國立臺灣科技大學
電機工程系

**Master Thesis**

Student ID : M10107806

# Modification of Ancillary Market for Consideration of the Wind Power Generation

**Student:** Le Hong Lam

**Advisor:** Dr. Ming-Tse Kuo

**Taipei, 30 June 2014**

[redacted]

M10109606

Thesis Advisor:Ming-Tse Kuo

# 碩士學位論文指導教授推薦書

## Master's Thesis Recommendation Form

Department : Department of Electrical Engineering

Student's Name: Lam Hong Le

Thesis title: MODIFICATION OF ANCILLARY MARKET FOR CONSIDERATION OF THE WIND POWER GENERATION

This is to certify that the thesis submitted by the student named above, has been written under my supervision. I hereby approve this thesis to be applied for examination.

Advisor:Ming-Tse Kuo

Co-advisor:

Advisor's Signature: Ming - Tse Kuo

Date: 2014 / 01 / 30 ( yyyy/mm/dd )

[redacted]
M10107909
Thesis Advisor:Ming-Tse Kuo

# 碩士學位考試委員會審定書

## Qualification Form by Master's Degree Examination Committee

Department:Department of Electrical Engineering

Student's Name:Lam Hong Le

Thesis Title:
MODIFICATION OF ANCILLARY MARKET FOR CONSIDERATION OF THE WIND POWER GENERATION

This is to certify that the dissertation submitted by the student named above, is qualified and approved by the Examination Committee.

Degree Examination Committee

Members' Signatures: Ching-Nan Chu

Cheng-Chien Kuo

Ming-Tse Kuo

Advisor: Ming-Tse Kuo

Program Director's Signature:

Department/Institute Chairman's Signature: Chia-Tai Chen

Date: 2014 / 06 / 30 (yyyy/mm/dd)

# 摘要

現今電力系統面臨的挑戰之一為風力機組大量併入電網，其中需克服風力輸出的不確定性、管理頻率變化、變壓器降變動，與輔助服務市場。現今越來越多風場加入電力輔助服務市場。傳統上參與輔助市場的為傳統發電機組較多，然而越來越多新型風機的出產(雙饋感應發電機DFIG、直接驅動同步發電機DDSG)，使得風場越來越有能力參與電力系統服務市場。本論文基於最佳電力潮流(OPF)、節點邊際價錢(LMP)、實功率損失來計算提高電壓穩定度需支付參與風場多少虛功補償輔助服務價錢。本論文使用Power World實驗軟體來模擬風機(DFIG)與計算節點邊際價錢(LMP)，並使用9-Bus系統來模擬當負載增加時，加入風場輔助服務的好處。

關鍵字：虛功率、節點邊際價錢、最佳電力潮流、風場、輔助服務、Power World。

# Abstract

Rapidly growth of wind power sector present great challenge for power system operator. These challenges include the ability forecasting wind out- put, manage frequency and voltage variability, as well as ancillary market. Nowadays, through different set of control possibility, wind power plants are able to partly participate in provision of ancillary market.

Traditionally, ancillary market is supported by a lot of conventional generators. However, in recently years, with the penetration of new wind generations (Double Fed Induction Generator (DFIG) and Direct Drive Synchronous Generator (DDSG)) and through different set of control possibility, wind power plants are able to partly participate in provision of ancillary market. This thesis study the method to calculate price of reactive power with the purpose support wind farm provide reactive power in order to increase voltage stability for power system based on Optimal Power Flow, Locational Marginal Price and the loss of active power. This study used the Power World Program to simulate wind generator (DFIG) and calculate locational marginal price. 9-Bus_system is used to show the change of benefit of wind generator when the increasing load is applied.

Key world: Reactive power, Locational Marginal Price, Optimal power flow, Wind farm, Ancillary market, Power Word Program.

# ACKNOWLEDGEMENTS

First of all, I would like to sincerely thank my academic advisor, Dr. Ming-Tse Kuo for his valuable comments and enthusiastic supports. Without his patient guidance, this thesis cannot be finished. I also thank him for his very careful reading and insightful suggestions during the writing of this thesis, and his thoughtful guidance during my graduate study.

Special thanks to the members of defense committee for their valuable comments and helpful suggestions on this research.

I am always grateful to my parents, my brothers, for their love, financial supports, and never-ending encouragement during my entire graduate study.

Additionally, my especial gratitude to my advisor's master students, Mr. Wei, Mr. Roger, for their helpful ideas and suggestions on this thesis. I also want to give sincerely thanks to my dear Electrical classmates and my undergraduate friends for their constant support and concern.

Finally, I would like to thank National Taiwan University Science and Technology for giving me the opportunity to study and to develop my philosophy in my research work.

Le Hong Lam

June 30th, 2014

National Taiwan University of Science and Technology, Republic of China

## CONTENTS


摘要 ..... IV

ABSTRACT ..... V

ACKNOWLEDGEMENTS ..... VI

LIST OF FIGURES ..... IX

LIST OF TABLES ..... XI

CHAPTER 1 INTRODUCTION ..... 1

1.1 Research Background and Motivation ..... 1
1.2 Research Objective ..... 2
1.3 Thesis structure ..... 3

CHAPTER 2 LITERATURE REVIEW ..... 4

2.1 Power market and Ancillary market Overview ..... 4
2.2 Locational Marginal Price definition and calculation ..... 7
*2.2.1 Definition of Locational Marginal Price ..... 7*
*2.2.2 Location Marginal Pricing calculation ..... 8*
*2.2.3 Example for Market application ..... 11*
2.3 Global Wind Development Status ..... 13
2.4 Taiwan's environment for the development and current status of wind ..... 16
*2.4.1 Environment ..... 16*
*2.4.2 Cost ..... 17*
*2.4.3 Status ..... 18*
2.5 Wind Turbines ..... 21
*2.5.1 Fixed-speed induction generator ..... 22*
*2.5.2 Double Fed Induction Generators (DFIG) ..... 23*
*2.5.3 Direct Drive Synchronous Generator (DDSG) ..... 24*
2.6 Reactive power procurement in power market ..... 25
*2.6.1 Reactive power pricing based on load power factor (coefficient) rate: ..... 25*
*2.6.2 Reactive power pricing using postage stamps methods, graph theory [12] ..... 29*
*2.6.3 Uniform reactive power pricing – reactive production cost [13] ..... 30*

CHAPTER 3 USING OPTIMAL POWER FLOW AND SIMULATION FUNCTION IN POWER WORLD ..... 34

3.1 Optimal Power Flow and Locational Marginal Pricing in the power world ..... 34
*3.1.1 Optimal Power Flow ..... 34*

*3.1.2 Locational Marginal Pricing* ..... 35
*3.1.3 Simulator s' Optimal Power Flow (OPF) tool for analyzing power markets* ..... 35
3.2 WIND TURBINE MODELING ..... 48
*3.2.1 Wind Generator Models* ..... 49
*3.2.2 Generic Wind Turbine Models* ..... 49
*3.2.3 Wind turbine voltage control* ..... 50
*3.3.3 Wind Turbine Modeling* ..... 50
CHAPTER 4 REACTIVE POWER PRODUCTION COST OF DOUBLE FED INDUCTION GENERATOR ..... 57
4.1 THE METHOD TO CALCULATE REACTIVE POWER ..... 57
4.2 ALGORITHM ..... 60
CHAPTER 5 TEST AND RESULT ..... 61
5.1 TEST MODEL ..... 61
5.2 CALCULATION AND DISCUSSION ..... 62
*5.2.1 Case 1: Zero Reactive Power is Required From ISO* ..... 63
*5.2.2 Case 2: Mandatory 0.95 pf Requirement From ISO* ..... 64
*5.2.3 Case 3: Mandatory 0.9 pf Requirement From ISO* ..... 65
5.3 THE RESULT ..... 67
CHAPTER 6 CONCLUSION AND DISCUSSION ..... 69
6.1 SUMMARY OF THE RESEARCH ..... 69
6.2 SUGGESTIONS FOR FURTHER RESEARCH ..... 70
REFERENCES ..... 71

## LIST OF FIGURES

Figure 2.1: Transactional energy market ..... 5
Figure 2.2: Overview of service related to system functioning ..... 6
Figure 2.3: Three bus system with generator bids shown ..... 11
Figure 2.4: Schematic representation of the SCIG ..... 22
Figure 2.5: Schematic representation of the DFIG ..... 23
Figure 2.6: Schematic representation of the DDSG ..... 24
Figure 2.7: Method for calculating Lost Opportunity Cost by NYISO ..... 26
Figure 2.8: The mandatory (no payment) reactive power requirement and the ancillary service component that receives financial compensation in the California system ..... 27
Figure 2.9: Tender bid price structure for synchronized and available reactive power capacity . 28
Figure 2.10: Tender bid price structure for reactive power utilization ..... 29
Figure 2.11: Synchronous generator capability curve ..... 30
Figure 2.12: Synchronous generator reactive power production cost ..... 31
Figure 2.13: Reactive power offer structure of provider ..... 32
Figure 3.1: Three Bus ( example) ..... 36
Figure 3.2: Enforce transmission line limits ..... 37
Figure 3.3: B3 with Line limits NOT Enforced ..... 37
Figure 3.4: B3 with Line limits Enforced ..... 38
Figure 3.5: Verify Bus 3 Marginal Cost ..... 38
Figure 3.6: MVA Marginal Cost ..... 39
Figure 3.7: Both line to Bus 3 Congested ..... 39
Figure 3.8: LP OPF Dialog, Options: Constraint Options ..... 40
Figure 3.9: Penalty cost ..... 41
Figure 3.10: Specifying a Piece-wise Limit Cost with the Limit Groups ..... 42
Figure 3.11: OPF Line/ Transformer MVA Constraints Display ..... 42
Figure 3.12: LP OPF Dialog, Options: Common Options ..... 43
Figure 3.13: Modeling Generator Cost ..... 45
Figure 3.14: Cost of Energy, Losses and Congestion ..... 45
Figure 3.15: Cost of Energy, Losses and Congestion ..... 46
Figure 3.16: Wind capacity additions in 2008 were 8558MW, 12.5MW of Wind power were decommissioned ..... 48
Figure 3.17: Induction machine ..... 51
Figure 3.18: WT1G Power Speed Curve ..... 51
Figure 3.19: Type 2 Wind Generator Speed Curve ..... 52
Figure 3.20: Type 3 DFAG Model, Voltage Source Converter (VSC) ..... 52
Figure 3.21: Voltage Recovery ..... 54
Figure 3.22: Wind turbine MW Mechanical input and terminal output ..... 54

Figure 3.23: Generator 3 EXWTGE states ..... 55
Figure 3.24: Generator 1 – Turbine Power ..... 55
Figure 3.25: Pitch ..... 56
Figure 4.1: Capability Curves of DFIG ..... 57
Figure 4.2: Reactive power production cost function – Offer structure ..... 57
Figure 4.3: Algorithm to calculate profit for wind farm in ancillary market ..... 60
Figure 5.1: Diagram of 9_Bus_System ..... 61
Figure 5.2: The parameter of example in the Normal model ..... 62
Figure 5.3: The parameter of Buses in Case 1 ..... 63
Figure 5.4: The parameter of Branch State in Case 1 ..... 63
Figure 5.5: The profit of Generator in Case 1 ..... 63
Figure 5.6: The parameter of Buses in Case 2 ..... 64
Figure 5.7: The parameter of Branch State in Case 2 ..... 64
Figure 5.8: The profit of Generator in Case 2 ..... 64
Figure 5.9: Voltage at bus 3,5,6,8 after increasing the load significantly ..... 65
Figure 5.10: The parameter of Buses in Case 3 ..... 65
Figure 5.11: The parameter of Branch State in Case 3 ..... 66
Figure 5.12: The profit of Generator in Case 3 ..... 66
Figure 5.13: Voltage at bus 3,5,6,8 after increasing the load significantly ..... 67

## LIST OF TABLES

Table 2.1: Three bus LMP example – payments to pool ..... 12
Table 2.2: Three Bus LMP example – bilateral congestion charges ..... 13
Table 2.3: Green Energy Development Status ..... 14
Table 2.4: World wind power installed capacity of the top ten list of countries ..... 15
Table 2.5: 3 2011-2016 global new and cumulative installed capacity of wind turbines installed capacity ..... 16
Table 2.6: Offshore wind farm costs to construct the table ..... 17
Table 2.7: Terrestrial wind farms cost to construct the table ..... 17
Table 2.8: Problems faced by wind power ..... 18
Table 2.9: Years of wind turbine installation status [9] ..... 19
Table 3.1 Models of Wind Turbine ..... 49
Table 3.2: FAULT in example ..... 53
Table 5.1 : Parameter of $G_1$ and $G_2$ with Cost Model ..... 61
Table 5.2: Load at Buses in 2 scenes ..... 62
Table 5.3: The profit of Wind generator in 3 Cases by Q ..... 67
Table 5.4: The profit of Wind generator in 3 Cases by ΔP ..... 68