UNIVERSITI PUTRA MALAYSIA

DYNAMIC INVESTMENT MODEL FOR THE RESTRUCTURED POWER MARKET IN THE PRESENCE OF WIND SOURCES

MOHAMMAD TOLOU ASKARI SEDEHI ESFAHANI

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,

in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

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DEDICATION

Dedicated to my best companion in life, Saeideh,

and to my beloved parents to whom I owe my everything

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Mohd. Zainal Abidin Ab Kadir, PhD
Faculty : Engineering

The short term and long term revenues of the wind firm encounters more uncertainties which include the forecasted load, fuel price and output power of wind units. Furthermore, in short and medium terms the wind firm faces with Market clearing price's fluctuations, which is affected by some uncertain parameters including the demand, fuel price, wind fluctuations and the operational strategic behaviour of other investors. These uncertainties increase the risk of investment. Therefore, the private wind investors require a set of decision tools to evaluate and analyse the investment strategies in the long term planning by considering the existence of uncertainties, regulatory policies, which include the incentive policies for wind power plants and CO_2 tax, and the realities in the restructured power market such as the bilateral contracts.

The main objective of this thesis is to determine the long term optimal investment strategies of the hybrid wind-thermal investor in the restructured power market. To accomplish this purpose, three main steps have been conducted in this thesis. In the first step, the hybrid Autoregressive Moving Average – Monte Carlo method proposes to simulate the hourly wind speed as well as the hourly wind turbine generators. The uncertainties of the output power of wind turbine generators are modelled based upon the scenario-based method and data mining techniques. In the second step, a model developed in this work is proposed to simulate the medium term restructured power market. The scenarios of the output power of wind turbines, which are generated through the first step in terms of the outputs power of wind farm together with their occurrence probability, are used to estimate the maximum profit of investors as well as the average Market clearing price with the proposed model in the restructured power market. The stochastic uncertainties include the demand and fuel price fluctuations in the restructured power market simulated based on the Monte Carlo method. In addition to the stochastic uncertainties in the medium term power market which are considered in the proposed model, the operational strategic behaviour of other investors considered in this study is based upon the game theory concepts using the Cournot game. In the third step, the long term optimal investment strategies of the hybrid wind-thermal investor are determined based on the dynamic programming algorithm by considering the long term states of demand growth and fuel price uncertainties.

The proposed framework has been implemented in the hypothetical restructured power market using the IEEE Reliability Test System. Well-established renewable energy-based power generation in the countries like Spain and Germany for instance, can provide strong and useful information for this study. With that justification, fixed Feed in Tariff's incentive policy was adopted in the case of wind investor. Conducted case studies have confirmed that this framework provides robust decisions and precise information about the restructured power market for hybrid wind-thermal investors.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MODEL PELABURAN DINAMIK DI DALAM PASARAN KUASA TERSUSUN DENGAN KEHADIRAN SUMBER ANGIN

Oleh

MOHAMMAD TOLOU ASKARI SEDEHI ESFAHANI

Oktober 2014

Pengerusi : Mohd. Zainal Abidin Ab Kadir, PhD
Fakulti : Kejuruteraan

Jangka pendek dan jangka panjang pendapatan bagi firma tenaga angin melibatkan lebih banyak ketidaktentuan termasuklah beban yang diramalkan, harga bahan api dan kuasa keluaran unit tenaga angin. Selain itu, dalam jangka pendek dan sederhana, firma tenaga angin menghadapi kekangan dengan turun naik harga jelas pasaran yang terkesan oleh parameter ketidaktentuan termasuk permintaan, harga bahan api, turun naik angin dan tingkah laku strategik operasi pelabur-pelabur lain. Kesan-kesan ini meningkatkan risiko pelaburan. Oleh itu, pelabur tenaga angin swasta memerlukan satu kaedah keputusan untuk menilai dan menganalisis strategi pelaburan dalam perancangan jangka panjang dengan mempertimbangkan ketidakpastian wujud, dasar pengawalseliaan iaitu termasuklah dasar insentif bagi loji kuasa angin dan cukai CO_2, serta kesedaran dalam pasaran kuasa tersusun-semula contohnya kontrak dua hala.

Objektif utama tesis ini adalah untuk menilai dan menganalisis strategi pelaburan jangka panjang yang optimum bagi pelabur tenaga angin-haba yang digabungkan dalam pasaran kuasa tersusun-semula. Bagi mencapai tujuan ini, tiga langkah utama telah dijalankan di dalam tesis ini. Dalam langkah pertama, kaedah Autoregresi hibrid purata bergerak Monte Carlo dicadangkan untuk mensimulasikan kelajuan angin setiap jam serta penjanaan turbin angin setiap jam. Ketidaktentuan dalam kuasa pengeluaran WTGs yang dimodelkan berdasarkan kaedah kebergantungan-keadaan dan teknik perlombongan data. Dalam langkah kedua, model yang dibangunkan di dalam projek ini dicadangkan untuk simulasi pasaran kuasa jangka sederhana tersusun-semula. Senario kuasa keluaran turbin angin yang dihasilkan melalui langkah pertama dari segi kuasa keluaran oleh ladang angin beserta kebarangkalian kejadian, digunakan untuk menganggarkan keuntungan maksimum pelabur dan juga purata harga jelas pasaran dengan model yang dicadangkan dalam pasaran kuasa tersusun-semula. Ketidaktentuan stokastik termasuklah permintaan dan bahan api turun naik harga dalam simulasi pasaran kuasa tersusun-semula adalah berdasarkan kaedah Monte Carlo. Selain daripada ketidaktentuan stokastik dalam pasaran tenaga jangka sederhana yang dipertimbangkan dalam model yang dicadangkan itu, tingkah laku strategik operasi pelabur-pelabur lain dipertimbangkan dalam kajian ini berdasarkan konsep-konsep teori permainan dengan menggunakan permainan Cournot. Dalam langkah ketiga, strategi pelaburan yang optimum jangka panjang pelabur tenaga angin panas hibrid ditentukan berdasarkan algoritma

pengaturcaraan dinamik dengan mempertimbangkan jangka panjang pertumbuhan permintaan dan ketidaktentuan harga bahan api.

Rangka kerja yang dicadangkan itu telah dilaksanakan dalam pasaran kuasa tersusun-semula hipotesis menggunakan Sistem Ujian IEEE Kebolehpercayaan. Firma yang kukuh dalam tenaga boleh diperbaharui adalah berdasakan penjanaan kuasa di negara-negara seperti Sepanyol dan Jerman misalnya memberikan maklumat yang kukuh dan berguna untuk kajian ini. Dengan justifikasi itu, dasar-dasar insentif *Feed in Tariff* telah diterima pakai dalam kes pelabur tenaga angin. Kajian kes yang dijalankan mengesahkan bahawa rangka kerja ini dengan syarat keputusan yang mantap dan maklumat yang tepat mengenai pasaran kuasa tersusun-semula untuk pelabur hibrid tenaga angin-haba.

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I certify that a Thesis Examination Committee has met on 2 October 2014 to conduct the final examination of Mohammad Tolou Asakri Sedehi Esfahani on his thesis entitled "Dynamic Investment Modeling In The Restructured Power Market With The Presence Of Wind Sources" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohammad Hamiruce Marhaban, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Gorakanaga Arosha Chandima Gomes, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Wan Fatinhamamah binti Wan Ahmad, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Saifur Rahman, PhD
Professor
Vt Advance Research Institute
Virginia Polytechnic University- United States
(External Examiner)

NORITAH OMAR, PhD
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia
Date:

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd. Zainal Abidin Ab Kadir, PhD.
Professor
Faculty of Engineering
University Putra Malaysia
(Chairman)

Hashim b. Hizam, PhD.
Associate Professor
Faculty of Engineering
University Putra Malaysia
(Member)

Jasronita bt. Jasni, PhD.
Senior Lecturer
Faculty of Engineering
University Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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Declaration by Graduate Student

I hereby confirm that:

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This is to confirm that:

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Signature: _____	Signature: _____
Name of Chairman of Supervisory Committee: Zainal Abdin AB Kadir, PhD	Name of Member of Supervisory Committee: Hashim b. Hizam, PhD

Signature: _____
Name of Member of Supervisory Committee: Jasronita bt. Jasni, PhD

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