Institution: University of Glasgow
Unit of Assessment: B15: General Engineering
Title of case study: From refrigerators to power tools: Millions of electric machines produced with designs that have been developed using SPEED software.
1. Summary of the impact

Motors are at the heart of all electric machines. World-leading software developed at the Scottish Power Electronics and Electric Drives (SPEED) Laboratory at the University of Glasgow has been used to design thousands of new motors, enabling the manufacture of millions of machines across a range of industrial sectors. From compressors in refrigerators to the motors in power tools, SPEED has improved the design of products manufactured by over 60 companies across the world including Bosch, General Motors, Grundfos and Rolls Royce. In 2011, the SPEED Laboratory was purchased by CD-adapco, the world's largest independent provider of computer-aided engineering simulation software.

2. Underpinning research

For 25 years, research within the University of Glasgow's Scottish Power Electronics and Electric Drives (SPEED) Laboratory focussed on developing the theory for the design and control of electric machines. Professor Timothy Miller (Professor of Electrical Engineering, 1986-2011) led the research, with Mr Calum Cossar (SPEED Laboratory Manager, 1988-present) and Mr Malcolm McGilp (Chief Software Engineer, 1989-2011). The research led to the development of the most advanced and widely used Computer Aided Design software for electric motors and drives, comprising a suite of five software packages, each focused on a specific type of electric machine. All outcomes from SPEED research post-1993 were implemented into the software and released to the industrial consortium whose membership fees funded the core research.

From 1993, research introduced new techniques and enhanced the accuracy and application of the SPEED software, leading to its extensive impact on motor design. In 1995, Miller and David Staton (Fellow, 1989-1995), with PhD students Wen Soong (1990-94) and Rajesh Deodhar (1993-96) collectively developed a new, unified technique for the analysis and comparative evaluation of the average and the instantaneous torque in a wide variety of electrical machines, called the flux-MMF (magneto-motive force) diagram technique (FMDT). The generality of the FMDT meant that it could be applied to any rotor geometry, winding distribution and current waveform [1,2,3]. This enabled comprehensive analysis and real performance comparisons to be undertaken at the design stage.

The significance of this work was further realised when Miller extended the SPEED software by integrating a numerical Finite Element Analysis (FEA) tool in 1998. The coupling of FMDT with FEA made it much more powerful and applicable to a wide range of problems [4]. The FEA tool provided an efficient electromagnetic analysis to determine rapidly the flux-MMF diagram and was not constrained by any assumptions regarding linearity, geometry, saliency or mode of excitation. The integration of FMDT and FEA into the existing SPEED software proved a powerful combination, creating a unique design tool for electric motors that was experimentally validated by the SPEED Laboratory.

Further research undertaken by SPEED led to new approaches for specific types of motors. For example, line start permanent magnet machines are more efficient than conventional induction motors and are important to compressor manufacturers (e.g. in domestic appliances). In 2003, Dr Mircea Popescu (Research Assistant, 2000-08) developed a new and accurate approach to predicting the behaviour of these motors [5], enabling a new simulation model to be developed and integrated into the PC-BDC software package (for Brushless DC Machines), significantly increasing the commercial application of the software.

The SPEED Laboratory research also focussed on high performance control, sensorless control and fault tolerant operation of Switched Reluctance motors and generators. Switched Reluctance machines are characterised by a relatively simple mechanical design. There are no permanent

magnets and so power does not have to be delivered to moving parts. Consequently they contain a more complicated electrical design. This work was validated during a Department of Trade and Industry Link project with TRW Aerospace (1997-2000).

Research into iron loss calculations for electric machines was an ongoing activity within the SPEED Laboratory (2005-10). Iron loss, which can generate heat, can have serious consequences for electrical machines (e.g. compressors, especially in a refrigeration environment). This research resulted in a novel solution to the calculation of iron loss, requiring minimal experimental data, which was introduced into the SPEED software to enable improved designs which avoided machine overheating [6].

3. References to the research

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5. Popescu, M.; Miller, T.J.E.; McGilp, M.I.; Strappazzon, G.; Trivillin, N.; Santarossa, R., [2003] –Line Start Permanent Magnet Motor: Single-Phase Starting Performance Analysis, *IEEE Transactions on Industry Applications*, vol.39, no.4, pp.1021-1030, Jul/Aug 2003. doi: 10.1109/TIA.2003.813745
6. Popescu, M.; Ionel, D.M.; Boglietti, A.; Cavagnino, A.; Cossar, C.; McGilp, M.I., A General Model for Estimating the Laminated Steel Losses Under PWM Voltage Supply, *IEEE Transactions on Industry Applications*, vol.46, no.4, pp.1389-1396, Jul-Aug 2010. doi: 10.1109/TIA.2010.2049810 *

* best indicators of research quality

4. Details of the impact

Motors are at the heart of all electric machines including power tools, pumps and aircraft; a car alone can require hundreds of electric motors (including windows, steering, wipers, etc.). For 25 years, Miller and his team within the SPEED Laboratory at the University of Glasgow researched, developed and maintained the world's leading software for the design of electric machines. The University of Glasgow SPEED Laboratory has created significant impact by:

- improving motor design for industry across the world, underpinning the development of thousands of new motors for everyday machinery and a wide range of industrial products. Millions of machines have been produced as a result of the SPEED software.
- being successfully commercialised in 2011 and bought for an undisclosed sum by CD-adapco, the world's largest independent provider of computer-aided engineering simulation software for fluid dynamics and heat transfer. This secured excellent opportunities for the future design, research and innovation of electric machines.

In the 1980s, modern electrical machines demanded new motor designs. An experienced motor engineer could take weeks to develop a new design without knowing if the design was optimal. For more mature machine types (induction motor and brushed DC), there was no commercially available design package. The SPEED software overcame all these difficulties and was designed for a range of modern motor types. It was user-friendly and provided simulation solutions for optimised designs in hours rather than weeks. SPEED increased productivity, differentiated product ranges and enabled the design of better motors. In addition, the SPEED Laboratory provided documentation and comprehensive training packages for all companies who used the software tools.

From 2008, SPEED Laboratory research was funded through membership of an industrial consortium that included many of the world's leading manufacturers in the electric machines sector such as General Motors, Robert Bosch GmbH, Grundfos, Muirhead Aerospace, Tecumseh Company and General Electric Company. In addition, SPEED had distributors of its software based in the UK, USA, France, Germany, Australia, Japan, Korea and Taiwan. Together these generated around £600k p/a from membership and licence fees and funded ongoing research at the University of Glasgow, including the incorporation of new techniques and features into the SPEED software.

Until 2011 the research outputs of the SPEED Laboratory were shared with the consortium members through annual upgrades to the licensed SPEED software and via regular training courses in Glasgow and at the companies' premises across the world. Over 1000 engineers in more than 60 member companies utilised the software as a key tool for the design of electric machines.

As end users of SPEED, the following companies exemplify the impact it has created:

- Grundfos, the world's largest pump manufacturer, based in Denmark, identify six products developed from 2008 that have relied on the SPEED software. These new products/ranges all exceed European legislative requirements for energy efficiency. In the years 2008-2013 the annual volume of motors have been in the range from 10-14 million units/year and products associated with around 50% of sales have been designed or upgraded using SPEED software.
- Tecumseh Company, one of the largest manufacturers of hermetic compressors for refrigeration and air conditioning in the world adopted the Speed Software in 2009. One market sub-segment increased by 30% when a SPEED-designed compressor was introduced.
- General Motors rely on SPEED software to design the critical motors in their hybrid and electric vehicles, including those for propulsion and transmission. The Chevrolet Volt was introduced in 2010 and had sold over 38,000 worldwide by June 2013.
- The Power Tools Division of the Bosch Group is the world market leader for power tools, accessories and measuring devices. In 2011, it generated sales of some £1.2 billion from products introduced since 2009. SPEED software was used for the development of two of these product lines.
- Muirhead Aerospace recently used SPEED to '*design two concentrated winding brushless motors for a large European Aerospace company for a helicopter landing gear*' and '*sizeable orders have been received*.'

Taking into account the global companies who have used and continue to use SPEED, the research has contributed to the generation of many billions of pounds of economic impact.

In 2011, CD-adapco acquired the SPEED Laboratory as part of its strategy to remain competitive in a world of ever-increasing performance and efficiency, therefore propelling the company to the forefront of electric machine design. SPEED was combined with the existing STAR-CCM+ flow/thermal CFD-centric CAE software to introduce a new and unique process for the design of electric machines focused on their key markets of aerospace, automotive, industrial and refrigeration. Miller and McGilp joined CD-adapco in 2011 and the initial impact of their collaboration was the release of a new version of SPEED and an increase in end users to over

1500. In 2012, CD-adapco opened an office in Glasgow – securing employment for the staff from the University Laboratory and demonstrating the company's commitment to furthering electric machine design.

5. Sources to corroborate the impact

- The SPEED Laboratory's impact on the field of electric machines was recognised when Miller received the TESLA Award in 2008 for his 'outstanding contributions to the advancement of computer-based design and analysis of electric machines and their industrial dissemination'.
- CD-adapco brochure: CD-adapco take over SPEED laboratory
- News Release: SPEED 2011 release by CD-adapco
- CD-adapco website states millions of machines produced with SPEED.
- GM Chevrolet Volt sales Chevrolet Volt total sales by June 2013
- Bosch Power Tools income from new products introduced since 2009
- Staff Research Engineer, General Motors Global R&D Center (USA), will corroborate General Motors use SPEED software to design critical motors in their electric and hybrid vehicles including the Chevrolet Volt, the 2nd best selling plug-in vehicle.
- Electrical Machine Sector Manager, CD-adapco (Germany), will corroborate that CD-adapco acquired the SPEED laboratory from the University of Glasgow enabling them to grow their business and attract new customers.

Testimonials

- Senior Design Engineer, Muirhead Aerospace (UK), confirming the benefits SPEED software provides and that it has been used to design new products for their customers.
- Director, R&T Technology, Grundfos (Denmark), confirming the benefits of SPEED software. Lists product development highlights since 2008. ~50% of all products designed and upgraded will have benefitted from SPEED software.
- Project Manager, IMRA Europe S.A.S. UK Research Centre, confirms that SPEED software is used for all new product design, and has been used in seven major development projects since 2008.
- Head, Mechatronic Engineering, Robert Bosch GmbH (Germany), corroborates that Robert Bosch Power Tools use the SPEED software for the design of prototypes, saving them time in the design process and that they use the software for the development of two different product segments.