RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date:	1 January 2015
Project completion date:	31 December 2019

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1. Project Title: Sustainable Power Delivery Structures for High Renewables

2. Names and Academic Affiliations of Project Team Members#

Project Team	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the current reporting period
Project Coordinator	Professor David J. HILL/ Chair Electrical Eng (Leader Future Networks Team)	Dept EEE/HKU	15
(Co)-Principal Investigator(s)	Professor Ron S.Y.HUI/ Chair Power Electronics (Leader Smart Loads Team)	Dept EEE/HKU	7.5
	Professor Victor O.K. LI/ Chair Info Eng and Head	Dept EEE/HKU	5

	~~EEE~~ (Leader Information Networks Team)		
	Professor Li QIU/ (Leader Grid Control Team)	Dept ECE/HKUST	7.5
	Siew Chong TAN/ Associate Professor (Power Electronics, Microgrid Lab Development) #	Dept EEE/HKU	7.5
Co-investigator(s)	Shing Chow CHAN/ Professor (Signal Processing)	Dept EEE/HKU	7.5
	Kwok Tong CHAU/ Professor (Electric Vehicles)	Dept EEE/HKU	5
	Graziano CHESI/ Associate Professor (Control)	Dept EEE/HKU	5
	Yik Chung WU/ Associate Professor (Signal Processing)	Dept EEE/HKU	5
	Jin ZHONG/ Associate Professor (Power Networks)	Dept EEE/HKU	5
	Chi Kwan LEE/ Assistant Professor (Power Electronics)	Dept EEE/HKU	7.5
	Ka Cheong LEUNG/ Assistant Professor (Information Networks)	Dept EEE/HKU	5
	Yunhe HOU/ Assistant Professor (Power Networks)	Dept EEE/HKU	5
	Hayden K.H. SO/ Assistant Professor	Dept EEE/HKU	5

	(Distributed Computing)		
	Zhao XU/ Associate Professor (Power Networks)	Dept EE/PolyU	5
	Ling SHI/ Assistant Professor (Control)	Dept ECE/HKUST	5
	Danilo MANDIC/ Professor Signal Processing	Dept EEE/Imperial College London	5
	Thomas PARASINI/ Chair Industrial Control	Dept EEE/Imperial College London	5
	Balarko CHAUHDURI/ Senior Lecturer (Power Networks)	Dept EEE/Imperial College London	5
	Zhaoyang DONG/ Professor (Power Eng)	School EIE/USydney	2.5
	Jin MA/ Senior Lecturer (Power Networks)	School EIE/USydney	5
Collaborators			

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

\# The RGC has approved on 20th March 2017 to change the role of Dr S.C.Tan from Co-Investigator to Co-Principal Investigator.

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	**Percentage achieved**	**Remarks****
1. Develop an integrated approach based on all four key technical areas, including a novel ‘demand response’ *balancing paradigm* that implements the demand	100% +	This was an early emphasis with ongoing refinement over the remainder of the project. Results at HKU (modelling, scheduling) and HKUST (balancing) have

Objectives*	Percentage achieved	Remarks**
following generation (DFG) paradigm for real-time balancing of power generation and demand		established the foundations for static power balancing. The later work dealt with more dynamic aspects related to use of storage and demand-side control. New research directions have emerged in terms of 1) data-based and AI methods, 2) solving the so–called energy trilemma (emissions, prices, security).
2. Develop power electronic based *electric springs* into universal type smart load controllers, which locally achieve contributions to basic balancing (including a storage facility) and stability (frequency and voltage)	100%	This and #3 are the largest parts of the project. Great progress has been made on new versions (circuit topologies such as back-to-back converter topology and control methods such as a new controller for multiple ES functions) of electric springs and their implementation in AC and DC microgrids as an emerging fast demand response (DR) technology. Integrating droop and distributed control of ESs has been implemented successfully. A breakthrough in integrating PV panel and ES has been achieved. We have extended the research to cover cybersecurity of distributed power electronics equipment. Collaborations with the China Southern Power Grid on the control of ES have been successful with hardware built and installed in China for evaluation. Now State-Grid (the largest power company in China) and many universities have joined in ES research.
3. Integrate decision and control and information and communication strategies to study distributed *control algorithms* that can achieve the higher functions of the sustainable smart grid including self-healing, reduced peak	100%	Many algorithms have been established for distributed control structures related to frequency, voltage and stability control using DR and storage. The key concept of granulated control across three nominal has been achieved. Progress has been

Objectives*	Percentage achieved	Remarks**
demand and improved security with optimised wide-area communication and sensor networks		made on several specific tools needed, e.g. partitioning, structural analysis, and specific structures. The idea of networked microgrid systems (NMS) was developed as a future grid architecture and studied for balancing and frequency control. Distributed control schemes have deployed groups of ESs, implemented in hardware to demonstrate that the use of ES can facilitate a range of benefits in control, self-healing, reduced peak demand and resilience. This aspect of our research has further been extended to study the potential threats of cyber-attacks and counter-measures.
4. Integrate the outcomes of the above steps to incorporate further requirements on improving the *energy efficiency and reliability* of power system operation, including the needs for Hong Kong delivery to high buildings, islands and an interconnection to a large changing grid	100%	This and #5 were planned to be emphasised in later years of the project. The planned work has been done towards efficiency (loss minimization), security (restoration, cyber-physical) and reliability (resilience) in terms of the system structures. Several novel control strategies enabling voltage and frequency load sharing control by wind energy systems to support secure grid operation have been developed. Advanced planning algorithms to enhance secure and economic power system operation and expansion with solar energy and EVs were also achieved. New research directions have also emerged here in terms of data-based and AI methods. The HK buildings direction was addressed in routing and scheduling of mobile power sources and supplemented by opportunities with utilities in Guangdong (ES, granular control for high renewables).
5. Further enabling increased *consumer participation* in power system operation with various financial considerations, i.e.	100%	New methods have been made on load monitoring and analytics to assess customer DR capability and methods for customers to participate in DR and storage

Objectives*	**Percentage achieved**	**Remarks****
price-based mechanisms, reduced power prices, alongside the control-based mechanisms		control (including EVs). A novel distributed transactive energy trading framework was developed to facilitate local demand and DG balance at distribution grid level through dispersed market mechanism. Again data-based analytics emerged as a powerful tool with further possibilities than originally planned; and these mechanisms engage the energy trilemma – see #1 above. For instance, some work was done to integrate transactive energy into the bulk power market.
6. Establish a regional *research and educational hub* in energy harvesting and sustainable grid technology for university, industry and governments.	100%	The main focus initially was to build the proposed microgrid facility with associated software as a basic facility for establishing the hub. The facility as proposed has been fully operational since late 2016 with some ongoing enhancements to accommodate new ideas in microgrids; it is planned to continue further development separately after completion of the TbRS – see a report at Attachment 5.

+ *Percentages refer to progress relative to the original proposal; in some areas the work has progressed to new ideas as will be elaborated in Section 6.*

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

****** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list <u>*five or more*</u> *of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))*

The research carried out during 2015-2019 has been described over five progress reports, the last being submitted in 2019. Here the research highlights will be presented for the whole project as seven topics with one representative research output and discussion of impacts, collaboration and recognition.

The research was managed around four teams, namely *future networks* (FNT), smart loads (SLT), *information networks* (INT) and *grid control* (GCT) plus the development of a *microgrid laboratory*. The work in the smart loads area drew upon the high international level of power <u>electronics</u> at HKU. The remaining topics had a <u>systems and control</u> engineering style over all the partners. In the following a general description of the work undertaken in each team will lead to the selected highlight accomplishments.

Future Networks

The primary line of work aimed at implementing the proposed granular control concept. Briefly, granular control aims to implement distributed control sharing seamlessly across power levels as well as widely in a large network. The use of energy storage, demand-side control in distributed control structures implemented with appropriate communications offers ways to make the whole system operate effectively and reliably despite more variable generation sources. Several control situations were considered for balancing, voltage control, frequency control, security control with high renewables and usually with one aim to extend the granularity, where three levels is a natural aim. We first achieved three levels for frequency control. Towards the end of the project attention turned to a novel approach in the new area of networked microgrids. Further results dealt with newer priorities of system restoration, flexibility and resilience in grids with high renewables and storage including from EVs.

Another line of work used data-based approaches, with data from smart meters and PMUs in particular, to carry out state estimation, load monitoring and demand-response. Several projects used applications of optimization, game theory, economic mechanisms and control for placement, sizing and control of energy storage (related to fixed, mobile and EV-based storage) and demand response. These were carried out in collaboration with Co-Is based in the INT as well as Sydney University.

Selected highlights

1. Microgrid stability

Item: Y. Song, D.J. Hill, T. Liu, "Impact of DG connection topology on the stability of inverter-based microgrids," *IEEE Trans. Power Systems*, vol. 34, pp. 3970-3972, 2019. (Jp_FNT_song3_19)

This paper represents the value of the new subject of *power network science (PNS),* which is an outcome of the TRS project. It shows how grid structures that are standard in the traditional systems are not suitable for systems with high renewables and smart loads and control. PNS is inspired by network science emerging from physics and biology, but papers from the latter discussing power systems do not use models which even feature basic power flows. We have a series of papers which develop the subject for power networks. When this result was announced in the invited lecture by PC Hill at Cambridge University, May 2019 and in a major plenary talk, PowerTech, Milan 2019, it was greeted as sensational, i.e. the standard distribution structures could easily be unstable when used with proposed smart loads.

But it is one example of our approach giving very novel results. Another is the first distributed stability assessment approach for any kind of power network, in this case for microgrids (Jp_FNT_song2_17). The subject PNS was introduced in another major invited plenary talk, MTNS 2018. A recent monograph, Song et al., 2020 (Ja_FNT_song_20), which was invited by Prof Marija Ilic of MIT, has shown the subject developed more fully for angle stability. Prof Ilic has also invited the PC to be her co-editor for a major survey of the research needs for power grids looking decades ahead. She has openly said that our network-based approach is one of the most powerful developments in power grids research.

2. Demand-side control

Item: T. Liu, D.J. Hill, C. Zhang, "Non-disruptive load-side control for frequency regulation in power systems," *IEEE Trans. on Smart Grid*, vol. 7, pp. 2142-2153. (Jp_FNT_liu_16)

Distributed/granulated control was one of the three main technologies proposed. The trend away from large power plants to distributed energy resources (DER) requires the development of algorithms to coordinate large numbers of these devices including smart loads, demand-response actions, energy storage units (including EV charging).

This paper in the premier journal related to the TRS systems aspects (as distinct from electronic equipment aspects) laid a theoretical foundation for using demand-side control in a way that acts quickly to solve frequency deviations, but restores the load precisely and efficiently. The problem had been posed in a survey by Calloway and Hiskens from UC Berkeley and U Michigan respectively. This paper represents many that were written in the TRS project on distributed and granular control to manage frequency and voltages in high renewable grids. Some included the use of electric springs as the demand-side controls in collaboration between the FNT and SLT, such as Zheng et al., 2017 (Jp_FNT_zheng1_17). For the control of a multiple ESs, consensus control has been deployed in computer simulation studies with clear success.

3. Advanced inertia control of wind turbines

Item: Y.J. Li, Z. Xu, K.P. Wong , "Advanced control strategies of PMSG-based wind turbines for system inertia support," IEEE Trans. on Power Systems, vol. 32, pp. 3027-3037, 2018 (Jp_FNT_li3_17)

High penetration of power electronics-interfaced renewables such as solar PV and wind energy systems with little or zero inertia imposes great challenges for future power grids. In particular, with respect to how to stabilize system frequency under significantly reduced system inertia is a key issue to solve.

This SCI highly cited paper represents the latest advance on novel control strategies enabling inertia support by wind turbine systems to resolve the challenges facing future power grids. Without the frequency control through curtailing energy harvesting like in for example the traditional delta control scheme, the proposed control strategies innovatively utilize the dc-link capacitor energy and rotor kinetic energy for system frequency support while simultaneously harvesting wind energy as much as possible. Since its publication, this work received wide attention with total citation reaching at 91 by Dec 2020 per Web of Science.

Smart Loads

The TRS proposal featured smart loads, and Electric Springs (ES) in particular, as one of the three main basic technologies proposed initially after an early version had been developed. The project started with further types of ESs (namely version ES-1 that provides only reaction power compensation and version ES-2 that provides both active and reactive power compensation). New developments included both new circuit topologies such as the back-to-back ES (B2B-ES) and new control methods (such as the radial-cordal decomposition and d-q decoupled methods). Research on ES in both AC and DC power grids was carried out to test fast demand response technology.

For AC power grids, we have successfully developed 4 types of ES circuit topologies. Two new additions include: (i) the back-to-back converter topology (version B2B-ES) and (ii) a grid-connected bi-directional power inverter with a new battery management strategy (version ES-3). A Radial-Chordal Decomposition Control Method has been developed and successfully implemented for ES-1, ES-2 and B2B-ES. Several new functions of ES such as power balancing, reduction of energy storage and power quality improvement have been evaluated and confirmed. Practical implementation of the consensus control for a group of 5 ESs is underway for stabilizing mains voltage and frequency for AC power grid with intermittent renewable power generation. Further research involved the study of using multiple ESs in power systems through computer simulation, instantaneous detection methods for fundamental and harmonics, and mains frequency variations.

For DC power grid, we have practical confirmation of the ES concept in stabilizing DC microgrid with intermittent renewable power generation such as photovoltaic systems. Besides being able to reduce DC voltage fluctuation, the ES has the ability to reduce energy storage requirements.

The research in the SLT featured a strong collaboration with Co-Is at Imperial College London and made use of the microgrid laboratory developed within the project. For deployment of ES in control structures, there was collaboration with the other teams.

Selected highlights

4. Electric springs
   Item: Lee et al., "Electric spring and smart load: technology, system-level impact and opportunities," to appear *IEEE Journal of Emerging and Selected Topics in Power Electronics"* (online version) (Ja_SLT_lee_20)

The TRS proposal was based partly on a promising idea of electric springs as a smart load concept. Over the course of the project we developed this into a key component of the smart grid for high renewables in numerous publications. This invited survey reviews the whole development undertaken in the TRS project including the abovementioned more powerful versions of the ES and how they are used in distributed control strategies for different grid structures. As such it refers to most of the papers listed here that include the ES.

5. Microgrid storage
   Item: M.H. Wang, S.C. Tan, C.K. Lee, S.Y.R. Hui, "A configuration of storage system for DC microgrids," *IEEE Trans. on Power Electronics*, vol. 33, pp. 3722-3733, 2018. (Jp_SLT_wang1_18)

A major question with high renewables in all grids is how much storage capacity and/or demand-response capability is required to buffer the difference between the intermittent power generation and the load demand.

This paper represents a line of work which addressed this question for microgrids in both FNT and SLT. Microgrids have special characteristics and requirements which demand special attention. For a DC microgrid, a novel configuration comprising substantial PV panels, a series DC ES and non-critical loads is proposed to reduce the battery storage capacity. The optimized savings are experimentally tested on an isolated DC grid and by simulations for a grid-connected microgrid.

6. Microgrid laboratory
   Item: The laboratory, its control room and special equipment

A report as submitted for the fifth progress statement is attached again to show how the facility was and still is being developed and used for research into microgrids.

The full facility consists of two laboratories for software and hardware, used by all the teams, but the latter represents the specific chosen outcome being based on new power electronic devices and advanced real-time simulation facilities. In brief this facility was developed largely by the SLT, but enabled testing of ideas and algorithms from across the TRS project.

Information Networks

The INT brought expertise in communication networks into looking at new ways to control power flow. Numerous papers in the literature had dealt with EV charging, where experiences from telecommunications gives ideas to use. However, typically these works avoided consideration of the actual power grid.

The TRS research established analytical principles for the new developments of power flow routers, which brought Internet router ideas to energy flow in the power grid.

In addition, the abovementioned work on data analytics for on-line stability assessment was a collaboration between the FNT and INT. Further, the novel concept of a vehicular energy network was developed whereby, vehicles with energy storage and wireless charging could act to shift energy.

Selected highlight

7. Power flow routers
   Item: J. Lin, V.O.K. Li, K.C. Leung, A.Y.S. Lam, "Optimal power flow with power flow routers," *IEEE Trans. on Power Systems*, vol. 32, pp. 531-543, 2017. (Jp_INT_lin_17)

The power flow router (PFR) is motivated by the routers used for the Internet, which more flexibly control flows than is possible in conventional power flow and grid control. With variable sources of power, greater flexibility has become a focus topic to allow power flows to loads as the power generation shifts to different parts of the grid. The PFR emerged in this project as a concept which can add much greater control flexibility. Work on further development has continued after the TRS project finished.

Grid Control

The aim in the GCT was developing basic control methodology needed for the power system goals. As such new approaches for undertaken on a number of fundamental questions related to distributed control, demand-side management, network-based approaches and cyber-physical systems security, sensor scheduling, and change detection.

The work on network-based approaches to system dynamics has led to collaboration with the FNT.

Selected highlight

8. Differentiated energy services
Item: Y. Mo, W. Chen, L. Qiu, P. Varaiya, "Market implementation of multiple-arrival multiple-deadline differentiated energy services," *Automatica*, vol. 116, pp. 1-8, 2020. (Jp_GCT_mo_20)

In systems with high renewable power sources, the supply and demand balance of power becomes much more difficult being dependent on weather and human behaviour respectiveley. This paper takes a fundamental approach to leveraging flexibilities in demand. The TRS proposal introduced a *demand following generation* paradigm which has been explored in the ES deployed in control processes. Here the setting is electricity markets which provide the basic balancing. In the demand response, it is assumed different levels of flexibility in terms of duration, arrival time or later deadline or differentiated electricity services. Results show competitive equilibrium and maximum social welfare in a distributed manner. The work formed part of a collaboration with the University of California, Berkeley.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

The funding enabled a world-class integrated research program in the areas of smart loads and smart grids which facilitates the higher level goal of sustainable electrical power delivery. With high levels of renewable power the previous paradigm of *generation following demand* needs to be complemented by one of *demand following generation.* The published papers, including highlight items demonstrate that substantial progress was made in this goal via the development of distributed control, electric springs and demand response.

In the course of the project, new basic ideas emerged that add to those initially proposed. These included the much greater used of machine learning and data-based approaches in analysis. And a further flexibility of *network following* in the sense adaptively reconfiguring the grid emerged as a powerful mechanism. In the power electronic developments the role of wireless power transfer in creating novel sensing was explored.

Such a wholistic and novel program of research would not be possible with small GRF or CRF programs. This relates to the dynamic exchange of ideas amongst a team of students and researchers who all have a shared sense of the goals that have been promised in the TRS proposal.

6.3 If the project has not met its original objectives, why?

As discussed above, the goals of the project have all been met. Moreover, some new areas of investigation were opened up.

6.4 (a) Peer-reviewed journal publication(s) arising directly from this project:

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference. Please mark the symbol "#" next to the publications involving inter-institutional collaborations)

Please refer to Attachment 1 for the list of 197 journal publications for the whole project, appeared and accepted, in the required tabular format. Only pdfs are given where they have not been submitted previously in a final version, i.e. given as an online version, or are new publications since the last report. For the convenience of the RGC, a further table is given of the numbers of journal publications across all stages. The pdfs are accordingly in two groups: 2015 papers previously not submitted as final versions and recent papers for 2018-2020.

(b) Recognised international conference(s) in which paper(s) related to this project was/were delivered:

(Please attach a copy of each conference abstract)

Please refer to Attachment 1 for the list of 89 conference publications for the whole project, in the required tabular format. For the convenience of the RGC, a further table is given of the numbers of conference publications across all stages.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

NA

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

Within the TRS project, the main collaborations were active as evidenced by joint publications:

- HKU-HKUST- PolyU collaboration through project meetings and workshops
- HKU- Imperial College (led by Prof Hui)
- HKU- Sydney University (led by Prof Hill)

The PC Hill regularly visits Sydney and has visited Imperial College several times, while Co-PI Hui regularly visits Imperial College – see Progress Reports for lists of meetings.

Considering journal papers in Section 6.4(a) all collaborations can be seen as follows:

- Inter-team papers 17
- With Imperial College London 18
- With Sydney University 12
- With Universities in Mainland China 62

- With Universities in other countries 59, including US, Singapore, Sweden, Australia, Denmark, UK, Italy, Germany, Iran, Canada, Netherlands, Ireland

The key researchers have numerous active collaborations external to the project. The stronger connections for the Co-PIs are as follows:

- PC Hill with Tsinghua University, where the EE department has some of the world's leading research in power systems; three of their PhD graduates served as SRAs in the TRS project;
- Co-PI Qiu with several universities in the USA (UC Berkeley, UIUC, Louisiana SU, Stony Brook U, U Minnesota, Georgia IT, KTH Stockholm, Tongji U, Brunel U)

Students and postdocs from the project have so far gone to positions in China (SUSTech), the USA (U Michigan, U California) and Canada (U Waterloo).

6.6 Research students trained (registration/awards):

Graduated students in report period – 49

For details see Attachment 2; numbers refer to HK universities.

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

As stated above, the project was always reaching into future technologies for the electricity industry. This industry is notably conservative especially where, as in Hong Kong, the existing paradigm is not causing any major pressures like massive price rises (as in Australia), rejection of certain generation (as for nuclear in Germany) or policy decisions (as for greater self-reliance as in Denmark) that force consideration of the high renewable alternative. Also while firmed renewables are competitive for cost and reliability, the transition can only proceed with stages plant retirements. Nevertheless, we can claim that the ES technology has reached the stage of practical evaluation by the power industry. In particular, China Southern Power Grid has built the hardware for an internal trial of electric spring smart loads.

Similarly, opportunities are being explored for the control technologies developed in the project, but the last year of COVID restrictions and associated cost-cutting in industry has put this on hold.

6.8 Other education activities and/or training programmes developed:

The main educational activity was the training of research students.
The microgrid facility is available for advanced undergraduate and masters level projects.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

None

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

The project management as described in the first and second reports was used throughout the project. The management structure was based around an Executive Committee consisting of the PC, as the Chair, and Co-PIs who were also research team and laboratory facility leaders.

The research was managed around four teams, namely *future networks* (FNT), smart loads (SLT), *information networks* (INT) and *grid control* (GCT) plus the development of a *microgrid laboratory*. The EC provided overall management and coordinated research leadership towards achievement of the goals. The EC formulated policy, oversaw appointments of staff and approved all projects. Committee meetings were held regularly plus informal contact by e-mail on a daily basis.

Given that this project was aimed beyond the current business models of utilities so it was decided that their role was better in the Advisary Board. The project was driven by high level academics, who have a sense of what structures can look like over decades. Thus, the EC could function as a small (just five people) group who can keep the project focused on research activities.

The next point to make is that the money was definitely not divided up between teams who were left then able to operate semi-autonomously. There was a prior agreement on some SRA's in the key areas, and HKU provided funds for two RAP positions who should work with the TRS goals. These were appointed to the FNT/GCT teams and INT respectively.

Finally, the Co-Is had been selected for their capability to help achieve Goals, but a major role of the EC was to approve all appointments and discuss how they will contribute across the integrated research plan. After presentations by the PC, the Co-Is were invited every year to make bids for funding or co-funding projects. This process and regular Workshops were seen as the major tools to ensure that researchers stay on an approved plan.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

Several Hong Kong RGC GRF grants and one Australian grant with University of Sydney (as partner investigator) have pursued more specific aspects arising from the TRS work as follows:

2019 Hong Kong RGC GRF, *Planning questions for future grids*, HK$673,470

(D.J.Hill, Y.Hou and J.Ma)

Hong Kong RGC GRF, *Hierarchical and distributed control of networked microgrid systems,* HK$673,470 (T.Liu, D.J.Hill and Y.Hou)

2018 Hong Kong RGC GRF, *Stability issues for microgrids,* HK$495,086 (D.J.Hill, G.Chesi and T.Liu)

2017 Hong Kong RGC GRF, *New analytical issues in power grid voltage stability,* HK$600,000 (D.J.Hill)

Australian Research Council Discovery Project DP180103217

Power system security assessment given massive intermittent energy sources

A$402,934.00 (as PI with Z-Y Dong, Guo Chen and D.J.Hill)

2016 Hong Kong RGC GRF, *Fully responsive and non-disruptive load-based frequency control* HK$675,647 (T.Liu and D.J.Hill)

Hong Kong RGC GRF, *Real-time power balancing in electrical grids with vehicle-to-grid technology,* HK$675,647 (K.C.Leung, D.J.Hill, V.O.K.Li and S.Low)

Other funding has come from the Mainland China:

- A 1.2 Million RMB agreement has been signed between HKU led by Co-PI Hui and the China Southern Power Grid (CSPG) to build high-power Electric Spring prototypes for site tests in South China – see Attachment 2 for more details.
- PC Hill and Co-I Zhong have won a Key R&D Project "Energy Internet" of China State Science and Technology Department, awarded RMB 25M with China EPRI and Mainland China universities led by Xi'an Jiaotong, including Tsinghua, Northeastern and the Chinese Academy of Sciences (about RMB 3.75M for HKU)

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

See Attachment 3 for a list of invited talks.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

See Attachment 4 for leadership positions.

7.4 Any documentary proof of the application of technologies arising directly from this project?

Nil

7.5 Other awards and recognitions as a result of this project (please specify):

- D. J. Hill was elected to the Hong Kong Academy of Engineering Sciences (HKAES) in 2017. (The Co-PIs now have a total of 2 FHKEng, 1 FREng, 2 FTSE, 1 FAA in HK, UK and Australian academies).
- Z. Xu received 2017 the First Class State Natural Science Award (SNSA) (the sole one in smart grid area in 2017), in the Higher Education Outstanding Scientific Research Output Awards from the Ministry of Education, PR China.
- PhD student Xu Xu (supervised by Z. Xu) received The (only) Best Student Paper Award, IEEE Innovative Smart Grid Technology Conference (IEEE ISGT Asia), Singapore, May, 2018

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8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

A detailed statement was attached to the Stage 4 report. An updated summary aligned with the expected impacts stated in the Stage 2 report is as follows:

1. The Energy Systems group at HKU consisting of Power Electronics led by Co-PI Hui, Power Systems led by PC Hill and Electric Vehicles led by Co-I Chau has been assessed last year by the Faculty of Engineering as one of the five best groups of its kind in the world; the two TbRS projects, one led by Hui (R2) and this one by Hill (R4), have clearly been a major factor in achieving this recognition as “a world leader in innovative…technologies”.
2. The TbRS R4 project team is currently involved in five substantial follow-on projects in Mainland China with several more pending; these relate to commercial deployment of electric spring technology, wind power integration, advanced control and microgrids.
3. The aim to “play a major long-term role in helping China overcome its heavy pollution problems… climate change” is hard to assess at this stage but certainly all the above-mentioned projects make a contribution.
4. The “specific technologies” of ES and distributed control have advanced to trials aimed at further development in Mainland China; power flow routers are part of a pending project.
5. The “microgrid facility…resource” is already an important resource for research on AC and DC microgrids and is close to being used in advanced teaching so giving a special resource for HK.

In addition it can be mentioned that the TbRS teams receive frequent invitations to speak at conferences and workshops all based on the research supported by the TbRS. For instance PC Hill has been invited just this report year 2018-19 to speak at panels and workshops and to give keynote addresses at international conferences including: two workshops in the series Mathematics of Energy Systems, Isaac Newton Institute for Mathematical Sciences, Cambridge, UK; the Applied Energy “A+B” Conference, MIT, USA; an invited panel at IEEE PES General Meeting, Atlanta, USA and plenary speeches at MTNS2018, Hong Kong; PSCC, Dublin, 2018; and PowerTech, Milan, 2019 all on aspects of power grids related to the TbRS work.

8.2 Others (please specify):

Nil

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

As stated above several new lines of research which were not a part of the original proposal emerged including: 1) power network science for dynamic behaviour; 2) data-based and machine learning approaches; 3) energy harvesting and wireless power transfer; 4) power flow router.

9.2 Whether there are new projects evolved directly from this project?

The main follow-up was towards applied projects in Southern China where the development of renewable power is far more advanced than in Hong Kong. These projects face considerable administrative hurdles and have not yet reached establishment.

Professor Hui subsequently won another TRS project in wireless power transfer which had been studied in the TRS for some applications in smart grid technology.

9.3 Whether there are new collaborations developed directly from this project?

Numerous more minor connections were established in the reporting of results at meetings, e.g. people interested in our results, but the main ones for that underpinned actual joint research were already in place. Nevertheless, connections like that between Prof Hill and Tsinghua University became much stronger.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

The grants mentioned in 7.1 enabled the pursuit of topics that arose from the TRS work but are of the offshoot type.

Prof Hill is retiring from HKU in 2020 due to meeting HKU age limits, so has not applied for further funding to pursue the TRS work. Opportunities are being pursued in Australia where recently the uptake of renewables at all levels in the grid has become the fastest rate in the world.

Professors Victor Li and Ron Hui have each won new TRS projects as PC in somewhat different areas of environmental air quality monitoring and wireless power transfer respectively. These have some methodological connections to the TRS R 4 project but only in a very general sense.

The main mechanism for the work of the TRS to continue will be in the hands of younger faculty, researchers and students who have been involved in the TRS work. They will apply for their own GRF grants, projects in China.

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	196	89	1	4		

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons
None	

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

For a power network of any kind, low or high voltage, to operate with high levels of renewable power we cannot operate at a fixed frequency as previously where generation was controllable, i.e. whatever load power arose, the generation could be adjusted to get instantaneous balance and keep the frequency regulated. This is similar to how the power from a car engine must balance the friction powers in order to hold a set speed in cruise control mode. Imagine if the throttle produced a variable setting in your car? In a power system fortunately, we have ways to keep a balance by creating a buffer between the variable generation and the load power. This is achieved by using load variation or demand-response and extracting power from energy storage. Demand-response can be shared across all loads and so each will not notice any change if it is small and/or fast enough, e.g. a small change of set-point in an air-conditioning unit or a small delay in EV charging. Energy storage allows us to retrieve some energy at a set power level when the load is higher than generation and store some energy when the generation is higher. Further to these mechanisms, network reconfiguration can be useful to help shift power flows in favourable ways.

In order to achieve all this flexibility we use power electronic devices, special communications between equipment and optimization and control algorithms. This project has featured a special power electronic device called the electric spring. An electric spring attached to each non-critical load automatically enables the overall load demand to be shared in such a way that balance is achieved. This provides a demand-response mechanism. An analogy is given by how a set of mechanical springs, e.g. in a mattress, can hold up a large object by individually adjusting the extensions via Hooke’s Law. The balancing of powers by using demand-response, storage and reconfiguration requires careful coordination and control.

The contributions of the project have been in general terms:

- Computer algorithms for balancing the variable power generated and demand powers
- Many fundamental results on the capability and stability of power networks in terms of their structure and parameters
- Computer algorithms for allowing integration of various sorts of renewable power such as solar PV, on/off shore windpower
- Computer algorithms for assessing and improving the stability, reliability and resilience of power systems from smart grid data
- Power electronic devices for making smart loads that can adjust for balancing and help with frequency and voltage control