Institution: University of Leicester

Unit of Assessment: UoA 15 Engineering

Title of case study: Variwave: Safeguarding Air Quality by Radically Improving the Efficiency of Industrial Air Cleaners.

1. Summary of the impact:

The Leicester Variwave project, in relation to electrostatic dust precipitation, utilises a novel high voltage, high frequency, high power transformer within the power supply, which has enabled cuts in industrial emissions of ~50 per cent and considerable cost savings. Most new-build power stations and many other industrial sites now use technology based on that developed in Leicester. As well as fly ash and dust, the technology has the ability to trap sub-micron particulates thought to be partly responsible for the increase in the number of asthma cases during the past few decades. The MD of [Text removed for publication] states '*Through publications made by …Leicester …we were interested to learn how the team designed their high voltage transformer, and how that transformer operated with the high frequency, high power switched-mode electronics. They achieved that 'Holy Grail' combination [of high voltage, frequency, high power] in a 70 kW switched-mode power supply (SMPS) running at 20 KHz and at 50 kV. The publication in the IEEE Transactions on Power Delivery was very helpful, and enabled us to choose the direction when pushing the design boundaries in developing our own high power, high voltage technology for electrostatic precipitators*'. Dr Devine, a key member of the Leicester team between 1995 and 2000, was employed by [Text removed for publication] in 2001 purely on the basis of his knowledge of Variwave. [Text removed for publication] now have 200 units in operation. In 2002 Dr Devine was head-hunted for his knowledge of Variwave and moved to [Text removed for publication], who also developed commercial units. The uptake of the technology has been growing steadily since 2001. Exemplar data from one company on the associated reduction in emissions shows 195 switched mode power units installed in boiler plants worldwide by 2004 gave a reduction of around 60%. A 60% reduction in emissions is equivalent to a reduction from 40 $mg.m^{-3}$ to 16 $mg.m^{-3}$ of flue gas particulates. Since 2004 to date there are now estimated to be at least 5000 units installed worldwide.

2. Underpinning research:

For many decades large scale removal of industrial emissions, a market worth more than £4 billion a year, has been achieved through the use of electrostatic precipitators which charge the dust and particulates to a very high voltage and remove them through the force of attraction. Whilst effective, such systems used large, oil-filled, single phase 50/60 Hz power transformer fed rectifiers, or T/R sets, that were inefficient, costly and slow to control.

The conventional 50/60 Hz design became the standard issue due to a lack of topological progress (i.e. the topology of the transformer cores) since their initial introduction by Frederick Cottrell in the early 1900s. However, this kind of unit has severe drawbacks as far as operation is concerned, including, but not limited to:

- Low quality input currents and low power factor
- Sluggish operating characteristics
- Low power supply efficiency
- Large size, weight and civil engineering costs associated with the oil insulated transformer.

Conversion of AC mains voltages to controllable direct current is a key area of power technology which is a requirement of many industrial processes. There are particular challenges at very high voltages, such as in particulate emission control using electrostatic precipitators. Research conducted by Dr Paul Lefley and Dr. Philip Devine at Leicester showed that due to this need, very high power Switched Mode Power Supplies (SMPS) for industrial Electrostatic Precipitators (ESPs) were the way forward.

The aim was to provide a step change in technology and to implement a modern switched mode power supply to achieve a major improvement in the efficiency and effectiveness of electrostatic precipitators.

Realising the need for a high frequency switched mode based power supply, the team from the University of Leicester Engineering Department set about designing a system and a working prototype. This research prototype overcame design difficulties encountered with combining high frequency, high voltage and high power in a single power supply. It also served as a research tool to identify the usefulness of applying a variable waveform – including the addition of microsecond high voltage pulses – to the electrostatic precipitator for improved dust collection efficiency. In order to fulfil this technological achievement it was clear that a very special high voltage power transformer needed to be designed [**1**]; one that could withstand very high voltages (up to 100 kV), operate at high frequencies (20 kHz) and at high power (up to 70kVA), had low leakage reactance for fast response times, was capable of withstanding short circuits, and was greater than 90% efficient. Fothergill's input in the high voltage design included the novel use of insulating materials (nylon 66 and SF_6) and high electric field stress relief rings added electrical robustness to the new transformer [**1**]. The transformer, coupled to a phase shift controlled high frequency inverter and a three-phase power factor correction input stage, formed the basis of the new high voltage SMPS [**1-4**].

The high frequency approach has numerous advantages over the traditional mains frequency rectification equipment in that, with a switching period of 100 microseconds compared with 8 or 10 milliseconds the output waveform approaches pure DC and the recovery time following a flashover is considerably reduced. This enables the precipitator to operate at a much higher (average) voltage and hence performance, since the dust collection efficiency of any precipitator is proportional to the square of the operating voltage. In addition, electrical safety is increased because when the precipitators arc and spark the arc is extinguished much more rapidly than with what were the conventional transformer/rectifier (T/R) sets.

The work included methods of controlling the high voltage field in order to increase the dust collection efficiency. This included the injection of variable shaped voltage waveforms onto the high voltage field, not possible with a standard 50 Hz T/R set. Leicester's prototype 70 kVA switched mode power supply was built, installed and trialled at Didcot A power station in 1998. The ability to design and test the technology rested upon the underpinning research.

This research was funded by the EPSRC, the former DTI and industry [**G1**], and subsequently by the Teaching Company Directorate [**G2**]. There was also collaboration with RWE npower (formerly National Power plc), DDR Ltd. and Elequip Projects Ltd. (a division of Silvermines plc).

Staff included in the project were Dr. Paul Lefley (academic from 1992), Prof. John Fothergill (academic from 1985-2012 and now a Pro-VC at City University London) and Dr. Philip Devine (RA from 1995 until 2000).

3. References to the research

[1] 'A Novel Prototype Transformer for high Voltage, High Frequency, High Power Use', *Lefley P W, Fothergill J C, Devine P J,* IEEE Transactions on Power Delivery, Jan 2001 Vol.16, No.1, pp.89 -98. **The key reference.**

[2] 'High Voltage, High Frequency Transformer Design', *Lefley P, Devine P,* Transformers Analysis Design and Measurement, CRC Press Monograph, Chapter 21, ISBN 9788460995159, 2006.

[3] 'Breathe Easy', *Lefley P W, Parker K,* IEE Power Engineer Journal, Feb 2006, Vol 20, pp.38-43

[4] 'A New Breed of Power Supply for ESPs, *Lefley P W, Parker K,* SAIEE Energize Power Journal, July 2006, pp. 56-61

[G1] EPSRC Grant number: GR/K40925
EPSRC Grant value: £135k
Programme: LINK Programme - Power Electronics, Devices and Derived Systems (PEDDS) category.
Programme value: £465k, including EPSRC, DTI and industrial contributions.
Start date: 21/08/95
End date: 20/11/98 (Extended to 27/07/99)
Contributing partners: National Power PLC (now RWE npower), Lodge Sturtevant (UK based), Deakin Davenset Rectifiers Ltd., Rugby, UK

[G2] Teaching Company Scheme follow on project
TCS Programme number: 2751

Programme value: £81k
Start date: 06/04/1999
End date: 31/10/00
Contributing partners: Elequip Projects Ltd (Silvermines PLC), Deakin Davenset Rectifiers Ltd.

4. Details of the impact:

Dr Philip Devine, employed on the Variwave project at Leicester between 1995 and 2000 and then at [Text removed for publication] and subsequently [Text removed for publication] states:

'The goal of the "Variwave" project was to advance, what was at the time, predominantly old fashioned, inefficient, sluggish and large electrical hardware used to energise ESP's (electrostatic precipitators)…There were several manufacturers around at the time who were beginning to explore the issue however, we (Leicester) differed in that

- We weren't just "bolstering" an old system by introducing new technology here and there hoping the net result would be mild improvements in efficiency and performance like some manufacturers at the time seemed to be doing (for example introducing inverter technology yet being limited by low/medium frequency transformer/rectifiers).
- Leicester offered a completely innovative solution to the problem…..(pressurised SF_6 gas insulation technology utilised instead of traditional oil insulation, high frequency ferrite technology instead of low frequency iron core based technology, innovative transformer bobbin geometry and materials to minimise lossy parasitic elements and mitigate against electrical breakdown phenomena , high frequency (>20kHz) semiconductor switch operation).
- The culmination and goal of the project was to install a high power prototype in a "real world" installation (…at Didcot power station in 1998…) and conduct successful field trials…. which we did…with outstanding results…...Other teams seemed to be producing only low power, small scale (purely academic) prototypes without stepping up to the challenge of addressing the myriad of technical obstacles that realistic high power, practical systems would need to overcome.
- We provided a robust, economical solution. We (Leicester) seemed to overtake several commercial organisations in that we designed on (in comparison to industry) a shoestring budget, on time and delivered a fully functional prototype solution to industry which proved its potential for helping shape the technology that would eventually be adopted by key [Text removed for publication]
- The approval we received from National Power to install our prototype at a working coal fired power station and conduct trials was unprecedented and a major milestone' [**A**].

Dr Devine further states:
'In 2001 I was approached by [Text removed for publication] who were, at the time, starting to develop a commercial version of an ESP power supply with all the key qualities that had been previously and independently been identified by the team at Leicester and built into our prototype.

I was employed by [Text removed for publication] purely on the basis of the research I had undertaken at Leicester. Although there were differences between the Leicester prototype and what [Text removed for publication] were hoping to achieve in a commercial product , there was also striking similarities between the two and [Text removed for publication] were keen to learn how we had approached and solved the same technical challenges….The [Text removed for publication] power supplies are now in full production.

Later on I worked for [Text removed for publication] (2002-2004) both in the UK and [Text removed for publication], I was recruited again, purely due to my work with Paul (Lefley) at Leicester. [Text removed for publication] also market a high frequency switched mode ESP supply' [**A**].

He adds:
'It is fair to say that [Text removed for publication] was underpinned by research at Leicester, via the expertise I contributed to them when I worked at [Text removed for publication] [**A**].

[Text removed for publication] now have 200 units in operation worldwide [ii]. Leicester's expertise has fed into the development of [Text removed for publication] product, as can be seen from the design of the high frequency ferrite cored transformer in comparison with the design in our key paper in 2001 [1]. The Didcot power station prototype proved conclusively that Leicester had created a robust product with decreased emissions and an efficiency rating of more than 95 per cent, compared with around 60 per cent for the previous conventional technology.

Mr Stuart Morgan, Managing Director of [Text removed for publication], a UK-based manufacturer of switched mode power supplies, states [**B**], "Power supplies for industrial electrostatic precipitators are a particular challenge for any designer, combining high frequency and high power in the power electronics but also with very high voltages. The successful combination of these three parameters all at high levels has been a 'Holy Grail' for the power electronics industry. Through publications made by the University of Leicester from the late 1990's, we were interested to learn how the team at Leicester designed their high voltage transformer, and how that transformer operated with the high frequency, high power switched-mode electronics. They achieved that 'Holy Grail' combination in a 70 kW switched-mode power supply running at 20 kHz and at 50 kV. The publication in the IEEE Transactions on Power Delivery was very helpful, and enabled us to choose the direction when pushing the design boundaries in developing our own high power, high voltage technology for electrostatic precipitators." [Text removed for publication]

Switch mode power supply technology has been adopted by [Text removed for publication] since the University of Leicester's research was completed. In retrospect the University should have patented rather than published in 2001.

High frequency, high voltage, high power SMPS technology has now been installed in a large number (at least 5000 –see [**E**]) of major industrial complexes worldwide, and the impact on industrial emissions – and therefore air quality surrounding the complexes – has been significant. Exemplar data from one company on the associated reduction in emissions achieved by 195 switch mode power units installed at boiler plants worldwide has been around 60 per cent. (A 60% reduction in emissions is equivalent to a reduction from 40 $mg.m^{-3}$ to 16 $mg.m^{-3}$ of flue gas particulates) [**D**].

The main points of evidence:

1) Leicester was the first to produce a switched mode power supply with a combination of high frequency (20 kHz), high voltage (50 kV), and at high power (70 kW). (Statement by Genvolt Ltd. [**B**] and the journal paper in the IEEE Transactions of Power Delivery 2001 [1]).
2) Dr. Philip Devine's employment with [Text removed for publication] [**A**].
3) Close similarity between the design of the transformer in current units with the original design in the 2001 journal paper.

5. Sources to corroborate the impact

A. Statement by Dr. P Devine, [Text removed for publication].

B. Statement by Managing Director, [Text removed for publication]

C. Unfortunately all at Didcot power station staff involved with this have now retired.

D. Table 1 data courtesy of ABB/Alstom from a paper presented at the 9th ICESP Conference in South Africa (2004), published by the International Society for Electrostatic Precipitation.

E. Data courtesy [Text removed for publication]