CRF 8G (Revised Dec 08)

RGC Reference HKU10/CRF/10
please insert ref. above

The Research Grants Council of Hong Kong
Collaborative Research Fund Group Research Projects
Completion Report

(*for completed projects only*)

Part A: The Project and Investigator(s)

1. Project Title

Smart Grid 智能電網

2. Investigator(s) and Academic Department/Units Involved

Research Team	Name/Post	Unit/Department/Institution
Project Coordinator	Victor O. K. Li Chair Professor	EEE/HKU
Co-investigator(s)	Felix Wu Emeritus Professor	EEE/HKU
	Xiren Cao Chair Professor	ECE/HKUST and Shanghai Jiaotong University
	S. Y. R. Hui Chair Professor	EEE/HKU
	Henry Chung Professor	EE/CityU
	Jin Zhong Assoc. Professor	EEE/HKU
	Lucas Hui Assoc. Professor	CS/HKU
	Ling Shi Assist. Professor	ECE/HKUST
Others		

3. Project Duration

	Original	Revised	Date of RGC Approval *(must be quoted*)
Project Start Date	March 1 2011		
Project Completion Date	Feb 28 2014		
Duration (*in month*)	36		
Deadline for Submission of Completion Report	Nov 30 2014		

5. Project Objectives

5.1 Objectives as per original application

1. Integration of information technologies and electric energy delivery technologies to design innovative methodologies to manage and control the electric delivery network.

2. Demonstration of such methodologies and designs in a smart grid testbed.

5.2 Revised objectives

N.A.

6. Research Outcome

6.1 Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

The key objective of this joint project by the University of Hong Kong, the Hong Kong University of Science and Technology, and the City University of Hong Kong is the integration of information technologies and electric energy generation and distribution technologies to design innovative means to manage and control the electricity generation and distribution network. For example, to better control the power grid with dynamic power generation, Phasor Measurement Units (PMUs) may be deployed. These devices sense the currents and voltages in real time, providing data to help the power grid operator better control the system to avoid blackouts and control the transmission system more reliably. However, due to the high costs of PMUs and the limitations of communication facilities, it is impractical to deploy PMUs everywhere on the grid. We have developed optimal PMU placement strategies to minimize the costs. We have also been studying a new concept called "electric springs" which may be used to achieve power balance. Electric appliances with the electric springs embedded can be turned into a new generation of smart loads, with power demands following the power generation. It is envisaged that electric springs, when distributed over the power grid, will offer another power system stability solution. Yet another possibility of accommodating highly volatile renewable generation is an energy storage system. We have developed an optimal control algorithm of a battery system for the grid-connected wind-storage system. Customer participation may also help stabilize the grid. For example, differential pricing encourages customers to consume electricity when demand is low, while demand response allows the grid to reduce supply to selected customers (incentivized with reduced rates) when demand is high. To facilitate such participation, an Advanced Metering Infrastructure (AMI) with real-time two-way communications and a smart meter deployed at each customer premises are required. To counter possible cyber attacks, we must ensure network security and preserve customer privacy. Without proper security, an attacker may generate fake power requests, or even unauthorized control signals in the power grid. We have developed a secure power request scheme. Customer privacy is also important. If a smart meter is compromised, an attacker may determine which household incurs low electricity consumption, thereby inferring which customer is away from home and a target for burglary. We have developed a system in which users' privacy information such as their daily electricity usage patterns are kept secret from third parties as well as from the power operator, while ensuring the power operator will be paid properly. A smart grid testbed has been developed. The physical simulators of wind power, PV panel, and energy storage are set up for the testbed. A real micro-grid with AC loads, DC loads, programmable loads, smart home, and Lithium battery banks are connected to the testbed. Hardware boxes are developed and connected to the wind power and PV simulators to generate random wind and solar data. A central control system has been developed to monitor and control the devices, as well as coordinate the battery charging / discharging with intermittent renewable energy generations. Furthermore, the hardware of frequency-variable power source is developed. This device can be used to connect the testbed with the power grid of the local utility. Research results developed in this project provide the foundations on which further research on smart grid may be built.

6.2 Potential for further development of the research and the proposed course of action
(maximum half a page)

Building on research results developed as part of this project, and drawing on additional expertise from newly recruited staff and from our international collaborators, the team has submitted and successfully won a TBRS project on sustainable power delivery structures for high renewables.

6.3 Research collaboration achieved *(please give details on the achievement and its relevant impact)*

There were various research collaborations. For example, the team led by V.O.K. Li (EEE, expertise in networking protocols), Lucas Hui (CS, expertise in network security), and J. Zhong (EEE, expertise in power systems) has produced several papers addressing the security and privacy issues in smart grid. FF Wu (EEE, expertise in power systems) and R Hui (formerly CityU, now HKU, expertise in power electronics) worked together and invented the "electric spring." There are also international collaboration. For example, the international collaboration between HKU (led by R. Hui) and Imperial College (led by B. Chaudhuri) in electric springs, has resulted in many publications. This particular collaboration exploited the equipment available at Imperial but not yet available in Hong Kong. VOK Li (HKU) and K. Poolla (UC Berkeley) are working together on Phasor Measurement Unit research. Li's PhD student M. Wen is now visiting UC Berkeley on a Fulbright Fellowship, and the team has just submitted a paper entitled, "Phase identification in distribution networks with micro-synchrophasors" for publication. Such collaborations form the foundation on which further research may be built, and is instrumental in the team winning a TBRS project on sustainable power delivery structures for high renewables.

7. The Layman's Summary

(describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)

Concerns with global warming prompted governments throughout the world to pursue policies aiming at increasing renewable energy generation so as to reduce greenhouse gases due to electricity generation with fossil fuels. However, due to the intermittent characteristics of renewable energy sources such as wind and solar, it is a challenge for a system with large renewable generation capacities to implement real-time power balance. Recently, many countries have announced smart grid research programs to re-vitalize their electricity generation and distribution infrastructures using modern technologies such as communication network, sensor network, power electronics, and control technologies to manage the power grid more effectively, and to cope with such complexities as fluctuating energy sources and consumption. The key objective of this proposed project is the integration of information technologies and electric energy generation and distribution technologies to design innovative means to manage and control the electricity generation and distribution network. A novel hybrid simulation laboratory has been built to test our research results in innovative designs for efficient communication, computing and control of smart grids.

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Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research 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.)

The Latest Status of Publications				Author(s) *(denote the corresponding author with an asterisk*)*	Title and Journal/Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of RGC *(Yes or No)*
Year of publication	Year of Acceptance (For paper accepted but not yet published)	Under Review	Under Preparation (optional)					
2012				Hui S.Y.R., Lee C.K. and Wu F.F	Electric Springs—A New Smart Grid Technology, IEEE Trans. on Smart Grid, Vol. 3, No.3, Sept. 2012, pp. 1552-1561.	2012	No	Yes
2012				L. Shi and H. Zhang	Scheduling Two Gauss–Markov Systems: An Optimal Solution for Remote State Estimation Under Bandwidth Constraint, IEEE Trans. on Signal Proc.,Vol. 60, No. 4, Apr 2012, pp. 2038-2042.	2012	No	Yes*
2012				L. Shi and L. Xie	Optimal Sensor Power Scheduling for State Estimation of Gauss–Markov Systems Over a Packet-Dropping Network, IEEE Trans. on Signal Proc.,Vol. 60, No. 5, May 2012, pp. 2701-2705.	2012	No	Yes*
2012				K. Yuen, H. Chung, and V.S.P. Cheung	An Active Low-Loss Motor Terminal Filter for Overvoltage Suppression and Common Mode Current Reduction, IEEE Trans. on Power Elect.,Vol. 27, No. 7, pp. 3158-3172.	2012	No	Yes
2012				T.W. Chim, S.M. Yiu, Lucas C.K. Hui and V.O.K. Li	Privacy-Preserving Advance Power Reservation, IEEE Communications, Vol. 50, Issue 8, pp.18 - 23, August 2012.	2012	No	Yes

2014				K. Yuen and H. Chung	Use of Synchronous Modulation to Recover Energy Gained from Matching Long Cable in Inverter-fed Motor Drives, IEEE Trans. on Power Electronics, vol. 29, no. 2, pp. 883-893, Feb. 2014.		Yes	Yes
	2014			Xi-Ren Cao	Optimization of Average Rewards of Time Nonhomogeneous Markov Chains, IEEE Trans. on Automatic Control		No	Yes
2014				Xi-Ren Cao, De-Xin Wang, and Li Qiu	Partially Observable Markov Decision Processes and Separation Principle, IEEE Trans. on Automatic Control, Vol. 59, 921-936, 2014		Yes	Yes
2014				Li Xia, Qing-Shan Jia, and Xi-Ren Cao	A Tutorial on Event-Based Optimization -- A New Optimization Framework, Discrete Event Dynamic Systems: Theory and Applications, Vol. 24, 103-132, 2014.		Yes	Yes
2013				Yuzhe Li, Daniel E. Quevedo, Vincent Lau and Ling Shi	Optimal Periodic Transmission Power Schedules for Remote Estimation of ARMA Processes, IEEE Trans. on Signal Processing, Vol. 61, No. 24, pp. 6164-6174, 2013.		Yes	Yes
2013				Dongfang Han and Ling Shi	Guaranteed Cost Control of Affine Nonlinear Systems via Partition of Unity Method, Automatica, Volume 49, Issue 2, pp. 660-666, 2013.		Yes	Yes
2013				Lidong He, Dongfang Han, Xiaofang Wang and Ling Shi	Optimal Linear State Estimation over a Packet-dropping Network using Linear Temporal Coding, Automatica, Vol. 49, No. 4, pp. 1075-1082, 2013.		Yes	Yes
	2014			T.W. Chim, S.M. Yiu, V.O.K. Li, L.C.K. Hui and J. Zhong	PRGA: Privacy-preserving Recording & Gateway-assisted Authentication of Power Usage Information for Smart Grid, IEEE Trans. on Dependable and Secure Computing		Yes	Yes
	2014			Yan, S., Tan, S.-C Lee, C.-K.,	Electric Springs for Reducing Power Imbalance in Three-Phase Power Systems, IEEE		Yes	Yes

				Chaudhuri, B., Hui, S.Y.R	Transactions on Power Electronics			
	2014			Luo, X., Akhtar, Z., Lee, C.K., Chaudhuri, B.,Tan, S.-C., Hui, S.Y.R.	Distributed Voltage Control with Electric Springs: Comparison with STATCOM, IEEE Trans. on Smart Grid		Yes	Yes
2014				Chaudhuri, N.R.,Chi Kwan Lee, Chaudhuri, B., Hui, S.Y.R.	Dynamic Modeling of Electric Springs", IEEE Trans.on Smart Grid, Vol. 5, Issue 5, 2014, pp. 2450- 2458.		Yes	Yes
2013				Chi Kwan Lee, Chaudhuri, B., Hui, S.Y.R.,	Droop Control of Distributed Electric Springs for Stabilizing Future Power Grid, IEEE Trans. on Smart Grid, Vol. 4, Issue 3, 2013, pp. 1558- 1566.		Yes	Yes
2013				Lee Chi Kwan, Hui Shu Yuen	Reduction of Energy Storage Requirements in Future Smart Grid Using Electric Springs, IEEE Trans. on Smart Grid, Vol. 4, Issue 3, 2013, pp. 1282- 1288.		Yes	Yes
2013				Tan Siew-Chon g, Lee Chi Kwan, Hui, S.Y.	General Steady-State Analysis and Control Principle of Electric Springs With Active and Reactive Power Compensations", IEEE Trans. on Power Electronics, Vol. 28, Issue 8, 2013, pp. 3958- 3969.		Yes	Yes
2013				Lee Chi Kwan, Chaudhuri, B., Hui Shu Yuen	Hardware and Control Implementation of Electric Springs for Stabilizing Future Smart Grid With Intermittent Renewable Energy Sources, IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 1, Issue 1, 2013, pp. 18- 27.		Yes	Yes
	2014			Lin, J., Leung, K.C., and Li, V.O.K	Optimal scheduling with vehicle-to-grid regulation service, IEEE Internet of Things Journal.		No	Yes
2014				Wen, M.H.F. and Li, V.O.K.	Form follows function: Designing smart grid communication systems using a framework approach, IEEE Power & Energy Magazine, Vol. 12, No. 3,		Yes	Yes

2013				Wen, M.H.F., Xu, J., and Li, V.O.K	May/June 2014, pp. 37 – 43. IEEE Trans. on Power Systems, Vol. 28, No. 4, Nov 2013, pp. 4134 - 4143.		Yes	Yes

*Please note that HKUST has established a different account no. for the HKUST portion, namely, HKUST11/CRF10, and this no. is used in the acknowledgement.

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each conference abstract)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of RGC *(Yes or No)*
June, 2012, Shenyang, China	Minimum Sensor Duty Cycle with Guaranteed Estimator Performance	IEEE International Conference on Information and Automation	2012	No	Yes
Jul. 2012 San Diego, USA	Optimal Incremental Placement of PMUs for Power System Observability	IEEE General Meeting	2012	No	Yes
Jun. 2012 Hong Kong	Optimal Control of battery for Grid-connected Wind-Storage System	IEEE International Conference on Harmonics and Quality of Power	2012	No	Yes
Oct. 2012 Auckland, New Zealand	Frequency Regulation for a Power System with Wind Power and Battery Energy Storage	IEEE PES International Conference on Power Systems Technology	2012	No	Yes
Nov 2012 Tainan, Taiwan	Capacity Management of Vehicle-to-Grid System for Power Regulation Services	IEEE International Conference on Smart Grid Communications	2012	No	Yes
Oct 2011 Brussels, Belgium	PASS: Privacy-preserving Authentication Scheme for Smart Grid Network	IEEE International Conference on Smart Grid Communications	2012	No	Yes
Nov 2011, San Antonio, USA	Credential-based Privacy-preserving Power Request Scheme for Smart Grid Network	IEEE Globecom	2012	No	Yes
Oct 2012 Hong Kong	Selling Power back to the Grid in a Secure and Privacy-preserving manner	International Conference on Information and. Communications Security	2012	No	Yes

Mar 2013 Long Beach, USA	A very low-loss motor overvoltage suppression filter using energy recovery concept	IEEE Applied Power Electronics Conference & Exposition		Yes	Yes
Aug 2014 Cape Town, S. Africa	Sensitivity Analysis to Non-linear Performance with Probability Distortion	IFAC Congress 2014		Yes	Yes
May 2014 Cachan, France	How Does Perturbation Analysis Work in Finance and Economics?	IFAC/IEEE Workshop on Discrete Event Systems		Yes	Yes
Jun 2013 Grenoble, France	A Novel Overcurrent Protection Method based on Wide Area Measurement in Smart Grid	PowerTech 2013		Yes	Yes

Jul 2013 Vancouver, Canada	A Multi-Period Power Flow Model including Battery Energy Storage	IEEE PES General Meeting 2013		Yes	Yes
May 2012 Orlando, Florida, USA	Smart Dispatch of Controllable Loads with High Penetration of Renewables	IEEE/PES Transmission and Distribution Conference and Exposition		Yes	Yes
Apr 2014 Cordoba, Spain	An Optimal Long-Term Generation Expansion Planning considering CO2 Reduction Policies and Mechanisms	International Conference on Renewable Energies and Power Quality		Yes	Yes
Sep 2013 Denver, USA	Use of Hooke's law for stabilizing future smart grid — The electric spring concept	IEEE Energy Conversion Congress and Exposition		Yes	Yes
Jun 2014 Galway, Ireland	Reducing Three-Phase Power Imbalance with Electric Springs	IEEE Conf. on Power Electronics for Distributed Generation Systems		Yes	Yes
Dec 2013 Atlanta, USA	Optimal phasor data concentrator installation for traffic reduction in smart grid	IEEE Globecom		Yes	Yes

	wide-area monitoring systems				
Feb 2013 Washington DC, USA	Optimal PMU placement for wide-area monitoring using Chemical Reaction Optimization	IEEE PES Innovative Smart Grid Technologies Conference		Yes	Yes

10. ***Student(s) trained*** (please attach a copy of the title page of the thesis)

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Xiao Luo	PhD	Sept 2011	
Shuo Yan	PhD	Sept 2012	
Simon Ng, Kwok Kei	PhD		Aug 2012(title page submitted in 2012)
Miles Haofu Wen	PhD	Sept 2011	
Jason Lin	PhD	Sept 2012	
Ching Bon Chan	MPhil	Sept 2011	
Kuen Faat Yuen	PhD	July 1 2009	Apr 1 2014 (title page attached)

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Patent applications

1. Lee C.K., N. Chaudhuri, B. Chaudhuri and S.Y.R. Hui, "Droop-control method for distributed power systems" Patent application UK 1206316.8, filed 10 April 2012 [Joint application between HKU and Imperial College London].
2. Lee C.K. and Hui S.Y.R., "Input AC Voltage Control Bi-Directional Power Converters", US Patent application filed on 01 June 2012, Application No. 61/654,628 [HKU].
3. Zhong, J. et al. "Fast Generation Adjustment Algorithm for an Energy Management System (EMS)," Application number PCT/CN2014/090980.
4. S.Y.R. Hui, C.K. Lee and F.F. Wu, "Power control circuit and method for stabilizing a Power Supply", US Patent Application 13/251823, Oct. 3, 2011.
5. C.K. Lee and S.Y.R. Hui, "Input voltage control bidirectional power converters", US patent application, US2013/0322139, filed 31 May, 2013.

Awards

1. Best Paper Award for the IEEE Conference on Power Electronics for Distributed Generation, Galway, Ireland, June 2014.
2. 2015 IEEE William Newell Power Electronics Award (IEEE Technical Field Award), for Prof. Ron Hui.

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Book

Smart Grid Applications and Developments, ISBN 978-1-4471-6280-3, edited by P. Hills, D. Mah, V.O.K. Li, and R. Balme, Springer, June 30 2014.