

Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt /Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Low Loss Hydraulic Power Transmission for Wind Turbines

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

This addresses improvements in the design of hydraulic transmission systems, for vehicular and renewable energy generation systems, by replacing the mechanical gearboxes to reduce their significant energy losses. This ERPE design of novel digitally controlled hydraulic transmission systems has culminated in the licensing, manufacture and production of high efficiency hydraulic gearboxes, now registered as the Digital Displacement[®] (DD[®]) patented technology.

This novel technology enabled the formation of the spin-out company Artemis Intelligent Power Ltd., with 30 staff in 2008, which was acquired by Mitsubishi Heavy Industries Ltd., in 2010, enabling the growth to 50 employees today.

2. Underpinning research (indicative maximum 500 words)

The research team comprised Professors Salter (Emeritus) and Wallace, Senior Lecturer Chick (all in post throughout), Kiprakis (Lecturer from 2011) with former research staff: Rampen, Caldwell and Taylor (who all left in 2008).

The important research contribution here underpinning Artemis were:

- invention and design of high-speed electromagnetically-driven valves to control the flow of high pressure oil into multiple chambers in hydraulic pumps [1, 4].
- To then effect the design of a “hydraulic gearbox” [2].
- To enable Artemis to examine its application to improving the performance and reliability of wind and tidal turbines [3, 5], large off-road and other vehicles [6].

ERPE (Salter, Rampen) is well known for its innovative design of digitally controlled hydraulic drive technologies. Originally invented in 2001/2 to efficiently and flexibly convert variable, reciprocating, slow-speed high-torque wave power [1] to uni-directional, constant high-speed drive power for generators, the technology was translated into the independent control of single and distributed drive trains. The internationally recognised technical achievement was the invention, design and refinement of high-speed electromagnetically-driven valves (programmable and time-selected by a digital microcontroller) to individually control the admission and discharge of very high pressure oil into multiple chambers in hydraulic pumps and motors on a stroke by stroke basis.

This technology is fundamentally enabling for the future of tidal and wave energy converter applications [3] and has current application in wind turbine systems [5] and large and small vehicle drives [6]. This is evidenced by invitation to deliver keynote lectures at both the Scandinavian International Conferences on Fluid Power, Linköping, 2009 and 2013.

Operating with ring-cam rollers, driving pistons distributed working stresses over multiple lines of force and overcame the fundamental limitations of previous technologies. From the earlier quasi-static control design [4], the concept achieved fully dynamic control using the principle now registered as DD[®] technology [2]. Individual electronic control of the inlet poppet valves on each cylinder in pumps (and on the discharge in motors) increased the efficiency by enabling high efficiency pumping strokes to be combined with very low parasitic loss idle strokes to meet the instantaneous flow requirements. Discharging the oil into high-pressure accumulators provided smoothing and energy storage. The reversible nature of the motors allowed them to return regenerated energy to store in the accumulators. Developing adaptable algorithms that matched valve timing to shaft speed, pressure and flow established a fluid power technology that offered increased part-and full-load efficiency over a wide range of input and output speed variation. Operating valves at near zero flow velocities reduced losses and noise. Operating with multiple cylinders in radial geometry that can be stacked axially offered modular construction and increased

power. The high pressure (350 b), low flow operating principle offered very high power density and compact machine volume, thereby addressing the space constraints in vehicle engine bays and wind-turbine nacelles. The fine control addressed the need for precision in materials handling in applications from forklift trucks through front- and back-hoe excavators to large earthmover drives.

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

References identified with * are those which best indicate the quality of the underpinning research.

- [1]* Salter, S.H., Taylor J.R.M. and Caldwell, N.J., “Power Conversion Mechanisms for Wave Energy”, Proceedings Institution of Mechanical Engineers, Part M: Journal of Engineering for the Marine Environment, Vol. 216, pp. 1-27, June 2002. DOI:[10.1243/147509002320382103](https://doi.org/10.1243/147509002320382103). 55 Google Scholar (GS) citations.

With the ERPE group research at the centre this paper compares and contrasts energy conversion techniques from several international groups presenting 14 clear and concise design conclusions. It shows in detail the application of the Artemis DD[®] technique for wave energy conversion.

- [2]* Rampen, W., Ehsan M. and Salter, S.H., “Modeling of digital-displacement pump-motors and their application as hydraulic drives for nonuniform loads”, Transactions of American Society Mechanical Engineers (ASME) Journal of Dynamic Systems, Measurement and Control, Vol. 122, No. 1, pp. 210-215, March 2000. DOI:[10.1115/1.482444](https://doi.org/10.1115/1.482444). 11 GS citations.

A paper showing the fundamental operating characteristics of the DD[®] machines, also revealing transformation of fluid power along the common crankshaft for energy regeneration to an accumulator.

- [3]* Payne, G.S., Kiprakis, A.E., Ehsan, M., Rampen, W.H.S., Chick J.P. and Wallace, A.R., “Efficiency and Dynamic Performance of Digital Displacement[®] Hydraulic Transmission in Tidal Current Energy Converters”, Proceedings Institution of Mechanical Engineers Part A: Journal of Power and Energy, Vol. 221, No 2, (Paper 207), pp. 207-218, March 2007. DOI:[10.1243/09576509JPE298](https://doi.org/10.1243/09576509JPE298). 19 GS citations.

A paper in which a large transmission is proposed for a horizontal-axis marine current turbine. The study involved efficiency calculations and dynamic simulations of system performance.

- [4] Salter, S.H. and Rampen W.H.S., “The Wedding Cake Multi-eccentric Radial Piston Hydraulic Machine with Direct Computer Control of Displacement”, in Way, N., (ed) BHR Group 10th International Conference on ‘Fluid Power – The Future for Hydraulics’, Brugge, Belgium, 5-7 April 1993. Available on request.

This was the first, ground breaking, exposition of the hydraulic drive system.

- [5] Rampen, W., Riddoch, F. and Taylor, J.R.M., “Gearless Transmissions for Large Wind Turbines”, DEWEK –Conference of the German Wind Energy Association, Bremen, Nov. 2006. <http://www.artemisip.com/sites/default/files/docs/2006-11%20Gearless%20Transmissions%20Bremen.pdf>

This describes the DD[®] transmission for multi-megawatt wind turbines, revealing the general layout of an integrated pump and main rotor, with twin motor and generator units.

- [6] Taylor, J.R.M., Rampen, W., Robertson, C. and Caldwell, N., “Digital Displacement[®] Hydraulic Hybrids”, Japanese Society of Automobile Engineers Annual Congress 2011. <http://www.artemisip.com/sites/default/files/docs/2013-04-12%20Digital%20Displacement%28R%29%20Hydraulic%20Hybrids%20.pdf>

A paper detailing a bus drive system design, funded by the Technology Strategy Board.

4. Details of the impact (indicative maximum 750 words)

ERPE (Rampen, Salter) pioneered the adoption of the hydraulic transmission technology by spinning out a company with an initially small team of engineers to develop the core hydraulic technology for commercial applications [S1]. Artemis/MHI holds a portfolio of 87 patent families and has been extremely effective at supplementing its licence income with grants, winning strategic investment of over £3.5M from Scottish Enterprise, Energy Saving Trust, Carbon Trust, Technology Strategy Board and the Department for Energy and Climate Change (DECC). Without relying on venture capital monies Artemis grew to 45 staff of whom 20+ are graduate engineers including 5+ PhDs. It has become a new energy transmission and storage technology development services and its facilities, operating outside Edinburgh since 2008, are now a state-of-the-art development platform.

Artemis subsequently successfully refined and commercialised their DD[®] technology. It developed four major partnerships - with the major oil company Conoco, with two Tier One automotive suppliers Dana and with Sauer Danfoss, a leading manufacturer of off-road mobile hydraulics, to apply its core technology in their sectors. In the course of this it built many component and technology demonstrators for both small and very large applications. *“As Chairman at Artemis I confirm that the early ERPE research to develop digitally controlled hydraulic pumps and the design, technical assessment and subsequent refinement of the initial small scale prototypes was instrumental in proving the concept that ultimately became the patented Digital Displacement[®] technology. This highly innovative ERPE research laid the secure foundation and enabled the growth of Artemis into the significant 50 person company that it is today and also to securing the major inwards investment from Mitsubishi”*, Chairman, Artemis Intelligent Power Ltd. [S2]

In December 2010 Artemis, which was still owned by its employees, was acquired by Mitsubishi Heavy Industries as part of a £100M inwards investment to establish the Mitsubishi Centre for Advanced Technology in Edinburgh. This is a significant impact in employment across the range of skills from craft-level through graduate training to post-doctoral research. *“As Chairman of Mitsubishi Power, I can advise you that the highly innovative hydraulic transmission technology, developed by Artemis, was the key attraction for our selecting Central Scotland for this significant investment and deciding to establish our new Centre for Advanced Technology close to this company”*, Chairman Mitsubishi Power. [S3]

The hydraulic transmission has been extended for application in a hybrid car, completed under an Energy Saving Trust (EST) grant, using the full DD[®] transmission in 2008, which achieved a 50% reduction of *urban* fuel consumption and CO₂ emissions - without any reduction in the vehicle performance. [6] shows the further application of DD[®] to a bus transmission system. Sauer Danfoss now hold the rights for this deployment in materials handling and larger off-road vehicles. They have also moved from research into product development with pilot installations under test on customer premises, and they have launched a full range of DD[®] based transmissions.

Fixed ratio conventional mechanical gearboxes are the critical limitation on technological and economic viability of up-scaling large wind turbines for on-, and more especially, off-shore application. Due to mechanical failure and poor reliability and availability, all the gearboxes at the Scroby Sands, Great Yarmouth, offshore wind-farm had to be replaced over an 18-month period. Replacing a 50 tonne gearbox in a nacelle 80 metres above sea level requires specialised heavy lift crane barges that can cost £50k per day and weather windows that allow safe working. Replacement capital costs and lost production revenue are very significant for the suppliers and owners. While blade aerodynamics are well-optimised for fixed speed operation, energy yield can be optimised by the use of continuously varying speed ratios that allow the blade speed to match varying mean wind speeds. Doubly-fed induction generators and on-board power electronic converters allow some speed variation, but do not offer the network support of fixed speed synchronous generators.

The Artemis designed onshore (2.4 MW rating) wind turbine transmission system [2, 5], part-

Impact case study (REF3b)

funded by the Carbon Trust reduced the weight of the gearbox it replaced by two-thirds, from 50 to 17 tons, enabled the use of synchronous generators and led on to successive investment in the technology by DECC. Mitsubishi performance-tested the on-shore prototype in Yokohama before Artemis up-scaled the technology in 2013 for offshore application in the SeaAngel wind turbine, one of the world's largest offshore wind turbines rated at 7 MW, at the Hunterston offshore wind turbine test facility. [S4]

Innovation and translation of the DD[®] technology has reduced the cost of renewable electricity, by reducing capital and maintenance or replacement costs, increasing reliability and energy yield, and is accelerating deployment of larger offshore wind technologies. Salter continues to serve as director and consults on technical issues such as overcoming cavitation effects, and provides new applications for their DD[®] technology.

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

- [S1] Technology Director, Technology Ventures Conoco Phillips (UK) Ltd., can confirm that the ERPE research led directly to the formation of Artemis.
- [S2] Artemis Intelligent Power Ltd, see comments included in Section 4.
- [S3] Chairman, Mitsubishi Power, see comments included in Section 4.
- [S4] Sea Angel turbine: <http://www.mhips.com/resources/documents/products/mpse-sea-angel-brochure.pdf>