MULTI-STAGE FLEXIBLE EXPANSION CO-PLANNING UNDER UNCERTAINTIES IN A COMBINED ELECTRICITY AND GAS MARKET

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B.E.

M.Sc.

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DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

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June, 2014

To all my family

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My Ph.D. research experience in Australia was like an amazing journey. There were plenty of wonderful and memorable stories along the journey. Every day in the journey was full of happiness, surprise and achievement. This thesis becomes an important milestone in my life, marking the completion of my Ph.D. study journey and the new start of my academic career. I would like to take this precious chance to express my deepest gratitude to those who helped and supported me during my research.

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NOMENCLATURE FOR ABBREVIATIONS

AC	Alternating current
ACP	Annual capital payment
ADLC	Average duration for each load curtailment
AEMO	Australian energy market operator
CDF	Cumulative distribution function
CRF	Capital recovery factor
CS	Compressor station
DC	Direct current
DE	Differential evolution
DG	Distributed generation
DISCOs	Distribution companies
DSM	Demand-side management
EA	Economic adjustment
ECP	Expansion co-planning
EDLC	Expected duration of load curtailment
EEs	Extreme events
EENS	Expected energy not supplied
EFLC	Expected frequency of load curtailment
EIR	Energy index of reliability
EP	Expansion planning
EUE	Expected unserved energy
FACTs	Flexible alternating current transmission system
FADE	Fuzzy adaptive differential evolution
GA	Genetic algorithm
GENCOs	Generation companies
GPG	Gas-fired power generation
HDDE	Historical driven differential evolution
ISO	Independent system operator
KKT	Karush-Kuhn-Tucker
LNG	Liquefied natural gas
LOEE	Loss of energy expectation
LOLC	Loss of load cost
LOLE	Loss of load expectation
LOLP	Loss of load probability
LP	Line-pack
MC	Monte Carlo
MNSP	Market network service provider
MTTF	Mean time to failure
MTTR	Mean time to repair
NERC	North American Electric Reliability Coporation

NEM	National electricity market
NPV	Net present value
NSW	New South Wales
OPF	Optimal power flow
PDF	Probability density function
PLC	Probability of load curtailment
POE	Probability of exceedance
PSO	Particle swam optimization
QLD	Queensland
RRN	Regional reference node
SA	South Australia
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SIS	Sequential importance sampling
STTM	Short-term trading market
TAS	Tasmania
TEP	Transmission expansion planning
ToP	Take-or-pay
TRANSCOs	Transmission companies
UC	Unit commitment
UGS	Underground gas storage
WPFs	Wind power farms
VCR	Value of customer reliability
VIC	Victoria

LIST OF PUBLICATIONS INCLUDED AS PART OF THIS THESIS

The following publications as the major Ph.D. research results of this candidate are included as part of this thesis.

[P1] K. Meng, Z.Y. Dong, Y. Zheng, **J. Qiu** and K. P. Wong, "Optimal allocation of ESS in distribution systems considering wind power uncertainties", *Proc. 2012 the International Conference on Power System Control, Operations and Management (APSCOM),* Hong Kong, Jul. 2012.

[P2] F. J. Luo, Z. Y. Dong, Y. Y. Chen, E. Pozorski, **J. Qiu**, Y. Zheng, Y. Xu and K. Meng, "Constructing the power cloud data centre to deliver multi-layer services for smart grid", *Proc. 2012 APSCOM,* Hong Kong, Jul. 2012.

[P3] **J. Qiu**, Z. Y. Dong, K. Meng, Y. Zheng, Y. Y. Chen and H. Q. Tian "Risk sharing strategy for minimizing imbalance costs of wind power forecast errors", *Proc. 2013 IEEE Power and Energy Society (PES) General Meeting,* Vancouver, Canada, Jul. 2013.

[P4] **J. Qiu**, Z. Y. Dong, G. Chen, H. Q. Tian, Y. Y. Chen, and F. J. Luo, "Expansion co-planning with uncertainties in a coupled energy market", *Australian Universities Power Engineering Conference (AUPEC2013),* Tasmania, accepted to be published.

[P5] H. Q. Tian, Z. Y. Dong, **J. Qiu**, G. Chen, Y. Y. Chen, and W. F. Yao, "A new reliability criterion for energy market expansion planning", *AUPEC 2013,* Tasmania accepted to be published.

[P6] **J. Qiu**, Z. Y. Dong, H. Q. Tian and Y. Zheng, "Apply theories of motivation to project-based power planning entities", *International Conference on Management Innovation and Business Innovation (ICMIBI) 2013,* Singapore, accepted to be published.

[P7] Y. Zheng, Z. Y. Dong, F. J. Luo K. Meng, **J. Qiu** and K. P. Wong “Optimal allocation of energy storage system for risk mitigation of DISCOs with high renewable penetrations,” *IEEE Trans. Power Systems*, vol. 29, no. 1, pp. 212-220, Jan. 2014.

[P8] Y. Zheng, Z. Y. Dong, Y. Xu, K. Meng, J. H. Zhao and **J. Qiu** “Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning,” *IEEE Trans. Power Systems*, vol. 29, no. 1, pp. 221-229, Jan. 2014.

[P9] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, H. Q. Tian and K. P. Wong “Expansion co-planning with uncertainties in a coupled energy market”, accepted by *2014 IEEE PES General Meeting*, Washington D. C., USA, Jul. 2014.

[P10] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and D. Hill, “Expansion planning of integrated gas and power markets in a coupled energy market,” accepted for *submitting full paper to the special issue on low carbon economy on IEEE Trans. Power Systems*, 2014.

[P11] F. J. Luo, J. H. Zhao, **J. Qiu**, J. Foster, Y. Y. Peng and Z. Y. Dong, “Assessing the transmission expansion cost with distributed generation: an Australian case study,” accepted by *IEEE Trans. Smart Grid*, 2014.

In addition, the candidate has submitted ten manuscripts for publication, which are currently under review. These submitted manuscripts are listed below.

[SP1] Fengji Luo, Z.Y. Dong, Y.Y. Chen, K. Meng, **J. Qiu**, J.H. Zhao, Eric Pozorski, and K.P. Wong, “Cloud computing infrastructure for next-generation power system: conception, prospective, and applications, ” *IEEE Trans. Industrial Informatics*, current under 2nd review.

[SP2] Y. Y. Chen, Z. Y. Dong, F. J. Luo, K. Meng, **J. Qiu** and K. P. Wong, “A multi-constrained optimal power flow method with discrete control variables”, *IEEE Trans. Power Systems*, submitted.

[SP3] Y. Y. Chen, Z. Y. Dong, F. J. Luo, K. Meng, **J. Qiu** and K. P. Wong, “A collector system layout optimization model for large-scale offshore wind farms”, *IEEE Trans. Sustainable Energy*, submitted.

[SP4] **J. Qiu**, Z. Y. Dong, J. H. Zhao, Y. Xu and Y. Zheng, “Multi-stage flexible expansion co-planning with uncertainties in a combined electricity and gas market,” *IEEE Trans. Power Systems,* submitted.

[SP5] **J. Qiu**, Z. Y. Dong, K. Meng, F. J. Luo and K. P. Wong “Coordination of transmission and generation capacity planning in a coupled energy market,” *IEEE Trans. Power Systems,* submitted.

[SP6] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “Expansion co-planning considering gas impacts on electricity markets,” *IEEE Trans. Power Systems,* submitted.

[SP7] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and H. Q. Tian “Insurance strategy for minimizing imbalance costs of wind power in real-time markets,” *IEEE Trans. Sustainable Energy,* current under 2nd review.

[SP8] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, F. J. Luo and K. P. Wong “An economic adjustment approach for probabilistic transmission expansion planning,” *IEEE Trans. Power Systems,* submitted.

[SP9] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “Expansion co-planning for shale-gas integration in a combined energy market,” *IEEE Trans. Power Systems,* submitted.

[SP10] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “A linear programming approach for expansion co-planning in energy markets,” *IEEE Trans. Power Systems,* submitted.

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ABSTRACT

Power system planning plays an essential role in maintaining the economic, secure and reliable operations of power systems. Following the deregulation of electricity industry, power system planning encounters many challenges as a result of the advent of various market participants, such as market uncertainties and conflicting objectives. Moreover, due to the growing concerns on climate change around the world, natural gas becomes more economically competitive among traditional fossil fuels, leading to the proliferation of gas-fired power generation (GPG) in the power sector. In a market environment, the access to affordable and reliable gas sources can significantly influence the competitiveness of market participants, and then the power system operations consequently. Therefore, power system planning should integrally take into account the gas infrastructure.

Fuel availability and prices are treated as uncertain inputs in conventional power system planning methods, which usually suffer from inaccurate market signals (e.g. congestion costs) and insufficient knowledge of network weakness. This thesis research focuses on the proposal of an expansion co-planning framework for gas and electricity transmission infrastructure in a combined energy market. The expansion co-planning approach is able to reflect the dynamic, nonlinear and non-convex nature of the integrated gas and electricity systems. In addition to the reliability/security planning criterion, this research aims to enhance the market efficiency of assets through the planning practice, e.g. facilitating competition, alleviating congestion, improving social welfare, minimizing risks, etc.

The proposed expansion co-planning framework can be used to guide the energy industry to form a holistic approach to the strategic planning of future grids including gas and electricity networks, subject to various interacting constraints. It has covered a variety of aspects in planning, including a generalized reliability evaluation method for coupled gas and electricity networks, market timeline mismatch, multi-objectives, tackling interactive constraints, stochastic programming, risk management, energy networks’ vulnerability to extreme events

caused by climate change, and linearization techniques. With regard to planning solution techniques, a range of up-to-date methods have been applied or developed, including differential evolution, decision making analysis with the fuzzy particle swarm optimization, historical driven differential evolution with variance reduction techniques, fuzzy adaptive differential evolution with parallel implementation, linear programming, mixed-integer programming, iterative algorithm, etc.

A number of benchmark test systems have been used to demonstrate the effectiveness of the proposed expansion co-planning approach. Comparative studies to existing approaches in the literature, where applicable, have also been conducted. The real applicability of the proposed approach has been verified by simulation results.