Institution: Queen's University Belfast

Unit of Assessment: UoA 13

Title of case study: Integrated High-speed Generation Set Controllers

1. Summary of the impact

Novel integrated control systems together with their application within a holistic operational strategy have been created as a result of research with Caterpillar. Caterpillar the world's largest manufacturer of high-speed diesel generator sets (gen-sets) has invested (text removed for publication). This activity yields significant commercial advantage in both performance and efficiency bringing benefits for the environment, through reduced emissions, and major customer operational savings.

2. Underpinning research

Key Researchers involved *John Morrow, (Lecturer [1991-2000], Senior Lecturer [2000-2007], Reader [2007-2011], Professor [2011-]), Michael McAardle (PhD student [1999-2002]), David McGowan (PhD student [2000-2004], now Research Fellow (PT) [2004-]), Keith Chambers (PhD student [2000-2008], now 'Gen-set Performance Specialist', Caterpillar Electric Power Division [2008-]), Alan Cooper (PhD student [2008-2011], now Engineer with EDF Energy).*

Time period, *1996 to 2012*

A Royal Society Industrial Research Fellowship (1996) allowed Morrow to be seconded from the UoA to Emerson Electric diesel generator manufacturing plant. In 1996 Emerson formed a joint venture with Caterpillar Inc. www.cat.com/ which acquired it in 1999.

Underpinning research commenced with an appraisal of traditional gen-set control systems and the interactions of these with the individual items of non-linear plant being controlled. This highlighted that the use of linear control systems (generally fixed gain PID) are not best suited to highly non-linear plant, such as that found on a gen-set. In addition, a number of situations were identified where the lack of communication between the individual control systems, in particular engine governor and alternator automatic voltage regulator, AVR, resulted in sub-optimal overall gen-set performance. Of particular concern is the instance of initial load acceptance of a gen-set in a standby or mains failure application. Load acceptance is the ability of the generator to deliver power when it is first switched on following an interruption in the electrical utility supply. Here the gen-set is required at operational capacity within a few tens of seconds. This is problematical since an internal combustion engine has impaired capability to deliver its rated output until it has reached normal operating temperature.

To address this problem the research undertaken first deployed a digital excitation controller to replace the analogue AVR in the alternator. This controller employed fuzzy logic as a control technology better suited to the deterministic control of highly non-linear plant across a range of differing operating conditions. Second, fuzzy logic was used to implement a digital engine governor again resulting in better performance across the complete operating range than offered by traditional or existing techniques. It was found that when the governor and an enhanced AVR operated in a co-ordinated manner sharing information that improvements in delivered power quality was achieved across the entire operating range and significant improvements could be readily achieved in a number of more challenging operating conditions. In the case of the initial load acceptance, for example, this can be improved from the 40% of rating achieved with traditional control to 70% by application of the co-ordinated or integrated, fuzzy logic approach developed, [1, 2].

To aid control system design, modelling of plant was undertaken, [3], and validation and initial implementation was on performed on state of the art plant both at Queen's University and at a

number of international Caterpillar test facilities, patent protection was also conducted [4].

3. References to the research

Publications Underpinning Research

Publications covering/underpinning this research are listed below. These have undergone rigorous peer review. The research was funded through the externally peer-reviewed external grants whose details are given. The three highlighted papers* are indicative of the quality underpinning the research.

IEEE Transactions on Energy Conversion is peer reviewed top 10 worldwide publications in the Power & Energy sector. (Impact Factor 2.272).
IET Electric Power Applications is a peer reviewed top 10 worldwide publication in the Power & Energy sector. (Impact Factor 1.173).

1. *McGowan, D. J., Morrow, D.J., Fox, B., Integrated Governor Control for a Diesel-Generating Set. *IEEE Transactions on Energy Conversion*. Vol. 21, No. 2, June 2006, pp. 476-483, DOI: 10.1109/TEC.2006.874247.

2. *McGowan, D. J., Morrow, D.J., Fox.B., Multiple Input Governor Control for a Diesel Generating Set. *IEEE Transactions on Energy Conversion*. Vol. 23, No. 3, September 2008, pp. 851-859, DOI: 10.1109/TEC.2008.918623 .

3. *Cooper, A., McGowan, D., Morrow, D.J., Temperature-Dependant Voltage Regulator Operation for Optimal Load Acceptance on a Diesel Generator. *IET Electric Power Applications*, Vol. 6, No. 8, September 2012, pp. 553-560, DOI: 10.1049/iet-epa.2011.0218.

4. Morrow, D.J., Paresh, R.D., Hill, S.F., Gordon, P.T.A., McGowan, D.J., Chambers, K.D.R., Gen-set Control System Having Proactive Load Relief, *US Patent No. PCT/US2007/012804* , 31st May 2007 [This PCT application was taken into three national phase applications Europe EP2162812 (A1), US US2010241283 (A1) and China CN101689056 (A)] US patent 8560201 granted 2013. http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20100317&DB=worldwide.espacenet.com&locale=en_EP&CC=EP&NR=2162812A1&KC=A1&ND=4.

Research Grant funding
UOA Academics John Morrow (Lecturer -PI)
Funding "Royal Society Industrial Fellowship**",** The Royal Society / EPSRC, 1996–1997, £26,197, facilitating an industrial placement for an academic.

Research Grant funding
UOA Academics John Morrow (Lecturer, Senior Lecturer, Reader, Professor - PI),
Funding Caterpillar Inc., 1996–2012, £316,500, direct industrial funding

4. Details of the impact

From November 2007 the project was subject to technology transfer for implementation by Caterpillar Electric Power Division (EPD) in association with the UoA. EPD funded, and have been intimately involved in the gen-set control research and associated technology transfer, and are its principal beneficiaries[1].

The underpinning research described above gives Caterpillar a technology edge through which increased market share could be obtained due to its ability to offer a more competitive, class defining, gen-set product to its customers. Primarily this is because, while recent advances in engine technology have seen the power developed from, for example, a 9-litre engine, increase from 200kW to about 300KW, paradoxically, there is a decline in load acceptance. The load acceptance capability of gen-set packages is typically of the order of only 40% of the steady-state

rating. This means that owners of a 1 MW site must typically purchase a 2.5MW gen-set to ensure adequate load acceptance capability and this in turn leads to operational inefficiencies and proportionally higher emissions. The key benefit of the UoA's novel advanced non-linear control system is that load acceptance has been raised to approximately 70%. This negates the necessity to significantly oversize gen-sets simply to meet initial load acceptance requirements. Hence, the size of gen-set required is reduced, as is fuel consumption, resulting in lower gaseous and particulate emissions, as well as lower operating costs.

(text removed for publication)

The first of these projects made extensive use of the UoA world class gen-set test facility and depended heavily on UoA expertise[2]. The UoA's involvement in the second development was through design specification consultancy, as well as endurance testing and prototype development[1,2].

(text removed for publication)

Three advanced control products based on this research have been developed and are currently being marketed by Caterpillar. EM10[a], EM15[b], excitation modules are power electronics modules designed to provide excitation current to the generator and are used in association with a gen-set controller that is capable of executing the Integrated Voltage Regulator (IVR) control algorithm[c]. These three products are compatible for use with Self Excitation, Internal Excitation and Permanent Magnet generator excitation types. Together they operate to provide robust, precise closed-loop control of the generator voltage and optimized transient performance.

(text removed for publication)

5. Sources to corroborate the impact

[1]Engineering Manager, Electronics & Systems Integration, Caterpillar Electronics)
Caterpillar Inc.
USA

[2]Technology Manager
Caterpillar Electric Power Division
Larne
UK

Dealer information for customers, available on request from UoA.
[a] Data sheet for Caterpillar EM10 Excitation Module
[b] Data sheet for Caterpillar EM15 Excitation Module
[c] Data sheet for Caterpillar Integrated Voltage Regulator
[d] C15-C18 Product News