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Congestion management in competitive power market: A bibliographical survey

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Abstract

Congestion management is one of the major tasks performed by system operators (SOs) to ensure the operation of transmission system within operating limits. In the emerging electric power market, the congestion management becomes extremely important and it can impose a barrier to the electricity trading. This paper presents papers/literature on congestion management issues in the deregulated electricity markets. There are 211 citations referenced in this bibliography. The general electronic web sites and the web sites dealing with the issue of congestion management are also listed.

Keywords: Electricity market; Congestion management; Bibliographical survey; Electronic information

1. Introduction

Existence of transmission system constraints dictates the finite amount of power that can be transferred between two points on the electric grid. In practice, it may not be possible to deliver all bilateral and multilateral contracts in full and to supply all pool demand at least cost as it may lead to violation of operating constraints such as voltage limits and line over-loads (congestion). The presence of such network or transmission limitation is referred to as *congestion.* Congestion in a transmission system, whether in vertically integrated or unbundled electric systems, cannot be tolerated except briefly, since this may cause cascade outages with uncontrolled loss of load. The cost associated with necessary remedial measures to relieve congestion can increase to a level that could present a barrier in electricity trading. Therefore, congestion management has been at the center of debate over facilitating competition in electricity industry.

With difficulties in building new transmission lines due to problem of right-of-the-way and financial crunch and the significant increase in the power transactions associated with the competitive electricity markets, maintaining system security has become one of the main concerns for market and system operators than ever. Transmission congestion may prevent the existence of new contracts, lead to additional outages, increase the electricity prices in some regions of the electricity markets, and can threaten system security and reliability [12,17,23,28]. In USA, these problems are eventually concerned with general agreement on parallel paths (GAPP) [59]. With the issuance of Federal Electricity Regulatory Commission (FERC) order no. 2000, a major policy step has been taken encouraging the efficient energy markets.

The problem of transmission congestion management and pricing has been identified as one of the critical and important tasks of the independent system operator (ISO) for the smooth functioning of competitive electricity markets [5,11,48].

In recent years, a considerable amount of literatures have been published on congestion management issues in electricity market. Hence, there is a need of a comprehensive

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survey at one place so that academicians, utility engineers and researchers in this area can easily get information related to the important references and websites to understand methodologies and practices of congestion management. In the present paper, a year-wise bibliographical survey with citation of 211 references and some of the electronic web sites has been reported.

2. Congestion management approaches

The system operator (SO) in a competitive electricity market is responsible for determining the necessary actions to ensure that no violations of the grid constraints occur. The comprehensive set of actions or procedures are referred as congestion management (CM), which principally consists of re-dispatch of generation and load levels so as to establish a system state without violations of system constraints. The cost of congestion management plays a major role in attaining such a state. In addition, SO may divide a grid into separate pricing zones to manage congestion.

Based on the literature review, the three forms of the congestion management have been adopted in deregulated electricity market (EM) around the world [59]. One form is based on centralized optimization with some form of optimal power flow program or depending upon the control measures executed by the SO for congestion relief. A second form is based on the use of price signals derived from ex ante market resolution to deter congestion by constraining scheduled generator output prior to real time operation. A third form seeks to control congestion by allowing or disallowing bilateral transmission agreements between a producer and a consumer, based on the effect of the transaction on the transmission system.

Congestion management approaches are based on issuing orders by the SO to various parties to reschedule their contracts, re-dispatch generators, use various control devices, or shed loads in the extreme conditions when these measures are not able to mitigate congestion [12,52,59]. Other solutions are based on finding new contracts that redirect flows on congested paths. Phase shifters, tap change transformers, and FACTS controllers may play a vital role in a deregulated electricity markets to mitigate transmission congestion problem [103,200].

California ISO uses the grid portioning into a number of preferred zones [176]. The auction-based results provide preferred schedules established by the several scheduling coordinators (SCs) in the bilateral markets. In case the market dispatch results the congestion even after re-adjustment bids, then it is eliminated using re-dispatch with zonal partitioning. Congestion re-dispatch provides zonal prices and transmission usage prices with the interface flows. On the other hand, new markets for Firm Transmission Rights (FTR) have been introduced as a way to negotiate the ownership of congested paths and to provide market mechanisms to improve economic efficiency in the use of transmission network.

England and Wales market has only one zone and no constrained interfaces are considered for market dispatch. In the congestion re-dispatch stage all the constraints of the system are considered and every bus becomes a zone. The loads do not participate in congestion management. Generators are re-dispatched by ISO and may receive compensation due to congestion. The additional congestion charge is distributed to consumers as part of uplift. Generators that are selected for relieving transmission congestion are "constrained on" regardless of their bid prices. Locational market power screen is also currently used in New England market for congestion management.

In Pennsylvania–Jersey–Marryland (PJM), ISO conducts a centralized market dispatch for each time in the scheduling interval. In the market dispatch, nodal prices are computed corresponding to specific constraints. During congestion, each node is a zone with its zonal price and each line is the inter-zonal interface. Electric Reliability Council of Texas (ERCOT) balancing energy market includes two submarkets: zonal portfolio congestion management market and local unit specific congestion management market. The function of the first market is to purchase portfolio balancing energy bids to maintain power balance between qualified scheduling entity's generation schedule and ERCOT short-term load forecast and manage any zonal congestion. The function of the second market is to deploy unit specific balancing energy up and down bids to manage local congestion.

In Nord Pool, two main methods of zonal pricing for inter-zonal and counter purchases for intra-zonal congestion are used for congestion management. In zonal pricing based method, the system is partitioned into price zones. The counter purchasing consists of constraining off some generators on the grid as regard to congestion location and constraining on better-placed generators to manage congestion.

Congestion management with optimally placed FACTS controllers has been presented in [62,103]. Verma et al. [102,109] proposed a simple and efficient model for location of unified power flow controller (UPFC) for congestion management. Wang [124,137] proposed FACTS devices in FTR optimal auction model to manage congestion. Brosda and Handschin [117] described integration of FACTS devices into different congestion management schemes in order to assess the reduction of cost of congestion in the presence of different FACTS controllers. Huang and Yan [129] examined the impact of FACTS devices in congestion management by reducing transaction curtailment and total transfer capability (TTC) improvement issues. Optimal location based on generation cost minimization of phase shifters using mixed integer LP (MILP) is presented in [139]. Utilization of other FACTS controllers for congestion management is presented in [158,164,165,174,187,200].

Congestion may be prevented to some extent by means of reservations, ownership rights, and congestion pricing [3,8,10,17,114,126]. Efficient reactive power management in the electricity markets may play an important role in con-

trolling congestion effectively [154,195]. The application of tracing based approach in [36,166] and power flow based method in [87] have been adopted for the congestion management. Some of the papers [134,136] discussed the real time congestion management for hybrid market structures. Applications of information technology have been discussed in [145,184].

Shirmohammadi et al. [29] defined SO as a generic operator of an open access transmission system and identified congestion management as one of the important responsibilities of the SO. In papers [21,30,42,64], the role of California ISO (CAISO) has been described for efficient and secure operation of markets. Allen et al. [35] presented the information known to SO in three energy market structures for establishing efficient transmission strategy. Role of regional transmission operator (RTO) in congestion management has been described in [127,148,152]. Yamin [178] described effective models of RTO and their key function to manage congestion. Yoon et al. [110] described the role of transmission provider on market management. Several books are now also available for electric power markets design and management [1,22,31,84–86,125,126]. Gaming approach is also fully utilized in electric market management [63].

Based on the literature review, the congestion management methods can be categorized as:

- sensitivity factors based methods;
- auction based congestion management;
- pricing based methods;
- re-dispatch and willingness to pay methods;

The literature on these methods is presented in the next section.

3. Sensitivity factors based methods

Linear sensitivity factors based approaches for congestion management have been presented in [15,79,135,160,195]. Ning [32] proposed congestion clusters based on DC power transfer distribution factors for an efficient congestion management. Alvarado [33] proposed power system application data dictionary to implement efficient codes in MATLAB used for congestion management. Network congestion assessment methodology by introducing congestion cost index is proposed in [94]. Bialek et al. [67] proposed improvements in National Electricity Regulatory Commission's (NERC) transmission loading relief (TLR) procedures based on power transfer distribution factors (PTDFs) and congestion management process by allowing multilateral trades. Overbye [92] discussed assessment of impact of PTDFs in TLR procedures in NERC's congestion management.

Vlachogiannis [78] proposed formulae to express the contribution of each generator to the power flows, loads, and losses in power systems and these formulae are tested to relieve transmission congestion. Nimura and Niu [156] proposed simple and transparent set of indices to represent the level of agreeable load curtailment in congestion conditions. Kumar et al. [193] proposed congestion clusters based on AC load flow approach to manage congestion. Same authors proposed an efficient zonal congestion management approach using real and reactive power rescheduling based on AC transmission congestion distribution factors considering optimal allocation of reactive power resources [194]. A statistical method to predict line congestion, which can help ISO to alleviate congestion, is presented in [177]. Liu and Gross [143,203] provided systematic study on the role and effectiveness of distribution factors in congestion revenue right (CRR) application for congestion management.

4. Auction based congestion management

Hogan [2] proposed a concept of contract network and introduced FTR to hedge the financial risks of congestion-induced price variations. Chao et al. [6,76] proposed flow gate right (FGR) to price each congested line explicitly. Seeley et al. [43] examined integrated auction mechanism to prevent congestion. A combined zonal and FTR scheme has been presented to manage congestion in [4,9,14,47]. Bushnell [49] discussed the issue of transmission congestion contract (TCC) to manage congestion. It is proved in [51] that both flow gate right (FGR) and FTR arrive at the same social welfare. Yu [58] proposed an algorithm for long-term values of transmission rights (TR) to manage congestion. A generalized algorithm for fixed transmission rights auction to manage congestion is proposed in [68].

A decentralized optimization based auction mechanism to manage inter-ISO congestion is presented in [105]. David [53,146] presented locational marginal price (LMP) and FTR for congestion management. Transmission rights for congestion management and market power is presented in [75]. Issues of financial transmission rights to manage congestion are presented in [83,89,91,133]. Ritcher et al. [99] presented FTR options as a new product to manage congestion. Yoon and Ilic [113] examined secondary markets for transmission rights and compared its performance with TCC and FTR. Yoon et al. [112] described market mechanism for inter-regional transmission management. Interruptible physical transmission contracts mechanism to ensure optimal curtailment policy for congestion management is presented in [108].

Congestion management options in three southeastern states based on LMP, FTR, and rescheduling of generation resources are presented in [119]. Analysis of five market-based methods are presented and described in [115]. Oren [134] presented necessity of tradable physical flow gate rights for congestion relief across multiple regions. Conejo et al. [175] presented an auction-based mechanism for congestion management. Ma et al. [153,183] presented the developments of LMP based markets, FTR market for congestion hedging, and ancillary services markets evolving towards standard market design (SMD).

Bruno et al. [186] introduced financial hedging tools to replicate interruptible load supply contracts in transmission management. The article [192] described empirical analysis of New York ISO's (NYISO) TCC market for hedging congestion risks. Neill et al. [90,172,191] defined contingent financial transmission rights for the future SMD. Liu et al. [199] presented a mathematical framework for design and analysis of congestion revenue rights financial markets for congestion management. A static simulation model is proposed and developed for nodal and zonal dispatching incorporating marginal theory for congestion management system (CMS) under FTR and FGR [204]. Hamoud [202] described a simple method for determining TCC and LMP. An auction-based model is proposed in [209] for the ISO operating in bilateral contract market, for real time selection of interruptible load offers for congestion management.

5. Pricing based methods

Finney et al. [16] presented a method for decomposition of spot prices to reveal congestion cost component in a pool model. Price area based congestion management in Norway and Buyback method in Sweden is illustrated in [20,26]. Congestion management based on nodal congestion price signal is presented in [13,25,27]. Gedra [37] provided tutorial review to calculate optimal bus prices and congestion costs using DC load flow based approach. LMP based congestion management for PJM is presented in [41,161]. Hyman [45] discussed the key issues of transmission pricing and congestion in electricity markets.

Gribik et al. [46] presented nodal and path based marginal pricing for congestion management. The various congestion management methods are illustrated and evaluated in [50,55,59,65,176]. Bompard et al. [70] investigated relationship between real and reactive nodal prices and evaluated the impact of congestion to develop appropriate price signals in the pool paradigm. Chen et al. [72,132] presented a method to decompose nodal prices into generation, congestion, and voltage limitations. The impact of load elasticity in congestion management and pricing has been investigated in [71]. The influence on social welfare of planned expansion of transmission system and congestion management for network security and reliability is presented in [81].

A congestion cluster pricing method for congestion management formulated as a stochastic optimization problem is described in [111]. An optimization based approach to estimate congestion rent for day-ahead and hour-ahead markets is proposed in [107]. An OPF based on the two-sided auction market structure reducing nodal price volatility and allows congestion relief is presented in [116]. A multi-agent simulation model, which takes into account the potential impact of congestion management on market prices, is presented in [168]. A new congestion management system based on locational pricing with two new approaches for locational power market screening is presented in [128,130]. Pricing signals as shorter-term solution to congestion management has been presented in [144].

A decomposition method is proposed in the Electric Reliability Council of Texas (ERCOT) portfolio zonal congestion management market to set feasible clearing prices [149,150]. A method to manage transmission congestion based on ex ante congestion prices is presented in [173]. A decentralized approach for congestion management based on the previous work of [6,34,51] is proposed in [171] to discover the congestion price in spot market. A multi-objective OPF with voltage security constraints considering transmission congestion using LMP is presented in [182]. An estimation of contribution of market participants to congestion component of nodal prices is presented in [196]. DC and AC power flow methods are compared for LMP calculation and revealing congestion patterns in [197].

6. Re-dispatch and willingness-to-pay methods

Pool and bilateral contract dispatches and the priority arrangements for line congestion and curtailment strategies are discussed in [18]. Srivastava and Kumar [61] presented an OPF based model for reducing the congestion with minimum curtailment of contracted power. David [19] developed mathematical model for pool, bilateral, and multilateral dispatch coordination including congestion and transmission charges. An overview of short, medium, and long-term scheduling of generators along with congestion management for Norway electricity market is given in [38]. Optimal transmission dispatch methodology considering willingness to pay premium for minimum curtailment strategy is proposed in [40,44].

An integrated strategy to manage congestion in a real time operational environment is proposed in [39,56,60,138]. Reliability management considering optimal dispatch under transmission congestion is determined in [54]. A simple and efficient algorithm for assessing feasibility of bilateral transactions, which can help system operator (SO) to manage market, is proposed in [57]. Merit order curtailment for managing congestion is presented in [69,93]. An efficient procedure minimizing the adjustments in preferred schedules to manage congestion is proposed in [74]. Optimal dispatch considering dynamic security constraints is presented in [73]. Optimal dispatch model to manage congestion for the feasible contracts is presented in [77]. A Lagrangian relaxation method to congestion management is presented in [96,122].

Congestion management based on corrective measures is proposed in [95]. Fast LP algorithm to manage congestion by rescheduling generation in Chinese electricity market is presented in [88]. A congestion management problem with ramping constraints for day-ahead and hour-ahead markets is presented in [100]. A probabilistic approach for assessing congestion risk associated with the transfers exceeding available transfer capability (ATC) is presented in [101]. AC load flow based OPF maximizing overall satisfaction degree of all participants to manage congestion is presented in [120]. A

counter-trade congestion management approach and optimal re-dispatch of generation is proposed in [118,147].

An evolution strategy to manage congestion with minimum corrective dispatch of generation is proposed in [121]. OPF based approach for congestion management and ATC determination is presented in [123]. Galiana et al. [131] proposed an OPF to dispatch the pool with bilateral contracts accounting both losses and congestion. Optimal power flow based interruptible load services for congestion relief is presented in [141]. Bruno et al. [142] proposed dynamic approach for congestion management through contract curtailment strategy.

Yamin [140,179] described a coordination process between Gencos and ISO for congestion management reducing the risk of failure to supply loads. Secure system dispatch solving a minimum load curtailment problem, to manage congestion is proposed in [157,181]. Padhy et al. [154] presented an efficient and practical hybrid model using both real and reactive power transaction to manage congestion. Basic functions of spot and congestion market are described in [151]. A multi-area congestion management approach through cross border coordinated re-dispatching is presented in [155]. On line energy trading platform to cater for congestion management using DC load flow is presented in [162]. A congestion management approach using rescheduling of generation and loads considering voltage security constraints is presented in [163,185]. Losi [164] proposed trade curtailment strategy to maintain transmission security.

Kockar et al. [169,170] formulated optimization problem of mixed pool/bilateral coordination with contract curtailment. A new method for decentralized solution of the DC-OPF to manage congestion is presented in [188]. Congestion influence on the bidding strategies is modeled as a three level optimization problem in [189]. A new Bender's decomposition approach using DC-OPF to manage congestion is presented in [180]. AC-OPF based formulation for procuring pricing and settling ancillary services in integrated market system including congestion revenue is presented in [201]. A problem of inter-regional congestion management using an approach to avoid mismatches between supply and demand considering a sport market is proposed in [198]. A new technique is suggested in [206] to analyze, manage, and price transmission congestion based on simple-auction mechanism. The proposed technique is an iterative generation rescheduling and load curtailment technique relying on "on-line" evaluation of transmission congestion constraints. A computationally simple method for cost efficient generation rescheduling and load shedding for congestion management is proposed in [208].

7. Congestion cost allocation methods

Many methods for congestion cost allocation have been proposed and implemented in various markets. The concept of nodal pricing was proposed by Scheppe et al. [1] and further developed by Hogan [2]. Singh et al. [24] proposed DC-OPF based approach to compute congestion cost. Wu and Varaiya [7,34] proposed that the surplus collected by the SO from congestion charge in Hogan's method [2] can be shared by generators and consumers as the profit that lead to economic operating point.

Baran et al. [66] investigated bid based congestion management scheme and new method of allocating congestion cost to the bilateral contracts. Rau [80] proposed AC-OPF based re-dispatch problem to alleviate congestion along with congestion cost allocation. Yu [106] proposed a new method to calculate and settle zonal congestion cost for a pool and bilateral model. Lo et al. [104] proposed a new congestion management model for inter-scheduling coordinator (SC) trade and introduced a concept of congestion charge compensation between SCs.

Tao and Gross [159] proposed a physical flow based congestion management allocation mechanism for multiple transaction mechanism. Monroy et al. [167] proposed algorithm to determine contribution of each transaction to line congestion and congestion cost allocation to each transaction. Jung et al. [190] proposed a multi-stage method for congestion cost allocation in a pool model. Game theoretic approach for congestion cost allocation is proposed in [97,98]. A load flow based cost allocation concept for congestion management is proposed in [82].

8. Other issues in congestion management

There are some other important issues like unit commitment (UC) problem, locational market power, and reserve models, which are closely related to congestion management. The problem of UC refers to optimizing generators resources to satisfy load demand at a least cost with an objective of minimizing operational cost called as Price Based Unit Commitment (PBUC). The efficient procedure for the ISO that can include contingency limits during congestion mitigation, minimize the number of adjustments, and increase the efficiency of the system eliminating interactions between inter- and intra-zonal sub-problems. Yamin et al. [179] described a coordination process between GENCOs and the ISO for congestion management. The ISO executes congestion management and contingency analysis for minimizing the line flow violations and the risk supplying loads. If the transmission flow violations persist after the adjustments are made, the solution would provide a signal to GENCOs for modifying their bids.

The paper [185] described generalized iterative algorithm based on Bender's decomposition for active/reactive coordination between GENCOs and the ISO for managing congestion. A solution of unit commitment problem with network constraints and FTR's using non-linear prices is proposed in [207]. In the paper, a nodal non-linear pricing alternative based on coordination functions inside a Lagrangian relaxation algorithm is presented to solve transmission constrained

UC problem. In [205], review of existing congestion management methods with their pros and cons in Spanish market based on security constrained unit commitment algorithm, and security constrained optimal power flow algorithms is presented.

During the congestion, the locational prices at the nodes are quite different. There are situations where market participants create the intentional congestion, which is known as locational market power. The issue of locational market power screening has been well documented in number of recent works. Gan and Bourcier [130] proposed two new approaches for locational market power screening, first one is based on zonal network model and the second is based on nodal transmission model. In zonal market power screen, a basic requirement in the design of market power screen is to identify market conditions under which competition is not viable. In the companion paper, the findings have been examined using game theoretic approach [128].

In power systems, it is very important to maintain certain amount of operating reserve to avoid shortage of power during generator outage, line outage contingencies, and load fluctuations. Thus, the efficient management and pricing of operating reserve is an important issue in the competitive environment to maintain system reliability and security in the case of contingencies. Wang et al. [138] proposed a model on coordinated scheduling of reserves, contracts, and supplemental energy. Reference [210] highlights various issues in operating reserve model. A comprehensive theory for procurement and pricing schemes for operating reserve is presented in [211]. The theory is based on capacity–reliability correlation analysis and is compatible with electricity auction in the context of electricity supply industry deregulation.

9. Electronic information

A significant amount of information is easily accessible electronically via the world-wide web (www). The list of the web sites provided below can serve as starting point for information search relating to transmission congestion issues. The sites provided include other general sites containing links to a variety of topics related to energy and power engineering including transmission open access issues.

Few general web sites related to energy market are:

- http://www.energyonline.com;
- http://www.ece.iit.edu/~power/power.html/;
- http://www.nerc.com;
- http://www.epri.com;
- http://www.ieee.org;
- http://electrotek.com;
- http://caiso.com;
- http://ksghome.harvard.edu/~whogan.cbg.Ksg;
- http://www.ferc.gov/Electric/.

The web sites devoted to congestion management issues include:

- http://www.pjm.com for PJM market;
- http://www.nyiso.com for NYISO market;
- http://www.nemmeco.com for NEM market;
- http://www.ercot.com for ERCOT market;
- http://www.iso-ne.com for ISO-NE market;
- http://www.energyonline.com: 80/wepex/reports;
- http://www.nordel.org for Nord pool market;
- http://www.nyiso.com/services/documents/tie/pdf/tccrev7.pgf for New York ISO TCC;
- http://www.etso-net.org for evaluation of congestion management methods for cross-border transmission;
- http://www.omel.es/en/reglas-contrato/ for electricity market of mainland Spain;
- http://www.pubs.pjm.com/dynaweb/PJMpubp/m06 for PJM manual for FTR.

10. Conclusions

In this paper, a comprehensive bibliographical survey of the literature on transmission congestion management and the related issues has been reported. The various general websites and websites related to congestion management issues have also been provided. The citations listed in the present bibliography provide year-wise information about the congestion management issues worldwide existing in different deregulated electricity markets. The survey presented in this paper will be very informative and useful to research scholars, utility engineers, and academicians. Periodic update on this topic will be useful as the deregulated electric industry continues to evolve worldwide.

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