Institution: University of Strathclyde

Unit of Assessment: 13

Title of case study: Advanced monitoring technology for high voltage equipment creates economic impact through substantial UK export business

1. Summary of the impact (indicative maximum 100 words)

Innovative research at Strathclyde University, embodied in its spinout Diagnostic Monitoring Systems (DMS) Ltd, has enabled the Glasgow-based company to become the premier supplier of ultra-high frequency (UHF) systems for detecting harmful partial discharge (PD) activity in high-value gas insulated substations and power transformers. Annual sales rose from £6.7M in 2008 to £11M in 2012, and its staff doubled to 56 employees. DMS' equipment is utilised in 27 countries, with total exports over 2008 – 2013 exceeding £45M. A sustained partnership with Strathclyde has yielded new sensor technologies and secured mainstream international recognition for UHF PD detection techniques, which are being incorporated within a new IEC standard. Economic value of Strathclyde's UHF technology was further emphasised in 2009 when DMS was acquired by Qualitrol, part of the US $46B Danaher Corp that owns numerous global engineering brands including Tektronix, Fluke, Leica Microsystems and Gilbarco Veeder-Root.

2. Underpinning research (indicative maximum 500 words)

Context: Research activities that led to the impact are founded on the discovery that partial discharges in gas-insulated substations (GIS) radiate electromagnetic signals in the UHF range (300–3000 MHz). These signals propagate for some tens of metres within the coaxial busbars of GIS, and Strathclyde research demonstrated that they provide a unique and effective basis for on-line monitoring of entire substations in order to prevent sudden, unexpected outages of these critical assets due to flashover of the gaseous SF_6 insulation. Benefits include improved reliability and quality of supply together with the avoidance of repair costs and financial penalties, which can amount to £500k/day for outages of key substations.

Global exports of UHF monitoring systems for GIS have formed the core business of Strathclyde's spin-out DMS since its foundation and that market continues to expand. Nevertheless, GIS are relatively specialised, high-value installations. In contrast, power transformers are used throughout electricity transmission networks. Many of these transformers are operating well beyond their designed life expectancy, particularly in developed countries. Failure of a transformer due to undetected internal PD or arcing can have severe environmental and safety consequences, as well as being costly. In the UK, a modest 60 MVA transmission transformer has a replacement value of about £500k while a large 400/275kV autotransformer would typically cost £2.5M. Additional financial implications of transformer failure are location dependent, but at the upper end of the scale, loss of connection to a substantial wind farm could lead to penalties in the region of several £100k/day. These issues emphasise the need for more effective monitoring of transformer fleets, which, underpinned by the sustained programme of UHF monitoring research at Strathclyde, has opened up international markets into which DMS continues to expand.

Key Findings: EPSRC-funded research (1993-1996) at Strathclyde underpinned investigations that (i) established the fundamental processes of UHF signal excitation by PD pulses, (ii) characterised their propagation, and (iii) introduced new techniques and sensors for coupling them from within the high voltage (HV) metal-clad equipment. The principal journal publication from this project remains the most highly cited work in its field [1]. Working in collaboration with Scottish Power and National Grid, Strathclyde staff (Farish, Hampton, and Pearson) applied the UHF technique in a world-first pilot installation of a continuous UHF condition monitoring system [2] at Torness Nuclear Power Station in East Lothian, which is linked to the grid through a 400 kV GIS. A further EPSRC grant (1996-1999) awarded to the same team led to the invention of a calibration system for UHF PD sensors. Reported in [3] (a paper that was awarded the IEE Ayrton Premium), this breakthrough gained further recognition through the award of First Prize in the Frontier Science category of the 'Metrology for UK Manufacturing Awards' (1997). The calibration technique was adopted as the basis for the UHF coupler sensitivity specification issued by National Grid (Technical Guidance Note 121), which has become the de-facto international standard for UHF

sensors, with more than 16,000 sensors installed around the world having been designed or calibrated to this specification.
The researcher (Judd) employed on the first two EPSRC projects subsequently won a prestigious 5-year EPSRC Advanced Research Fellowship (1999-2004), which focussed on applying UHF techniques to locate PD inside large power transformers and led to a subsequent EPSRC/industry project (2004-2007), in which key discoveries were made concerning the relationship between UHF PD detection methods and the conventional IEC60270 standard, as reported in [4]. Several Knowledge Exchange projects with DMS on the transformer work flowed from this activity, most notably a KTP (2007–2009) that delivered an integrated system for UHF detection, location and visualisation in three dimensions of the position of insulation defects inside large power transformers. The accumulated research findings were recently consolidated in a book chapter [5], which includes case studies on UHF PD location applied both in the field and at manufacturers' HV test facilities.

Key Researchers: All key researchers were employed in the Department of Electronic and Electrical Engineering, University of Strathclyde at the time of the research. Martin Judd: Research Assistant (1993) to Professor (present); Owen Farish: Professor (left in 2001); John Pearson: Senior Lecturer (left in 2000); Brian Hampton: Senior Research Fellow (left in 1998).

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

Refs 1, 2 and 3 best exemplify the quality of the body of research. Ref 4 is being returned within the UoA 13 REF2014 submission.

[1] M D Judd, O Farish and B F Hampton, "Excitation of UHF signals by partial discharges in GIS", IEEE Trans. Dielectrics and Electrical Insulation, Vol. 3, No. 2, pp. 213-228, April 1996.
[2] J S Pearson, O Farish, B F Hampton, M D Judd, D Templeton, B M Pryor (SP) and I M Welch (NG), "Partial discharge diagnostics for gas insulated substations", IEEE Trans. Dielectrics and Electrical Insulation, Vol. 2, No. 5, pp. 893-905, October 1995.
[3] M D Judd, J S Pearson and O Farish, "UHF couplers for gas insulated substations - a calibration technique" (awarded the IEE Ayrton Premium 1997), IEE Proc. Science, Measurement and Technology, Vol. 144, No. 3, pp. 117-122, May 1997.
[4] A Reid, M Judd, T Fouracre, B Stewart and D Hepburn, "Simultaneous Measurement of Partial Discharges using IEC60270 and Radio-Frequency Techniques", IEEE Trans. Dielectrics and Electrical Insulation, Vol. 18, Issue 2, pp. 444-455, April 2011.
[5] M D Judd, "Partial discharge detection and location in transformers using UHF techniques", Chapter in *Electromagnetic transients in transformer and rotating machine windings*, Editor: Charles Q Su, IGI Global, ISBN13: 9781466619210, pp. 487-520, July 2012.

Other evidence for Quality of Research
Key EPSRC research grants: *Excitation of UHF Resonances by Partial Discharges in Gas Insulated Substations* (GR/J08898); Farish, Hampton, Pearson; £154k; 1993–1996. *Advanced UHF partial discharge detection techniques for gas insulated substations* (GR/L34785); Farish, Hampton, Pearson; £196k; 1996–1999. *A New Approach to Partial Discharge Measurements for Testing Electrical Insulation Systems* (GR/S86747); Judd, Fouracre; £133k, 2004–2007.

- First Prize awarded to Judd & Farish for *Pulsed calibration of UHF sensors* in the 'Frontier Science' category of the UK Metrology for World Class Manufacturing Awards, 1997. Presented by Industry Minister John Battle during a National Awards Ceremony at the NEC.
- EPSRC Advanced Research Fellowship (GR/A90398) awarded to Judd, *Electrodynamics of Discharge Sources and Sensors in Power Systems*; £243k, 1999–2004. Competitive, peer reviewed award granted annually to only 25 researchers from all engineering and physical science disciplines across the UK. Established the efficacy of UHF monitoring for PD location in transformers.

4. Details of the impact (indicative maximum 750 words)
Process/events from research to impact:
Diagnostic Monitoring Systems (DMS) Ltd was founded in 1995 by key researchers Farish, Hampton and Pearson to commercialise UHF technology for monitoring gas insulated substations, initially as a joint venture between Scottish Power, National Grid and the University of Strathclyde.

Fundamental research during 1993-1999 yielded key innovations, laying the foundation for market leadership. Growing rapidly, DMS came to dominate the world market, ousting rival UHF products including systems introduced by ABB and Siemens. DMS' early business successes were recognised through awards such as the Scottish Council for Development & Industry's Award for Outstanding Achievements in Exports (2005) and the Queen's Award for Enterprise (International Trade, 2006).

Types of Impact

Expansion of spin out company: In 2009, DMS was acquired by Qualitrol Company LLC, part of the giant US-based Danaher Corp, which owns many well-known international engineering brands such as Tektronix, Fluke, Keithley Instruments, Leica Microsystems and Gilbarco. Danaher has a track record of growth through strategic technology acquisitions and global business development - its total sales in 2012 exceeded US $18B (Source A). In 2010, with this backing, DMS expanded into substantial new premises in the heart of Glasgow, which were fully refurbished as a state-of-the-art manufacturing / R&D facility. Qualitrol itself is a well-established supplier of components and monitoring equipment for power transformers. Consequently, Qualitrol-DMS has been able to reinforce its position as the leading provider of monitoring technologies and services globally within a much expanded market for UHF-based systems. (Source B corroborates all information on Qualitrol-DMS.)

Employment: Skilled jobs have been created in Glasgow as DMS has grown. For example, between 2010 and 2012, the workforce increased from 37 to 56 staff, which included 8 new R&D posts and 5 additional production staff.

Provision of KE and consultancy: Recognising a growing need for monitoring of power transformers and the pioneering research in this field being carried out at Strathclyde, DMS set up a Knowledge Transfer Partnership with the University (KTP ref. 6231, *UHF monitoring and partial discharge location system for power transformers*; Judd, Moore; £159k; 2007–2009). This delivered the first practical UHF-based system for detecting, locating and visualising in three dimensions PD sources inside large power transformers. From the KTP, the on-going partnership between Strathclyde and DMS led to the introduction of new UHF sensor technologies and calibration systems, and has opened up the power transformer monitoring field to UHF PD detection technology. Strathclyde has played a leading role in discovering the capabilities and advantages of UHF monitoring for power transformers and disseminated the findings through publications, contributions to international working groups and knowledge exchange activities. In April 2008 Judd was a member of a group of international transformer experts producing a final report for the International Council on Large Electric Systems (CIGRE), a non-profit association for promoting collaboration with experts from around the world. The report (Technical Brochure 343) recognised the role of UHF PD detection and location and recommended that additional valves for installing UHF sensors be specified on transformers that form important links in the transmission network.

Consultancy services were provided to DMS by Judd to evaluate UHF PD location trials during factory tests at ALSTOM (Stafford, 2008), Brush Transformers (Loughborough, 2009), VonRoll (Tel Aviv, 2010) and Sunbelt (Texas, 2013) and consultancy services were provided by Judd at the request of Singapore PowerGrid in 2010/11 (Source C).

International sales and market penetration: Qualitrol-DMS is the preferred supplier of PD monitoring systems to major international manufacturers of gas insulated substations including Siemens, ABB, Areva and Hyundai. By 2012 sales had increased by 82% to £11.1M, compared with £6.1M at the end of 2007. More than 90% of sales value represents exports from the UK. By 2012, the company had doubled its annual profits compared with pre-2008 figures and total exports for 2008 – 2013 have exceeded £45M (Source B). Further growth is ensured through expansion into the transformer monitoring market, fostered by Strathclyde's pioneering research activities in this field. Notable examples of penetration into the transformer market include:

- UHF sensors and monitoring system have been installed on gas-insulated transformers at Scottish Power's flagship Dewar Place substation in Edinburgh, which supplies the capital's financial district. The SF_6-filled transformers and reactors manufactured by Toshiba Corp are

the first of their kind to be installed in the northern hemisphere and the first to be equipped with UHF monitoring. Ten individual gas-insulated units are fitted with a total of 36 UHF sensors to a design based on the original capacitive sensors developed at Strathclyde. All of these were calibrated on Strathclyde's frequency response measurement system.

- AEP (American Electric Power), the largest US Transmission company, spread over 11 states, operating 3500 substations and 5500 transformers, has adopted the UHF PD monitoring technique within its evolving smart grid strategy. Six transformers manufactured in 2012 were equipped with 4 UHF sensors each to enable continuous monitoring once in service. These units are the first of an initial batch of 42 large power transformers with a 'built-in' UHF monitoring capability that AEP is deploying as part of its network upgrade strategy.
- SP Energy Networks (SPEN) policy document for Lifecycle Management of Large Power Transformers (rev. Feb. 2013) states that, "*All new large power transformers will be fitted with four additional 50DN ball valves fitted with blanking plates for the possible installation of through tank probes utilised in PD monitoring*" and goes on to define the positioning of the probes based on recommendations for sensor location deriving from Strathclyde research (Source D and E).
- SPEN has also deployed continuous UHF monitoring on 4 power transformers at its Clyde North wind farm substation. One of these units is also equipped with the first on-line monitoring system that allows PD location to be carried out using time-of-flight measurements inside the tank. This system was developed collaboratively between Strathclyde and Qualitrol-DMS within a KTP project, originally as a diagnostic tool used by an expert on-site. This new implementation provides a platform for complete automation of the process.

Benefits to the consumer: UHF PD monitoring technology resulting from Strathclyde research and commercialised through DMS is providing diagnostic services for electrical equipment in 27 countries that include Brazil, China, Russia, USA, Korea, Singapore, Malaysia, India, Australia and six Gulf states (Source F). In these nations, electrical utilities that use the UHF technology benefit financially by avoiding unplanned outages of these critical gas insulated substations, which result in emergency repair costs, damage to corporate reputation and can often lead to regulatory financial penalties for causing loss of supply to customers. Consumers (both domestic and commercial) who depend upon a continual source of electrical power also benefit from improved quality and reliability of supply. Power disruption has potentially severe consequences for industrial processes (e.g. semiconductor foundries) and society (e.g. hospitals, computing installations). UHF monitoring technology contributes to the maintenance of a continual electricity supply by providing early warning of developing insulation defects in HV equipment, allowing maintenance to be scheduled in a way that avoids supply disruption.

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

A. http://secfilings.nasdaq.com/edgar_conv_html%2f2013%2f02%2f22%2f0000313616-13-000026.html#FIS_BUSINESS. Provides details of Danaher businesses as of 31 Dec. 2012.
B. Chief Technical Officer of Qualitrol DMS can be contacted to confirm all details of the company's sales, exports, employment, growth and collaboration with Strathclyde.
C. Deputy Director, Smart Grid Projects, Singapore Power Group can be contacted to confirm that Judd provided consultancy services on UHF monitoring for power transformers during 2010/11
D. Document - SP Energy Networks (SPEN) policy document for Lifecycle Management of Large Power Transformers (quote from section 10.3.6).
E. Lead Engineer of SP Energy Networks can be contacted to confirm that Scottish Power transformer procurement documents require all new transmission transformers to be equipped with facilities for installing at least 4 UHF sensors, placed in accordance with Strathclyde recommendations.
F. Partial Discharge Specialist, ABB Schweiz AG can be contacted to confirm the global impact of UHF PD monitoring technology as well as its basis in Strathclyde research.