Institution: Newcastle University

Unit of Assessment: 13 Electrical and Electronic Engineering Metallurgy & Materials

Title of case study: Sensorless control of high efficiency drives for consumer appliances

1. Summary of the impact

Newcastle University has a substantial background in researching novel control methods for electric motors. This case study concerns the impact that our work on sensorless control systems has had upon Dyson consumer products.

One of our sensorless control schemes has been adopted by Dyson for their vacuum cleaner drive systems offering benefits of ruggedness, flexibility and being inexpensive to implement, leading to reduced production costs and improved ergonomics derived from the ability to eliminate bulky sensor components and separate control electronics from the motor.

Dyson has invested £5M in a new production line for products using this sensorless control system which have production volumes of around 5 million units per annum. The Company estimates the cost savings accruing from the use of our designs at around £2M per annum.

2. Underpinning research

Newcastle University is home to one of the world's leading motor control and design groups with a long history going back almost 100 years. Our interests in the specific topic of sensorless control originated in the research of Prof P Acarnley who identified a novel method of determining motor position based upon the use of motor terminal voltages and line currents to estimate winding flux linkages and thus predict motor position [**P1**]. Acarnley continued to be a major contributor to the development of various sensorless control methods ([**P3**] and [**G4**]) and his work was further supplemented by Atkinson, Jack and Mecrow [**P2**] who applied sensorless position estimation and control methods to fault tolerant drives.

Newcastle research in this area is particularly relevant to the design of consumer products, such as vacuum cleaners, which provide greatest efficiency and minimum mass when operating at ultra high speeds. Almost all consumer products use brushed motors because of the high cost of power electronics and control for brushless alternatives. This has resulted in inefficient systems, with maximum speed typically limited to less than 40,000 revs/min by the brushgear. Newcastle has been working to overcome this by researching and implementing low cost brushless drives operating at speeds of 100,000 revs/min or greater [**P4**], enabling them to be both smaller and more efficient. The research areas have included new motor topologies, use of new materials, new drive topologies and novel control schemes, based upon our extensive history of researching these topics.

A key research project, part funded by Dyson, investigated low cost sensorless schemes for ultra high speed drives. The research built on Newcastle's expertise in sensorless control schemes to develop a controller for single phase drives of the type used by Dyson. Single phase drives pose particular problems. Unlike three- phase drives, the single phase winding is always active, which immediately rules out most existing sensorless schemes. Two low cost sensorless schemes were developed: the first scheme is used during current control mode and determines the rotor position from analysis of the active waveforms in the phase windings; the second scheme is used in voltage control mode and indirectly determines the rotor position by estimation of the back emf via some low cost hardware. When used together the schemes operate across all loads and the entire speed range – from standstill to over 110,000 rev/min. This research has resulted in 2 patent applications [**E1**, **E2**].

The reported research was conducted by the Power Electronics Drives and Machines (PEDM) Group at Newcastle University over the period 1997 to 2013 and was led by Prof Barrie Mecrow (97-date), Prof P Acarnley (94-09) and Prof Alan Jack (97-10), with further significant contributions

from Prof J Finch (97-09) and Dr DJ Atkinson (97-present), all of whom were employed at Newcastle University.

The PEDM group research in this area in the period 1993-date has attracted over half a million pounds of Dyson direct funding [**G1**, **G2**, **G3**] in addition to ESPRC support in the form of individual and platform grants [**G4**, **G5**].

3. References to the research

Publications (Key Publications P1, P2, P4)

[**P1**] Ertugrul, N., Acarnley, P. "A new algorithm for Sensorless operation of permanent magnet motors." IEE Trans on Industry Applications, 30 (1) , pp 126-133 Jan/Feb 1994. *This presents a new way to achieve sensorless motor position control. It is important because it is the first to identify the way to significantly reduce cost and improve performance of position control by eliminating the mechanical sensor.*

[**P2**] Green, S.,Atkinson, D.J., Jack, A.G., Mecrow, B.C. "Sensorless operation of a fault tolerant PM drive." IEE Proc. Electric Power Applications 150 (2) pp117-125 Mar 2003. *This extends the concepts embodied in the previous work to a broader range of applications (specifically aerospace)*

[**P3**] Acarnley, P.P. and Watson, J.F. "Review of position-sensorless operation of brushless permananet magnet machines." IEEE Trans Industrial Electronics 53 (2) pp 252-262 April 2006

[**P4**] Bateman, C.J. , Mecrow, B.C. , Clothier, A.C. , Acarnley, P.P. , Tuftnell, N.D. " Sensorless operation of an ultra-high-speed switched reluctance machine." IEEE Trans on Industry Applications, 46 (6), art. no. 5559420, pp. 2329-2337, 2010. *This paper is the link between the original thread of work and the specific implementation of this class of sensor to consumer products – it focuses on a low cost and robust implementation of Sensorless control of the type required for consumer device implementation.*

Patents

[**A**] Patent Application GB1203911.1 and GB1203913.7: Sensorless Control of a Brushless Permanent-Magnet Motor.

[**B**] Patent Application GB1210371.9 and GB1210372.7: Method of Determining the Rotor Position of a Permanent-Magnet Motor.

Funding

[**G1**] Dyson Technology Centre Funding , Value £169,000, 2007-13.

[**G2**] Dyson Industrial PhD sponsorship (4 Students), Principal Investigator B.C.Mecrow, Value £252,000, 2007-2013.

[**G3**] Dyson Engineering Doctorate Research project, Principal Investigator B.C.Mecrow, Value £80,000, 2005-2009

[**G4**] EPSRC Grant GR/J07129/01 "Position estimation in rotor-position switched electric drives.", Principal Investigator P. Acarnley, Value £137,061 May 1993 – Nov 1996.

[**G5**] EPSRC Platform Grant EP/F067895/1 "High Efficiency Electrical Energy Conversion", Principal Investigator B. C. Mecrow, Value £762,626, Feb 2009 – Jan 2014.

4. Details of the impact

Newcastle University's PEDM group has a substantial history of research collaborations with manufacturers of consumer products, including Black and Decker, LG and Electrolux and in particular we have had a fruitful research relationship with Dyson spanning the last decade. Dyson have incorporated many of the group's innovations into their products and their recent (2011-2013)

use of a specific, novel sensorless control scheme is the topic of this case study. It will be appreciated that because of the need to protect commercially sensitive intellectual property the Dyson information contained here is necessarily limited.

Key elements of the sensorless control work were subject to April 2012 patent applications [**E1**, **E2**] which have yet to come into the public domain.

Dyson have chosen to implement the sensorless control system on all their new drive systems because the design offered the following:

- Lower manufacturing costs and improved sales margins, estimated by Dyson at £2M/annum.
- Ergonomic benefits of flexibility and simplicity in product realisation, particularly in small machines, because there is no longer any need to incorporate a position sensor.
- Reduced complexity in the production line, leading to increased production rates and reduced costs.
- Less variation in performance within a production run and across the entire population of drive systems manufactured.

The sensorless design allows, through the elimination of the position sensor, the control electronics and motor to be separated and in turn this provides much more ergonomic flexibility in designing the product's external envelope. Dyson is noted for the ergonomic design of its machines and the new control system contributes to cost savings by allowing reductions in component count and assembly complexity.

In the period April 2011 – March 2013 the Newcastle research team provided close support to Dyson staff based at Newcastle whilst the sensorless control system was made production ready for manufacture in Singapore. In parallel Dyson has invested £5M in a new production line to manufacture vacuum cleaner products incorporating our sensorless designs.[**E3**]

Dyson's Director of Motors & Power Systems makes clear the exclusive and fundamental nature of his Company's relationship with Newcastle University in this field and the scale of products impacted by that relationship, stating "*Our research collaboration with the Power Electronics Drives & Machines Group at Newcastle University has had a fundamental impact upon the design of Dyson products. In particular, the patented sensorless control technology has been implemented in products with annual sales of 4.5 - 5 million units per year and annual sales values of approximately £0.5Bn. We have invested around £5M in a new Singapore based production line to manufacture these products and we estimate that the sensorless designs will yield annual production cost savings of around £2M. On a more general note, the Company has benefited from its relationship with Newcastle University via the transfer of ideas and realisations as well as the transfer of personnel. We collaborate exclusively with Prof Mecrow's group in this field and the core of our Motors & Power Systems team has been recruited from within the Newcastle research group*." [**E3**]

5. Sources to corroborate the impact

[**E1**] Patent Application GB1203911.1 and GB1203913.7: Sensorless Control of a Brushless Permanent-Magnet Motor.

[**E2**] Patent Application GB1210371.9 and GB1210372.7: Method of Determining the Rotor Position of a Permanent-Magnet Motor.

[**E3**] Director of Motors & Power Systems, Dyson Ltd. Testimonial letter outlining research work. and financial benefits.