Institution:	**Imperial College London**
Unit of Assessment:	**13A – Electrical & Electronic Engineering**
Title of case study:	**Case 5 - Design and optimisation methods for power networks impacting industrial strategies and government policies**

1. Summary of the impact

The Power Systems research team at Imperial made pivotal contributions in the design of power transmission networks, the equipment within these networks, and non-conventional electricity systems. Since 2008, the impact of their research has been to:

I1) influence government policies by contributing to House of Common Select Committee (2010);

I2) support the Fundamental Review of Supply Quality and Security Standards;

I3) assist National Grid in defining new investment affecting £3bn worth of network assets now approved by the regulator (2013);

I4) provide tools to develop the first offshore networks design standards in 2008, saving an estimated £500m by 2013 to date and a projected overall saving of £1-2bn by 2020;

I5) advance Alstom's design concept for next generation HVDC converter stations for offshore wind connection from TRL 1 in 2009 to TRL 4 in 2013 supported by 3 new patents;

I6) enable UK Power Network to plan network investment of £1.18bn and make savings of £130m (2013) through applying new technologies and demand response;

I7) facilitate a scheme for off-grid energy kiosks for electrification in rural Africa yielding social gains and a business opportunity.

2. Underpinning research

Prof. Tim Green and his team began work on multi-level converters in 1996 and applied this to transmission networks in 1998. This eventually developed into multi-level converters for High Voltage DC (HVDC) technology for offshore wind generation and for medium voltage distribution. The team was significantly strengthened with the arrival of Prof. Goran Strbac in 2005, and together they extended their research direction towards power network planning and optimisation, with particular focus on renewable generation such as offshore wind farms. The underpinning research that produced the aforementioned impact has the following three related themes:

1. **Cost-benefit Analysis and Modelling of Power Networks [R1-3; I1-4, I6]:** The incorporation and widespread adoption of diverse renewable generation sources in existing and future networks created new challenges in analysing, modelling and optimising electricity transmission systems. The energy production patterns of such sources of generation are often intermittent and unpredictable, varying from steady to very fast changing. Our team identified that stochastic and Monte Carlo extensions to the traditional Optimal Power Flow formulation were necessary. Fine time-resolution analysis of a large number of cases is needed to expose numerous conditions such as corner cases, which becomes an analytically challenging large-scale stochastic optimisation problem. This problem was pursued by the team at Imperial as part of the FutureNet (2003-07) [GR/S28082/01] and the FlexNet (2007-2012) [EP/E04011X/1] projects. Based on cost-benefit analysis (CBA), the team created a network planning and optimisation tool that yields a solution requiring lower asset investment than the existing method of redundancy provision. This tool achieved the goal of providing security of supply while producing optimum asset investment decisions based on local topology, specific seasonal risks and generation type. This work was first described in [R1]. The team later conducted further studies based on [R1] as part of the Centre for Sustainable Energy and Distributed Generation (SEDG) funded by the Department of Trade and Industry [R2]. This work was extended in 2011

to provide long-term investment planning tools for distribution networks [R3].

2. **Technologies for Power Transmission [R4-5; I5]:** In the FlexNet project, the Imperial team also pursued specific technologies such as corrective control of transmission systems, new HVDC power converters and power electronics for distribution networks. Multi-level power converters (for HVDC etc.) were analysed by Green in 1996-2002, as were factors determining trade-offs between topology, level-number, total harmonic distortion and passive component volume [R4]. Innovation in AC/DC converters to create the right properties for forming HVDC networks between offshore wind farms was the focus in 2007-2012. [R5] is the first description of the Alternate Arm Converter that included means to balance energy between its cells and the means to control flow of current into AC-side and DC-side faults. Managing DC faults is a major step toward forming HVDC networks. [R5] demonstrates these features together with an efficiency of 99% and only requiring reasonable volume of cell capacitors: important for offshore platforms use. The key advance was using analysis (rather than simulation) to support complex system trade-offs by designers.

3. **Rural Electrification in Developing Countries [R6; I7]**: Strbac's planning tools were extended to consider micro-grids for off-grid situations (EU-FP6 MicroGrids 2006-09, SES6-019864) while Green examined photovoltaic energy for ICT in African villages. Trade-off studies of technology options for rural electrification in developing nations were used to provide quantitative evidence on whether grid, microgrid or load-charging energy kiosks represent the best route to electrification [R6].

3. References to the research (*References that best indicate quality of underpinning research.)

R1* **Strbac G**, Shakoor A, Black M, Pudjianto D and Bopp T, "Impact of wind generation on the operation and development of the UK electricity systems", Electric Power Systems Research, Vol. 77, No. 9, pp. 1214 – 1227, (DOI 10.1016/j.epsr.2006.08.014) 2007

R2 Djapic P, **Strbac G**, "Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems", BERR Centre for Sustainable Energy and Distributed Generation (SEDG), July 2008, (accessed Oct 2013 at http://www.berr.gov.uk/files/file47242.pdf)

R3* Gan CK, Mancarella P, Pudjianto D, **Strbac G**, "Statistical appraisal of economic design strategies of LV distribution networks", Electric Power Systems Research, Vol. 81, pp:1363-1372, (DOI 10.1016/j.epsr.2011.02.001) 2011

R4* Soto-Sanchez DE and **Green TC**, "A comparison of high-power converter topologies for the implementation of FACTS controllers" IEEE Trans on Industrial Electronics, Vol. 49, No. 5, Pages 1072-1080, (DOI 10.1109/TIE.2002.803217), 2002

R5 Merlin M, **Green TC**, Mitcheson PD, Trainer D, Critchley R and Crookes RW, "A New Hybrid Multi-Level Voltage-Sourced Converter with DC Fault Blocking Capability", IET ACDC 2010, London UK Pages 1-5 (DOI 10.1049/cp.2010.0987), 2010.

R6 Baziliana M, Welscha M, Divan D, Elzinga D, **Strbac G**, Howells M, Jones L, Keane A, Gielen D, Murthy Balijepalli VSK, Brew- Hammond A, and Yumkella K, "Smart and Just Grids for sub-Saharan Africa: Exploring options", Renewable and Sustainable Energy Reviews, Vol. 20, pp. 336–352, (DOI 10.1016/j.rser.2012.11.004) 2013

4. Details of the impact

We now provide details of the 7 aforementioned impacts and their link to underpinning research:

I1) **Influence Government Policies** [E1]: The research in [R1] and the results in [R2] form the basis of evidence supplied by Strbac to the House of Common's Energy and Climate Change Committee. This was included in their report to Parliament entitled "The future of Britain's electricity networks" (10th Feb 2010) [E1]. In this report Strbac or his evidence were referenced 38 times. One section extracted from the report states [E1]:

"*… Strbac argued that the (existing) SQSS (*Supply Quality and Security Standards*)*

… present a barrier to a range of other solutions … these include … advanced network control and innovative decision-making tools. …. This is important because these alternative approaches could not only …facilitate the connection of greater amounts of wind … but also … play a key role in the development of a smart grid."

I2) **Support development of two standards** [E2]: Recommendations from [E1] led to the "Fundamental Review" of SQSS chaired by Andy Hiorns, Electricity Network Development Manager from National Grid, to develop a set of standards on supply quality and security. Hiorns provided corroboration evidence to the impact of our research in a letter stating that the Imperial team *"… provided the analytical basis for the design of emerging low-carbon electricity transmission networks*" [E2]. Since 2008 Imperial's cost-benefit methodology [R1-2] was used for the development of the first Offshore Network Design Standards, and for the support of the Fundamental Review of SQSS. Imperial's research demonstrates that offshore networks will be over-invested if built to onshore design standards. Hiorns stated that [E2]:

"The cost-benefit analysis (CBA) undertaken by Strbac (and his team)… demonstrated … no case for redundancy given the high cost of offshore cables … balanced against the low load factor (<40%) of offshore wind farm generation, the low security value of offshore wind and the absence of demand offshore."

I3) **Assist National Grid in planning network investment** [E2]: As a result of the SQSS review and the new Offshore Network Design Standards, National Grid developed a "Smart Transmission Zone" to experiment with new solutions. Furthermore, National Grid now uses Strbac's transmission investment model (known as DTIM) to perform cost-benefit analysis of transmission investment. According to Hiorns, based on this analysis they were able to demonstrate the case for reinforcing Great Britain's network through a new investment plan worth more than £3bn. This plan was subsequently approved by the Regulator, Ofgem [E2].

I4) **New standard leading to savings by National Grid [E2]:** According to Ofgem, there are 20 offshore wind farms with network connections worth an estimated £2.5bn. Hiorns stated in [E2] that:

"…. I [Hiorns] estimate that the design with the new standard, based on the methodology developed by Prof Strbac and his team, made savings of more than £500m … It is presently envisaged that some 11GW of Round-3 windfarms will be required, with potential further savings of £1-2bn."

I5) **New approach to HVDC with Alstom** [E3-4]: Imperial's work on analysing design trade-offs in multi-level converters in 1996-2002 [R3], and particularly in the new Alternate Arm Converter 2007-2012 [R4], demonstrated to Alstom how excellent fault management capabilities could be achieved alongside high efficiency and low volume. The impact of our work on Alstom's high voltage DC (HVDC) business is corroborated by the testimonial from Colin Davidson, Chief Technology Officer (HVDC) of Alstom Grid [E3]. Key control innovations on cell balancing, fault blocking and active filtering have been jointly patented with Alstom [E4a-c]. The analytical approach to design trade-offs has enabled Alstom to refine its "second generation" Voltage Source Converters (VSC) to minimise footprint for offshore HVDC use. Our team's role in advancing Alstom's second generation VSC from a concept (at TRL-1) to key plank of Alstom's strategy at TRL-4 is evidenced by the 3 joint patents through which, as Davidson states in [E3], the Imperial team:

"…. have provided Alstom with the detailed technical analysis, creative novel solutions and with commercial considerations that we hold in the highest regard. The research undertaken has strengthened Alstom's IP portfolio supporting our exploitation plan with technical publications and progressed a new technology for HVDC from investigatory to likely commercialisation. … We consider this technology to now be at TRL 4".

I6) **Assist UK Power Networks in their network investment programme** [E5]: Extending the principles of [R1, R2] to future power electronics options has created novel long-term distribution network investment planning tools as reported in [R3]. In [E5], Barry Hatton, UK Power Network's Director of Asset Management, says:

> *"… given the unique modelling capability developed by Imperial College team led by Professor Strbac, in 2011 UK Power Networks and Imperial commenced a joint project. … [to] apply a novel Load Related Expenditure Network Model … We have employed this innovative Imperial model to develop our network investment programmes,…with the total asset value of £1.18bn quantified by the model. … We have estimated that more than £130m could be saved through the application of demand side response, dynamic rating technologies and various active network management techniques, and we have included this in our business plan."*

I7) **Provide societal benefits in Africa** [E6]: Through the *Vessel* project (2006-2009) [EPSRC EP/E007198/1] and the Bboxx start-up company [E6], Imperial has exploited its expertise in photo-voltaic integration and techno-economic analysis [R6] to promote the "Energy Kiosk" model over conventional grid electrification. *Vessel* pursued the photo-voltaic energy option to support IT in Kenyan villages and Bboxx has rolled out Energy Kiosks with portable lighting in rural Africa and India. There are clear developmental advantages in providing electric lighting for children doing homework and families running a business and health benefits from avoiding paraffin smoke. The impact of the research is seen in the success of Bboxx in creating a sustainable business model of charging portable lamps in kiosks that could be rolled out as a business without subsidy.

5. Sources to corroborate the impact

E1 House of Commons Energy and Climate Change Committee, "The Future of Britain's Electricity Networks", Second Report of Session 2009-10, quotations from paragraph 56 on page 24 that leads to recommendation at paragraph 59 (repeated as recommendation 9 on page 64) plus additional remarks on Strbac's evidence in paragraphs 20, 53, 67, 77, 109, 126 and 140. Archived here on 23/10/2013. http://www.publications.parliament.uk/pa/cm200910/cmselect/cmenergy/194/19402.htm

E2 Letter from Chair of the SQSS Review Panel and also Electricity Network Development Manager, National Grid, stating impact of Strbac's work on network planning and investment onshore and transmission standards offshore.

E3 Chief Technology Officer, HVDC, Power Electronics Activities, Alstom Grid. Letter stating the impact of Prof. Green's work in Converter Optimisation on their product development for High Voltage DC transmission.

E4a D.R. Trainer, R.W. Crookes, **T.C. Green and M.M.C. Merlin**, "HVDC Converter comprising full-bridge cells for handling a DC side short circuit", WO Patent WO/2012/013,248 (30th July 2010). (Imperial inventors shown in bold.)

E4b **T.C. Green**, **M.M.C. Merlin**, N. Okaeme and D.R. Trainer, "A Method of Voltage Source Converter Cell Voltage Balancing using Circulating Current", PCT/EP2010/066278, (27th October 2010).

E4c D.R. Trainer, **D.E. Soto-Sanchez, T.C. Green and M.M.C. Merlin**, "DC Network Active Filtering using VSC", PCT/EP2011/060907, (29th June 2011).

E5 Director of Asset Management, UK Power Networks. Letter stating the impact of Strbac's work on investment costs for network reinforcement in the London, South East and Eastern England distribution licence areas.

E6 http://www.bboxx.co.uk/our_story.php . Archived on 23/10/2013 at https://www.imperial.ac.uk/ref/webarchive/d1f,