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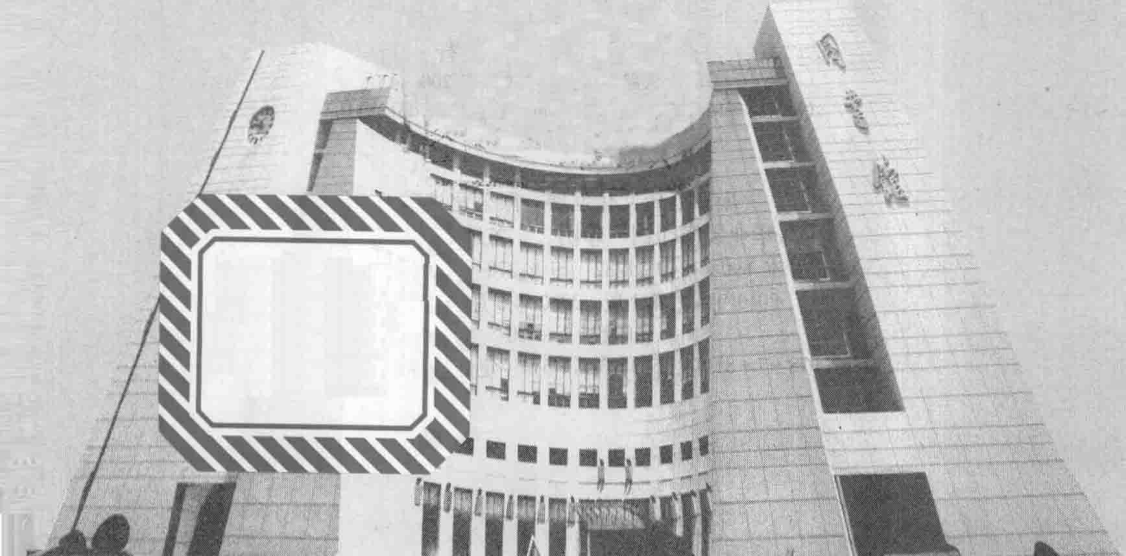

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答辩委员会对论文的评语

鉴于全球性电力工业结构重组和解除管制的市场化改革，带来了电力系统运行方式和模式的深刻变革，在电力市场环境下，市场参与者需要密切关注自己的决策行为及其产生的后果，而市场监管者更需要研究不同市场模式下的市场特性和效率。论文选题对我国大规模复杂电力市场均衡问题的研究具有重要的理论和现实意义，具有前瞻性，论文主要贡献如下：

1. 首次提出了采用非线性互补方法来求解复杂的大规模均衡问题，为求解此类问题提供了一条有效的途径。

2. 针对竞标联运模式的电力市场，进行了计及输电网络约束的多个发电商的线性供应函数均衡分析。

3. 建立了一个考虑跨时段负荷响应的电力市场多时段LSFE模型，并分析了其引入后对整个电力市场均衡结果的影响。

4. 建立了一个计及输电网络约束的区域双边电力市场线性供应函数均衡模型，并采用非线性互补方法求出市场均衡解。

5. 研究发电商在远期合同市场和现货市场中的联合竞争问题，建立了一个两市场的联合均衡模型，采用非线性互补方法求解。

论文论述严谨，条理清楚，文笔流畅。答辩过程中阐述

清楚，回答问题正确。在电力市场均衡分析的前沿研究中取得创新成果，是一篇优秀的博士论文。

以上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。

答辩委员会表决结果

经答辩委员会表决，全票同意通过王晛同学的博士学位论文答辩，建议授予工学博士学位。

答辩委员会主任：**程浩忠**

2006年6月24日

摘　要

全球性电力工业结构重组和解除管制的市场化改革，带来了电力系统运行方式和模式的深刻变革。在电力市场环境下，市场参与者需要密切关注自己的决策行为及其产生的后果，而市场监管者更需要研究不同市场模式下的市场特性和效率，因此科学合理的电力市场决策分析模型和方法的研究具有重要的理论和现实意义。电力工业的特性使得电力市场表现出明显的寡头竞争特征，因而基于博弈论的各种寡头均衡模型可用于研究各市场参与者的策略行为以及对其整个市场产生的影响，进而为市场管理者提供科学的决策依据。本论文主要涉及大规模复杂电力市场均衡模型的建立与求解，以及不同市场模式下的均衡分析研究。主要工作包括：研究利用一种特殊的非线性互补函数来求解电力市场复杂均衡问题的方法；Pool 模式下的基于直流潮流输电约束的电力市场均衡分析；计及输电约束和跨时段负荷响应的电力市场多时段均衡问题研究；计及输电网络约束的区域双边电力市场均衡问题研究；考虑输电网络约束时策略性远期合同市场和现货市场的联合均衡问题研究。具体地讲，本论文的主要内容和创新点如下：

首先，在国内外率先提出采用非线性互补方法来求解复杂的大规模均衡问题。该方法是将各博弈者的一阶优化条件(KKT 条件)组合在一起，形成一个混合的非线性互补问题，然后采用有关非线性互补函数，把非线性互补问题转化为一组非线性代数方程的求解，从而求得市场的均衡解。通常，考虑了

输电约束后的大规模电力市场均衡问题是一个复杂的数学问题,其求解一般是很有难度的。本文提出的方法为求解这些大规模复杂均衡问题提供了一条有效的途径,同时也为后续研究提供了一个坚实的方法基础。这是本论文的重要创新点。

其次,考虑到竞标联运(bid-based-pool, BBP)的发电市场竞争模式仍是目前各国电力市场中应用非常广泛的交易模式,本文采用非线性互补方法,进行了BBP模式下计及输电网络约束的多个发电商的线性供应函数均衡(linear supply function equilibrium, LSFE)分析。该均衡模型中每个发电商的决策问题为一个两层的优化问题,利用下层优化问题的KKT条件将每个发电商的两层优化问题转变为具有均衡约束的数学规划问题(mathematical program with equilibrium constraints, MPEC),因此由所有发电商竞争构成的均衡问题可归结为一个具有均衡约束的均衡问题(equilibrium problem with equilibrium constraints, EPEC),可利用非线性互补方法求解。通过3节点系统算例和IEEE 30节点的标准测试系统算例,验证了本文模型和算法的有效性。结果表明,不论是发生输电阻塞还是电力相对短缺,发电商均可通过策略性投标持留其部分出力来行使市场力。这是本论文的主要创新工作之一。

第三,针对在电力市场环境下用户负荷对价格的响应具有跨时段的特性,本论文在计及输电约束的基础上,研究用户响应价格的程度对市场均衡结果的影响,建立了一个考虑跨时段负荷响应的电力市场多时段LSFE模型。该均衡问题也可归结为一个EPEC问题,可利用非线性互补方法求解。给出的算例证明了该模型的合理性,并且表明:跨时段负荷响应对用电需求可以达到“削峰填谷”的作用,同时可以缓解由于阻塞造成的用电不合理分配,从而提高全系统用户的总体利润,达到鼓励

用户合理安排用电的效果。另一方面,跨时段负荷响应的引入可有效抑制发电商的市场力,降低整个市场的均衡价格,并且跨时段负荷响应程度越大其效果越明显。这也是本论文的一个主要创新。

第四,针对电力市场中出现的更加开放的双边交易模式以及区域电力市场的组建趋势,本文建立了一个计及输电网络约束的区域双边电力市场 LSFE 模型。该均衡模型中采用一种基于线性直流潮流模型的传输阻塞定价机制,并引入了多个套利者来消除电力市场中的不合理节点价格差。对于均衡模型求解中出现的非线性互补问题,采用非线性互补方法求解。利用 30 节点的 IEEE 测试系统作为算例,验证了模型和算法的有效性,而且表明:不论网络的阻塞程度如何,套利者的出现均可以起到降低市场电价、限制发电商市场力的作用,同时有利于整个市场社会福利的提升和消费者的利益。这是本论文的又一个主要创新工作。

最后,面对当前国内外电力市场的实际运营要求,在计及输电网络约束的基础上,研究发电商在策略性远期合同市场和现货市场中的联合竞争问题。采用 LSFE 模型来描述发电商在现货市场的竞争行为,用古诺模型来模拟其在策略性合同交易中的竞争行为,建立了一个两市场的联合均衡模型。该模型可归结为一个 EPEC 问题,可用非线性互补方法求解。通过一个 3 节点算例验证了模型的合理性和算法的有效性,并且表明:不论输电网是否阻塞,发电商都将自愿参与策略性远期合同交易,从而可使整个市场均衡价格下降,有效地抑制发电商的市场力。当输电网没发生阻塞时,具有成本优势的发电商更愿意通过现货市场来获利。而当输电发生阻塞时,处于阻塞有利地位而更具有地方市场力的发电商,更趋于通过合同市场来牟

利。整个市场的策略性合同份额还与市场需求弹性和发电成本密切相关。这也是本论文的主要创新性工作之一。

关键词 电力市场,均衡分析,非线性互补方法,输电约束,跨时段负荷响应,区域双边交易,策略性远期合同

Abstract

The worldwide restructuring and deregulation of electric power industry has being significantly changed the operation style of power systems. In the deregulated market environment, participants are required to pay much attention to the consequence of their own decisions, while market regulators need to understand the corresponding market features and efficiency of different market modes. As such, developments of reasonable decision-making models and methods have significant implications in both theoretic and practical respects. The unique features of electric power industry make the electricity market more akin to an oligopoly. Consequently, a variety of oligopolistic equilibrium models are used to quantitatively examine the strategic behaviors of market participants and their impacts on the whole market. These examinations are extremely helpful for market regulators' decision-makings. This dissertation addresses issues of equilibrium analysis of large-scale, complicated power market systems. The main research work includes: solution approach to equilibrium models of complicated electricity markets using a special nonlinear complementarity function, equilibrium analysis of a bid-based-pool (BBP) generation market with DC power flow

constraints, multi-period equilibrium analysis of electricity market taking into account cross-time response of load demand and transmission constraints, equilibrium analysis of regional bilateral electricity markets using a DC transmission model, joint equilibrium analysis for electricity forward and spot markets with transmission constraints. The main work and key contributions of this dissertation are as follows:

First, this dissertation launches the introduction of nonlinear complementarity approach in the solution of large-scale complicated equilibrium models. The proposed method involves gathering the Karush-Kuhn-Tucker (KKT) conditions of each participant to form a mixed nonlinear complementarity problem (NCP). Using a special nonlinear complementarity function, the mixed NCP is reformulated as a set of nonlinear algebraic equations. Then the market equilibrium can be obtained by solving these equations. Since equilibrium problems for large-scale electricity markets with transmission constraints are sophisticated mathematical programs, the proposed method provides an efficient way to the solution of these equilibrium models, and also paves the way for our subsequence research work. This part is one of the key contributions of this dissertation.

Second, a LSFE model with DC power flow constraints is developed to analyze the generators' competition behaviors in BBP generation markets. In this model, each generator forms its decision-making problem as a two-level optimization problem, which can then be transformed into a mathematical program with equilibrium constraints (MPEC) using KKT conditions of the lower level problem. Therefore, an equilibrium problem with equilibrium constraints (EPEC) can be formed by combining all generators' MPEC, and can be solved by the nonlinear complementarity method. To illustrate the effectiveness of the above method, numerical examples of 3 - bus system and 30 - bus IEEE test system are conducted. It can be shown that the generators will exercise their market power through strategic bidding and withhold their capacity in case of either power shortage or transmission congestion.

Thirdly, a multi-period LSFE model of electricity markets is proposed, with cross-time load demand response and transmission constraints included. This equilibrium model can be categorized as an EPEC and be solved by a nonlinear complementarity method. Numerical examples are presented to validate the reasonableness of the model. It is also shown that with cross-time load demand response, the customers' load can be shifted from on-peak time to off-peak time, and also the unreasonable allocation of loads caused by transmission congestion can be relieved. As a result, the customers' whole profits can be increased and thus customers' reasonable arrangement of electricity consumption can be achieved. On the other hand, with cross-time load demand response, the equilibrium prices of the whole market are decreased apparently, and thus the market power abuse of generators can be effectively mitigated. Furthermore, the more the degree of cross-time load response, the larger the above effects will be. This work is also one of the main contributions of this dissertation.

Fourthly, a LSFE model for regional bilateral electricity power market is developed which includes a congestion pricing scheme for DC transmission constraints. Arbitragers are considered to eliminate those nodal price differences that are non-cost based. The nonlinear complementary approach is used to solve the mixed NCP arising from the solution of equilibrium model. Simulations based on the 30 - bus IEEE test system are presented to validate the reasonableness of the model and the method. It is revealed that no matter what degree of transmission congestion is, the presence of arbitragers is helpful to mitigate the market power abuse of generators and lower the market prices, uplift the social welfare and customers' surplus.

Finally, facing the practical requirements of electricity markets currently implemented around the world, generators' gaming in both forward contract markets and spot markets is addressed. A joint equilibrium model is proposed taking transmission constraints into account. The LSFE model is used to emulate the generators' bidding in the spot market, while the contract market is modeled with Cournot competition. The whole equilibrium model can be formulated as an EPEC, which can be solved by a nonlinear complementarity method. Numerical examples are presented to validate the reasonableness and effectiveness of the

proposed model and solution method. It is shown that strategic generators will voluntarily participate in strategic forward contracting regardless of transmission congestion, and thus their market power abuse can be effectively mitigated and the equilibrium market prices can be lowered. It can also be demonstrated that the generators with lower generation costs are more willing to make profits in spot markets when there is no transmission congestion. In contrast, when transmission congestion occurs, the generators with localized market power are more inclined to make profits in contract markets. The volume of the strategic forward contracting is closely related to generators' cost parameters and demand elasticity. This work is also one of the main contributions of this dissertation.

Key words Electricity market, Equilibrium analysis, Nonlinear complementarity method, Transmission constraints, Cross-time load demand response, Regional bilateral trading, Strategic forward contracting