSTRACT

Directional coupler theory states that an optimised directional coupler response to a pd signal would give a signal of positive magnitude on the coupler output nearest the pd source and a negligible signal on the coupler output furthest away from the source [1]. However this is difficult to achieve in practice. This paper examines the effect on the coupler sensor response of varying its dimensions, construction and materials. The coupler has been implemented on a short section of XLPE cable and its performance assessed under screened laboratory conditions.

The results are presented and discussed with the aim of establishing whether conventional directional coupler theory can be accurately applied to the case of on-line pd monitoring of XLPE hv cables. The responses of the coupler to various changes in construction are discussed and the key influencing factors of the couplers response highlighted. An understanding of directional coupler construction is presented so that sensor performance can be optimised for on-line pd monitoring of an XLPE hv cable.

INTRODUCTION

The standard method for electrical detection of partial discharge (pd) according to IEC 270 within the laboratory using commercially available pd detectors is difficult to implement on a cable in service [2-3]. It is generally assumed that most breakdowns of XLPE insulated cables will occur in their accessories, i.e. joints that have been mounted on site [4-5].

Directional couplers have been used in commercial on-line systems to detect pd sources within XLPE cables [6-7]. Theory states that a directional coupler uses both the capacitive and inductive effects [1] of the pd pulse propagating along the cable to induce two different output signals. Directional couplers have the advantage over other detection methods as the two output signals of the couplers can be used to determine the direction of the pd source from the sensor and to discriminate between pd signal, and noise. Both channels have an equal response to noise, however, signals that create an unequal response on each output can be assigned as pd signals [6-7].

EXPERIMENTAL SET UP

For the purposes of these experiments a 1.3meter length of 33kV cable, with a characteristic impedance of 36Ω was used. The cable consisted of a 21mm diameter stranded copper conductor and bulk insulation of diameter 54.9mm with semi-conductive layers between the conductor and insulation and on the outer of the insulation. A tin foil screen was wrapped around the outer layer of the semi-con to simulate a sheath.

A 300mm section of the foil was removed in the centre of the cable and a polyethylene film placed over the semi-con. An arbitrary senor of length

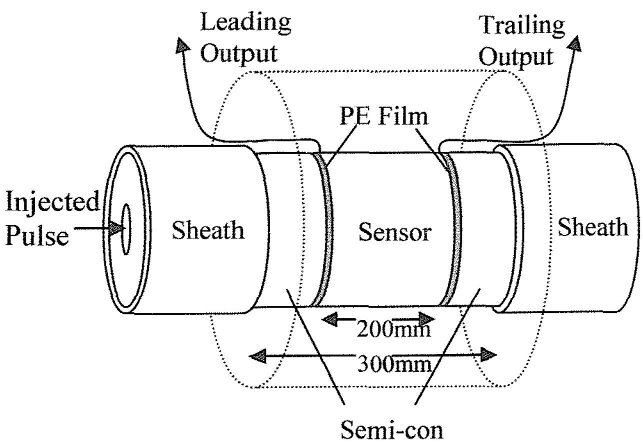

Figure 1 Coupler Construction

200mm was then mounted on the pe film and thus was insulated from the semi-con. 50Ω Coaxial leads were then connected at each end of the sensor and their earths to the sheath of the cable. Finally bubble wrap was mounted around the sensor and foil over that to shield, as shown in Figure 1.

Using the experimental circuit shown in Figure 2 pulses were injected into a length of XPLE cable via a matching circuit and the responses of the coupler outputs were measured and recorded. A series of different experiments were conducted varying a single coupler design parameter each time and comparing the different responses obtained, to determine which parameter had the greatest effect. Directional couplers are used to discriminate between pd signals and noise from on-line cables using the difference between the two outputs of a coupler. The greater the difference between the two outputs the easier it is to discriminate between pd and noise, hence the coupler design parameters were varied to find the greatest output signal ratio.

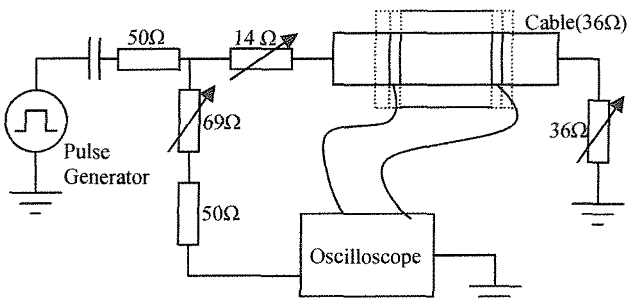

Figure 2 Experimental Set Up

Response to Diameter

A simple coupler was implemented on the outer semi-con of the cable, of arbitrary length 200mm, with an insulation gap between the coupler and earth sheath of 50mm each end. The coaxial distance between the sensor and earth sheath was then varied, therefore varying the capacitance and inductance between the two. Each time the diameter of the earth sheath was changed the response of both outputs was recorded. In particular the amplitude of the initial pulse was recorded, and a ratio between the two calculated. A typical response for a coupler is shown in Figure 3.

It can be seen in Figure 4 that as the diameter of the earth sheath is varied, the larger the diameter the better the ratio of the responses from a directional coupler.

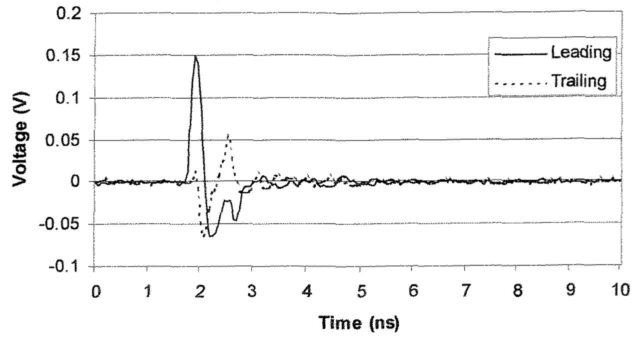

Figure 3 Typical Coupler Response

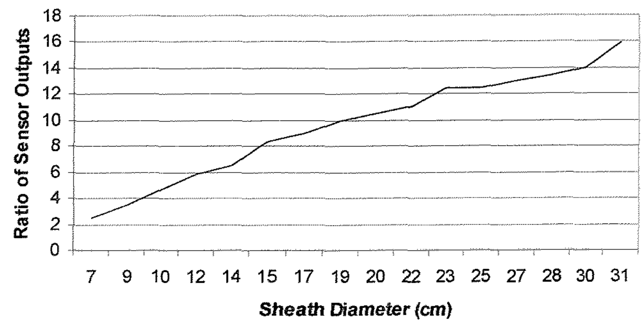

Figure 4 Coupler Diameter Response Ratios

Response to Length

Theory states that the response of a directional coupler is proportional to its characteristic impedance, which in the case of a coaxial system is proportional to the inductance per unit length divided by the capacitance per unit length. Thus the characteristic impedance of the coupler should be independent of length. In order to verify this theory the diameter of the coupler was fixed and the length varied from 600mm to 50mm. However, it was found that the coupler response was not independent of length and that the shorter the coupler the larger the ratio between the two outputs became and hence the better the response was, as seen in Figure 5.

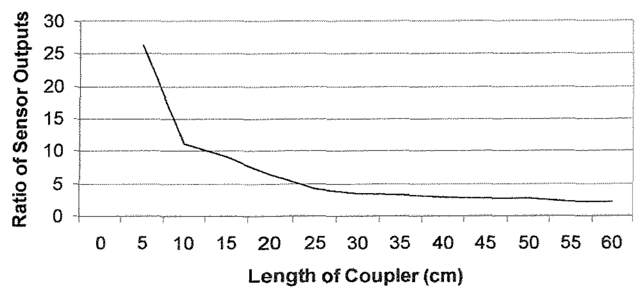

Figure 5 Coupler Length Response Ratios

Response to Materials

If the response of a directional coupler is proportional to its characteristic impedance and hence its characteristic inductance and capacitance then the materials used in the construction of the coupler should affect the response of the coupler. Previous couplers were implemented using basic materials, e.g. tin foil for the sensor and bubble wrap for insulation. Constructing the coupler using a material of higher permeability than aluminium foil changes the inductance of the coupler and using a material of higher permeability for the insulation changes the capacitance of the coupler. Thus it should be possible to alter the characteristic impedance of the coupler and hence it's response ratio.

Four different coupler arrangements were implemented on the cable: 1) an aluminium foil sensor with bubble wrap insulation; 2) a mu metal sensor with bubble wrap insulation; 3) an aluminium sensor with polyethylene insulation; and 4) a mu metal sensor with polyethylene insulation.

The earth sheath diameter was varied over a small range and the responses of each set up recorded. However it was found that the responses and ratios of the outputs were not greatly affected by different materials.

Patch Couplers

Instead of using a coupler that completely encircled the cable patches that only partly encircle the cable were implemented on the cable to investigate what effect if any it had on the response of the coupler. A patch consisting of a square of foil attached to the cable was connected the same way as the other couplers and the response recorded over a range of different earth sheath diameters. The size of the patch was also varied from a patch that encircled half of the cable to a 20mm wide strip and again the earth sheath diameter was varied.

The sensors were connected to the oscilloscope via coaxial leads. The leads had a point contact with the sensor, so in theory not all of the sensor will carry any current. Therefore if the part of the sensor that is not conducting is removed it should not affect the response of the coupler.

Figure 6 shows that the differences in the output ratios for a full, patch and strip coupler are similar. Thus, by removing the part of the sensor that is not conducting the response of the coupler is not greatly affected.

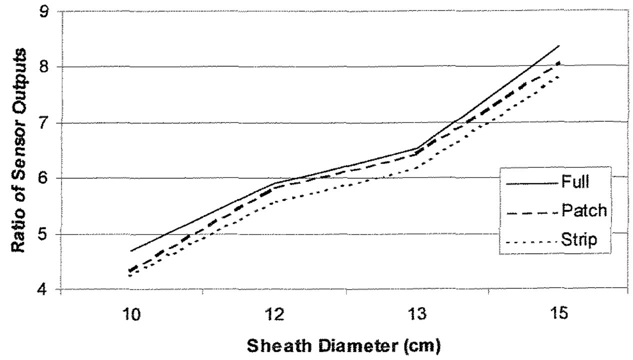

Figure 6 Patch Coupler Responses

SIMULATION

Software based circuit modelling was used to simulate the experimental circuit and coupler. The variations in coupler design parameters were simulated by varying the model circuit's component values and the results were recorded. The model coupler's component values were calculated using finite element modelling for the values of capacitance and inductance.

Using conventional theory the simulation circuit used is shown in figure 7, where C_2 and C_3 represent the capacitance between the cable and the sensor, C_4 and C_5 represent the capacitance between the sensor and the earth sheath and M_1 represents the mutual inductance between the cable and the sensor.

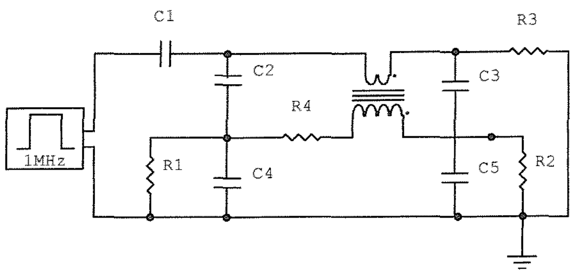

Figure 7 Simulation Circuit model

However from experimentation it was found that directional couplers are predominantly capacitive, as the responses of each output remain almost unchanged if the other output is disconnected. Conventional directional coupler theory is based on two parallel lines, where a capacitive current and an inductive voltage are set up in the second line. If one of the outputs of the second line is removed then no inductive voltage can be set up, as there will be no return path. Also, in case of partial discharge detection in XLPE cables a directional coupler is used in a coaxial system.

From experimentation on patch couplers it has been shown that only a relatively small strip of the coupler is actually conducting. Finite element analysis has shown that the mutual inductance term for a strip coupler is comparatively small and when used in the simulation circuit the capacitive effects dominate the response.

If the response is not directly related to conventional directional coupler theory, i.e. the characteristic capacitance and inductance, then coupler response will not be independent of length. Therefore as the length of the coupler is varied so the response will change also, as found experimentally.

If the inductive effect of a directional coupler is almost negligible then altering the permeability of the sensor will have little effect on the response of the coupler. Whereas replacing bubble wrap with polyethylene as the insulator between the sensor and the earth sheath will make the response of the coupler worse. Polyethylene has a higher permittivity than air and hence by using polyethylene the values of C_4 and C_5 will increase, thus decreasing the response of the coupler.

CONCLUSIONS

Directional couplers when used in a coaxial system as for partial discharge detection in XLPE cables do not behave the way conventional directional coupler theory states. Conventional theory is based on two parallel lines, whereas in a coaxial system there are three parallel conductors: the cable core, the sensor and the earth sheath. Also the whole of the sensor is not conducting, the inductive effect of the coupler is almost negligible, thus the capacitive effects dominate the response.

For the best response from a directional coupler the following should be implemented:

- a short sensor
- large sheath diameter
- materials appear to make no difference
- a strip/patch sensor is as effective as a full sensor.

It should also be born in mind that while a large sheath diameter will give a better response, it is only necessary to make it large enough so that reliable discrimination between the two outputs can be made.

ACKNOWLEDGEMENTS

The financial support from National Grid Company is greatly appreciated for this project. This paper is dedicated to the memory of Professor Tony Davies.

REFERENCES

[1] B M Oliver, "Directional Electromagnetic Couplers", Proceedings of the IRE, pp 1686-1692, November 1954

[2] "Partial Discharge Measurements" IEC Publication 60270, 1981

[3] Y Tian, "Partial Discharge Detection in Cable Systems", Ph.D Thesis, University of Southampton, Department of Electronics and Computer Science, 2001

[4] T Heizmann, T Aschwanden, H Hahn, M Laurent, L Ritter, "On Site Partial Discharge Measurements on Premolded Cross Bonding Joints of 170kV EPR Cables", IEEE Transactions on Power Delivery, Vol.13, pp330-335, April 1998

[5] U Schichler, "A Sensitive Method for on-Site Partial Discharge Detection on XLPE Cable Joints", Proceedings of the 5th International Conference on Properties and Applications of Dielectric Materials, Vol. 2, pp. 1099-1102, 1997

[6] D Pommerenke, T Strehl, R Heinrich, W Kalkner, F Schidt, W Weißenberg, "Discrimination Between Internal PD and Other Pulses Using Directional Coupling Sensors on HV Cable Systems", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 6, pp. 814-824, December 1999

[7] D Pommerenke, T Strehl, W Kalkner, "Directional Coupler Sensor for Partial Discharge Recognition on High Voltage Cable Systems", 10th International Symposium on High Voltage Engineering, August 25-29 1997