Institution:	The University of Liverpool
Unit of Assessment:	UoA12 Engineering
Title of case study:	A comprehensive simulation tool to aid the digital design of high voltage circuit breakers

Period when the underpinning research was undertaken: 2001-2020

Details of staff conducting the underpinning research from the submitting unit:

Names(s):	Roles(s) (e.g. job title):	Period(s) employed by submitting HEI:
JD Yan	Professor	2001 - present
MTC Fang	Professor	1970 – 2003, (Em. 2003 to present)
JW Spencer	Professor	1990 - present
JL Zhang	Senior research fellow	1998 – 2006
C Dixon	PDRA	2000 - 2004
Q Zhang	PDRA	2015 - 2017

Period when the claimed impact occurred: 1st August 2013 – 31st July 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

All modern economies are heavily reliant on a continuous supply of electrical power. High voltage circuit breakers are crucial equipment to mitigate network faults and maintain the stability of power delivery networks. Low carbon footprint system components are increasingly important. A comprehensive digital design tool developed by the Liverpool team enabled two international manufacturers to shorten their product development time from 5 years to 2 years, resulting in savings in development cost and additional revenue totalling GBP [text removed for publication] and at the same time lower significantly the carbon footprint through a 30% reduction in the materials required. Liverpool's research also enabled a third international manufacturer to develop a circuit breaker that employs 'greener' insulation gases that have a global warming potential (GWP) < 1% of that of the currently used gas (SF_6) which has been used for over 50 years and has a GWP of 23,800 times that of CO_2.

2. Underpinning research

A complex problem: A high voltage circuit breaker is required to interrupt a damaging network fault current up to 60kA within a time scale of 50ms. This is achieved by first producing an electrically conducting arc plasma (ionised gas) between two separating electrodes to temporarily maintain the flow of the fault current and then using high speed gas flow to cool the arc and eventually convert it into an insulating gas, when the alternating current crosses its zero point. The performance of this complex system depends on the collective effect of the interwoven physical mechanisms: switching arcs burn in transonic flows of gas mixtures with fast changing species concentration; high temperature gas (~25,000K) emits megawatts ultra-violet radiation leading to severe polymer ablation; strong magnetic pinch interacts with the gas pressure and flow field; and turbulence enhanced energy transfer dominates the arc cooling near current zero. All these contribute to a very complex system to model.

Liverpool research: Previous research in Liverpool had focused on experimental and computational investigation into simple nozzle arcs at low current in pure SF_6 gas. Key research for a digital simulation tool to model the arcing process and aid circuit breaker design started in Liverpool in 2001 and took 4 critical steps. 1) The ablation by radiation of the arc confining polymer nozzle was studied and modelled by Fang, Yan and Zhang (J) during 2001 – 2003, by solving a specific concentration equation for polymer vapour and verified by experiments. The required thermodynamic properties and transport coefficients of SF_6-polymer vapour mixture were calculated using fundamental theory [3.1], extending the arc model to self-blast circuit breakers (relying on polymer nozzle ablation for current interruption), the most advanced high voltage circuit breaker to date. 2) In 2002-2005, the validity of a simplified and fast radiation transfer model was verified by Dixon, Yan and Fang by comparing the results with those from more accurate but computationally prohibitively expensive models [3.2]. 3) Collaborative research with Pinggao from 2007 to 2013, resulted in a novel arc root modelling method that dramatically reduced the inaccuracy of arc voltage prediction from 35% to 10% [3.3,3.4], yielding a key step forward for the modelling of commercial circuit breakers. 4) The work of Yan, Liu and Zhang (Q) [3.5,3.6] over the period of 2013 – 2018 identified the theoretical links between the arc quenching capability of a high-speed gas and its material properties [3.5,3.6], providing clear guidance on the selection and synthesis of 'greener' gases to replace SF_6. A method was developed to handle this $C_4F_7N+CO_2$ gas mixture and its material properties resulting from the non-recombination of the fresh mixture when subject to arc discharges. The digital modelling tool was also upgraded to accommodate the $C_4F_7N+CO_2$ gas mixture that has a global warming potential of less than 1% of that of SF_6 and is also the most favoured gas mixture worldwide to replace SF_6 in the power industry.

Development of Liverpool's simulation tool with circuit breaker manufacturers: The development of the simulation tool was made possible by Liverpool's experience with commercial computational fluid dynamics software and knowledge of numerical algorithms based on the finite volume method. Code developed at Liverpool, specifically for the tool, was seamlessly integrated into the commercial software by the team, to simulate the operation of pressure valves and other moving objects in transient high temperature gas flows. This made it possible in 2005 to model the arcing process in self-blast circuit breakers with full consideration of the breaker geometry and functional components (Figure 1), and was subsequently tested on ABB circuit breakers during 2005-2006. The tool was enhanced by the arc rooting method and fully verified in 2010 using test results from three international manufacturers and with additional results from Spencer.

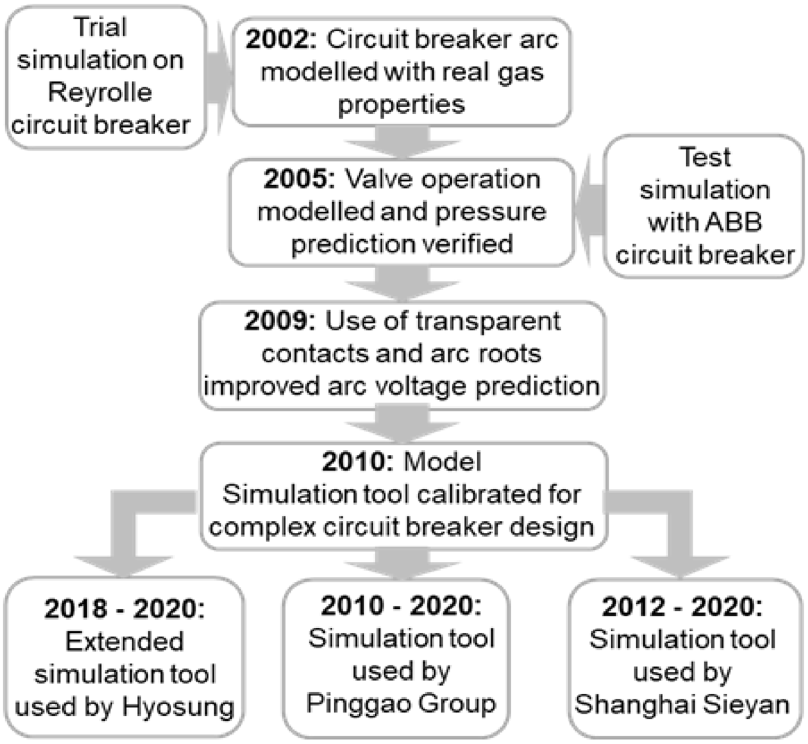

Figure 1: Timeline for simulation tool development and its use in industrial design. Reyrolle was the only high voltage circuit breaker manufacturer in the UK and became purely a manufacturing base after it was acquired by Siemens in 2005.

3. References to the research

[3.1] Zhang JL, Yan JD, Murphy AB, Hall WB and Fang MTC, "Computational investigation of arc behaviour in an auto-expansion circuit breaker contaminated by ablated nozzle vapour", IEEE Trans. on Plasma Science, Vol. 30, pp. 706-719, 2002. doi:10.1109/TPS.2002.1024273

[3.2] Dixon CM, Yan JD and Fang MTC, "A comparison of three radiation models for the calculation of nozzle arcs", J. Phys. D: Appl. Phys. Vol. 37, pp. 3309-3318, 2004. doi:10.1088/0022-3727/37/23/013

[3.3] Yan JD, Han SM, Zhan YY, Zhao HF and Fang MTC, "Computer simulation of the arcing process in high voltage puffer circuit breakers with hollow contacts", invited talk (published in conference proceedings, copy available from UoL on request) at the XVIII Symposium on Physics of Switching Arcs, Brno, Czech Republic, 2009.

[3.4] Pei Y, Zhong J, Zhang J and Yan JD, "A comparative study of arc behaviour in an auto-expansion circuit breaker with different arc durations", J. Phys. D: Appl. Phys., Vol. 47, 335201, 2014. doi:10.1088/0022-3727/47/33/335201

[3.5] Liu J, Zhang Q, Yan JD, Zhong J and Fang MTC, "Analysis of the characteristics of DC nozzle arcs in air and guidance for the search of SF_6 replacement gas", J. Phys. D: Appl. Phys., Vol. 49, 435201, 2016. doi: 10.1088/0022-3727/49/43/435201

[3.6] Guo Y, Zhang H, Yao Y, Zhang Q, and Yan JD, "Mechanisms responsible for arc cooling in different gases in turbulent nozzle flow", Invited talk, the XXIIth Symposium on Physics of Switching Arcs, Brno, Czech Republic, 2017. Published in Plasma Physics and Technology, Vol. 4, pp. 234–240, 2017. doi: 10.14311/ppt.2017.3.234

4. Details of the impact

A comprehensive digital design tool developed by the Liverpool team has enabled impact to be made on two fronts: commercial, and environmental via reduction in greenhouse gas emissions. This impact has been achieved via two international manufacturers who have shortened their product development time from 5 years to 2 years, resulting in savings in development costs and generating additional revenue totalling GBP [text removed for publication], and also reducing the carbon footprint through savings in materials by 30%. Liverpool's research also enabled a third international manufacturer to develop a circuit breaker that uses greener insulation gases that have notably less global warming potential (less than 1% of that of SF_6).

The impact of the research is a direct result of active industrial engagement of Liverpool researchers. The first collaborator, Pinggao Group, is the largest switchgear manufacturer in China with 10,000 employees. The collaboration with Pinggao was initiated in 2006 when the Director of Pinggao's Technology Centre attended Yan's lecture series given at Xi'an Jiaotong University. In a subsequent visit to Pinggao in the same year, Yan spent three days presenting Liverpool's approach for arc modelling and giving seminars on switching arc theory, which convinced Pinggao of the benefits of mutual collaboration.

4.1 Game-changing design practice leading to the shortening of product development time from 5 years to 2 years (Impact on manufacturing process)

A cash stream totalling GBP1,425,586, through 8 individual projects, was committed by the three international manufacturers to further improve and test the arc model through fundamental and applied research, enabling the simulation tool to accommodate a wide range of design features (puffer and self-blast types, double motion type, dual hollow moving contacts, etc.) and become more intelligent, reducing the engineering design effort required to run the simulation tool**.** Pinggao commenced using the digital simulation tool in 2010 to develop new circuit breakers and 13 products have been successfully developed and rolled out into market. The simulation tool has been so useful that it became an essential tool for Pinggao's circuit breaker product design. Any initial design has to be optimised and verified by the simulation tool before it goes to the prototype stage. As is stated by the Director of Pinggao's Technology Centre in his letter [5.1],

"*Using Liverpool's tool to evaluate and optimize new product design has become an essential step in our R&D activities. The average development time for the new products developed with the aid of Liverpool's tool is less than 2 years. This is much shorter than the average time of 5 years before*."

The tool was also transferred to Shanghai Sieyuan Electrical Co. Ltd for product design and 2 new products were successfully developed within two years (from 2014 to 2016 and from 2015 to 2017, respectively), significantly accelerating their product development speed and ensuring the delivery of the circuit breaker product to customers under commercial contracts [5.2]. This is acknowledged in particular by Dr Wei Gu, the product development team leader at Shanghai Sieyuan, in his witness letter [5.3],

"*Our team of 5 engineers completed both the designs and tests within an average of 2 years from absolutely nothing to pass the complete set of Type Test. For a similar product, it would take 5 years in the past to develop.*"

4.2 Commercial impact - Reduction of product development cost and time to market

A total of 15 different product series have been developed and sold by Pinggao and Shanghai Sieyuan. The total savings in development cost to Pinggao is estimated to be GBP [text removed for publication] in the period August 2013 to July 2020 [5.1]. For Pinggao, the earlier access to the market by the new products created an additional revenue of GBP [text removed for publication] over the period of August 2013 to July 2020 [5.1]. At Shanghai Sieyuan, a team of 5 engineers designed, using Liverpool's simulation tool, a 300kV and a 420kV self-blast circuit breaker within 2 years (2014-2016 and 2015-2017 respectively) [5.3]. In addition, the R&D cost has been reduced by GBP [text removed for publication] for each product [5.2]. As stated in Sieyuan's letter [5.2],

"The use of Liverpool's numerical simulation technology minimizes the time from laboratory to market, which has helped the company to create an additional sale of [text removed for publication] GBP in the period 2014 – 2020."

4.3 Environmental impact - Contribution to green electricity transmission

Globally, the annual SF_6 production is around 8,000 tons [5.4]. Based on atmospheric measurement data, global SF_6 emissions were 8,100 tons [5.5]. This essentially creates a production-emission scenario because there is no natural sink for SF_6. These emissions are equivalent to the annual greenhouse footprint of 40 million cars.

Using the simulation tool, Pinggao was able to minimise the size of the design of their 1000kV Ultra High Voltage (UHV) circuit breaker (Figure 2 shows a single-phase section, a unit has three phases), leading to a weight reduction from [text removed for publication] tons for a three-phase unit, land use reduced by 20% and manufacturing cost (mainly material) reduced by 30% [5.1]. The use of SF_6 per unit was also reduced

Figure 2: A new design of a single-phase of the 1100kV circuit breaker at Pinggao, enabled by the use of Liverpool's digital design tool. It has dimensions of [text removed for publication] m (length by width by height).

significantly, by 37% from [text removed for publication] kg, equivalent to 21,150 tons of CO_2 per unit.

Following an invited talk presented by Yan at an international conference (FSO 2017) on SF_6 replacement and subsequent technical discussions, collaboration with South Korea's largest switchgear manufacturer, Hyosung Corporation, was formally established in March 2018 to extend the digital simulation tool to aid the design of high voltage gas blast circuit breakers based on gases with low global warming potential, a mixture of C_4F_7N and CO_2. The digital simulation tool was transferred to Hyosung in late 2018. A 170kV circuit breaker based on the environmentally friendly gas mixture, which represents the highest voltage level of circuit breakers using alternatives to SF_6 around the globe, has been developed in collaboration with Liverpool. As identified above, this has reduced enormously the global warming potential (GWP) due to switching gases. The GWP of SF_6 is 23,800 times that of CO_2) [5.6].

For the electricity industry, direct replacement of SF_6 based asset (retrofitting) is of paramount importance. This is evidenced in the letter from Hyosung [5.6],

"Moreover, we have successfully kept the size of the new product the same as that of the old one using SF_6 gas – which is exactly what our customers such as KEPCO (Korean national grid) want for retrofitting existing assets."

The newly developed SF_6 free circuit breakers are being supplied in large quantities as part of a commercial contract between Hyosung and KEPCO (Korean National Grid) [5.6].

4.4 Development and consolidation of long-term industry-university collaboration

The team at the University of Liverpool not only transferred the digital simulation tool to industry to help product design, but also organised a series of training sessions and workshops for the design engineers from the collaborators. 5 engineers from Pinggao Group spent 3-6 months at Liverpool where they undertook training on advanced arc physics, switching process and practical skills on arc modelling. 2 senior engineers from Shanghai Sieyuan visited for 3 months in 2012 to be trained on arc modelling. 2 engineers from Hyosung have attended two workshops at Liverpool in 2018 to be trained on arc physics and arc modelling and another also spent three months (June – August 2018) at Liverpool to study switching theory. These efforts have helped the establishment of long-term collaborations with the industry, the successful transfer of knowledge to our industrial collaborators and sustained continued research funding to the University of Liverpool.

5. Sources to corroborate the impact

[5.1] Letter from Pinggao Group stating the factual changes enabled by Liverpool's digital design tool in their product design process and the financial impact.

[5.2] Letter from Shanghai Sieyuan stating the factual changes enabled by Liverpool's digital design tool in their product design process and the financial impact.

[5.3] A witness statement provided by a senior engineer of Shanghai Sieyuan Electrical Co. Ltd, who led the development of new circuit breaker products.

[5.4] Global production of SF_6, (last accessed 18 12 20) https://www.epa.gov/sites/production/files/2016-02/documents/conf00_damsky_paper.pdf

[5.5] Global emissions of SF_6, (last accessed 18 12 20) https://www.environment.gov.au/system/files/resources/71fad794-d98d-4014-95e6-53e9ce6493bf/files/australian-hfc-pfc-emissions-2015.pdf , p. 20.

[5.6] Letter from Hyosung on the impact of Liverpool's research on their product design.