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(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Characterization and Control of a System with Multiple Offshore Power Inverters Connected in Parallel with Long Cables
基於長電纜線連接的近岸多逆變器並聯系統的特性分析與控制研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof Henry Shu-hung CHUNG	Prof Weimin WU
Post	Chair Professor	Professor
Unit / Department / Institution	Department of Electrical Engineering, City University	Electrical Engineering, Shanghai Maritime University
Contact Information	eeshc@cityu.edu.hk	wmwu@shmtu.edu.cn
Co-investigator(s) *(with title and institution)*	Prof Marco LISERRE (Kiel University)	Prof Frede BLAABJERG (Aalborg University)

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01-Jan-2016		
Project Completion date	31-Dec-2019		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31-Dec-2020		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Formulate mathematical models that describe the static and dynamic characteristics of a system with multiple inverters connected in parallel via long cables
2. Investigate into a new predictive control scheme for the voltage and current regulation in each inverter that can provide tight steady-state and fast transient response
3. Research on a damper at the point of common coupling to stabilize the power quality of the whole system
4. Study on a fault self-diagnosis for multi-inverters-based distributed power system to reduce the operation and maintenance cost

5.2 Revised Objectives

N.A.

6. Research Outcome

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

A boundary controller using second-order switching surface with direct current tracking capability, reduced number of current sensors, and fixed frequency operation of three-phase three-wire grid-connected inverter [J1] and virtually-grounded three-phase grid-connected inverter [J4] with inductive- capacitive-inductive (LCL) filter has been studied [C1], [C3], [C5]. Such technique can avoid dealing with the challenges caused by the interactions among three independent current regulators. Sensitivities of the system transfer characteristics to the parametric variations have been investigated.

A comprehensive overview on the inverter- and grid-side damping measures has been disseminated in [J2]. Based on the concept of the impedance-based stability analysis, all damping methods can ensure the system stability by modifying the effective output impedance of the inverter or the effective grid impedance. Classical damping methods for industrial applications have been analyzed and compared. Finally, the future trends of the impedance-based stability analysis, as well as some promising damping methods, have been discussed [J7].

In order to study the interactions between inverter and long cable, a preliminary study on inverter drive for motor has been studied. In [J3], a passive overvoltage suppression technique has been developed. The modeling technique of the long

cables is used to study the system stability for multiple offshore inverters connected in parallel with long cables. The results are disseminated in [C2].

A single-phase transformer-less unified power quality conditioner has developed and disseminated in [J5], [C4]. Apart from having no isolation transformer, the proposed structure utilizes four switching devices only, forming two half-bridge voltage-source inverters - one connected in parallel with the load and another one connected in series with the AC mains. The two inverters share the same DC link. A DC-link capacitor voltage balancing control that coordinates the operations of the hysteresis and boundary controllers is designed. Modeling, design, and analysis of the whole system have been investigated. The architecture has been applied for power flow control of large-scale LED lighting networks (Please refer to Sec. 10).

An active grid impedance cancelator using the concept of series active filter to suppress the effect of the grid disturbance and stabilize the single-phase grid-connected inverters with an LCL filter operating under variable grid conditions has also investigated [J6], [C6]. The technique has been further extended to a cancelator for system with multiple inverters [C7].

By using the passivity-based analysis, detailed stability study on the LLCL-filter-based grid-tied inverter has been carried out, when the grid reactance varies in a wide range. Based on the analysis, an exact and robust parameter design of system has been proposed in [J7].

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

The concept proposed in [J6], [C6], and [C7] can be extended. A wideband harmonic voltage cancelator that is used to mitigate the adverse effect of unknown grid impedance and loading condition on the stability of a microgrid connecting with multiple grid-connected inverters can be studied. Such concept is based on the use of a series voltage source inverter to compensate for the harmonic voltage across the equivalent impedance appeared at the point of common coupling, forming a virtually zero impedance path. The bandwidth of the inverter should be wide, ranging from the second harmonic of the AC mains to 8kHz, which is slightly higher than the cut-off frequency of typical grid-connected inverters. Such fast-dynamic characteristic can be achieved by a fixed-frequency predictive control scheme with nonlinear switching surface. The control scheme can reduce the order of the entire system transfer function, thus avoiding resonance caused by the output filter in the cancelator. As the cancelator handles harmonic power only, its volt-ampere (VA) rating is much lower than the power rating of the entire distributed generation system. The research work on this new area can be done in collaboration with industry with the support of the General Research Fund and Innovation and Technology Fund.

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)

An emerging trend in the electricity industry is a paradigm shift from large-scale centralized power plant to small-scale distributed energy resources (DERs). Regardless of DER type, inverters, which convert DC into AC power, are crucial devices for injecting generated energy into the macro-grid. In order to offer a high degree of modularity, scalability, adaptability, maintainability, and autonomic behavior, it is more advantageous to use multiple low-power parallel-connected inverters than a single high-power inverter unit. Due to possible mismatch among the output impedances of inverters, cable impedance, load characteristics, and grid impedance, the entire system could be dynamically unstable. Furthermore, high-order output filters in the inverters exhibit multiple resonant frequencies that would cause output oscillation. An existing remedial measure to alleviate this problem is to apply a passive damper in the power stage or an active damping technique in the controller, but they would cause either extra power loss or limit the system dynamics.

This project aims to enable a breakthrough in multi-parallel-connected inverter technology by investigating 1) interactions among the inverters, cables, loads, and power grid, 2) predictive control algorithms for controlling active and reactive power flow, 3) an active damping technology, and 4) a fault diagnosis technique for DERs.

Part C: Research Output

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

(Please attach a copy of each 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) ***(bold** the authors belonging to the project teams and 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 this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2017				[J1]	[J1]	Yes, 2018	Yes	Yes	Yes
2017				[J2]	[J2]	Yes, 2018	Yes	Yes	Yes
2017				[J3]	[J3]	Yes, 2018	Yes	Yes	Yes
2017				[J4]	[J4]	Yes, 2018	Yes	Yes	Yes
2018				[J5]	[J5]	Yes, 2018	Yes	Yes	Yes
2018				[J6]	[J6]	Yes, 2018	Yes	Yes	Yes
2019				[J7]	[J7]	No	Yes	Yes	Yes

[J1] Y. He, **H. Chung***, C. Ho, and **W. Wu**, "Direct Current Tracking Using Boundary Control with Second-Order Switching Surface for Three-Phase Three-Wire Grid-Connected Inverter," *IEEE Transactions on Power Electronics*, vol. 32, no. 7, pp. 5723-5740, Jul 2017.

[J2] **W. Wu***, L. Yuan, Y. He, **H. Chung**, M. Liserre, and F. Blaabjerg, "Damping Methods of Resonances Caused by LCL-Filter-Based Current-Controlled Grid-tied Power Inverters - an Overview," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 7402-7413, Sept. 2017.

[J3] J. Jiang, **W. Wu***, Y. He, **H. Chung**, and F. Blaabjerg, "A New Passive Filter Design Method for Overvoltage Suppression and Bearing Currents Mitigation in a Long Cable Based PWM Inverter-Fed Motor Drive System," *IEEE Transactions on Power Electronics*, vol. 32, no. 10, pp. 7882-7893, Oct 2017.

[J4] Y. He, **H. Chung***, C. Ho, and **W. Wu**, "Modified Cascaded Boundary-Deadbeat Control for a Virtually-Grounded Three-Phase Grid-Connected Inverter with LCL Filter," *IEEE Transactions on Power Electronics*, vol. 32, no. 10, pp. 8163-8180, Oct 2017.

[J5] V. Cheung, R. Yeung, **H. Chung***, A. Lo, and **W. Wu**, "A Transformer-less Unified Power Quality Conditioner with Fast Dynamic Control," *IEEE Transactions on Power Electronics*, vol. 33, no. 5, pp. 3926-3937, May 2018.

[J6] Y. He, **H. Chung***, C. Lai, X. Zhang, and **W. Wu**, "Active Cancellation of Equivalent Grid Impedance for Improving Stability and Injected Power Quality of Grid-Connected Inverter under Variable Grid Condition," *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9387-9398, Nov. 2018.

[J7] Z. Zhang, **W. Wu***, Z. Shuai, X. Wang, A. Luo, **H. Chung**, and F. Blaabjerg "Principle and Robust Impedance-Based Design of Grid-tied Inverter with LLCL-Filter under Wide Variation of Grid-Reactance," *IEEE Transactions on Power Electronics*, vol. 34, no. 5, pp. 4362-4374, May 2019.

8. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

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 this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Sep/2016/USA	[C1]	[C1]	Yes, 2018	Yes	Yes	Yes
Oct/2017/USA	[C2]	[C2]	Yes, 2018	Yes	Yes	Yes
Oct/2017/USA	[C3]	[C3]	Yes, 2018	Yes	Yes	Yes
Oct/2017/USA	[C4]	[C4]	Yes, 2018	Yes	Yes	Yes
Oct/2017/USA	[C5]	[C5]	Yes, 2018	Yes	Yes	Yes
Mar/2018/USA	[C6]	[C6]	No	Yes	Yes	Yes
Oct/2019/USA	[C7]	[C7]	No	Yes	Yes	Yes

[C1] Y. He, **H. Chung**, N. Ho, **W. Wu**, and W. Fan, "DC Bus Splitting Voltage Feedforward injection Method for Virtually-Grounded Three-Phase Inverter," in *Proc. IEEE Energy Conversion Congress and Exposition*, Milwaukee, WI, USA, Sep 18-22, 2016.

[C2] X. Zhang, **H. Chung**, L. L. Cao, J. Chow and **W. Wu**, "Impedance-based Stability Criterion for Multiple Offshore Inverters Connected in Parallel with Long Cables," in *Proc. IEEE Energy Conversion Congress and Exposition*, Cincinnatti, OH, USA, Oct 1-5, 2017, pp. 3383-3389.

[C3] X. Zhang, **H. Chung**, Y. He, C. Lai and **W. Wu**, "DAH-FF Approach to Improve the Current Quality and Stability of the LCL Type Grid-Connected Inverter," in Proc. IEEE Energy Conversion Congress and Exposition, Cincinnatti, OH, USA, Oct 1-5, 2017, pp. 3390-3397.

[C4] S. Cheung, S. Yeung, **H. Chung**, W. Lo and **W. Wu**, "A Transformer-Less Unified Power Quality Conditioner having Fast Dynamic Control," in Proc. IEEE Energy Conversion Congress and Exposition, Cincinnatti, OH, USA, Oct 1-5, 2017, pp. 2962-2968.

[C5] Y. He, C. Lai, **H. Chung** and **W. Wu**, "Comparative Evaluations on Three High Resolution Sampling Schemes for Digital Boundary Control," in Proc. IEEE Energy Conversion Congress and Exposition, Cincinnatti, OH, USA, Oct 1-5, 2017, pp. 1452-1456.

[C6] Y. He, C. Lai, **H. Chung,** X. Zhang and **W. Wu**, "Use of Series Negative Impedance to Cancel the Effect of Equivalent Grid Impedance on the Grid-Connected Inverter Stability in the DPGS," in *Proc. 2018 IEEE Applied Power Electronics Conference and Exposition*, San Antonio, Texas, Mar. 4-8, 2018, pp. 2368-2373.

[C7] C.T. Lai, **H. Chung**, **W. Wu**, "Series Harmonic Voltage Cancellator for Mitigating Effect of Grid Impedance," *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Baltimore, MD, USA, Sept 29 – Oct 3, 2019, pp. 4447-4454.

9. 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
HE Yuanbin	PhD	Aug 1 2013	Nov 30 2016

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

The team organized a special issue on the topic:

[1] W. Wu, M. Liserre, and H. Chung, Special issue on New Technique Trends for Power Converters in Distributed Power Generation Systems - Part I, *IEEE Transactions on Industrial* Electronics, vol. 64, no. 9, pp. 7399-7401, 2017.

[2] W. Wu, M. Liserre, and H. Chung, Special issue on New Technique Trends for Power Converters in Distributed Power Generation Systems - Part II, *IEEE Transactions on Industrial* Electronics, vol. 65, no. 1, pp. 673-675, 2018.

A patent application, entitled "Transformerless Single-Phase Unified Power Quality Conditioner (UPQC) for Large Scale LED Lighting Networks", *US Patent Application US 2019/0182917 A1*, Jun 13, 2019, has been filed. The work was in collaboration with Prof. Carl Ho of the University of Manitoba. The idea has been applied for large-scaled LED lighting networks in Canada.

The agent for preparing the patent application made a mistake on the inventor list. My name is not on the list. Prof. Ho had already asked the agent to correct it. Please refer to the attached email correspondence.

The idea is based on the concept described in the following articles:

[J5] V. Cheung, R. Yeung, **H. Chung***, A. Lo, and **W. Wu**, "A Transformer-less Unified Power Quality Conditioner with Fast Dynamic Control," *IEEE Transactions on Power Electronics*, vol. 33, no. 5, pp. 3926-3937, May 2018.

[C4] S. Cheung, S. Yeung, **H. Chung**, W. Lo and **W. Wu**, "A Transformer-Less Unified Power Quality Conditioner having Fast Dynamic Control," in Proc. IEEE Energy Conversion Congress and Exposition, Cincinnatti, OH, USA, Oct 1-5, 2017, pp. 2962-2968.