2004年上海大学博士学位论文 65

# 电力市场中机制设计理论的应用研究

作　者：方　勇
专　业：控制理论与控制工程
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Shanghai University Doctoral Dissertation (2004)

# Application of Mechanism Design Theory in Electricity Markets

**Candidate:** Fang Yong
**Major:** Control Theory and Control Engineering
**Supervisor:** Prof. Li Yu-zeng

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# 上 海 大 学

本论文经答辩委员会全体委员审查，确认符合上海大学博士学位论文质量要求.

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| | | |
|---|---|---|
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| 徐耀良 | 教授，上海电力学院 | 200090 |

# 答辩委员会对论文的评语

方勇同学的博士学位论文《电力市场中机制设计理论的应用研究》立足于电力市场研究的前沿，系统而深入的研究了电力市场中不完全信息问题．该论文应用机制设计理论、供应函数均衡、Cournot 模型、Stackelberg 模型探讨了发电侧中发电商的策略性行为、激励性发电上网竞价机制，以及需求侧中可中断负荷管理的意义和实施方法、激励性可中断负荷合同的设计和应用等问题，取得了丰富的成果．其主要贡献如下：

(1) 应用供应函数均衡模型分析了统一价格机制下信息对发电商策略性行为的影响和默契勾结持留容量的形成过程，提出了一种能合理回收容量成本的激励性发电上网竞价机制．该机制能引导发电商披露真实信息，从而实现经济调度，还能根据报价信息评定机组的容量成本，引导发电容量投资．

(2) 针对具有风险特性的供电公司在电力市场中应用激励性可中断负荷合同的设计问题，从可置信威胁角度研究了供电公司在电力市场环境下应用可中断负荷管理的方法，提出的模型为供电公司参与市场竞争提供了一种新的思路．

(3) 提出了考虑用户最大可中断负荷的激励性可中断负荷合同模型，并研究了其在电力市场中的应用方法．

本博士论文选题具有重要的理论意义和现实意义，具有前瞻性，文笔流畅、条理清楚，在电力市场中机制设计理论的研究前沿取得了较大的创新成果，对我国电力市场的交易机制和需求侧

的可中断负荷管理的研究具有指导意义. 所取得的研究成果表明作者具有扎实的理论基础和系统深入的专门知识,具有独立从事科研工作的能力, 在答辩过程中回答问题正确. 本论文是电力市场研究领域中一篇较优秀的博士论文.

## 答辩委员会表决结果

答辩委员会经无记名投票表决,一致同意通过方勇同学的博士论文答辩, 并建议授予工学博士学位.

答辩委员会主席: **程浩忠**

2004 年 6 月 26 日

# 摘　要

电力系统的特点和市场环境下的不完全信息问题引发了发电商的各种策略性行为，从而带来了市场价格的急剧波动，影响了电力市场的安全性和经济性，资源优化配置无法实现. 而稳定市场价格、合理配置资源，系统应从供需两侧加强. 本论文应用机制设计理论、供应函数均衡、Cournot 模型、Stackelberg 模型探讨了发电侧中发电商的策略性行为、激励性发电上网竞价机制，以及需求侧中可中断负荷管理的意义和实施方法、激励性可中断负荷合同的设计和应用等问题.

首先，应用供应函数均衡模型分析了统一价格机制下信息对发电商策略性行为的影响和默契勾结持留容量的形成过程. 应用供应函数均衡模型时，同时考虑发电商策略性报价和容量持留这两种实施市场力的行为，分析了发电商从单独容量持留阶段向默契勾结持留容量阶段的演变过程. 分析发现，前一阶段容量持留和负荷水平、市场结构有关，发电商公布持留容量信息会降低容量持留发生的负荷域值；后一阶段的默契勾结会导致持续的高电价，负荷水平较高时将出现市场价格的飞升. 进一步提出了抑制市场力作用的方法，并用算例说明了分析结果. 因此，对发电商策略性行为的分析表明信息会影响发电商行为和市场价格，因而发电上网竞价机制应充分考虑市场环境下的信息不对称问题.

其次，提出了一种能合理回收容量成本的激励性发电上网竞价机制. 针对电力市场中管理者和发电商之间的信息不对称而引发发电商的策略性报价问题，本论文基于机制设计理论，提出

了一种具有激励相容特性的电力竞价机制. 该机制能引导发电商披露真实信息，从而实现经济调度，还能根据报价信息评定机组的容量成本，引导发电容量投资. 特别是该机制给予边际机组相对较多的容量成本补偿，有助于风险回避的峰机组投资商的进入. 此外，新机制的电价反映出负荷变动的趋势，能激励发电商积极响应负荷的变化，增强了系统安全性. 算例采用蒙特卡罗方法，其结果证实了新机制的良好特性. 这是本论文工作的主要创新之一.

第三，从可置信威胁角度研究了电力公司在电力市场环境下应用可中断负荷管理的方法. 电力公司实施可中断负荷管理时，电力公司与发电商的不同行动次序会产生不同的效果. 基于 Stackelberg、Cournot 模型，本文分别分析了电力公司先行动、后行动、和与发电商同时行动的市场均衡. 分析结果表明，相对于其它行动方式，电力公司先行动能中断更多负荷，也即先动优势，而更能抑制发电商的市场力. 但是，如果电力公司的行动是不可置信的，均衡结果和与发电商同时行动时相同. 进而分析了电力公司如何使其行动可置信，然后为电力公司在电力市场环境下实施可中断负荷管理的方法提供了一种解决方案. 这是本论文工作的主要创新之一.

第四，研究了具有风险特性的供电公司在电力市场中应用激励性可中断负荷合同的设计，提出的模型为供电公司参与市场竞争提供了一种新的思路. 需求侧的缺乏弹性和电力系统的特性导致电力价格剧烈波动，给供电公司带来了很大的价格风险，同时供电公司也获得了盈利的机遇. 考虑供电公司的风险偏好，本论文应用机制设计理论建立了一种用户类型离散的可中断负荷合同模型. 分析和算例表明，无论供电公司的风险偏好如何，该

合同模型均能引导用户披露真实信息，实现电力资源的有效配置，且供电公司能从中节约供电成本. 因此，激励性可中断负荷合同不仅能提高用户需求弹性，还有助于供电公司回避市场风险. 尤其是对于风险进取的供电公司，可中断负荷合同将成为其进行市场竞争和风险管理的有力工具. 这是本论文工作的主要贡献之一.

最后，从实用性出发，提出了考虑用户最大可中断负荷的激励性可中断负荷合同模型，并研究了其在电力市场中的应用方法. 针对电力公司与用户之间存在的信息不对称性可能会导致可中断负荷管理的低效问题，本文发展了一种具有激励相容特性的可中断负荷管理合同模型，可引导用户自愿披露真实缺电成本信息. 该模型能考虑用户的最大可中断负荷限制，并能适用于负荷中断分配的不同优化目标，如电力公司利润最大或用户缺电成本最小等. 然后，从电力公司、系统运行人利润最大化的角度研究了该激励性可中断负荷合同在电力市场环境下的三种应用：电力公司参与市场竞标、电力公司与风险回避的大用户签订可中断的供电合同、互联区域的系统运行人之间的互为备用的双边合同，探讨了三种应用中电力公司或系统运行人的行为，发展出三种优化模型，并提出了一般的求解方法. 这是本论文工作的主要创新之一.

综上，本文工作的第一、第二点是研究了发电侧的竞价机制和发电商的策略性行为，第三、四、五点探讨了需求侧可中断负荷合同的意义、应用方法和设计，从而共同构成了本论文提出的从电力供需两侧稳定市场价格、有效配置资源的思想.

**关键词** 电力市场，机制设计，电力竞价机制，可中断负荷合同，博弈论，蒙特卡罗

## Abstract

In electricity markets, the distinguishing features of electric power systems and the asymmetry of information between market manager and generation companies will cause some tactful bidding, which leads to acute price and will be harmful to the security and economy of electricity markets, as well as the optimal allocation for electric power resources. In order to stabilize the market price and allocate electric power resources effectively, the system should be enforced from both supply and demand sides. Based on mechanism design theory, Supply Function Equilibrium (SFE) model, Cournot model and Stackelberg model, this dissertation discusses the generators' strategic behaviors on the supply side, the bidding mechanism with incentive compatibility, the merit and implementation of interruptible load management on the demand side, and the design of incentive interruptible load contracts and its applications.

Firstly, the SFE model is employed to analyze the influence of information upon the generators' strategic behaviors and the formation of tacit collusion in withholding capacity under the uniform price mechanism. Considering the two generators' strategic behaviors, i.e., strategic bidding and withholding capacity, the transformation from the withholding capacity of individual generator to the tacit collusion of all generators is developed by SFE model.

The analysis shows that the amount of generators' withholding capacity is concerned with system load level and market structure in the former period of transformation, meanwhile the load threshold value in which withholding capacity emerges will decline if generators published their information on withholding capacity; the generators' tacit collusion will lead to durative acute prices in the latter period of transformation, and price spikes will emerge in peak load. Then the suggestions to retrain market power are put forward, and the analysis results are illustrated by numeral examples. Therefore, the analysis of generators' strategic behaviors shows that information could influence generators' behaviors and market price, so the generation bidding mechanism should sufficiently take the asymmetry of information in electricity markets into account.

Secondly, an incentive generation bidding mechanism, which can reasonably recover capacity cost, is developed. Aimed at the generators' strategic bidding behaviors resulting from the asymmetry of information between market manager and generation companies in electricity markets, a new generation bidding mechanism with incentive compatibility is designed. Based on mechanism design theory, the new mechanism is able to lead generators to publish their true information, so an economic dispatching can be carried out, moreover, it can evaluate the capacity cost of the generating unit using bidding information and attract investments for generation capacity. Specially, the new mechanism would compensate the marginal units more for capacity cost than other units, thus it would conduce to entities of these peak unit investor with risk disgust. In addition, the new mechanism can reflect the tendency of load variation and encourage generators to respond it, and enhance the system security. The illustration using Monte Carlo demonstrates the merits of the proposed mechanism. So this is one of the original contributions in this dissertation.

Thirdly, this dissertation researches the implementation of interruptible load management by utility in electricity markets from the aspect of credible menace. The different order of utility and generators moving will lead to different outcomes when utility implements interruptible load management. Based on Stackelberg and Cournot models, this dissertation respectively analyzes the market equilibriums of utility first-move, second-move and moving together with generators. The results show that the load curtailed will be more if utility moves firstly, i.e. first-mover advantage, which will be more effective to restrain market power of generators than other moves of utility. The equilibrium outcomes, however, will be identical with the ones of utility moving together with generators if utility's moves are not credible. Then this dissertation analyzes that utility how to make its moves credible, and then put forward a scheme to implement interruptible load management by utility in electricity markets. This part is one of the original contributions of this dissertation.

Fourthly, this dissertation researches the design of incentive interruptible load contracts for distribution companies with risk preference, and the proposed model will be a new way to compete in electricity markets for distribution companies. The inelasticity of demand-side and characters of electric power systems induce the electricity price dynamics, which makes distribution companies exposed to immeasurable risk, meanwhile, distribution companies get a chance to obtain more benefit as well. Taking risk preference of distribution companies into account, this dissertation designs an incentive interruptible load contract model for discrete customer types using mechanism design. The analysis and illustration both show that the proposed model can lead customers to voluntarily reveal their true information and the electric power resources to be allocated efficiently, and in the meantime distribution companies benefit from the cost saving of electric power supply whatever the risk preference of distribution companies is. Therefore, incentive interruptible load contracts not only improve customers' demand elasticity, but also help distribution companies to avoid market risk. Especially, the proposed model will be a powerful tool to compete and manage risk efficiently for risk-taken distribution companies in electricity markets. This part is one of main contributions of this dissertation.

Finally, an incentive interruptible contract model, which can take customer maximum interruptible load constraints into account, is developed from the aspect of practicability, and then its applications are researched in electricity markets. The presence of informational asymmetry between utility and customers may cause immeasurable inefficiencies in interruptible load management program, this dissertation develops an incentive compatible contract model for interruptible load management, which can lead customers

to voluntarily reveal their true outage costs information. The proposed model allows customers having maximum interruptible load constraints to be taken into account and can apply to different optimization objectives for dispatching the interruptible customers, such as maximizing the utility's benefit or minimizing the total outage cost of customers. Then, maximizing the profit of utility or system operator, this dissertation studies three applications of the proposed model in electricity markets: electric power company bidding in a spot market; an interruptible generation contracts between utility and big risk-avoided customers; the contracts between system operators of interconnected regions acting as reserve capacity. The behaviors of utility or system operator are discussed in the three applications and three optimal models are developed, then a general solution method is put forward for the three models. This part is one of the original contributions of this dissertation.

In summary, the first and second work researches into the bidding mechanism and generators' strategic behaviors on generation side, the third, fourth and fifth work discusses the merit, implementation and design of interruptible load contracts on demand side. So the above work composes the idea proposed by this dissertation that the system should be enforced from both sides of supply and demand in order to stabilize the market price and allocate electric power resources efficiently.

**Key words** electricity market, mechanism design, electricity bidding mechanism, interruptible load contracts, game theory, Monte Carlo

# 目　录