2003年上海大学博士学位论文 10

输电当量电价方法论及其应用

作 者：辛洁晴
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上海大学出版社
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Shanghai University Doctoral Dissertation (2003)

The Transmission Electricity Value Equivalent Methodology and Its Implementations

Candidate: Xin Jieqing
Major: Control Theory and Control Engineering
Supervisor: Prof. Yan Maosong

Shanghai University Press
• Shanghai •

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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答辩委员会对论文的评语

输电定价是电力市场环境下电网运营的关键问题，又是电力市场中一个难题. 作者针对这一问题进行了系统、深入的研究，其选题具有重要的理论意义和应用价值.

论文的研究工作取得了显著的创造性成果. 论文的主要创新点包括:

1. 将其导师提出的“发电实用当量电价法”发展和推广到输电服务的定价，首次提出了输电当量电价的概念，建立了相应模型，为解决输电电价即能反映经济信息、又能回收投资和运行成本提出了新的方法，并论证了其优点;

2. 为了适应市场发展的不同阶段，作者基于输电当量电价理论，提出了两种风险程度不同的输电定价方法，以有利于引导投资的高效率;

3. 基于输电当量电价的概念，论文提出了阻塞管理的模型与方法，发展了过网运行备用辅助服务定价的新方法，这些方法和输电当量电价方法形成完整的体系，具有很好的实用意义;

4. 论文提出了新的市场力指标，即按负荷侧销售市场的占有份额来考虑市场力，该指标可计及网络阻塞引起的市场力.

论文的工作量较大，写作严谨，条理清楚. 论文提出的输电当量电价理论具有重要的理论意义和潜在的实用价值. 该论文是一篇优秀的博士学位论文.

论文表明作者具有宽广的专业知识，综合分析能力和独立从事科学研究的能力，在课题研究上做出了创造性的成果，达到了博士论文水平. 答辩中回答问题正确清楚.

答辩委员会表决结果

经答辩委员会表决，全票同意辛洁晴通过博士学位论文答辩，并建议授予其工学博士学位.

答辩委员会主席：王锡凡

2003 年 6 月 26 日

摘　要

电力市场改革为输电网的运营带来一系列新的问题. 厂网分离后，输电网要独立生存，资源优化配置要靠自愿的交易行为和价格的引导，电网的发展要适应市场需求、投资要靠利益驱动，输电网的垄断运营需要监管；并且，随着双边交易的发展，现存输电容量很可能无法满足市场运行的需要，电网的安全可靠运行也将面临挑战. 在这些问题中，输电定价是基础和关键，良好的定价方法能使其他问题迎刃而解. 因此，本文针对“库联营+双边交易”的市场模式，从设计输电定价方法出发，论及阻塞管理、双边交易过网及其运行备用服务、市场势力监测等问题. 它们都是电网运营的基本问题，又是尚未得到良好解答的难题.

由于输电网的规模经济性，市场效率和充分回报是输电定价的两难问题，所有现存方法都未很好解决. 为此，本文提出“输电当量电价（TEVE）方法论”，它依据和发展了经济学原理，主张：必须首先保证交易市场上的资源配置效率、维护经济调度潮流不被扭曲，在此条件下，可以在定价中采用嵌入容量成本的方法，实现总量充足的输电费初分配（第 1 输电市场原则）；逐线收支平衡本质是各投资者之间收益分配的公平性问题，应当在市场之外、通过线路间输电费的再分配解决（第 2 输电市场原则）. 如何嵌入线路容量成本而不改变经济调度潮流是其中的难点，TEVE 的办法是将全网容量费总需求比例于线损分摊到各线路、并可变化，与线损成本构成线路当量成本，进而构成当量成本最小化的边际成本定价问题. 该方法的本质是将容量费作为线路

等比加长后虚拟的线损成本收取；如果节点注入是恒流源，且网络是无源网，则线路等比加长、潮流基本不变，从而能较好地做到市场效率和充分回报的矛盾统一. 对此，论文作了理论证明和算例检验.

根据线路容量成本可变化中单位容量成本（过路费率）设置的不同，论文发展了TEVE-I和TEVE-II两种输电定价方法. I型的过路费率有单位容量社会一般投资的含义，监管部门通过设置宏观参数间接控制输电价格水平，而实际的输电费还与交易市场上线路的利用率有关，这能激励网公司开放电网的使用和优化输电投资决策. II型则严格比例于线损分摊全网会计学容量成本来设置过路费率，且容量费与潮流的关系较弱，网公司很大程度上规避了风险，但也损失了相应的激励机制. 两种方法蕴含的"宏观调控、风险回报"机制是现有的定价方法所不具备的；而两种方法相比，I型更符合市场原则，II型则可在市场初期使用.

两种TEVE定价在建模上具有共同的良好特性. 第一，定价目标中的发电成本部分采用"发电实用当量成本"，它计入了可变的发电容量成本但又不改变电量成本排序，从而在维护经济调度潮流的同时，使阻塞价格项兼顾线路扩建节省系统容量和电量成本两方面的效益，为电网扩建筹集充足而合理的资金. 第二，定义"线路线损系数"线性化线损，同时采用DC潮流，使定价成为计算上高效的线性规划问题. 第三，定义"传送"作为新的决策变量，它不同于注入和潮流，表示发电-负荷节点间独立的电力交易，从而在优化中实现交易、潮流的解耦和线路容量费在用户间的合理分摊；论文还通过算例说明了该方法与现有的潮流跟踪法的差异. 第四，将双边交易等值为库联营交易计入定价模型，统一解耦，得出过网价格. 上述特性为解决输电网运营的其他问题

提供了条件.

在阻塞管理问题上，目前一般只注重于短期市场上线路过负载的消除，而本文从短期和长期两个角度考察该问题. 从短期来看，当价格引导的发电计划调整（间接阻塞管理）无法完全消除线路过载时，论文提出将用户“支付意愿”引入 TEVE 定价模型，以市场效率为目标进行负荷削减（直接阻塞管理）；从长期来看，阻塞本质上反映线路容量不足，需要通过电网优化发展、从根本上加以解决，而基于 TEVE 的阻塞管理，其阻塞价格项能为线路扩建合理地积累更多的资金.

对于双边交易，网公司不仅要提供过网服务，还要根据交易方的要求提供各种辅助服务，其中重要的一项是运行备用. 本文主张备用容量在日前 Pool 市场上统一计划采购，并基于这种备用采购方式，对过网备用定价提出了一种概率学的方法. 该方法首先通过随机生产模拟找出次日期望加载的发电单元，并应用“随机性发电实用当量电价法”评定其容量和电量费的期望值；进而在期望交易状态下进行 TEVE 定价，利用 TEVE 模型的交易解耦特性，找出双边交易买方的期望电力来源、即备用电源，并将相应的备用费予以合理分摊. 过网的运行备用定价是一个崭新的领域，本文的工作为此提供了一条新的思路.

衡量市场势力常采用市场份额和集中度指标. 然而，电力市场中，由于输电约束和输电成本，占整个市场份额不大的发电厂商仍可能垄断局部负荷供应；而且，发电容量或出力的大小并不能反映厂商的市场势力，市场势力根本上表现为厂商能占据多大的电力销售市场. 为此，论文发展了经济学中“相关地理市场”的概念，提出在负荷侧划分“电力相关市场”的方法，进而利用 TEVE 模型的交易解耦特性，评定厂商在相关市场内的销售量占有率和

集中度新指标. 算例验证了新指标的正确性，并表明评定发电厂商的市场势力有必要计入输电网的影响.

论文最后给出了一个具有我国华东电网背景的算例. 算例在"n-0"、"n-1"、"n-2"三种电网运行状态下，通过与短期边际成本（SRMC）法的比较，对 TEVE 法进行了检验. 结果表明：TEVE 定价能保持与 SRMC 法一样的经济调度潮流，但后者的节点电价平均仅为前者的 60%，输电价格平均不到前者的 50%，网公司收入仅为前者的 21%~50%；如果对三种运行状况作概率加权平均，网公司采用 SRMC 法的年输电费约为 2.07 亿元，而采用 TEVE 法可达 8.61 亿元，并且，这种增益不同于任何会计学方法下输电费的简单增长，因为 TEVE 的阻塞价格项比之 SRMC 法有所增长，且能跟随市场需求给出合理的线路扩建激励. 此外，论文还对我国区域电力市场的运作作出了一些有益的初步结论.

关键词 电力市场, 输电定价, 过网定价, 阻塞管理, 运行备用, 市场势力

Abstract

The power industry restructuring brings a series of new challenges to the operation of the transmission networks. Firstly, the grid has to survive independently after unbundled from the generation sector; secondly, efficient resource utilization depends on voluntary transactions and the guidance of price signals; thirdly, networks shall be developed according to market demands while transmission investments turns to be profit-driven; fourthly, supervision must be loaded on the transmission monopoly; and finally, with increasing bilateral transactions, the existing networks are likely not have enough capacities for market operation, and system security and reliability might also be challenged. For these issues, transmission pricing is the key and foundation; a good pricing methodology can make the others easily solved. Therefore, under the assumption of a "Pool + bilateral transactions" market environment, this dissertation starts with the design of a transmission pricing method, then remarks other unsolved elementary transmission problems, including congestion management, wheeling and its operating reserve service, as well as measurement of the generators' market power.

Due to economies of scale of the transmission networks, market efficiency and revenue sufficiency are hard to be harmonized in transmission pricing. None of the existing pricing methods gives good reconciliation to these two sides. A "transmission electricity value equivalent (TEVE) methodology" is therefore presented in this

dissertation, which is based on such two market principles: 1) optimal resource utilization manifests itself as the optimal power flows by economic dispatch; on condition that the optimal power flows keep undistorted, line capacity costs can be embedded in the pricing objective so as to gather sufficient revenues for the grid as a whole; 2) revenue reconciliation of every individual line essentially reflects the fairness of income allotment among the network investors, and therefore shall be realized out of the market by redistributing the transmission revenues among the lines. A difficulty wherein is how to embed the lines' capacity costs without distorting the optimal power flows. The solution of TEVE is to first allot the grid capital cost among all the lines in proportion to the line losses, variating the allotments and then adding to the loss costs to define the lines' equivalent costs, and finally constructing a marginal cost pricing problem with an equivalent-cost-minimizing objective. The essence of this method is to charge line capacity fees as increased loss costs when all the lines are fictitiously lengthened by a same rate. Since power flows in a passive network nearly don't change if nodal injections can keep constant when all the lines are lengthened by a same rate, the new method can basically maintain market efficiency at the same time of producing sufficient transmission revenues. This feature is proved by analytical derivation and numerical examples in the dissertation.

By differently defining the variated capacity costs (or passing rates) of the lines, two pricing methods titled as TEVE-I and TEVE-II are developed. For the former, passing rate is the socially general investment on per unit MW of a line. The supervision entity controls the transmission price level indirectly by setting certain macro-regulation parameters; the ultimate network revenues, however, also relate to the use of the transmission facilities on the market. Grid companies are hence stimulated to optimize their transmission investment decisions and to maintain the open use of the networks. In contrast, passing rates in TEVE-II are defined by allotting the grid accounting capital cost strictly in proportion to the line losses, network revenues being loosely related with the power flows. Grid companies can almost evade risks, but the stimulus functions are vitiated accordingly. The two methods both follow the market rules of "macro-regulation" and "risk-bearing investment" which are not incorporated by any other existing transmission pricing methods; but when compared with one another, TEVE-I is more suitable for a developed market environment, while TEVE-II might be used at the elementary stage of the power markets.

The two TEVE methods have several common good features in modeling. First, "practical generation electricity value equivalents (GEVEs-p)" are used instead of generation variable costs in the objective. As GEVEs-p incorporate generation capacity costs but keep the same order of the variable costs, the TEVE pricing can maintain the economic dispatch solution and at the same time, derive congestion rents conceptually reflecting the benefits of line expansions in sparing both the system variable costs and capacity investments. Second, "line loss rates" are defined for loss linearization and DC flow equations are used, so that the TEVE pricing can be modeled as a computationally efficient linear programming problem. Third, a new decision variable named "delivery" is introduced in the pricing model. Unlike nodal injections or power flows, delivery is decomposed transaction from a generation node to a load node. Transactions and power flows are hence decoupled directly in the process of pricing for rationally distributing the passing costs among the network users. This new decomposition method is compared with the existing flow tracing one by a numerical example. Fourth, wheeling of every bilateral transaction is treated as virtual Pool unit and load, being decomposed uniformly and then priced in the model. The above characteristics in TEVE modeling facilitate the solution of the following problems in transmission.

As for congestion management (CM), the existing methods generally only focus on the relief of line overloads in short-term operation; this dissertation, however, solves the CM problem from both the short-term and the long-term views. In the short term, when price-induced redispatch (the indirect CM method) cannot relieve line overloads thoroughly, "willingness-to-pays" of the network users are introduced into the TEVE model to curtail the loads under the goal of market efficiency (the direct CM method). In the long term, congestion reflects shortage of transmission capacity and should be solved radically by network expansion; the congestion rents derived by the TEVE method can reasonably gather more funds for this purpose.

Apart from wheeling of power, the bilateral traders may also ask the grid company to arrange various ancillary services for them. One important ancillary service for wheeling, the operating reserve, is studied in this dissertation. It is first recommended that operating reserves be scheduled on the day-ahead Pool market, then a stochastic method is offered for pricing reserve services in wheeling. By the method, the generation units expected to be loaded in the next day are first determined through stochastic production simulation, their expected capacity values and electricity costs being evaluated by the "stochastic GEVE-p pricing method"; next, the TEVE pricing is executed under the expected transaction conditions and due to the transaction decoupling function of the TEVE model, the expected electricity sources (i.e. the reserve suppliers) of the contracted buyers can be specified and the reserve costs can be allotted accordingly. Wheeling pricing incorporating reserve services is still an area with little research findings till now, and this dissertation provides a possible solution for it.

Market share and concentration indices are usually used for measuring sellers' market power. In power markets, however, due to transmission constraints and costs, a generator not occupying a large share of the whole market, may still monopolize electricity supplies in local areas; meanwhile, it is not shares of generation capacities or outputs, but shares of electricity sales that really show the market power of the generators. In these lights, this dissertation develops the economic concept of relevant geographic market and presents a method for dividing electricity relevant markets on the load side; the sales' shares and sales' concentrations of the generators are further evaluated within the scopes of relevant markets by implementing the decomposition function of the TEVE model. A case study is provided to examine the validity of the new indices; the results also show that it is necessary to incorporate the impacts of transmission networks when measuring the generators' market power.

A numerical example with a background of the East China regional power system is provided at the end. The TEVE method is examined by comparison with the SRMC one under three network conditions of "n-0", "n-1" and "n-2". The results show that the TEVE pricing keeps the same optimal power flows as the SRMC method, but nodal prices by the latter averagely take only 60% of those by the former, transmission prices averagely not reaching 50%, and the grid revenue ranging 21%~50%; the probabilistic average of the grid yearly revenues under the three network conditions is no more than 207 million yuan by the SRMC method, while reaches 861 million yuan by the TEVE method. The increments are different from those could derived by the accounting pricing methods, since it is shown that the increments also come from the increase of the congestion rents which can vary with the use of the lines' capacities, reflecting the worth of expansions corresponding to the market demands. Besides, some conclusions are made from the results of the example, which are expected to be helpful to the regional market operation in China.

Key words electric power market, transmission pricing, wheeling pricing, congestion management, operating reserve, market power