Institution: University of Manchester

Unit of Assessment: UoA13b Electrical and Electronic Engineering

Title of case study: HV Asset Modelling and Management

1. Summary of the impact

Analysis of partial discharges for management of high-voltage assets has become commercialised in the last 20 years. Work at the University since 1993 has improved asset management techniques used by companies world-wide. This was achieved in two ways: first, improving power network reliability, enabled through two start-up companies employing 59 people and turning over £5m/annum; and second, by providing techniques for testing and verifying safety of new electrical power components for aerospace applications (e.g. A380). In four illustrative case studies, over £3m savings are identified for end-users through improved reliability of power networks. Further impact has been delivered by ensuring the reliability of power networks in aircraft.

2. Underpinning research

The impact is based on research that took place in Manchester from 1993 to the present day.

The key researchers were:

- Brian Varlow, Professor, employed 1993 to 2003
- David Auckland, Professor, employed 1993 to 2004
- Roger Shuttleworth, Senior lecturer 1993 to present
- Lee Renforth – PhD student graduated 1993
- Colin Smith – PhD student graduated 1993, RA 1993-1994
- Ian Cotton, Professor, employed 1998 to present

The focus of the research was, and continues to be, the experimental determination of defects in insulation systems using partial discharge techniques. The work has been focused on power system plant, but has more recently been developed in the context of aerospace requirements.

Key research findings were:

- Distinguishing between discharges arising from different high-voltage sources by converting the acoustic emission signal from the time domain to the frequency domain by fast Fourier transformation and recognition of the signature frequency spectra [1].
- Development of Fast Fourier transformation and neural networks methods of signal recognition in ultrasonic and acoustic noise from bushings, transformers, switchgear and cables [4]. These techniques were extended to real substations leading to the recognition that hourly averaged data could be used for data mining and correlation pattern recognition [5].
- The development of a new software simulation package for optimising actuators used in medium voltage (MV) switchgear and autoreclosers. The lumped reluctance model enabled optimisation in energy terms, since it simulates the actuator electrical, magnetic and mechanical effects. This overcame many of the difficulties of using finite element analysis [2].
- Identification of the mechanisms underlying susceptibility to partial discharge of higher voltage systems in aircraft and the development of procedures by which equipment can be aged to ascertain the probability of it degrading over its life [3].
- The development of a methodology for calculation of the safe voltage rating of unscreened insulated wires within an aircraft. The tools used have been verified with experimental measurements at various pressures. It was shown that the optimal operating point for an aircraft power system does not imply the use of the highest voltage possible. A trade-off between wire weight and power transfer is required [6].

3. References to the research (indicative maximum of six references)

References [2 and 3] are published in top-quartile journals for their field (Scopus). Refs [1, 4, 5, 6] are the natural home for the work. All but paper [3] are papers written with co-authors who are now

in the companies exploiting the work, including IPEC, HVPD, and Rolls-Royce.

Key References

[1] 'Acoustic emission analysis of high voltage insulation' Varlow, B.R.; Auckland, D.W.; Smith, C.D.; Zhao, J.; *IEE Proc. Science, Measurement and Technology*, 146 , 1999 , pp 260 – 263; DOI: 10.1049/ip-smt:19990471 Google Scholar citations 22

[2] 'Optimal design of autorecloser electromagnetic actuator' Li, Z.; Varlow, B.R.; Renforth, L.A.; Auckland, D.W.; Shuttleworth, R.; *IEE Proceedings Electric Power Applications*, 147 , 2000, pp.431-435, DOI: 10.1049/ip-epa:20000559 Google Scholar citations 6

[3] 'Partial Discharge Testing Of Equipment For Aerospace Electrical Systems', Al-Rumayan, F.; Cotton, I.; *IEEE Transactions on Aerospace & Electronic Systems*, Volume 46, 2010, pp 848-863, DOI: 10.1109/TAES.2010.5461661

Supporting references

[4] 'Substation monitoring by acoustic emission techniques' Zhao, J.; Smith, C.D.; Varlow, B.R.; *IEE Proc. Science, Measurement and Technology*, 148 , 2001 , pp. 28 – 34, DOI: 110.1049/ip-smt:20010134 Google Scholar citations 10

[5] 'Application of ultrasound to the inspection of insulation' Auckland, D.W.; McGrail, A.J.; Smith, C.D.; Varlow, B.R.; Zhao, J.; Zhu, D.; *IEE Proc. Science, Measurement and Technology*, 143 , 1996 , pp 177 – 181, DOI: 10.1049/ip-smt:19960353 Google Scholar citations 21

[6] I Christou, I.; Nelms, A.; Cotton, I.; Husband, M.; 'Choice of optimal voltage for more electric aircraft wiring systems', *IET Transactions On Electrical Systems in Transportation*, Volume 1, 2011, pp 24-30, DOI: 10.1049/iet-est.2010.0021

4. Details of the impact

Context

Early detection of impending faults avoids unnecessary interventions and prevents failure. While it is inherently difficult to estimate the value of successful asset management, the avoided cost is orders of magnitude larger than the cost of the service. The cost of the New York blackout in 2003 has been estimated as 11 deaths and $6Bn [A], and illustrates the issue of simple local faults cascading to large societal costs [B].

Eurelectric has estimated the cost of power outages on industrial customers at 1000 €/kWh and residential customers at 1-5 €/kWh. In comparison the typical long distance transmission costs are 1-2 € cents/kWh [B].

Pathways to Impact

The main pathway to impact in power utility networks is via the spin-out companies established as the result of this research. The first company to emerge from the work described was IPEC in 1995, founded by the three academics and two of their research students Lee Renforth and Colin Smith. IPEC continued to work with the University and contribute to the research described above. This led to the formation of a second company High Voltage Partial Discharge Ltd (HVPD) in 2009. Smith and Renforth's post-doc research directly contributed to the technology platforms of the companies and they are the present Managing Directors of IPEC and HVPD respectively.

In the aerospace sector we have worked directly with manufacturing companies, receiving funding from Rolls-Royce and the EU, influencing design policies and test methods directly, and gaining access to major European manufacturers. Cotton has travelled extensively to manufacturing centres in e.g. the USA, Germany, and India to ensure transfer of the research globally. The work has already been exploited in manufacturing companies as detailed below and is becoming formalised through SAE aerospace information report AIR6127 which is a pre-cursor to a technical standard on the use of high voltages in aerospace systems.

Reach and Significance of Impact

The significance of the impact from this research in utilities extends beyond the two companies created (59 jobs and ~£5m annual revenue at present) and its major effect is on the asset management activities of their clients, and subsequent operational savings.

IPEC and HVPD

IPEC, headquartered in Manchester, currently employs 11 staff and had a turnover in 2012 of £1m of which 40% is export business [C], the Managing Director is Dr Colin Smith. HVPD has established itself as one of the market leaders in the growing field of on-line partial PD test and monitoring technology for high-voltage plant and cables with agents and partners in more than 80 countries around the world. Based in Manchester, in 2012 HVPD had a turnover of £3.9m of which £3m was exports. The company currently employs 45 staff in the UK and 3 overseas [D]; its Managing Director is Dr Lee Renforth. Throughout its history – both before the spin-out from IPEC and since – HVPD has been active in supporting research at the University of Manchester. This has led directly to a number of important impacts for the company. The development of a patented continuous condition monitoring system for HV motors operating in hazardous conditions [E] and securing contracts based on the technologies developed with global companies as shown by the recent award of a contract valued at more than £1m for condition monitoring technology to the oil company Chevron [D].

In addition, research conducted with IPEC [2] led to the development of a new software simulation package for optimising actuators used in MV switchgear and autoreclosers. This resource has been licenced to a number of large switchgear manufacturers in Europe and the USA including Siemens, Schneider, ABB USA, G&W Electric, Resead Peru, and Powell Switchgear. Approximately 20 companies are using the designs. Each license is granted for an initial development set up fee of approximately £120K and further royalties (confidential) are paid on use [F].

Examples of impact for utility end-users

As stated previously the benefits of avoiding network failure can have very large numbers attached to them. This is illustrated by four examples where the companies' technology has been used.

- Olympic Park June/July 2012: Monitoring of 62 km of cable and 170 (ring main units) RMUs identified 5 RMUs with faults. These were tested twice a day during the Olympics to ensure no loss of power to the venue which would have interrupted live TV coverage of the event [G].
- Steel Plant CSC (Taiwan) 2008: Monitoring of 33kV cables that were about 25 years old identified a fault in a joint. Replacing the joint removed the fault and eliminated the risk of shutdown of a 10m tonne capacity steel plant with an estimated cost of failure at $1m [H].
- UK Power networks 132kV Transformer 2011: Following failure in a 132 kV cable termination, monitoring was installed and within 3 weeks detected a fault on the 11 kV side of the substation. The previous fault on this termination cost UK Power Networks an estimated £1.5m [I].
- UK Power Networks (UKPN) now uses a partial discharge monitoring system on more than 1000 cable circuits installed across their network, as in integral part of their on-going asset management program. Over the past few years, this has enabled UKPN to carry out six preventive interventions on equipment and 12 cable replacements estimated to have avoided £900k of costs [J].

Electrical Systems for the Aerospace Sector

Research carried out at the University of Manchester has led to the development of test techniques which have been used for the qualification of cabling, electrical machines, wind de-icing systems and a range of other components. As a consequence the University has been the main contributor to the SAE aerospace information report AIR6127 which is a pre-cursor to a technical standard on the use of high voltages in aerospace systems [K].

Methods developed to perform ageing tests, have been used on electrical machines used in the

airbus A350. The companies Moog [L], GKN, Ultra Electronics, Goodrich, Rolls Royce, and Liebherr [M] have all exploited this work and as a result supply product to Airbus and Boeing for A350 and 787 aircraft.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. http://www.scientificamerican.com/article.cfm?id=2003-blackout-five-years-later report on the US 2003 blackout.
B. http://www.energy.siemens.com/us/pool/hq/power-transmission/HVDC/Global_Blackouts.pdf discussion of causes and costs of cascading failures
C. Letter from Managing Director IPEC ltd providing turnover and employment details
D. Letter from Managing Director HVPD ltd confirming company size, role of research in staffing and product development.
E. http://www.hvpd.co.uk/news/2012-09-IEEE-PCIC.html detailing the launch of patented Ex/ATEX condition monitoring in hazardous environments.
F. Pdf of E-mail from HVPD confirming licensing agreements [confidential report]
G. Olympic park pdf http://www.ipec.co.uk/wp-content/uploads/2013/07/olympic-park-discharging-rmus.pdf showing the use of technology to support the London Olympics
H. Case study demonstrating technology in a major industrial setting. http://www.ipec.co.uk/wp-content/uploads/2013/07/steel-plant-mv-cable-pd-location.pdf
I. 132kV transformer pdf http://www.ipec.co.uk/wp-content/uploads/2013/07/pd-in-termination-on-132kv-transformer.pdf Case study demonstrating technology in a UK transformer substation.
J. Letter from Technology Innovation and Coordination Manager, UK Power Networks confirming utilisation of partial discharge monitoring resulting in avoided costs of circa £900k.
K. E-mail from US Air force confirming Cotton's role in forming AIR 6127
L. Letter from Aircraft Group Electrical Eng Manager of Moog Inc confirming the role of the University in their technology development
M. Liebherr-Aerospace confirming the adoption of test techniques developed in Manchester. [confidential report]