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Development of a new high current, Hybrid 'Ferrite-Rogowski', high frequency current transformer for partial discharge sensing in medium and high voltage cabling

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Abstract

Partial discharge is an ionization-induced, electrical discharge across a portion of the insulation of medium voltage (MV) and high voltage (HV) cables and plant, usually due to localized points of degradation within the insulation. Where partial discharge has occurred, there is a higher risk of total dielectric failure, which can be catastrophic. Insulation failure is responsible for the majority of failures in HV equipment. While it is possible to test for partial discharge off-line, this has the disadvantage of requiring plant shut-down. Hence, on-line testing is an attractive approach to asset monitoring. High Frequency Current Transformers (HFCT) are a widely used sensor detecting partial discharge signals in service cables and plant. Simple HFCTs are not suited to high current (~1kA) because of core saturation. Insulation gaps in the ferrite core improve saturation performance but reduce the sensitivity of the current transformer. This paper reports on the design and testing of a hybrid óFerrite-Rogowskiô HFCT that has a sensitivity of over 10x that of a standard, air-cored Rogowski Coil sensor, with Transfer Impedance (T_F) of 1.3q over a greater than five octave frequency range of 200 kHz to 10.5 MHz and has a saturation current of >1000 A.

Keywords: partial discharge measurement; power cable; high frequency current transformers

1. Introduction

Ferrite-based High Frequency Current Transformers (HFCTs) offer a convenient solution for on-line partial discharge (PD) testing and monitoring of HV plant and cables as they can be installed óliveô onto in-service plant, in many cases, without the need for an outage. The HFCT sensor inductively detects the high frequency PD current impulses that flow in both the HV conductor and the earth screen of the plant/cable under test. PD pulses typically have durations from a few nanoseconds (in pulses from óLocal PDô originating nearby the sensor) up to several microseconds (with óCable PDô pulses which originate some distance away from the sensor). Due to this wide range of signals, the sensor must thus be able to detect signals across a wide frequency band, from around 200 kHz to >10 MHz.

There is a restriction to the use of HFCTs if they are to be installed around conductors carrying high power frequency currents of >300 A. With 50/60 Hz currents of >300 A the ferrite core used in standard HFCT designs becomes saturated, adversely affecting the measurement of the high frequency PD signals. This issue is important when the sensor is required for PD testing and monitoring of larger MV (6.6-13.8 kV voltage class) rotating machines with power ratings in the 5-15 MVA category.

When the HFCT becomes saturated, its Transfer Impedance (T_F) varies across the 50/60Hz power cycle and therefore its overall sensitivity to the short duration PD pulses within the power cycle is compromised. This means that HFCTs must have a larger saturation point than the largest possible 50/60Hz current that may flow in the conductor it is installed around. Air gaps in the HFCT sensorõs transformer core increase magnetic curve linearity but force a trade-off between saturation point, transfer impedance and bandwidth. Air-cored Rogowski coil inductive sensors are often used but are typically 20-40 times less sensitive than ferrite-cored HFCTs.

A proposed insulation gap size between the split ferrite core, which makes the sensor as sensitive as possible and maintains a high saturation point was researched. A commercially available óStandardô ferrite-based HFCT was used as a basis for the new hybrid óFerrite-Rogowskiô high current model. The target was to design a new sensor which could operate without saturation with up to 1000A of 50/60Hz current passing through it, making it suitable for installation on machines rated up to 7MVA (6.6kV working voltage), 11MVA (11kV working voltage) and 14MVA (13.8kV working voltage).

1.1 Partial Discharge

Partial Discharge (PD) is defined as ñlocalised electric discharge resulting from ionization in an insulation system when the voltage stress exceeds the critical value. This discharge partially bridges the insulation between electrodesò [1] and is produced by incipient faults in both MV and HV insulation. Therefore asset management on these systems is considered vital in order to reduce the chances of these failures. By obtaining early measurements of PD, plant owners can take restorative action during planned outages. Figure 1 shows electrical trees in power cable paper insulation caused by partial discharges. Figure 2 shows the damage caused by surface discharges on a rotating machine end winding.

Figure 1. Tracking in Paper Insulation

Figure 2. Surface discharge damage on rotating machine end windings

1.2 Sensor Types

For monitoring PD activity in high-current (>300A), medium voltage rotating machines, there are two main sensor options presently available. These are high voltage coupling capacitors (CC) and air-cored, Rogowski Coil sensors.

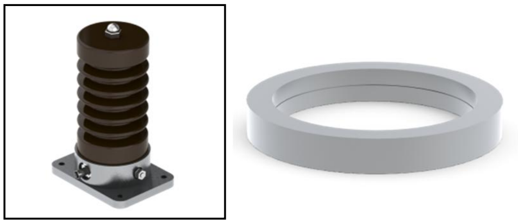


Figure 3. Left: High Voltage Coupling Capacitor, Right: Air-cored, Rogowski Coil Sensor

Both sensors are designed for permanent installation, inside the machine’s cable box, with one sensor per phase and the signal connections brought out to a sensor termination box which is mounted on the outside of the machine’s cable box. The permanent sensor installation enables PD measurements to be made at any time, without the need for an outage. An example of a high voltage coupling capacitor installation, with a sensor on each phase of the machine, is shown by Figure 4.

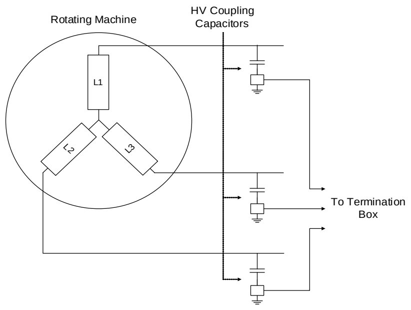


Figure 4. HV coupling capacitor sensor connection diagram

In the case of the HV coupling capacitors, galvanic contact to the HV connections provides the highest sensitivity to PD signals. The coupling capacitors require an outage to install and thus are not well suited to temporary installations for on-line PD measurements.

Rogowski Coil sensors are easier to install than the coupling capacitors as they work inductively and have no direct galvanic contact. As the Rogowski's have an air core, this prevents core saturation and provides a linear response across the frequency range of interest without problems of saturation. However, one of the main limitations of the Rogowski Coil sensors is that they have a poor sensitivity when compared to HV coupling capacitors and HFCT sensors. Table 1 shows a comparison between typical transfer impedances for each of the sensor types. It can be noted that a HV Coupling Capacitor will typically have a sensitivity of 100x that of the Rogowski Coil Sensor.

Sensor Type	Transfer Ratio (at 1MHz)	Saturation Current (50/60Hz)
HV Coupling Capacitor	10	N/A
Rogowski Coil	0.08-0.15	+4000A
‘Standard’ HFCT	2.0-4.0	300A

Table 1. Sensor technical specifications

In comparison, ferrite-based HFCT sensors have much higher transfer impedances (T_F) than Rogowski coils. The trade-off here is that the HFCT core will saturate under high power frequency currents. Normalisation of frequency responses for each of the sensors allows a graph of normalised gain against frequency to be obtained, as shown by figure 5.

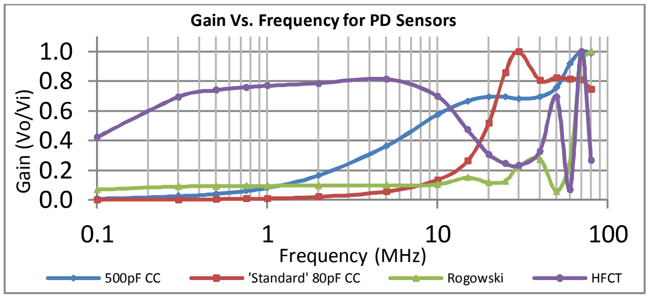


Figure 5. Sensor types frequency response

With reference to Figure 5, the HV coupling capacitors have good higher frequency response above 10MHz however the low frequency response of these sensors is considerably lower when compared to the HFCT sensor in the frequency range 1-10MHz, which has a very flat frequency response up to around 12MHz. In comparison, the Rogowski sensor has the lowest overall gain and this can be seen to become unreliable after 10MHz.

2. HFCT Sensors

HFCT sensors consist of a wound toroidal ferromagnetic core that is placed around the unscreened power cable conductor or earth sheath to inductively measure the magnetic field from the PD current pulses in the cable and connected plant. The construction is similar to that of the air-cored Rogowski coils which also work via inductive pick-up. With this topology the secondary wire is fed back through the winding so that the two ends are co-located which reduces the effective loop area to external electromagnetic interference, thus reducing such interference and hence noise. The placement of the coil around a linear primary ensures that the flux links with the coils of the secondary but only in a limited way with the fed-back wire. The result is a current transformer that inductively couples well to the PD signal but, despite the relatively low sensitivity, has a high noise (EMC) immunity.

The sensors are characterised by their Transfer Impedance (T_F), which is the ratio between the secondary (output) voltage and the primary current (from the PD pulse being measured). Clearly, a higher transfer impedance improves both the range and resolution of the PD current measurements. The measured current impulses can also then be integrated to obtain the total energy or charge of the PD pulses to quantify the PD level in picoCoulombs (pC).

There are various sensor installation points possible for the HFCT sensor, depending on the plant under test. For PD test and monitoring of PD activity in the stator on MV rotating machines it is normal for the sensor to be installed around the insulated core of each phase cable whilst maintaining sufficient clearance between the sensor and HV connections. A typical, split-core HFCT sensor is shown in Figure 6 whilst Figure 7 shows a typical installation of 3x HFCT sensors on each phase of a rotating machine.

Figure 6. A ‘Standard’ High Frequency Current Transformer Sensor

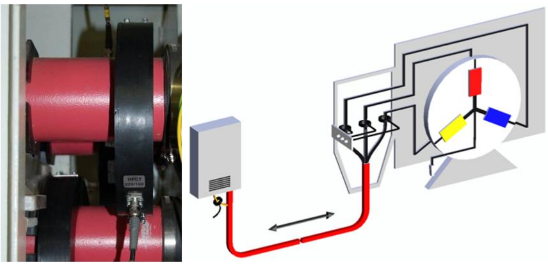


Figure 7. HFCT installed on each phase in rotating machine terminal box

3. High Current HFCT

The main application for the new high current, hybrid HFCT design is for making PD measurements on rotating machines, with 50/60Hz currents of up to 1000A. In the past Rogowski coils have been used for this purpose due to their good high current performance, as previously discussed. However, in order to improve the sensitivity and the resolution of the PD measurements, it is proposed that the hybrid, óFerrite-Rogowskiô HFCT has a number of advantages.

Managing the HFCTs 50/60Hz saturation point is vital to ensuring the performance of the sensor at high currents of up to 1000A. Saturation occurs due to the magnetic flux density in the ferrite core of the HFCT becoming no-linear with applied magnetizing field (this is dependent on the ferromagnetic properties of the ferrite material itself). The commercially available HFCT design evaluated in this project uses a ferrite core which saturates with approximately 300A of 50Hz current passing through it. This design uses a small insulation gap between the split ferrite core and has a transfer impedance of 3.2q at 1MHz.

It is postulated that through the insertion of additional gaps between the 2x split ferrite cores, the 50Hz current saturation point of the HFCT sensor will be increased whilst still maintaining a much higher transfer impedance when compared to the Rogowski coils. The purpose of the study reported in this paper was to determine the maximum saturation current that can be achieved with a magnetic cored current transformer based on the Rogowski design, therefore creating a hybrid óFerrite-Rogowskiô sensor.

The purpose of the air gaps in a magnetic core is to increase the reluctance of the circuit, which reduces the flux: effectively ótuningô the permeability of the core so that saturation takes place for a higher current. The trade-off with this is that more secondary turns may be required to maintain sensitivity.

The following section presents an experimental study of the effect of varying the gap size.

4. High Frequency Transfer Impedance

Additional insulation or air gaps between split ferrite cores has been shown to improve saturation performance of the magnetic core: ñincreasing the linearity of the magnetic curveò [2]. However, there is a trade-off between the saturation point and the transfer impedance due to the increased reluctance and hence effective reduction in flux density.

It is possible to investigate the effects of inserting additional gaps between the split ferrite cores on the transfer impedance, over a frequency sweep of 100kHz to 30MHz (a suitable frequency range to monitor PD), keeping the number of secondary turns (N) constant, using the circuit shown in figure 8.

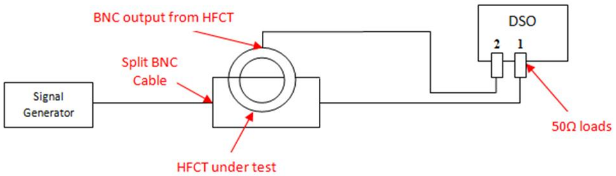


Figure 8. Frequency Response Circuit (DSO is Digital Signal Oscilloscope)

Between 20MHz and 30MHz the frequency response becomes very unreliable as numerous peaks and troughs. +20MHz is outside of the working frequency of the HFCT and therefore is not important. Figure 9 shows the transfer impedance against the insulation gap size using 1MHz as a characteristic frequency. The 1MHz characteristic frequency is chosen as this is inside the bandwidth of the HFCT under test.

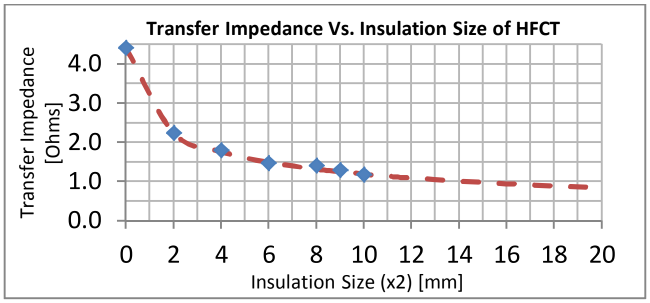


Figure 9. Transfer Impedance versus Insulation Gap Size at 1MHz

The results suggest that the transfer impedance is asymptotic to a value of just less than 1.0q. However, in practice, the insulation would eventually cause the HFCT to behave more like an air-cored sensor.

Upon calculation of this it is also important to calculate the saturation current of the HFCT, to confirm it is fit for purpose, as demonstrated below.

5. High Current Saturation

It has been shown that increasing the insulation gap size reduces the transfer impedance and the HFCT core saturation from the 50/60Hz current. A high current test jig was set up, with varying 50Hz current (0-100A). Using 10 primary turns around the HFCT, up to 1000A was yielded to flow through the HFCT. The frequency response test jig was used (shown in figure 8), in conjunction with the high current test jig. The overall test set-up is shown in figure 10.

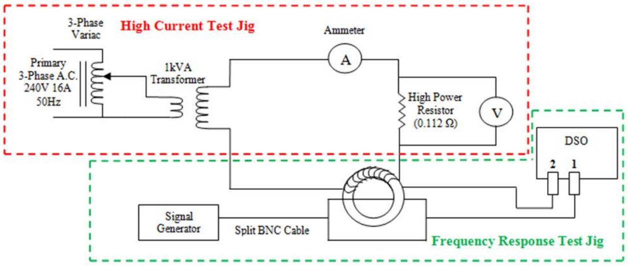
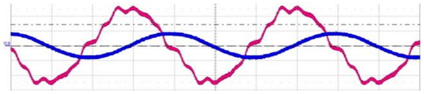


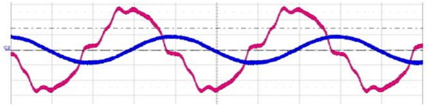
Figure 10. High Current Test Jig

The transfer impedance was measured for stepped values of the primary 50Hz current, maintaining a constant 1MHz characteristic sine wave input from the signal generator. Saturation occurs when the transfer impedance varies and becomes unreliable. This can then be recorded for every variance of insulation gap size. Alternatively, the HFCT output can be observed with respect to the primary 50Hz current. Saturation can be seen to occur where the sine wave begins to deteriorate and the amplitude of the wave no longer increases. Initial saturation test results, for the chosen 'standard' HFCT show the saturation point to be 300A, as seen by Figure 11 (Pink traceï HFCT output, Blue trace ï primary 50Hz current).

280A



300A



350A

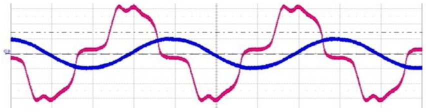


Figure 11. Present HFCT Saturation

Continuing this method for numerous insulation gap sizes produces a graph of saturation current against gap size, as shown by Figure 12.

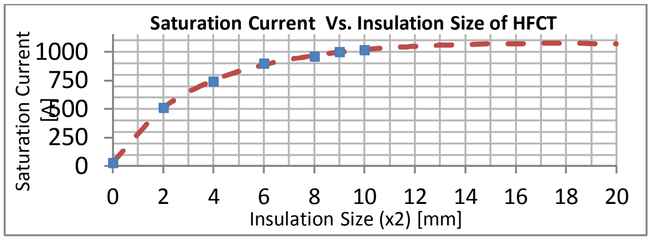


Figure 12. Current versus Gap Size

Figure 12 shows that the saturation current is asymptotic to around 1075A and the limit of the HFCT saturation current for that particular ferrite core has been reached.

5.1 50Hz Saturation

The effect of the 50Hz saturation on the HFCT high frequency response can be demonstrated by inputting a 1Vpp, 5kHz pulse with a width of 200ns into the HFCT with 6mmx2 insulation gap size between the split ferrite core and observing the HFCT output (channel 2 ï pink) with respect to the primary 50Hz current (channel 1 ï orange). Once the HFCT reaches its saturation point the HFCTs output is decreased at the peaks and troughs of the primary, sine wave current, thus making the measurements unreliable, as shown by Figure 13.

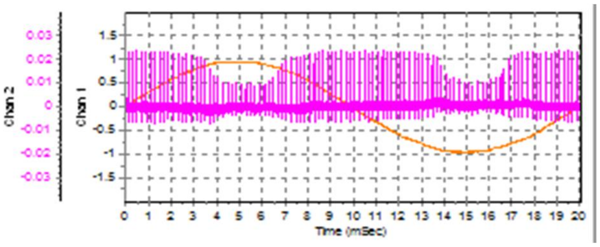


Figure 13. High Current HFCT Saturation

Alternatively, the variability in output from the HFCT sensor to the 200ns pulses, over the power cycle when the ferrite core is saturating can be observed using the oscilloscope persistence capture mode (over a period of 20 seconds). This is shown before and after saturation, in Figures 14 and 15 (x-axis is time with 50ns/div and y-axis is voltage with 10mV/div).

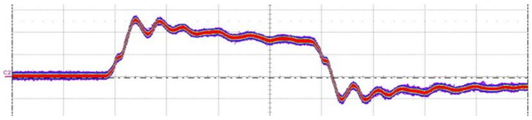


Figure 14. HFCT Output Pulse - 0A

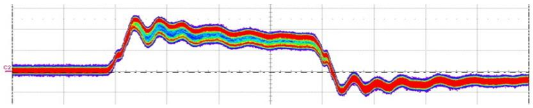


Figure 15. HFCT Output Pulse - 1000A

Figure 15 shows how the HFCTs output pulse can vary significantly and is thus unreliable once the 50Hz current is higher than the saturation point of the HFCT.

6. Overall Results

As demonstrated earlier in Figure 12, the size of the gaps can only be increased up to around the 2x16mm size, before the maximum saturation current is reached. With this insulation gap size the HFCT has a saturation current of 1075A. However, with such a large gap, the frequency response is not as flat over the frequency range of interest, when compared with smaller sizes of air gaps. This can be demonstrated by comparing two different insulation gap sizes, as shown by Figure 16.

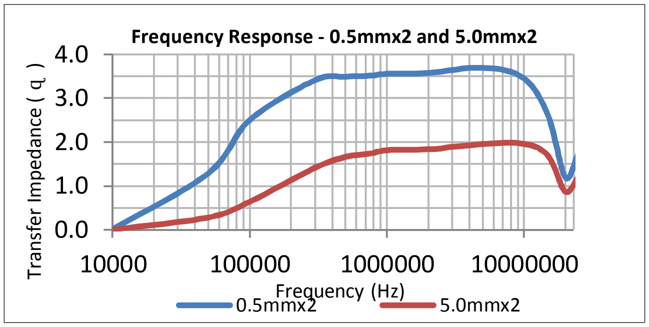


Figure 16. Frequency Response ï 0.5mmx2 and 5.0mmx2

Using the results from this paper, it can be concluded that the split ferrite core HFCT with 9mmx2 insulation spacing gives a saturation current of 1000A and an acceptably flat working frequency, with a transfer impedance of 1.3q at 1MHz. The working frequency range of this high current HFCT (as set by the lower and upper -3dB points marked in Figure 17) is from 200kHz to 10.5MHz.

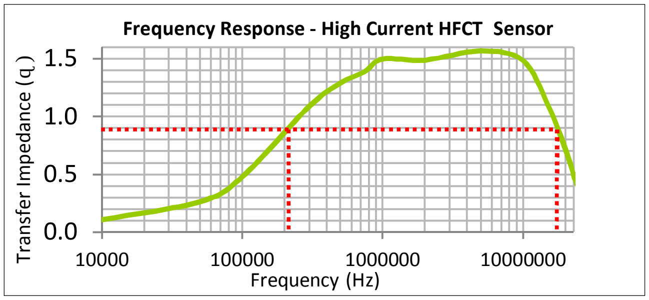


Figure 17. Frequency Response ï 9mmx2 Gap

7. Conclusion

HFCT ferrite cores increase sensitivity and signal to noise ratio when compared to air-cored Rogowski Coil sensors. By adding additional air gaps between the split ferrite cores of the HFCT, the saturation performance of the magnetic core improves. However, there is a 'trade-off' between the saturation current and the transfer impedance/sensitivity of the sensor. The frequency response results show that as the insulation gap is increased, the frequency response becomes stable for shorter periods and the transfer impedance is reduced.

Using pulse measurements it is possible to conclude that the new, high current, hybrid HFCT sensor with 2x9mm insulation gaps between the split ferrite core has a rise time of around 100ns and a fall time of around 1.0µs which is adequate for measuring PD pulses in MV and HV plant and cables.

The hybrid óFerrite-Rogowskiô sensor reported in this paper has a Transfer Impedance (T_F) of 1.3q (at 1MHz) which is around 13 times more sensitive than Rogowski Coil sensors (these have a T_F of around 0.1q). This means that it is possible to use the new hybrid sensor to detect smaller PD signals whilst also measuring larger signals with a much improved resolution.

The final hybrid óFerrite-Rogowskiô sensor can be thus used on MV and HV cables systems carrying currents of up to 1000A without saturation, whilst also achieving a measurement bandwidth of 200kHz to 10.5MHz to measure PD signals across the frequency range of interest. The knowledge gained from this research can also be transferred to other HFCT designs in order to increase their saturation point for use of high current machines and maintain as much sensitivity as possible.

8. References

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[2] Eric Laboure Patrick Poulichet, Francois Costa, "IEEE Transaction on Magnetics," *High-Frequency Modeling of a Current Transformer by Finite-Element Simulation*, vol. 39, no. 2, pp. 998-1007, March 2003.

9. Biographies

Marc J. Foxall was born in Manchester, UK in 1989. He obtained a First Class BEng(Hons) degree from De Montfort University, Leicester in 2010 in Electronic Engineering. He was awarded the óIET outstanding achievement awardô and óDepartment of Engineering Best Final Year Projectô. Having worked for HVPD during a summer placement in 2009 he is currently furthering his final year project research with HVPD in Manchester. He is also a member of the IET.

Alistair P. Duffy was born in Ripon, UK, in 1966. He obtained a First Class BEng(Hons) degree from University College, Cardiff, in 1988 in Electrical and Electronic Engineering, and the MEng degree the following year. He joined Nottingham University in 1990 receiving a PhD in 1993 for his work on experimental validation of numerical modelling. He also holds an MBA.

He is currently a Reader in Electromagnetics and, until recently, was Head of the Engineering Division at De Montfort University Leicester, UK. He is currently head of Electronic and Electrical Engineering (E3). He has particular research interests in CEM validation, communications cabling and technology management. He has published over 100 papers in journals and international symposia. He is currently a Board member of the IEEE EMC Society, the Applied Computational Electromagnetics Society and the IWCS. He is a past IEEE EMC Society Distinguished Lecturer.

John Gow received an MEng in Electronic and Electrical Engineering from Loughborough University in 1993, and a Ph.D in power electronics in 1998. He subsequently continued research in the area of power conversion systems for building-integrated and large scale solar photovoltaic installations. Subsequent industrial opportunities in power electronics and embedded control led to him acting as a senior design engineer developing hardware and software for high speed DSP and microcontroller based embedded control systems and power chains for inverters, industrial drives and uninterruptible power supplies. He developed a working knowledge of RF hardware design through a further industrial position developing hardware for radio frequency identification systems as well as a lifelong interest in amateur radio. He now works as a Senior Lecturer at De Montfort University with research interests in power electronics, high speed embedded systems for control applications and software radio.

Malcolm Seltzer-Grant received a BEng(Hons) degree in Electrical and Electronic Engineering from The University of Manchester in 2005. Since 2005 he has been with HVPD whilst studying for a PhD degree at The University of Manchester School of Electrical and Electronic Engineering. This was awarded in 2010 for research into measurement techniques and applications of on-line partial discharge detection in power cables. At HVPD his main work is in the development of HVPD's PD test software and PD measurement devices. He is also a part of the PD test team and has carried out a number of on-line partial discharge test and training projects around the world for electricity transmission and distribution utilities and industrial customers. Malcolm is a member of the IET.

Lee Renforth studied Electrical and Electronic Engineering at the University of Manchester between 1986 and 1990. He was sponsored throughout this 4-year industrially-linked course by BICC cables. Lee graduated with a BSc, MEng degree in 1990 and was awarded his PhD when his thesis on the topic of the breakdown of high voltage insulation was published, also at Manchester University in 1993, sponsored by the National Grid Company.

Lee is currently Managing Director and Sales and Marketing Director of High Voltage Partial Discharge (HVPD) Ltd which has now established itself as one of the market leaders in the growing field of on-line partial discharge test and monitoring technology for high voltage plant and cables. He oversees the relationships with HVPD's customers, agents and partners in more than 40 countries worldwide.