PRACTICAL NON-INVASIVE TEST METHOD FOR PARTIAL DISCHARGE ON CABLES

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ABSTRACT

Partial Discharge is a not well understood phenomenon that can cause catastrophic failure of electrical assets. It can exist at initial commissioning or occur only after decades of use. Testing cables for partial discharge in the field can be divided into online and offline. Traditionally offline methods require long outages, invasive techniques, and large, expensive test equipment, all of which limit its usefulness as a condition monitoring method.

Online cable partial discharge testing and monitoring has been increasingly deployed over the past 10 years. This paper highlights the basics of online partial discharge testing in cables and covers the non-invasive online techniques available today. Both periodic surveying and full- time monitoring are covered. Case studies of successful detection of partial discharge in cables are presented.

INTRODUCTION

Medium and high voltage cables are key components in any electrical system. Their reliability is important to maintaining continuity of supply to industrial, commercial and residential customers. Cable systems are owned and maintained by utilities, renewable energy providers, and industrial customers. It has been long established that failure rates on aged cables can be reduced through periodic testing as discussed in Reference (1). Unfortunately, it has traditionally been very difficult to assess their condition and determine if there are impending failures. Cables may be buried or otherwise inaccessible for most of their length. Their terminations are either wholly contained inside a sealed metal enclosure or if exposed, have limited access.

Taking cables out of service for testing is time consuming, invasive, and costly. Traditionally, testing has only been done at commissioning and after repairs. With advances in technology, online, non-invasive partial discharge testing has become effective, safe, and inexpensive. This paper will explain the problem, the technology of testing and give some field results.

ONLINE PARTIAL DISCHARGE TESTING OF CABLES

Partial Discharge

The dictionary definition of partial discharge is “A flashover of part of the insulation system due to a localized electric field greater than the dielectric withstand capability of that part where the overall insulation system remains capable of withstanding the applied electrical field.” Partial discharge has been shown to be a leading indicator of impending failure in cables, switchgear, transformers and insulators. The discharge has a number of negative side effects, the most troubling being heat and nitrous oxide generation. The nitrous oxide is generated from surface discharge ionizing the air. Nitrous oxide combines with humidity to form nitric acid. Nitric acid causes irreparable harm to electrical insulation and this in turn increases the discharge.

There are a number of side effects of discharge that are actually helpful. The discharge causes a high frequency current pulse that is useful in detection. Ultrasonic emissions, radio emissions, and presence of Transient Earth Voltages are all helpful in detection.

Partial discharge can be caused by a variety of factors from age and contamination to physical damage and workmanship. Each part of the electrical system suffers from discharge in different ways.

Partial Discharge in Cables

Partial discharge has long been accepted as a major cause of failure of HV/MV switchgear and non-intrusive instruments for the detection of PD are widely used by many utilities with excellent outcomes. Reference [2] provides details of results from a large national distribution company where the number of outages due to MV switchgear failure were reduced by 71% over a 5 year period resulting in over 470 fewer failures per year. A high proportion of these faults were identified on cable terminations, one example is shown in Fig. 1. Whether the cable termination problems are classed as cable issues or plant (switchgear / transformer) issues is an ongoing debate. However, what is apparent is that the non-intrusive detection of these defects using Transient Earth Voltage (TEV) and ultrasonic techniques is well established and effective in detecting termination faults. The rest of this paper will therefore concentrate on the detection of faults down the cable.

Partial Discharge damage on Cable Terminations

Figure 1

Detecting Partial Discharge in cables with RFCT

Once a PD event has occurred through the electrical insulation of a shielded cable, a set of radio frequency current pulses both equal in magnitude but opposite in polarity are seen on the line conductors and the earth conductor/shield. On-line PD detection utilizes this effect by measuring these pulses using Radio Frequency Current Transformers (RFCTs) placed on the earth sheath of the cable. One example of this is shown in Fig.2. There is a very important and practical consideration that needs to be taken into consideration when looking at the applicability of taking these on-line measurements. If the RFCT is placed over both the line conductor and the earth cable at the same time, the discharge currents are cancelled. The connection must therefore always be made by monitoring the earth cable only (or the line conductor after the earth has been taken off, provided the line current is low).

Example of Radio Frequency Current Transformers installed on Sheath Grounds

Figure 2

Dealing with noise

When carrying out on-line testing with the cable in service a difficulty that will be encountered is dealing with noise on the cable earth system. Noise will often occur in the same frequency band as PD signals and will be detected by the RFCT sensor. Simply measuring amplitude can therefore provide false alarms of PD and will only have limited application. Simple devices will typically utilize in-built filters to try and overcome the effect of noise e.g. a high pass filter in the 1.4 – 1.8MHz range. This has the effect of blocking much of the noise on the earth system but at the same time reduces the ability of the instrument to detect PD signals far down the cable. As the current pulses transmit down the conductor and earth cable from the discharge source, the signals attenuate and 'flatten' effectively cutting off the higher frequencies to the point that they are filtered out. Despite the use of high pass filters, simple measurements can still be prone to false alarms and have not been found to be particularly effective for initial widespread screening of cables for PD.

Table 1 demonstrates this from the results of recent testing of a representative sample of circuits on a utility network. The circuits chosen were from a number of different substations in different geographic locations on primary and distribution networks using XLPE cables operating at 11kV and 33kV. The samples included a mixture of 3-core cable measurements and single-phase cable measurements.

TABLE 1

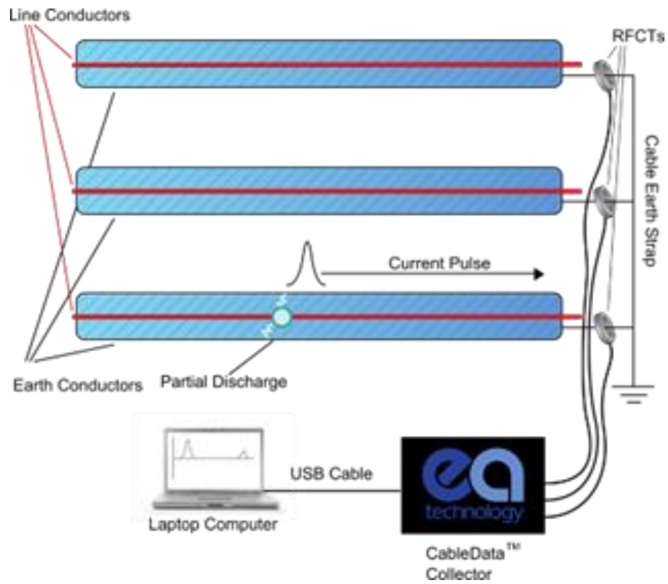
PD Testing of 14 XLPE Cables on Distribution Network and Use of Simple RFCT Amplitude Device with Different Filters

Signal	Green	Amber	Red
Cable group A – all 12 cables are good (Green)			
No Filter	0	0	12
500kHz Filter	0	3	9
1.8MHz Filter	8	3	1
Cable group B – 2 cables are moderate (Amber)			

No Filter	0	0	2
500kHz Filter	0	0	2
1.8MHz Filter	0	2	0

Table 1 shows that of the 14 cable XLPE cable circuits tested, 12 (cable group A) had no PD and 2 (cable group B) had moderate levels of PD. Without the application of any filtering all 14 indicated Red, with a 500kHz filter 9 indicated Red and the remainder amber. Even with the application of a 1.8MHz filter 1 sample was classified erroneously as serious red-level discharge and 3 erroneously as amber-level discharge. False readings are highlighted in red. Therefore 4 out of 12 or 33% of this small sample incorrectly suggested further investigation was warranted when no PD was present.

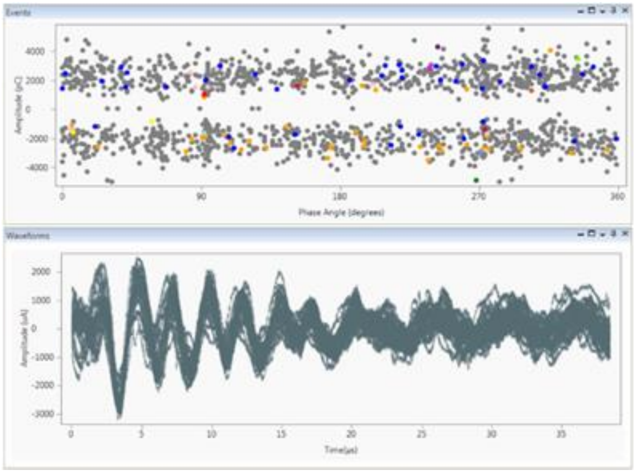
To improve the diagnostic capability from this simple amplitude-only measurement we need to capture information on the pulse shape and reference captured signals to the 50/60Hz supply frequency. To capture this information, additional processing capability is required, as per the equipment shown in Fig. 3.



Equipment for 3-phase On-line measurement of cable PD.

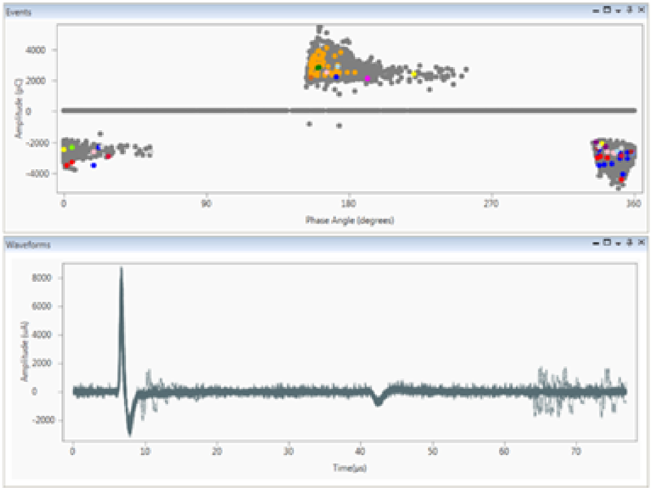
Figure 3

To help with the analysis, the equipment makes use of a supply frequency reference or if one is not locally available the instrument will detect the reference from the connected RFCTs. In the case of this particular CableData Collector instrument a series of filters are automatically applied during the capture process as well as capturing raw unfiltered data. This enables better subsequent interpretation of the data but with automatic application of filters the data capture process is simple, quick, accurate and a non-specialized function. The improved analysis is demonstrated in Fig.4 and Fig. 5. Both of these show similar amplitudes recorded by the instrument of 3000 – 4000pC, clearly in the red zone for XLPE cable. Looking at the waveform and the phase-resolved plot of Fig. 4 it is a relatively simple matter to conclude that there is no phase related signal and the waveform is not consistent with partial discharge. Fig. 5 on the other hand shows as clear phase resolved nature to the activity with a pulse shape indicative of PD.



On-line measurement of cable with noise on the earth system

Fig. 4



On-line measurement of cable with partial discharge

Fig. 5

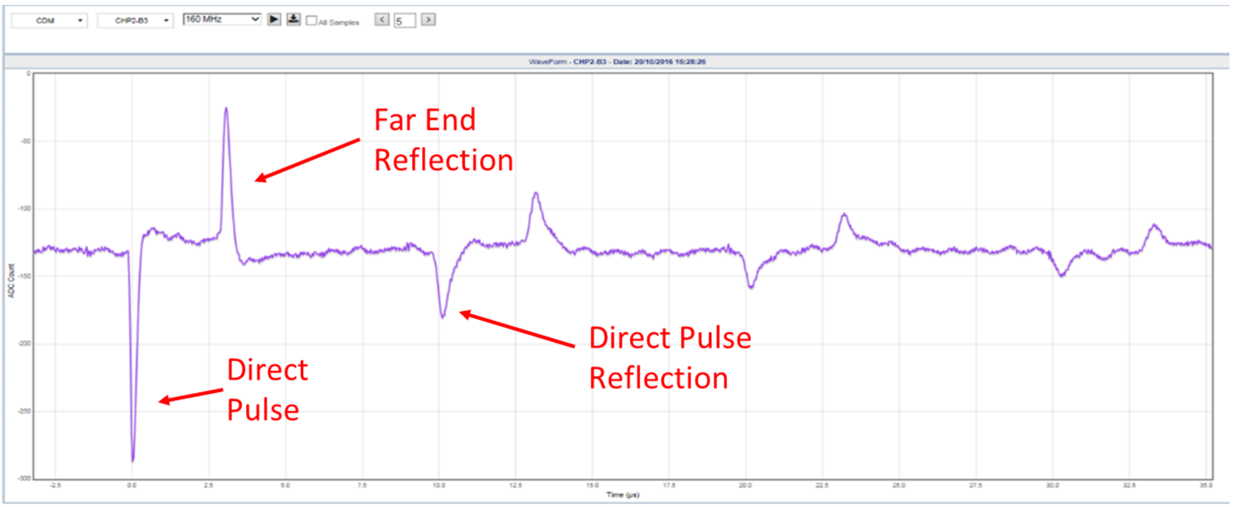
Without the ability to look at the waveform or reference signals to the 50/60Hz supply, both of these measurements would be classified as serious PD. Therefore, for equipment to be used for screening of networks, it is important to have this ability. Without this, as demonstrated in Table I and Fig. 4, there can be a high, potentially unacceptable number of false positives. Along with taking up valuable engineering resource and time to investigate these false positives, it can quickly lead to loss of confidence in the use of on-line technology to detect PD and be a barrier to adoption of a useful tool for the asset manager.

Another point to note about noise on the earth is that these measurements were taken on an electricity distribution network. On industrial networks with higher numbers of potential interference sources such as Variable Speed Drives etc., the instances of high noise interference has typically been found to be worse.

Locating PD in cables

When PD has been successfully detected, knowing exactly where on the cable the problem is occurring is highly valuable. With limited access to the span of the cable, knowing even approximately where a defect is located is a great benefit. The use of time domain reflectometry (TDR) is well established for determining a change in properties n a great number of linear assets. For example, TDR can be used in concrete pilings to determine their depth and the depth of any cracks. This uses ultrasonic pulses reflected back from discontinuities. In fiber optics, TDR using laser light pulses can give the distance to fiber damage.

In shielded cables, the actual live PD current pulse can be used to find the location of the disturbance. The phenomenon that current pulses will reflect from any point where there is a change in impedance, causes reflected waveforms we can use. TDR has long been part of offline PD testing. In an offline test, the cable is removed from service, disconnected at both ends, and a clean PD free waveform is applied. If PD occurs, the initial pulse and its reflections are analyzed. Figure 6 shows a PD current waveform with multiple reflections.



Cable partial discharge current showing reflections

Fig. 6

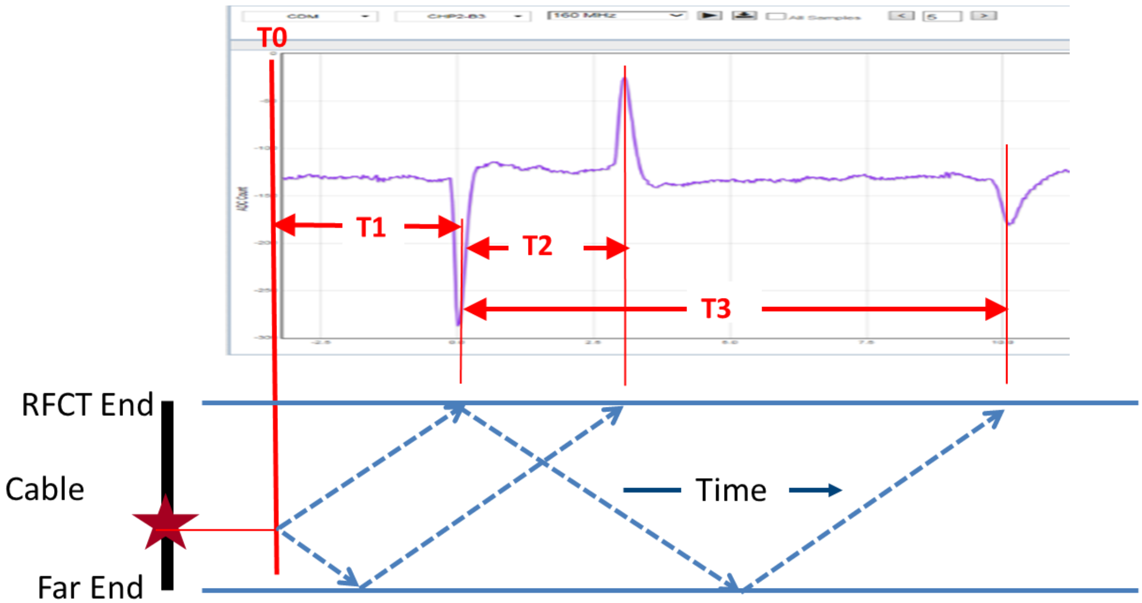
The waveforms represent the current reflecting off the far end of the cable where the disconnected end give a massive change in impedance. From the waveforms we can take a number of time measurements and from that, calculate the location of the PD event. In Figure 7, T0 is the event start and T1 is the time from T0 to the first detected pulse. T1 cannot be measured directly. It can however be calculated by the following formulae.

$$T3 = 2 * \text{length of cable}(L) / \text{propagation speed } (Vp) \quad (1)$$

$$T1 = (T3 - T2) / 2 \quad (2)$$

$$\text{Distance to PD} = T1 * Vp \quad \text{Ergo} \quad (3)$$

$$\text{Distance to PD} = (T3-T2)/2*(2 * L)/T3 \quad (4)$$



Cable partial discharge reflection timing

Fig. 7

When performing online testing the goal is not necessarily to locate the distance to the PD event but rather identify at risk cables for further study. Determining the location of PD in an online test is made more difficult by two factors. The reflection from the far end of the cable is not as significant because the impedance change in a connected cable is much less. Secondly, the cable is likely to have a higher noise level due to it's being in service as opposed to being offline. The ability to locate a smaller reflection amongst higher noise is not always possible. That said, when a reflection is detectable, the PD can be located precisely. It has been our experience that online location is possible approximately 25% of the time. It should be noted that the waveform shown in figures 6 and 7 is actually from an online test. The noise floor is very low and the reflection is very distinct and in this case, the PD location was precisely located.

Field results from periodic surveys

A major UK utility recently completed an evaluation of the technology with positive results. As this was a technology assessment, no attempt to address suspected cables was made during the trial. Over an 18-month period 188 33KV cables were tested with an online cable test device as described above. The cable results were classified into green, amber, and red as shown in table 2 below.

TABLE 2

XLPE Cable PD Classification for pC Reading

PD Value	Action	Color
0-1000pC	Normal	GREEN
1000 – 2000pC	Investigate Possible source, plan repair	AMBER
> 2000pC	Serious PD Activity	RED

Within the 18-month test period and six months afterward, 13 cables failed. The results below showed that the red and amber categories had significantly higher failure rates. This proved to the utility that this type of online testing was effective at identifying at risk cables. Table 3 shows how in this short time, a very significant percentage of cables in the Red and Amber failed. Had the customer addressed only the red cables, they would have had to fix less than 10% of the cables for a reduction in failures of over 50%. Had the user addressed all red and amber cables, they would have had to fix 16.5% of their cables for a 94% improvement in failure rate.

TABLE 3

PD related failures of 33KV cables

Cable category	Quantity Identified	Failed Within 2 Years
Green	157	< 2%
Amber	14	21%
Red	17	41%

The case for full time monitoring

The use of periodic measurement to understand the condition of cables immediately brings business benefits; enabling more effective management and informing replacement or expenditure decisions. Progressing onto permanent monitoring systems enables the same assets to be monitored under a variety of different operating and environmental conditions and of course can be a less labor-intensive way of collecting condition data. Online monitoring also provides benefits by warning of developing failure modes. Early warning can provide an opportunity to minimize the negative effects of failure and therefore reduce the potential for negative consequences such as loss of supply or costs such as damage to equipment and secondary consequences.

So, permanent monitoring has the ability to bring additional benefits to an organization. However, there will always be a calculation to be made weighing up the balance of additional benefit and the cost of implementation. One way of quantifying the economic benefits of on-line condition monitoring is to consider the decision in terms of risk reduction. Reference [3] demonstrates how using a means to quantitatively evaluate risk and understanding how on-line condition monitoring can be used to mitigate the risk associated with electricity assets, a significant proportion of the population of assets can often warrant the installation of permanent monitoring solutions.

An asset group where this approach often concludes in favor of permanent monitoring of assets is EHV cables. For these assets the consequence of failure is high elevating the calculation of risk (probability × consequence). Another factor adding to the justification of permanent monitoring is the difficulty in accessing such installations regularly.

Field results from full time monitoring

Fig. 8 shows a 220kV cable tunnel where a power authority chose to install a permanent PD monitoring solution for its cables. There were three circuits to be monitored, installed in two adjacent parallel tunnels. Each circuit was 3.4km in length with a total of 8 sets of grounding boxes for each circuit. Each grounding box required RFCT sensors to be installed on each side of the grounding point for each phase as PD signals will not pass along the total length of the cable circuit due to the change in impedance at these points. It is worth noting that due to these complex earthing arrangements on higher voltage installations the distributed monitoring system enables easier analysis of data when compared with individual spot check measurements.

220kV Cables in Tunnel requiring On-line PD measurement.

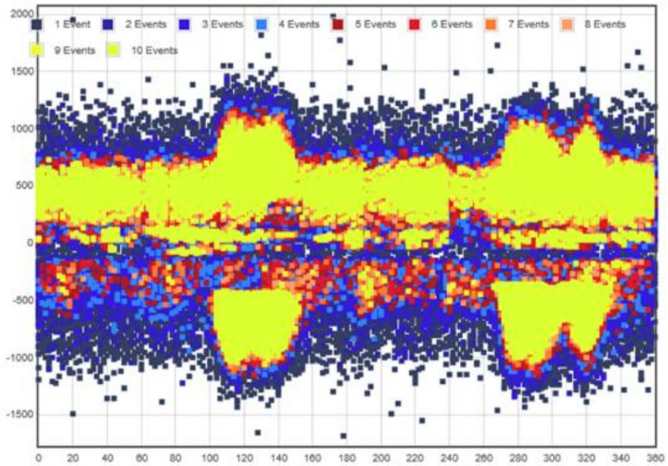
Fig. 8

Fig. 9 shows the RFCTs installed onto the earthing cables linking the cable joints to the grounding boxes. Each sensor connects to a local node unit near each grounding box. The nodes daisy-chain and communicate back to a hub server installed at the substation. The hub controls and monitors the system, collects data for analysis and provides some automatic configurable alarms to provide early warning of degradation. Due to the distances involved between nodes, links are made using fiber-optic cable. Each local node obtains a phase reference source.

RFCT sensors on earthing of 220kV Cables in Tunnel.

Fig. 9

Despite these significant changes in hardware, the principle of the analysis remains effectively the same with detection of amplitude, phase patterns and waveform analysis. The obvious benefit of early warning of unexpected degradation was realized soon after the monitoring system was commissioned on these circuits with phase resolved PD detected on one of the cable joints as shown in Fig. 10.



Phase Resolved Plot from Full Time Monitor

Fig. 10

CONCLUSIONS

The paper has demonstrated that the ability to monitor and effectively screen cable networks for PD activity on-line is available and shown to be effective. The work presented shows that effective screening of cables cannot simply rely on measurement of PD amplitude, as noise on the earthing system can cause a significant level of false positives. To determine if PD is present and to assess its severity, requires measurement of amplitude, analysis of the waveform and phase resolved analysis of the signals.

Automatic application of filtering and simple capture of data to allow remote analysis can reduce the need for specialist resource at site and make best use of this valuable time. Using the most appropriate resource to carry out the different elements of the task will enable up to date condition data for cable networks to be quickly and cost effectively gathered. Use of this information allows better informed asset management decisions to be made, can reduce or lessen the impact of failures and improve network performance.

Finally, the paper gave an example where the criticality and assessment of risk on three parallel 220kV cable circuits led to the decision to install a permanent partial discharge monitoring system and showed how immediate benefit had been delivered through the early detection of a defective joint.

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BIOGRAPHY

William G. Higinbotham, Senior IEEE Member, has been president of EA Technology LLC since founding it in 2013. His responsibilities involve general management of the company which is responsible for EA Technology activities in North and South America. William is also responsible for sales, service, support and training on partial discharge instruments and condition-based asset management. He is an author or co-author of several industry papers. EA Technology LLC is responsible for all activities in North and South America and the Caribbean / Bermuda.

Prior to EA, William was vice president of RFL Electronics Inc. Research and Development Engineering group since 1994. His responsibilities included new product development, manufacturing engineering, and technical support. He joined RFL in 1988 as a senior design engineer. In this period, he led the development of numerous products in the areas of utility communications and system protection. Bill is a senior member of the IEEE and is active in the IEEE Power Systems Relaying Committee. He has co-authored a number if IEEE standards in the field of power system protection and communications. He holds one patent in this area as well.

Bill received his BS degree from Rutgers, The State University on NJ, School of Engineering in 1984 and worked in the biomedical engineering field for 5 years prior to joining RFL. There he developed computer driven products to use in physical therapy and aids to the mentally and physically challenged.