

**Modeling and Analyzing the Effects of Operating
Constraints on Pricing Signals in the Competitive
Electricity Market**

by

Chaminda Amarasinghe

A dissertation submitted to the Faculty of Graduate Studies in partial
fulfillment of the requirements for the degree of
Doctor of Philosophy

The Department of Electrical and Computer Engineering

The University of Manitoba

Winnipeg, Manitoba, Canada

© December 2007

THE UNIVERSITY OF MANITOBA
FACULTY OF GRADUATE STUDIES

COPYRIGHT PERMISSION

**Modeling and Analyzing the Effects of Operating Constraints on Pricing
Signals in the Competitive Electricity Market**

BY

Chaminda Amarasinghe

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of
Manitoba in partial fulfillment of the requirement of the degree**

Of

Doctor of Philosophy

Chaminda Amarasinghe© 2008

**Permission has been granted to the University of Manitoba Libraries to lend a copy of this
thesis/practicum, to Library and Archives Canada (LAC) to lend a copy of this thesis/practicum,
and to LAC's agent (UMI/ProQuest) to microfilm, sell copies and to publish an abstract of this
thesis/practicum.**

**This reproduction or copy of this thesis has been made available by authority of the copyright
owner solely for the purpose of private study and research, and may only be reproduced and copied
as permitted by copyright laws or with express written authorization from the copyright owner.**

To my parents

Acknowledgements

I would like to express my deep appreciation and gratitude to Dr. Udaya Annakkage for his continuous advice, guidance and encouragement throughout the research work. It has always been a pleasure working under his guidance. I greatly appreciate the advice and assistance received from Dr. Ani Gole. I am also grateful to Dr. Alan Wang of Manitoba HVDC Research Center for useful inputs. I must also thank the technical staff at the Department of Electrical and Computer Engineering, especially Mr. Erwin Dirks for his support.

Conducting this work would have not been possible without the financial support received from Manitoba Hydro, Manitoba HVDC Research Center, Faculty of Graduate Studies at the University of Manitoba, and National Science and Engineering Research Council.

I must also express my gratitude to the management of the Manitoba HVDC Research Center, specially to the managing director Mr. Paul Wilson, for providing their facilities to carry out a part of this research, in addition to the financial support. Also, I would like to thank all my friends in the Power Tower and the staff of the Department of Electrical and Computer Engineering for their continuous encouragement and for making my years at the University of Manitoba a pleasant one.

This acknowledgement would not complete without thanking my family. I extend my heartfelt gratitude to my parents for their support and encouragement throughout my life. A very special thank to my sister for all the love and support over the years. Last but not least I would thank my wife for guiding me to achieve my goals, and my little son for keeping me happy all the time.

Chaminda Amarasinghe

December 2007

Abstract

In a competitive electricity market, market signals are the main driving forces or the incentives for the market participants to make their operational and investment decisions. Locational Marginal Prices (LMP) are the only prevailing market signals, and are determined using an Optimal Power Flow (OPF) program.

The present practice is mainly focus on real power dispatch by solving a LP-OPF together with LMP based settlement. Acquiring the required reactive power & other ancillary services, and ensuring the security (both static and dynamic) are performed subsequently, which may result in curtailments to the already agreed optimal real power dispatch. With such a dispatch mechanism, the resulting market signals are also impaired. Thus, correct market signals can only be analyzed, if the related constraints are suitably modeled in the OPF.

This thesis analyzes market signals after incorporating two such important constraints; reactive power and security issues into market dispatch. First, a reactive power model is proposed to suit the requirements of the competitive electricity market and is incorporated into the OPF. The recently proposed transient stability boundary is then used as a constraint in the OPF to ensure the secure operation of the system.

In determining market signals, the recently proposed method of analysis of LMP components is first presented. The network rental, which is the surplus collected by the system operator due to LMP based settlement of transactions, is then proposed as a method in market signal analysis by decomposing the network rental. The key advantage is that network rental components show how each consumer has actually overpaid due to each binding constraint and losses in a detailed manner, which is argued to be a supplementary pricing signal especially from the consumer's perspective.

Finally, implementation of a software tool using C++ to solve the OPF and extend it to incorporate the above market signal analysis methods is achieved. This allows market signals to be readily available along with the optimal dispatch. The potential of the proposed components of network rental in market signal analysis together with

the suitability of the proposed models in market dispatch are evaluated for different case studies using the developed software tool.

List of Principal Symbols

All notations and most of the terms used in the thesis are described in this section. The remaining terms are explained as they first appear in the text for the convenience in understanding.

i, j	node (bus) number
k	generator bid number
P	real power
Q	reactive power
g	generation
D	demand
P_{gi}	real power generation at bus i
Q_{gi}	reactive power generation at bus i
P_{Di}	real power demand at bus i
Q_{Di}	reactive power demand at bus i
B	bid
B_i	set of all bids at bus i
P_{ik}^B	real power bid quantity of the k^{th} real power bid at bus i
P_{ik}	real power dispatched from the k^{th} bid at bus i
S	price
S_{ik}^B	bid price of the k^{th} real power bid at bus i
S_i^Q	reactive power cost of generator at bus i
I	set of all buses
B_i	set of all bids at bus i
P_i	real power injection at bus i
Q_i	reactive power injection at bus i
Q_{g1i}	Block 1 (i.e., free) reactive power from the generator at bus i
Q_{g2i}	Block 2 (i.e., non-free) reactive power from the generator at bus i

Q_{gi}^{max}	maximum reactive power from the generator at bus i
Q_{gi}^{min}	minimum reactive power from the generator at bus i
T	set of all transmission lines
T_i	set of all transmission lines connecting to bus i
t	transmission line
V_i	voltage magnitude of i^{th} bus
θ_i	voltage angle of i^{th} bus
θ_{ij}	voltage angle difference between voltages of buses i and j
g_{ij}	conductance of the line connected between buses i and j
b_{ij}	susceptance of the line connected between buses i and j
PF_{ij}	real power flow along the line connected buses i and j
PF_{ij}^L	real power loss along the line connected buses i and j
P^L	real power loss in the system
Q^L	reactive power loss in the system
L	Lagrangian equation
max	maximum limit
min	minimum limit
λ	real power LMP at the reference bus
σ	reactive power LMP at the reference bus
λ_i	real power LMP at bus i
σ_i	reactive power LMP at bus i

The Greek symbols μ , β , α , γ , ϕ , ψ and η with suitable subscripts are used to denote the Lagrange multipliers associated with the equality and inequality constraints of the Optimal Power Flow problem.

Table of Contents

1	Introduction	1
	1.1 Characteristics of Electricity Markets	2
	1.2 Motivation Behind the Research	5
	1.3 Main Objectives of the Research	8
	1.4 Thesis Overview	10
2	Electricity Market Overview, Dispatch and Pricing Theory	12
	2.1 Electricity Market Overview	12
	2.2 OPF Problem	16
	2.3 Locational Marginal Pricing	18
	2.3.1 Marginal Pricing Theory	18
	2.3.2 An Example of LMP	21
	2.4 Concluding Remarks	25
3	Incorporating Reactive Power in Market Dispatch	26
	3.1 Present Reactive Power Management	27
	3.2 Modeling Reactive Power Supply in Market Dispatch	28
	3.3 OPF Problem	32
	3.4 Results	36
	3.4.1 Analysis of Price Components	39
	3.4.2 Market Signals Produced by the Proposed Model	41
	3.5 Concluding Remarks	42
4	Incorporating Dynamic Security in Market Dispatch	44
	4.1 Dynamic Security Constraint	46
	4.2 OPF Problem	47
	4.3 Case Studies and Results	49
	4.4 Concluding Remarks	53
5	Analyzing Market Signals	54
	5.1 LMP Components	56
	5.1.1 Traditional Approach	56
	5.1.2 Unbundling LMP Based on KKT Conditions	57
	5.1.3 Numerical Example to Evaluate the LMP Components	62
	5.2 Network Rental	66
	5.2.1 Components of Network Rental	68
	5.3 Calculating the Components of Network Rental Based on LP-OPF	68
	5.3.1 Neglecting Transmission Losses	69
	5.3.2 Including Transmission Losses	73
	5.3.3 Discussion	81
	5.4 Proposed Method of Calculating the Components of Network Rental	82
	5.4.1 Determining the LMP Difference Between Two Buses in Terms of Contributing Components	82
	5.4.2 Calculation of Components of Network Rental For a System Having a Single Load Bus	89

5.4.3	Separation of Network Rental Among Consumers Using Power Flow Tracing	94
5.4.4	Discussion	99
5.5	Concluding Remarks	100
6	Software Implementation	102
6.1	Implementing the Newton Based Approach	104
6.1.1	The Newton Approach	104
6.1.2	Handling the Inequality Constraints	107
6.1.3	Calculation of Marginal Prices, Components of LMP, Components of Network Rental	109
6.1.4	Algorithm and Implementation Issues of the Newton Method	112
6.2	Implementing the SLP Based Approach	115
6.2.1	Linearized Problem	115
6.2.2	Calculation of Marginal Prices, Components of LMP, Components of Network Rental	116
6.2.3	Algorithm and Implementation Issues of the SLP Method	117
6.3	Performance of the Developed Software Tool	119
6.4	Concluding Remarks	120
7	Case Studies and Results	122
7.1	Market Signal Analysis using the IEEE New-England 39 Bus System	122
7.1.1	LMPs	125
7.1.2	LMP Components	125
7.1.3	Network Rental Components	128
7.1.4	Discussion	130
7.2	Concluding Remarks	131
8	Conclusions	132
8.1	General Conclusions	132
8.2	Contributions	135
8.3	Suggestions for Future Research	137
A	Test Systems Data	139
A.1	IEEE 39 bus system	139
A.2	IEEE 30 bus system	142
B	Constrained Optimization	144
C	LMP Relationships	148
D	Power Flow Tracing using Bialek Method	150
	Acronyms	152
	Reference	154

List of Figures

2.1	Generator bidding to the market	19
2.2	Supply-demand curve and market surplus	20
2.3	3 bus system	21
2.4	LMPs - without line flow limits	22
2.5	LMPs - with 100 MW limit on line 1 – 2	23
2.6	LMPs - with 250 MW limit on line 1 – 3	24
2.7	LMPs - with 100 MW limit on line 2 – 3 and shifting the load to bus 2	25
3.1	Capability region of the synchronous generator	29
3.2	Proposed reactive power model for the generator	31
5.1	3 bus system	62
5.2	Average loss and marginal loss	67
5.3	Piece-wise linear approximation for losses	74
5.4	3 bus system	90
5.5	4 bus system	95
5.6	Real power flows for the 4 bus system	96
5.7	Generator contributions and apportioned losses for each load	97
6.1	Penalty function for the variable X	108
6.2	Algorithm of the Newton method	113
6.3	Algorithm of the SLP method	118
A.1	Single line diagram of IEEE New England 39 bus system	139
A.2	Single line diagram of IEEE 30 bus system	142

List of Tables

3.1	Generator bid data	37
3.2	Reactive power generation data	37
3.3	Generation dispatch with the proposed simultaneous model	38
3.4	Values of the multipliers given by the OPF	38
3.5	Real and reactive power LMPs	41
4.1	Generator bid data	50
4.2	Generation dispatch	51
4.3	LMPs for the three cases	52
5.1	Generator bid data	63
5.2	Dispatch for the Case 1 and Case 2	63
5.3	Components of LMP for Case 1	64
5.4	Components of LMP for Case 1	65
5.5	Components of LMP for Case 2	65
5.6	Components of LMP for Case 2	66
5.7	Generator bid data	90
5.8	Generation dispatch	90
5.9	Binding constraints	91
5.10	Network rental for the 3 bus system	91
5.11	Components of network rental	93
5.12	Generation dispatch	95
5.13	Binding constraints	95
5.14	Network rental for the 4 bus system	97
5.15	Components of network rental	99
6.1	For quadratic cost function	119
6.2	For bid/quantity pairs	120
7.1	Generator bid data	123
7.2	Reactive power generation data	123
7.3	Generation dispatch	124
7.4	Binding constraints	124
7.5	Network rental for the 39 bus system	126
7.6	LMP components	127
7.7	Generator contributions and apportioned losses to each load	129
7.8	Components of network rental	130
A.1	Real and reactive power loads for IEEE New England 39 bus system	140
A.2	Transmission line data for IEEE New England 39 bus system	140
A.3	Transmission line data for IEEE New England 39 bus system Contd.	141
A.4	Real and reactive power loads for IEEE 30 bus system	142
A.5	Transmission line data for IEEE 30 bus system	143

Chapter 1

Introduction

Electricity industry restructuring during the last two decades has made drastic changes to the traditional electricity structure and will continue for the next several decades. In the past, the electric power industry has been either a government-controlled or a government-regulated industry (i.e., single owner), which existed as a monopoly where the overall authority in generation, transmission, and distribution of power are within its domain of operation. Everyone including household, businesses, and industries were required to purchase their electricity from their local monopolistic power company. This was not only a legal requirement, but also the only source they had to rely on to fulfill their day to day requirements.

The restructuring has led the traditional electricity industry to become a competitive electricity market. The main driving forces for these reforms are due to economic inefficiencies and consumer dissatisfaction associated with the single owned electricity industry. Since electricity is an essential source of energy for everyone and due to its unique characteristics such as un-storability and lack of flexibility in controlling the power flow in transmission lines, the whole process of restructuring is a challenging and complex task [1].

Over the past two decades, however, countries have begun to split up these monopolies in favor of competitive markets to introduce commercial incentives in generation, transmission, and distribution. The main goals under a competitive market design are

efficient and reliable operation of the power system together with market incentives for all the participants [2]. This is done by creating competition between participants in the electricity market with open access.

1.1 Characteristics of Electricity Markets

The process of restructuring that led to electricity markets are not the same in all countries due to economic, political, and other local differences [3]. As a result, newly formed markets have taken different forms to suit their individual requirements. In some markets, competition is only among suppliers while in others both suppliers and consumers compete. Some markets are compulsory and others are voluntary. Some markets only trade real power and some trade reserves, reactive power and other ancillary services, with real power. Some markets use pool-based systems and others use bilateral contracts. While some markets use full nodal pricing, and others use zonal pricing arrangements, some use uniform prices. In some markets, settlement is only based on a real time market, whereas some others use forward markets in addition to the real time market.

However, there is a common basis and some similar characteristics that can be found in all competitive electricity markets. Generally, generation, transmission, and distribution services are the responsibilities of different companies in order to create the competition. Normally, the wholesale market is pool-based in nature with the provision for bilateral contracts. This means that all suppliers (i.e., generators) sell energy to a pool and consumers buy energy from that pool by bidding to the market (bid/quantity pairs). Furthermore, there can be financial contracts between participants outside the electricity market on long-term basis. Such long-term contracts are agreements between participants to mitigate or share the risk associated with price volatility due to the change in supply and demand conditions [4]. While generation and demand sides are competitive, the transmission remains a monopoly. The huge cost of investing in the transmission network as well as geographical reasons do not

allow the transformation of this service into a competitive market. In order to ensure open and fair access, the grid and the wholesale energy market are operated by an independent entity with no direct interests in the energy business. This entity is commonly known as the Independent System Operator (ISO) and is responsible to achieve the above-mentioned goals while maintaining the security and the quality of the supply.

One of the key concerns to any restructured market is the ability to operate the transmission system in a manner that is fair to all participants. In USA, the Federal Energy Regulatory Commission (FERC) oversees issues involving the transmission system. FERC presently believes that the only way in which everyone will be on a competitive environment is to create open access to all the participants. As stated in its white paper [5] on Standard Market Design (SMD), participants in wholesale power markets will have non-discriminatory open access to the transmission system. Further, it proposes Locational Marginal Pricing (LMP) as a way of settling the transactions between the participants. This is further insisted upon in their recent documents, subsequent to the SMD white paper [6], [7]. This pricing scheme is also called “nodal pricing” and the concept of nodal pricing was proposed in [8] long before the restructuring of the electricity industry started. LMP is the marginal cost of supplying the next increment of a quantity at a specific bus, considering marginal cost of generation and physical aspects of the transmission system. Due to operating the power system at limiting values of the constraints imposed by the physical and operational limits, which are commonly known as ‘binding constraints’, and due to the transmission losses, there exist different LMPs across the transmission network which provide a precise, market-based method for pricing energy that includes the cost of constraints and transmission losses.

An Optimal Power Flow (OPF) program is commonly used to obtain the optimal generation dispatch [9]. The present practice is based on solving a Linear Programming based OPF (LP-OPF), which has the advantage of simplicity and robustness

in the solution algorithm compared to Nonlinear Programming based OPF (NLP-OPF). Mathematically, LMPs are the dual variables of the power balance equations associated with the OPF. Therefore, once the OPF is solved, LMPs can be easily determined.

The state-of-the-art OPF is nonlinear in nature. The LP-OPF is a linear approximation of this standard NLP-OPF, which only requires linear network models commonly known as dc power flow models. Hence, transmission losses, reactive power related issues and security issues are not modeled in the LP-OPF. However, due to the fact that it does consider the line flow constraints, which has the most impact on real power dispatch, and due to the simplicity associated with the solution algorithms, LP-OPF is still dominating in all electricity markets.

The system losses, however, cause significant impact on generation dispatch depending on the topology of the power system network [10]. Therefore, in some electricity markets losses are incorporated into the LP-OPF with a piece-wise linear approximation for losses [11]. Alternatively, some markets use loss factors to represent the effects of the system losses [12]. All these methods are, however, based on approximations, and therefore do not accurately represent the transmission losses.

For the successful operation of the system, the ISO needs to procure some essential services other than real power, such as reactive power, spinning reserve, regulation, and black start capability, which are commonly known as ancillary services [13]. With the current practice, these ancillary services are not included in the dispatch algorithms, and are accrued in other ways such as long term contracts or having a separate auction similar to real power.

The system security is another crucial issue to be addressed in market dispatch. Unlike in single owner electricity industries, where the system operations are carried out in a carefully planned and cooperative manner, in a competitive electricity market no attention is paid by the market participants to the system security. This is because, each market participant has own interests to maximize its benefits. Thus, the ISO

has a key role in maintaining the system security by incorporating the security related constraints into market dispatch.

The success of a competitive electricity market relies on the competition between the participants. Market signals are the main driving force for the participants in achieving this objective. Correct market signals provide a clear and accurate indication of the price of electricity at every location on the grid. These signals in turn reveal the value of locating new generation, upgrading transmission, alleviating the constraints, increasing the competition, and improving the systems ability to meet power demand.

1.2 Motivation Behind the Research

In order to achieve the goals of restructuring, many outstanding engineering problems need to be investigated. Most of the tools used in single owner electricity industry are no longer valid and new tools need to be created. Most importantly, these related issues should be addressed early in the restructuring process.

One such pertaining issue is how to determine the correct market signals for the market participants. Unlike in the single owner electricity industry, participants in the restructured electricity market seek market signals for their operational and investment decisions, which eventually lead to a successful operation of the electricity market. These signals indicate the effects on the price of electricity at each location due to various factors such as system losses and binding constraints. For instance, new generation companies will have an incentive to locate their new generators at high priced locations, while new consumers will prefer low priced locations. On the other hand, the ISO can use these market signals to enhance the performance of the electricity market.

The present practice of market dispatch is based on solving a LP-OPF, where very little attention is given to the procurement of reactive power and other ancillary services, and ensuring the security (both static and the dynamic) of the system.

Typically, these related constraints are not used in the conventional OPF, and are procured or ensured in different ways after solving the OPF. This two-step approach, however, does not guarantee the optimal procurement of real and reactive power due to the subsequent adjustments made to the real power dispatch. Thus, to analyze the correct market signals, those underlying constraints must be correctly incorporated in the OPF.

The main advantage of including these constraints is that both technical and economical aspects related to these constraints are embedded in the OPF. Thus, it represents the actual operation of the network, and hence more accurate market signals can be obtained for the market participants for their operational and investment decisions. Despite the associated complexities due to nonlinear constraints, it could be feasible to solve a NLP-OPF in the future due to the continuous advancement in computing speed [1]. Therefore, how to include these additional constraints into the OPF and what methods should be used in analyzing the resulting market signals are important issues to be investigated.

As mentioned in Section 1.1, the ISO has the responsibility of acquiring the required amount of reactive power from suppliers at appropriate locations of the network. This is done in a sequential manner, where real power is dispatched first and then reactive power is dispatched subsequently as an ancillary service. Different reactive power models have been proposed in the literature for a sequential dispatch of real and reactive power. However, this process may result in adjustments to the already agreed real power dispatch and sometimes this could lead to an infeasible solution. Therefore, there is a need for a good reactive power model that captures both technical and economical aspects to suit the simultaneous dispatch of real and reactive power.

Typically, the Dynamic Security Constraint (DSC) is not used in the traditional OPF, due to the unavailability of such a constraint in the functional form compatible with the OPF. The current industry practice of determining the generation dispatch

that is secure from a dynamic stability point of view is by performing a dynamic stability simulation after solving the OPF [46], [47], or by performing the generation dispatch by some other means. Recently, there has been a motivation towards the development of Dynamic Security Constrained Optimal Power Flow (DSCOPF) programs in which the dispatch is ensured against the security of the system in one step. A novel technique to derive an accurate transient stability boundary is proposed for a given credible contingency in [51]. In this way, a separate DSC can be derived for each credible contingency. This can be used as a constraint in the OPF to obtain dynamically secured generation dispatch.

The LMPs, which represent the price of electricity at each location of the system, are considered to be the key market signals. Even though, LMPs provide valuable information at each location of the system, they do not provide a detailed description in terms of contributions coming from different constraints and marginal generators. Unlike in LP-OPF, where only line flow constraints are considered, with NLP-OPF, several other binding constraints also contribute to the LMP at a given location. The existing method of analyzing LMP components can be used to determine the effects of all the binding constraints explicitly, and hence can be used as better market signals for the participants than LMP itself. However, the effects of transmission losses cannot be seen explicitly from LMP components, which is a drawback of this method.

When LMPs are used for settlement of transactions, there exists a difference between what consumers pay to the ISO and what generators get paid by the ISO [17]. This difference is referred to as network rental in this thesis, and is accumulated with the ISO. Network rental is made up of two components known as the loss rental and the constraint rental. Loss rental is due to the difference in average losses and marginal losses. The constraint rental is due to operating the power system at binding constraints imposed by the OPF. Inclusion of the above additional constraints in the OPF leads to further accumulation of rental with ISO, and therefore, components

of network rental could be used as another way of analyzing market signals. In fact, since the network rental is an overpayment made solely by the consumers, the components of network rental show how each consumer has actually overpaid due to each binding constraint and losses. Therefore, the components of network rental can be considered as consumer oriented market signals. However, the available methods are not sufficient in determining these components separately. Hence, there is a need for a new method to decompose the network rental, so that these components can be effectively used as a tool in market signal analysis.

1.3 Main Objectives of the Research

The main objective of this research work is to analyze market signals using both proposed and existing methods, after incorporating two constraints that account for the reactive power and security issues in market dispatch. In this regard, first a reactive power model is proposed to be incorporated in the OPF for a simultaneous dispatch of real and reactive power. This OPF is then extended to incorporate the DSC to ensure the dynamic security of the system in a simultaneous manner.

Having incorporated these constraints, the associated market signals are then analyzed. The existing method of LMP components is first used to analyze market signals. This enables the determination of the effects of marginal generators and all binding constraints explicitly and quantitatively, which in turn can be used as better market signals. However, LMP components do not show the effects of losses explicitly.

Then, a theoretical background related to network rental is presented together with the proposed method to decompose the network rental into contributing components. These components of network rental are then proposed as supplementary market signals, to be used together with LMPs and components of LMPs in determining market signals. Finally, a software tool is developed using C++ to implement the OPF to include the above features. Thus, market signals can be determined together with the optimal dispatch.

In meeting the above objectives, the following steps have been accomplished.

1. Investigation of the operation of current electricity markets. This enables the comparison of different electricity markets and the determination of a common market framework for the work presented in this thesis. Further, it gives a better understanding of how reactive power is procured; dynamic security is ensured; and market signals are determined, in existing electricity markets.
2. Proposal of a new reactive power model for a simultaneous dispatch of real and reactive power, by considering the capability of the synchronous generator and the fairness of reactive power supply obligation to suit the competitive electricity market. The opportunity cost of supplying reactive power is implicitly modeled using the rating of the machine as a constraint. Fairness of the reactive power supplying obligation is also ensured by splitting the reactive power supplied by the generator into two components with the first component being proportional to real power dispatch.
3. Incorporation of the Dynamic Security Constraint (DSC) in the OPF, to investigate the effects on generation dispatch due to the DSC. This approach has been enabled by the availability of the DSC in a functional form in terms of nodal voltages and their phase angles.
4. Explanation of the existing method of breaking down of LMP into contributing components. The LMP at a given bus is made up of contributions coming from marginal generators and binding constraints, and therefore, explicit decomposition shows individual contributions due to each of the above factors. Thus, these LMP components serve as better market signals than LMP itself.
5. Explanation of the concept of network rental and proposing a novel technique to decompose the network rental among consumers into contributing components. This enables each rental component paid by each consumer to be quantitatively determined, which in turn can be used as supplementary market signals.

6. Implementation of the OPF in the C^{++} programming language to include the above features. The resulting software can be used as a tool to perform computational experiments to gain insight into the operation of electricity markets, to compare the results with benchmark models and to analyze market signals.

1.4 Thesis Overview

The thesis has eight chapters and four appendices, which are organized to allow a progressive discussion of the approach employed to achieve the above objectives.

Chapter 2 provides an overview to operation of the existing electricity markets. This includes historic evolution of electricity markets, analysis of present market structures and procurement methods, and associated problems in the current markets. The OPF program is then presented as it is used to determine the optimal dispatch in the electricity market. Finally, the widely accepted concept of LMP, which is also currently being used in most electricity markets, is presented together with some examples to demonstrate how these LMPs are calculated.

At the beginning of Chapter 3, the present reactive power procurement methods are explained. Then, different ways of modeling reactive power proposed in the literature are presented together with the limitations and the drawbacks of those methods. Finally, a new reactive power model for a simultaneous dispatch of real and reactive power is presented, by considering the capability of the synchronous generator and the fairness of reactive power supply obligation to suit the competitive electricity market. A case study with the proposed reactive power model is also presented to convince the suitability of the proposed model in market dispatch.

Chapter 4 starts with an introduction to the security of the power system and a brief summary of how dynamic security is ensured in the restructured electricity market. This is followed by an explanation to the technique proposed in [51] to derive an accurate transient stability boundary for a given credible contingency, which can be readily used as a constraint in the OPF. Then, the inclusion of DSC in the OPF

is presented together with a case study to determine the effects of DSC on LMPs.

In Chapter 5, different methods to analyze the associated market signals are presented. The chapter begins by presenting the existing method of analyzing components of LMP. Then, a method is proposed to analyze the components of network rental. This includes a novel method of decomposing the network rental among consumers and how these components can be used in analyzing market signals. Finally, some case studies are presented to numerically evaluate these individual components.

Chapter 6 describes the tool developed in C^{++} language that implements the OPF and incorporates the above market signal analysis methods. Based on the analysis of the capabilities of different OPF solving techniques described in the literature survey, Newton method and Sequential Linear Programming (SLP) method are used in this work to implement the OPF. This chapter gives an in-depth analysis and implementation issues of the above two methods and how each method can be extended to incorporate market signal analyzing methods. Finally, the performance and limitations of the developed software tool are presented. A commercially available optimization software tool called the Generalized Algebraic Modeling Systems (GAMS) is used as a benchmark to compare the results of the developed software.

Chapter 7 presents the results of a case study carried out using the developed software. In this study, the reactive power constraints and DSCs are included in the OPF and the resulting LMPs, components of LMPs and components of network rental are analyzed to determine the associated market signals.

Finally, in Chapter 8, conclusions of this research work are drawn. It is concluded that the components of network rental provide consumer oriented market signals, which can be considered as supplementary information, in addition to LMPs and LMP components. A few suggestions are given for future work covering the studied areas which need further research. The appendices introduce the mathematical derivations and details about test systems used in the main chapters of the thesis. References are made to the appendices wherever required.