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A leader–followers model of transmission augmentation for considering strategic behaviours of generating companies in energy markets

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ABSTRACT

This paper suggests an integrated mathematical framework developed based on the leader–followers game for augmentation of transmission networks. Transmission Network Service Provider moves first and designs the horizon year transmission system. Generating Companies compete for having the highest share from the energy market and they find their equilibrium point using the Nash equilibrium concept. Finally, Market Management Company receives the planning schedule of transmission system and the energy offer prices and clears the market. In addition to the exact mathematical modelling of the interested players of transmission planning problem, the methodology can design the future transmission system not only for improving the system social welfare but also for encouraging competition among horizon year generating companies.

1. Introduction

Transmission augmentation as a primary role of Transmission Network Service Providers, TNSP, has been researched in economic and engineering literatures. More and less, all of them define a good transmission expansion plan as the one with good economic effect while meeting reliability requirements [1–3]. Refs. [4–7] review different aspects of transmission planning problem with a list of issues regarding this problem. The definition of economic criteria to evaluate transmission projects, necessary reliability requirements, and the framework for accommodating the economic objectives and engineering constraints can be seen on top of their lists. Bridging the gap between the economic and engineering considerations, and the proper addressing of market mechanisms in the transmission augmentation framework have been concluded as two main issues in [8,9].

From an economic perspective, a common criterion in the assessment of transmission investment is its impact on social welfare. Using social welfare as the economic benefit of the transmission projects, Ref. [10] has designed a regulatory contract that induces TNSP to optimally expand the grid. In the proposed framework, the author has proved that the optimal transmission capacity is such that the expected marginal value of capacity equals the marginal cost for each line. Ref. [11] uses two heuristic procedures for measuring the effect of transmission capacity on social welfare. Congestion cost and congestion revenue as two by-products of dispatching module used by Market Management Company, MMC, have been employed in [12] for transmission expansion in competitive power markets. Refs. [10–15] have measured the economic benefit of transmission projects only in terms of improving the social welfare. As another example, "*Regulatory Test*" introduced by the Australian Competition and Consumer Commission, ACCC, for transmission augmentation is only based on the social welfare and cannot capture the whole value of transmission capacity upgrade.[1] Refs. [16–18] study the reliability aspect of the transmission augmentation policies. On the other hand, Ref. [19] showed numerically that transmission expansion reduces generators' market power. Ref. [20] has examined empirically the bidding behaviour of generators in England and Wales, including the impact of transmission constraints. Accordingly, Ref. [20] reports that in England and Wales generators protected by transmission constraints bid significantly higher than those without this status. Obviously, generating companies' strategic bidding is an ultimate outcome of market power. This could result in a transfer of transmission rents from MMC or owner of the transmission assets to the Generating Companies, GenCos. Using a simplified version of the power network in California, Ref. [21] has quantified the impact of local market power and transmission capacity. Refs. [22,23] show that generators benefit from a reduction in transmission capacity. Using a stylized version of the North America transmission system, Ref. [24] highlights the effect of transmission capacity on encouraging competition among GenCos. Unlike the efficiency effect of transmission

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[1] The "Regulatory Test" in Australia has been replaced by a recently introduced "Regulatory Investment Test–Transmission (RIT–T)".

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Nomenclature

TNSP	Transmission Network Service Provider
GenCo	Generating Company
MMC	Market Management Company
ACCC	Australian Competition and Consumer Commission
ISO	Independent System Operator
MPEC	Mathematical Programming with Equilibrium Constraints
EPEC	Equilibrium Problem with Equilibrium Constrantits

capacity, the competition effect has not received enough attention in transmission planning methodologies.

TEAM methodology introduced by the California ISO [25] can be acknowledged as a good model for market-based transmission augmentation. However, it has two drawbacks. Firstly, the strategic bidding of GenCos has been estimated through a tailor-made and empirical methodology which limits its application. Secondly, the whole framework is not based on an integrated mathematical structure. In addition, the interactions and interdependences among TNSP, GenCos, and MMC in the process of evaluating a transmission project must be addressed properly. TNSP can influence the decisions of GenCos on their energy offers and MMC on dispatching of the energy market. The proposed modelling must have the hierarchical nature of relevant players' communications.

Concluding the shortcomings, *the Lack of modelling of the competition effect*, *using empirical models for strategic bidding of GenCos*, *lack of integrated mathematical framework for transmission augmentation*, and *proper interaction modelling among TNSP, MMC, and GenCos* are the main issues which are addressed throughout this paper.

In the light of the electricity market in Australia, the owner and operator of the transmission network (the Transmission Network Service Provider, TNSP), is assumed to be a regulated monopoly business. The TNSP is required, amongst other things, to efficiently plan the transmission network and provide a competitive environment for market participants [27]. The GenCos are assumed to be independent commercial entities whose objective is to maximize their economic profit (revenues less costs). Finally, the Market Management Company, MMC, is assumed to play the role of manager and operator of the electricity market. The MMC is completely independent from both the TNSP and GenCos. We assume away strategic behaviours of the owners of the transmission assets, and retailers. All GenCos are assumed to be independent and accordingly there is no "multi-unit effect" [26].

The rest of the paper is organised as follows. Section 2 develops the mathematical framework of the proposed transmission augmentation model employing the leader–followers game. Section 3 deals with numerical solutions used for different modules of the model. To show the effectiveness of the algorithm, an example system based on the IEEE 14-bus system has been developed. The results of applying model on the example system have been reported and discussed. Finally conclusion remarks close the paper.

2. Mathematical derivation of the leader–followers model for transmission augmentation

The leader–followers model of the transmission augmentation can be explained in three steps as presented in Fig. 1. In *step 1*, the TNSP decides the planning schedule of transmission system for the horizon year, K signal. Also, the TNSP estimates the true marginal costs of generators in the horizon year of planning based on information about GenCo technologies and fuel, c signal. In *step 2*, MMC takes the planning schedule of the TNSP and the TNSP's estimation of the marginal costs and finds the social welfare, SW, of the electricity industry. *Step 3* models the competition among strategic GenCos. The Nash point of the Bertrand game is found first, b signal, and then the generators' surplus is calculated, Ω signal. Having calculated the generators' surplus under marginal cost biddings of GenCos, Ω^c signal, the monopoly rent of the electricity industry can be found as the output of *step 3*.

The following sections explain the exact mathematical formulation of different blocks of Fig. 1.

2.1. Transmission Network Service Provider (TNSP)

Suppose a *TNSP* has m upgrade options and n expansion options for augmenting of the high voltage transmission system in its given territory. For the m upgrade options, $f_l^u, l = 1, \ldots, m$ is an integer number of 0 or 1. Obviously, $f_i^u = 1$ or $f_l^u = 0$ means the approval or not approval of the upgrade option l. Similarly, for the n expansion options, $f_l^e, l = 1, \ldots, n$ can have an integer value of 0 or 1. The value of 1 corresponds to the building of the transmission expansion project and the value of 0 corresponds to the not building of the transmission project. $tc_l^u, l = 1, \ldots, m$ and $tc_l^e, l = 1, \ldots, n$ are the vectors of the investment cost for the transmission upgrade and expansion projects, respectively.

Since the TNSP pays the investment cost of upgrade or expansion, it is desirable to upgrade and/or expand the transmission system with the minimum cost. Mathematically, the TNSP's objective function can be formulated as

$$\begin{aligned} &\text{Max}_{f_l^u, f_l^e} \quad \Pi = [\![SW - \alpha(MR)\left(\sum_{l=1}^{m} f_l^u tc_l^u + \sum_{l=m+1}^{m+n} f_l^e tc_l^e\right)]\!] \\ &\text{s.t.} \qquad f_l^u \in \{0,1\} \quad l = 1, \ldots, m \\ &\qquad\qquad f_l^e \in \{0,1\} \quad l = m+1, \ldots, m+n \end{aligned} \tag{1}$$

According to (1), f_l^u and f_l^e are the *TNSP*'s design parameters. *SW* is the total surplus of the electricity industry defined in the following equation:

$$SW = \sum_{i=1}^{N_R} VOLL_i \cdot d_i^c - \sum_{j=1}^{N_G} c_j \cdot g_j^c \tag{2}$$

In (2), *VOLL* is the value of lost load for each retailer, c is the true marginal cost of each GenCo. g_j^c and d_i^c are the GenCo j generation and the served demand of the retailer i under marginal cost bidding scenario of GenCos. N_R and N_G are total number of retailers and GenCos in the energy market. *MR* is the monopoly rent of the electricity industry defined as

$$MR = \sum_{i=1}^{N_G} \max\{(\Omega_i - \Omega_i^c), 0.0\} \tag{3}$$

In (3), Ω_i is the profit of the ith GenCo under strategic bidding and is the profit of the same GenCo when it bids its true marginal cost. From the view point of economics, a firm has market power if it can change the price by changing its output and in doing so it earns extra profit [7]. Accordingly, if the strategic bidding of a GenCo can lead to the extra profit, it will be accounted in the *MR* index, else it will set to zero.

α is the weighting factor of the competition effect of transmission capacity. α is set by the electricity market regulator based on