Transmission Investment in Competitive Electricity Markets

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Abstract

The transition from a central operator to a decentralized decision making model has been successful, mainly because players could keep their freedom to select their best policy without substantially altering the entire system. However, there is no market counterpart to deal with the issue of planning and investment so far. The reason is that planning has traditionally been seen as a centralized task. An investment decision affects the entire network. Thus, the challenge is to create a new model for investment and investigate its policy implications.
This paper proposes the construction of an analytical framework for the expansion of the transmission network in competitive markets. To illustrate our framework, several case studies are presented and relevant conclusions are derived.

Introduction

An incontrovertible conclusion of the mega-blackout of August 14, 2003 is the fact that the transmission network is the weakest link of the restructured electricity business in the United States. In the past, the ownership, operation and planning of the transmission network were in the hands of a single central entity. However, the unbundling of the electricity business has raised new challenges that confront the restructured industry. The previous vertically-integrated structure has been replaced by a decentralized decision making paradigm. In this new model, the generators are owned by a number of different firms, the transmission ownership and control are vested in different hands and the load serving entities are the entities saddled with the obligation to serve. The large number of new players, the proliferation in the number of transactions on the networks, the markedly different utilization of the transmission than in the way it was planned have all contributed to the severe stress of the transmission network. This has resulted in frequent congestion situations with too many customers attempting to obtain what, in effect, are limited transmission services. Investments in the transmission network have failed to keep pace with the increasing demand. In the short term, the only way to deal with the congestion problem is through effective congestion management through the implementation of economically efficient procedures to coordinate the customers' desired uses of the transmission network with the system reliability strictly maintained. But congestion has, in addition, long-term impacts on markets and the decisions to fund new investments.

There is a detailed discussion of relieving transmission bottlenecks through effective investments in the National Transmission Grid Study [1]. In particular, the Study carefully articulates the various barriers to transmission investment. FERC, in its Standard Market Design (SMD) Notice of Proposed Rulemaking [2], also recognizes the sluggishness of transmission construction and the attendant impacts. FERC finds that the severe mismatches between those who benefit from the new facilities and those who pay for them often result in the new facilities not getting built. Furthermore, FERC recognizes that effective procedures must be set up to ensure recovery of tranmission investments in a timely manner.

The multiple facets of the transmission expansion/improvement problem pose a higly demanding challenge. One is the multiplicity and variety of players – existing owners, investors, regulators, the independent grid operator (*IGO*) and the broad variety of customers. Another is the time horizon of many years so that the sequence of decisions is appropriately undertaken. The imperfect nature of the electricity markets together with the possible opportunities for the exercise of market power by certain players constitute a major complicating factor. The short-run marginal costing information obtained from the hourly locational marginal prices (*LMP*s) do provide congestion signals but need to be effectively "translated" into long-run marginal cost information for the lumpy investment decisions. The effective integration of financial instruments, such as congestion revenue rights or more widely known financial transmission rights (*FTR*) pose an added level of complication. Underlying all these factors is the wide range of uncertainty in the actions of market players, the transmission investments to be undertaken, the transmission transfer *capability* and associated *FTR*, whose combined effect makes this problem inherently stochastic in nature.

This paper proposes the construction of an analytic framework for the transmission network investment problem in competitive markets to address the multiple challenges outlined above. The next section provides the description of the multi-layered analytic framework that has the capability to capture the various aspects of the transmission investment issues. We develop the mathematical model of social welfare maximization and transmission investment in the following section. After that, we present the financial transmission rights model. We illustrate our analytic framework by simple case studies to bring to the fore the salient characteristics. We conclude showing the relevant conclusions.

The Analytic Framework

We use as a starting point for the construction of the proposed framework the three-layer structure developed in [3]. We add an additional fourth layer to represent the investment decisions. The proposed framework is designed to be capable of comprehensively addressing the complex issues concerning transmission investment for competitive electricity markets. We describe each of the four layers and then discuss the interactions among them.

The Physical Layer

The physical network layer represents the transmission system. The relationship between the line power flows and the nodal injections are established and various physical network constraints are modeled. The mathematical characterization of congestion conditions is an integral part of the modeling of this layer.

The Commodity Market Layer

The commodity market layer contains the information on the electricity trades in the day-ahead hourly commodity markets and the bilateral transactions. The layer embeds a model of the bids/offers of the pool participants and the transmission requests from the bilateral transactions. The *IGO* decision-making process is simulated by solving the so-called transmission scheduling problem (*TSP*) which establishes the feasible transmission schedules for the pool players and the transmission services provided to the bilateral transactions for each hour of the day ahead. As a by-product of the *TSP* solution, the nodal prices or so-called locational marginal prices (*LMPs*) are determined. The *TSP* explicitly represents congestion in the network due to the inclusion of the transmission network constraints in the *TSP*. The *LMP*-based congestion management is also represented in the commodity market layer.

The *IGO* collects all the pool buyer bids, the pool seller offers and the transmission requests of the bilateral customers and schedules the transmission services so as to maximize the total *social welfare*. The total *social welfare* explicitly includes the net benefits associated with the bilateral transactions in addition to the total *producers' surplus* (the sum of all the individual producer surpluses of all sellers in the market), the total *consumers' surplus* (the sum of all the individual consumer surpluses of all buyers in the market) and the total *merchandising surplus* or *congestion rents*. A key metric of market behavior is the *market efficiency loss* or sometimes known as the deadweight loss since it provides a measure of the reduction in the total social welfare due to congestion effects [4].

The Financial Layer

The representation of the financial transmission rights (*FTR*), also known as congestion revenue rights (*CRR*) and the *FTR* markets constitute the financial market layer. *FTR* are financial instruments issued by the *IGO* that entitle the holder to be reimbursed for the congestion charges collected by the *IGO* in the day-ahead market. Here we establish the model for the *FTR* and the financial markets in which the *FTR* are issued, traded and deployed. We focus on the point-to-point *FTR*, but the analysis may also be extended to other of *FTR* types.

The Investment Layer

The investment layer is constructed to represent the investment decision-making process in new or upgraded transmission assets. This layer concerns long-term decisions in distinct contrast to the other two non-physical layers that are concerned with short-run decisions. The decisions involve the locations, quantities and timing with the modifications of the existing network via new asset additions or upgrades of the existing facilities. The new investments encompass any type of equipment/facilities aimed at improving the transfer capability of the modified network. The formulation of the investment decisions utilizes information on hourly data of the total social welfare. The problem has two distinct aspects: first, the specification of feasible transmission asset additions/upgrades and second the sequence of combinations of these assets over the investment time horizon. The sequential decision-making problem formulation is specified with the objective based on the evaluation of the accumulated total social welfare over the horizon. In this way, the optimal combination of resources is selected so as to also provide the maximum reduction in the market efficiency loss. Thus, by getting the maximum social welfare (or minimum market efficiency loss) congestion is also minimized. If the players are also holders of some hedging instruments such *FTR,* then such holdings may affect the way the offers/bids are formulated every hour. We examine how such phenomena may be integrated into the investment layer interactions with the commodity market layer. The tractability issues in solving this complex optimization problem are discussed.

The Information Flows

The interactions between the four layers are through the information flows, as depicted in Fig. 1. The information flows serve to interconnect the four layers into the integrated framework proposed here. A brief description of the nature of the flows is given.

We start from the investment layer. This layer receives hourly information from the commodity market layer on the values of the total social welfare and its constituent components and the market efficiency loss. This information and the short-run marginal cost data of the *LMP*s are used to determine candidates for future investment asset additions/upgrades. The impacts of the resulting modifications in the network topology are transmitted to the other layers.

We continue with the financial market layer. The inputs of the *CRR* markets are the *FTR* requests from the customers. The decision making process of the *IGO* involves interaction with the physical layer to test the feasibility of the network to meet the *simultaneous feasibility test* or the *SFT*. A tentative *FTR* set is sent to the network layer to check its feasibility. The result is fed back to the financial layer. If infeasible, the issuance quantities in the set are modified and the new *FTR* set is sent for checking the *SFT* conditions. Such iterations continue until a feasible set is identified.

As the outcomes of the financial markets may impact the customers' behavior in the commodity markets, the information flow from the financial layer to the commodity market layer is critical. Due to the importance of ensuring the non violation of the physical constraints, the solution of the *TSP* requires interaction between the commodity market and the network layers. Transmission schedules including bilateral transactions and their impacts on the nodal injections and withdrawals are represented. This information is used in the network layer to check the feasibility. The resulting system status and the set of congested lines is fed back to determine the *LMP*s. The *LMP*s are then sent to the financial market layer to compute the *FTR* payoffs.

The four-layer framework captures all the salient aspects of the various phenomena present in the transmission investment problems. The modularity of the framework is a highly attractive feature since it provides a good measure of flexibility. The generality of the proposed framework is emphasized in the discussion in the next sections.

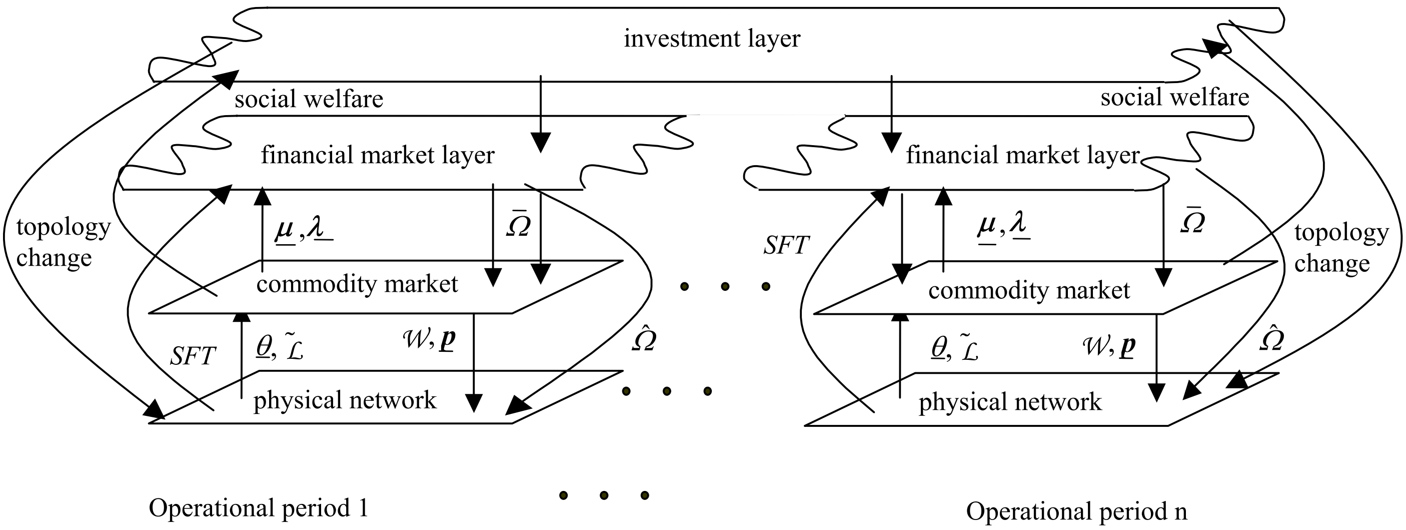

Figure 1. The four-layer framework structure.

Social welfare maximization and transmission investment

In this section, we focus on the commodity market layer, which is the basis of social welfare maximization. First, we have to present some definitions from the physical layer that are necessary to define the constraints of the social welfare maximization problem.

We consider a transmission network with $N+1$ buses and L lines. We denote by $\mathcal{N} \triangleq \{0,1,2,\cdots,N\}$ the set of buses, with the bus 0 being the slack bus, and by $\mathcal{L} \triangleq \{\ell_1, \ell_2, \cdots, \ell_L\}$ the set of transmission lines and transformers that connect the buses in the set $\mathcal{N}$. We associate with each element $\ell \in \mathcal{L}$ the ordered pair (i,j) and we write $\ell = (i,j)$. We adopt the convention that the direction of the flow on line ℓ is from node *i* to node *j* so that $f_\ell \geq 0$, where f_ℓ is the active power flow on line ℓ. We define $\underline{f} \triangleq [f_1, f_2, \cdots, f_L]^T$. The series admittance of line ℓ is $g_\ell - jb_\ell$. The net active power injection at node $n \in \mathcal{N}$ is denoted by p_n and we define $\underline{p} \triangleq [p_1, p_2, \cdots, p_N]^T$.

We denote by $\underline{B}_d \triangleq diag\{b_1, b_2, \cdots, b_L\}$ the $L \times L$ diagonal branch susceptance matrix and by $\underline{\bar{A}} \triangleq [\underline{\bar{a}}_1, \underline{\bar{a}}_2, \cdots, \underline{\bar{a}}_L]^T$ the augmented branch-to-node incidence matrix with

$$\underline{\bar{a}}_\ell \triangleq [0\cdots0\overset{i}{1}0\cdots0\overset{j}{-1}0\cdots0]^T \in \mathbb{R}^{N+1}.$$

Note that $\underline{\bar{a}}_\ell$ includes an entry corresponding to the slack bus 0. Obviously, the algebraic sum of the columns of $\underline{\bar{A}}$ vanishes:

$$\underline{\bar{A}}\,\underline{1}^{N+1} = \underline{0} \tag{1}$$

where, $\underline{1}^{N+1} = [1,1,\cdots,1]^T \in \mathbb{R}^{N+1}$. The augmented nodal susceptance matrix is

$$\underline{\bar{B}} \triangleq \underline{\bar{A}}^T \underline{B}_d \underline{\bar{A}} \tag{2}$$

and $\underline{\bar{B}}$ is singular since

$$\underline{\bar{B}}\,\underline{1}^{N+1} = \underline{\bar{A}}^T \underline{B}_d \underline{\bar{A}}\,\underline{1}^{N+1} = \underline{0}. \tag{3}$$

Next, we obtain the reduced incidence matrix $\underline{A}$ from $\underline{\bar{A}}$ by removing the row/column corresponding to the slack node

$$\underline{A} \triangleq [\underline{a}_1, \underline{a}_2, \cdots, \underline{a}_L]^T \in \mathbb{R}^{L \times N}. \tag{4}$$

Each $\underline{a}_\ell \in \mathbb{R}^N$, $\ell = 1,2,...,L$ and $\underline{A}$ is full rank. Analogously, we partition

$$\underline{\bar{B}} = \begin{bmatrix} b_{00} & \underline{b}_0^T \\ \underline{b}_0 & \underline{B} \end{bmatrix}. \tag{5}$$

The reduced nodal susceptance matrix

$$\underline{B} \triangleq \underline{A}^T \underline{B}_d \underline{A} \tag{6}$$

is nonsingular because $\underline{B}_d$ is nonsingular, as there is no line with 0 susceptance, and $\underline{A}$ is full rank.

Key characteristics of the transmission system may be described by the power flow equations and various constraints. Considering the irrelevancy of the reactive power flows to the *FTR* issues and the common use of the DC power flow model in the literature, we assume the power system to be lossless and the DC power flow conditions to hold so that

$$\underline{\boldsymbol{p}} = \underline{\boldsymbol{B}}\underline{\boldsymbol{\theta}}, \tag{7}$$

where $\underline{\boldsymbol{\theta}} \triangleq [\theta_1, \theta_2, \cdots, \theta_N]^T$ is the vector of voltage angles at the network nodes. The scarcity of the transmission capability is represented by various limits under both the base case and contingency cases. For simplicity, in this paper, we only represent the active power line flow limits under the base case:

$$\underline{\boldsymbol{B}}_d \underline{\boldsymbol{A}}\underline{\boldsymbol{\theta}} \le \underline{\boldsymbol{f}}^{max}. \tag{8}$$

We call the line ℓ congested whenever the corresponding inequality constraint becomes binding so that

$$b_\ell \underline{\boldsymbol{a}}_\ell^T \underline{\boldsymbol{\theta}} = f_\ell^{max}. \tag{9}$$

We call the transmission system congested if there is (are) one or more congested line(s) in the network. The management of the physical congestion in a way so as to accommodate as many of the bilateral transactions and pool customers' needs is a key concern in the competitive environment.

Now we describe in more detail the commodity market layer. In the day-ahead market, the pool customers submit their energy sale offers/purchase bids to the *IGO*. Without loss of generality, we assume one seller and one buyer at each node $n \in \mathcal{N}$ and denote by $\beta_n^s(p_n^s) / \beta_n^b(p_n^b)$, $n = 0,1,\cdots,N$ the seller's offer/buyer's bid price as a function of the active power supply/consumption[1]. We assume $\beta_n^s(p_n^s) / \beta_n^b(p_n^b)$ to be a continuous, differentiable and convex/concave function. We define $\underline{\boldsymbol{p}}^s \triangleq [p_1^s, p_2^s, \cdots, p_N^s]^T$ and $\underline{\boldsymbol{p}}^b \triangleq [p_1^b, p_2^b, \cdots, p_N^b]^T$. For the bilateral customers, we assume all transactions to be basic and represent them by the set $\mathcal{W} \triangleq \{\omega^1, \omega^2, \cdots, \omega^W\}$ [2], with each element denoted by the *ordered* triplet $\omega^w \triangleq \{m^w, n^w, t^w\}$ representing a basic transaction with receipt point (*from* node) m^w, delivery point (*to* node) n^w in the amount t^w *MW*. For each transaction, the customer requests the corresponding transmission services from the *IGO*.

The *IGO* collects all the pool bids, offers and the transmission requests of the bilateral customers and schedules the transmission services so as to maximize the total social welfare. The extent to which the transmission service requests of the bilateral customers are met depends on the customers' willingness to pay the charges for congestion. We assume all bilateral customers are willing to pay the charges – no matter how high – so that all their transactions are scheduled. The impact of these transactions is to introduce the active power injection p_n^t at each node n where

$$p_n^t = \sum_{w=1, m^w=n}^{W} t^w - \sum_{w=1, n^w=n}^{W} t^w, \quad n = 0,1,2,...,N. \tag{10}$$

We denote $\underline{\boldsymbol{p}}^t \triangleq [p_1^t, p_2^t, \cdots, p_N^t]^T$. The *IGO*'s process to determine the successful bids/offers of the pool customers may be represented by the transmission scheduling problem (*TSP*) that maximizes the *social welfare* subject to the network constraints:

$$TSP \begin{cases} max \quad s(p_0^s, p_0^b, \underline{\boldsymbol{p}}^s, \underline{\boldsymbol{p}}^b) = \sum_{n=0}^{N} \beta_n^b(p_n^b) - \beta_n^s(p_n^s) & \\ s.t. \quad p_0^s - p_0^b + p_0^t = \underline{\boldsymbol{b}}_0^T \underline{\boldsymbol{\theta}} & \leftrightarrow \mu_0 \\ \quad \underline{\boldsymbol{p}}^s - \underline{\boldsymbol{p}}^b + \underline{\boldsymbol{p}}^t = \underline{\boldsymbol{B}}\underline{\boldsymbol{\theta}} & \leftrightarrow \underline{\boldsymbol{\mu}} \\ \quad \underline{\boldsymbol{B}}_d \underline{\boldsymbol{A}}\underline{\boldsymbol{\theta}} \le \underline{\boldsymbol{f}}^{max} & \leftrightarrow \underline{\boldsymbol{\lambda}} \end{cases} \tag{11}$$

The day-ahead market is settled based on the optimal solutions of the *TSP*, which we assume to exist. The optimal values of the decision variables, (p_n^{b*}, p_n^{s*}), determine the quantities for the energy purchases/sales from/to the pool customers. Prices are determined based on the optimal values of the dual variables. μ_n^* is the *LMP* at the node *n* of the network. A seller (buyer) at each node *n* is paid (pays) the *LMP* μ_n^* by (to) the *IGO* for each *MWh* sold (bought) in the pool. The net income of the *IGO* from the pool, $\sum_{n=0}^{N} \mu_n^* \left(p_n^{b*} - p_n^{s*}\right)$, is called the *merchandising surplus* and is nonnegative. λ_ℓ^* measures the marginal change in social welfare with respect to change in the limiting capacity f_ℓ^{max} of line ℓ. Note that $\lambda_\ell^* \ge 0$ for $\forall \ell \in \mathcal{L}$ and $\lambda_\ell^* > 0$ implies that line ℓ is congested. Consequently, λ_ℓ^* is considered to be the congestion charges for each *MW* flow in line ℓ. We denote by $\tilde{\mathcal{L}} \subset \mathcal{L}$ the set of congested lines, then the total amount of congestion charges assessed from each transaction $\omega^w = \{m^w, n^w, t^w\}$ is

$$\xi^w = \sum_{\ell \in \tilde{\mathcal{L}}} \lambda_\ell^* \varphi_\ell^{\omega^w} t^w. \tag{12}$$

Note that the total *social welfare* can be also expressed as the sum of the total *producer's surplus* (the sum of all the individual producer surpluses of all sellers in the market: sum of all individual revenues at the nodal market clearing prices minus sum of all individual costs), the total *consumers' surplus* (the sum of all the individual consumer surpluses of all buyers in the market: sum of all individual consumer benefits minus sum of all payments at the nodal market clearing prices) and the total *merchandising surplus* $\sum_{n=0}^{N} \mu_n^* \left(p_n^{b*} - p_n^{s*}\right)$. Since for an unconstrained market there is a unique market clearing price, the merchandising surplus term disappears and the total social welfare is equal to the sum of total consumer and producer surpluses.

Finally, if we also consider the investment layer, the layer that decides how many transmission investment assets are available and when they are added to the system, we have to modify (11). Assuming that hourly data of the current social welfare (that includes producer, consumer and merchandising surplus) is obtained, decisions are taken based on this information. The problem has two distinct facets: first, we have to select which are the transmission assets that are available. Second, once the future investment assets are chosen, we have to decide how they are combined, taking into account that the investment time horizon can span several years. To accomplish both objectives (assuming that we know which are the resources available per year) we can calculate the corresponding total social welfare that year. That means that for every combination of resources we obtain, using the transmission scheduling problem objective function,

1 Multiple sellers/buyers at a node may be represented by a single composite seller/composite buyer with its corresponding offer/bid function constructed by combining the offers/bids of the constituent sellers/buyers.

2 In actual practice, a complex transaction is a linear combination of basic transactions.

$$max\ \ S = \sum_{h=1}^{8760} s_h$$

$$s.t.\begin{cases} max \quad s_h\,(p_0^s, p_0^b, \underline{p}^s, \underline{p}^b) \;=\; \sum_{n=0}^{N} \beta_n^b(p_n^b) - \beta_n^s(p_n^s) \\ \quad s.t. \qquad p_0^s - p_0^b + p_0^t \;=\; \underline{b}_0^T\underline{\theta} \qquad \leftrightarrow \quad \mu_0 \\ \qquad\qquad\quad \underline{p}^s - \underline{p}^b + \underline{p}^t \;=\; \underline{B\theta} \qquad \leftrightarrow \quad \underline{\mu} \\ \qquad\qquad\qquad\quad \underline{B}_d\underline{A\theta} \;\le\; \underline{f}^{max} \qquad \leftrightarrow \quad \underline{\lambda} \end{cases} \tag{13}$$

where S is the total social welfare using these new resources for the entire year, and s_h is the optimized social welfare at hour h, already calculated in the commodity market layer[3]. The combination of resources that yields the maximum social welfare is selected and the same process can be run in a multi-year framework by repeating this procedure. Note that (13) involves the possibility of sequential decomposition of the investment problem. That is a key characteristic of our investment modeling, since we can decompose the problem hour-by-hour to obtain the best overall solution for a whole year, for example. The formulation also allows for scenario analysis, such that different values of social welfare can be obtained, providing an uniform basis to compare.

Also note that the optimal combination of resources also provides the maximum reduction of market efficiency loss (the reduction in the total social welfare caused by congestion). Thus, by getting the maximum social welfare (or minimum market efficiency loss) congestion is also minimized. If the players are also engaged in some type of contracts, like *FTR* for example, this affects they way they bid every hour, so it can be easily incorporated into the model.

Financial Transmission Rights issuance

FTR are financial instruments issued by the *IGO* that entitle the holder to be reimbursed for the congestion charges collected by the *IGO* in the day-ahead market. Here we establish the model for the *FTR* and the financial markets in which the *FTR* are issued and traded. We focus on the point-to-point *FTR*, but the analysis may also be applied to other types of *FTR*.
The *FTR* are defined for a point of receipt (*from* node) m, a point of delivery (*to* node) n, a specified amount of transmission service γ in *MW* and a per *MW* premium ρ. We use the quadruplet $\Gamma \triangleq \{m,n,\gamma,\rho\}$ to denote the *FTR*. The *FTR* are issued by the *IGO* – the issuer – to the transmission customers – the holders. A holder of Γ is entitled to receive from the *IGO* a payment of

$$\chi \triangleq (\mu_n^* - \mu_m^*)\,\gamma \tag{14}$$

where μ_n^* and μ_m^* are the *LMP*s determined in the day-ahead market. We refer to this payment as the *FTR payoff*. The payoff may be positive, negative or zero and is independent of the usage, i.e., this payment occurs whether or not the holder requests any transmission services in the day-ahead market. As such, the *FTR* entails an obligation on both the holder and the issuer.

FTR may provide a full hedge against the congestion charges associated with the use of the transmission service. We consider a transaction $\omega^w = \{m^w, n^w, t^w\}$. A party involved in this transaction must pay the congestion charges of

$$\xi^w = (\mu_{n^w}^* - \mu_{m^w}^*)\ t^w \tag{15}$$

which are unknown prior to the clearing of the day-ahead market. If the party holds a *FTR* $\Gamma = \{m,n,\gamma,\rho\}$ with $m = m^w$, $n = n^w$ and $\gamma = t^w$, then the *FTR* payoff, $\chi = (\mu_n^* - \mu_m^*)\,\gamma$, reimburses all the congestion charges independent of the day-ahead market outcomes. In this case, the *FTR* perfectly hedges the congestion charges.
Clearly, the *FTR* payoff is a function of random variables whose values are unknown until the day-ahead market clears. The *FTR* is therefore a financial derivative. Indeed, the *FTR* embodies the salient attributes of *forward contracts* – the financial derivatives that require the holder to buy and the issuer to sell the underlying asset at the specified time for the specified price. For *FTR*, the particular attributes are:
- the *maturity time* is specified as the time when the *FTR* are exercised;
- the payoff is the linear function of the value of the *underlying asset*, the variable $\left(\mu_n^* - \mu_m^*\right)\gamma$; the *strike price* is *0*.

FTR are issued in a centralized auction. In the auction, customers submit bids that indicate the *from* node, *to* node and desired quantity of the requested *FTR* and the maximum premium they are willing to pay for it. The *IGO* determines the successful bids by maximizing its total income subject to the *Simultaneous Feasibility Test* (*SFT*). The *SFT* considers *FTR* $\Gamma_k = \{m_k, n_k, \gamma_k, \rho_k\}$ to correspond to a fictitious basic transaction $\tilde{\omega}_k \triangleq \{m_k, n_k, \gamma_k\}$ and check whether the transmission system can support all such fictitious transactions under the base case and all the contingency conditions. As a final result, the bidders have to pay the market clearing price resulting from the auction if they are the winners. Consequently, the price paid to the *IGO* –market clearing price– times the contract flow has to be subtracted from the profit that results from the *FTR* awarded to a bidder: nodal price difference times contracted flow. Since we do not study the auction of *FTR* in this paper, we do not consider the price paid by the winner.

Case study

We investigate the application of the proposed framework for transmission investment using a small system. For the sake of simplicity we assume that there is only one period of study, no bilateral transactions, and the bids and offers remain equal for all test cases. The numerical results provide an insight into the various complexities of this problem, due to the various combination of new resources involved. In particular, we evaluate the role of *FTR* in the transmission decision and the impacts of the network modification on the performance of the markets. The computational efficiency aspects are examined and discussed. The insights obtained serve to motivate the future directions for our research on this challenging topic.

3 Please note that, by a slight abuse of notation, s_h in (13) is the same s in (11), and all other variables in (13) are also hourly ones.

We use quadratic expressions for the costs and benefits functions for each player. In general, we use for a seller S_i the form

$$C^{S_i}(P^{S_i}) = \beta^{S_i} P^{S_i} + \gamma^{S_i} (P^{S_i})^2, \quad i = 1,2,\ldots,M^S \tag{16}$$

and for a buyer B_j the expression

$$B^{B_j}(P^{B_j}) = \beta^{B_j} P^{B_j} + \gamma^{B_j} (P^{B_j})^2, \quad j = 1,2,\ldots,M^B \tag{17}$$

It follows, then, that the offer function of seller S_i has the form

$$\sigma^{S_i}(P^{S_i}) = \beta^{S_i} + \gamma^{S_i} P^{S_i}, \quad i = 1,2,\ldots,M^S \tag{18}$$

And the bid function of buyer B_j is given by

$$\nu^{B_j}(P^{B_j}) = \beta^{B_j} + \gamma^{B_j} P^{B_j}, \quad j = 1,2,\ldots,M^B \tag{19}$$

M^S and M^B are the number of units belonging to a seller and a buyer, respectively. We refer to β^{S_i} and γ^{S_i} (β^{B_j} and γ^{B_j}) as the offer (bid) parameters of seller S_i (buyer B_j). Figure 2 provides the one-line diagram of the 3-bus system studied. For each line of the system, its reactance and its flow limits are given in Tables 1 to 3. Also, the maximum amount that seller S_i (buyer B_j) is willing to sell (purchase) is given by $[P^{Si}]^{\max}$ ($[P^{Bj}]^{\max}$).

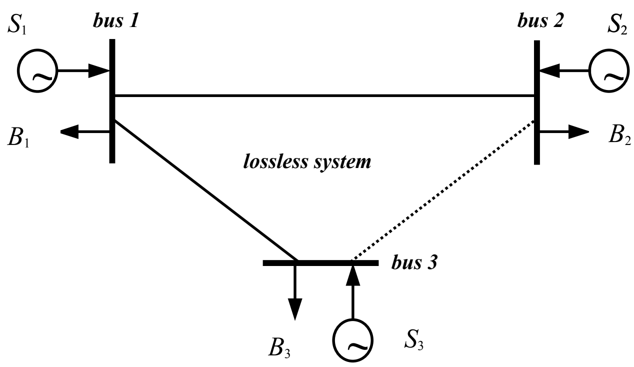

Figure 2. One-line diagram of the 3-bus system.

Table 1. Reactance and flow limit of each line.

line $l = (i,j)$		x_l	f_l^{max}
i	j	(p.u.)	(MW)
1	2	0.1	400
1	3	0.1	300
2	3	0.1	---

Table 2. Offer parameters of the sellers.

i	β^{Si}	γ^{Si}	$[P^{Si}]^{\max}$
1	3.0	0.001	1000
2	4.5	0.005	1000
3	4.0	0.003	1000

Table 3. Bid parameters of the buyers.

j	β^{Bj}	γ^{Bj}	$[P^{Bj}]^{\max}$
1	13	0.015	1000
2	23	0.02	1000
3	16	0.015	1000

Firstly, we analyze the initial system in Figure 2 with only two lines, from node 1 to 2, and from node 1 to 3. Assuming that the bids and offers are provided in Table 2, and that there are no *FTR* involved, the result of the transmission-constrained market dispatch follows. Nodal prices are $/MWh 4.76, 5.80 and 4.50, respectively. Producer surpluses are $771.11, $84.49 and $20.84, respectively. Consumer surpluses are $1132.65, $3698.02, and $2204.15, respectively. Merchandising surplus is $236.24 and social surplus is $8147.50. Flows through the lines are both 300 MW from node 1 to 2 and 1 to 3.

Now, we study the consequences of adding a new line of 100 MW between nodes 2 and 3 in two different scenarios: with and without *FTR*.

Line addition without FTR

In the first case, if the offers and bids are as before, the results are as follows. Nodal prices are all equal to 4.84. Producer surpluses are 850.69, 5.94 and 59.45, respectively. Consumer surpluses are 1108.49, 4120.20 and 2074.03, respectively. Merchandising surplus is 0 and social surplus is 8218.81. Flows through the lines are 356.63 from node 1 to 2, 293.85 from node 1 to 3, and 62.78 from node 3 to 2.

As it can be observed from these results, adding this new line to the system makes nodal prices equal and, consequently, the merchandising surplus disappears. Total social surplus increases as well. In addition, flow limits are not reached in any line. Thus, in terms of social welfare, the line is beneficial to the system as a whole. Nevertheless, some of the players do not improve their individual welfare: generator 2, and consumers 1 and 3. This is usually the case of line investments: due to the topology of the system and player's offers and bids, some of them increase their welfare and some not. Also, the free-riding phenomenon occurs when the players improve their surpluses only due to other players' actions. Finally, note that in terms of social welfare, a line improvement of 62.78 MW, not 100 MW, is enough to make nodal prices equal. This is due to the line limit reached in line 2-3, that does not change no matter how many MWs are added to the new line. The result is that 62.78 MW is the minimum line investment that would be socially beneficial.

Line addition with FTR

Adding a new line of 100 MW is also possible with previously awarded *FTR*. There are two possible cases: either the *FTR* belong to a player, or they belong to a private investor.

In the first case, we assume that generator 1 has been awarded 2 *FTR*: one to send 300 MW from node 1 to node 2 and another one to send 300 MW from node 1 to node 3. These *FTR* match the initial dispatch. Thus, the initial value of generator 1 *FTR* is given by: 300*(5.80 - 4.76) + 300*(4.50 - 4.76) = 236.24, which is also equal to the initial merchandising surplus. So, the initial benefit for generator 1 is given by: initial producer surplus + initial value of *FTR* = 771.11 + 236.24 = 1007.35. Now, after the line expansion, since all nodal prices are equal, the *FTR* become 0, because they depend on the difference of nodal prices. Therefore, the final benefit of generator 1 after line expansion is given by: final producer surplus + final value of *FTR* = 850.69 + 0 = 850.69. As a consequence, generator 1 will lose money and he will not back the expansion. Nevertheless, this result may be different if the initial nodal price differences were smaller (the initial *FTR* value should be also smaller) and the expansion profit for generator 1 may be enough to equal initial *FTR* and initial profit before expansion. Also note that if we had considered the price paid by the *FTR* winner (generator 1 in this example), generator 1 initial benefit should have been: initial producer surplus + initial value of *FTR* – (price paid to the *IGO* for *FTR*)*contract flow = 771.11 + 236.24 – *MCP1_FTR1**300 – *MCP2_FTR2**300. Therefore, the final benefit, 850.69, may be higher than the initial one if the sum of prices of the two *FTR* exceeded 0.522. In that case, generator 1 would carry out the expansion, otherwise not. We have not considered line cost in this case, but it may be added to decide whether to invest or not. As it can be seen, the generator who holds transmission rights may be biased in his decision due to the perverse incentives discouraging investment provided by his own *FTR*.

In the second case, initial *FTR* are awarded to generator 1 as before, but now there is an external investor interested in upgrading the system by adding a new line. The way to reward this investor is through new *FTR* using the *SFT* (Simultaneous Feasibility Test). In a way, the investor is provided with a new *FTR* which is the difference in power flow through the lines (after and before the expansion) times the new nodal price differences. That meaning that the newly awarded investor *FTR* have to make up for the change in line flow after the addition, to keep feasibility. Clearly, adding a 100 MW line would not reward the investor, because final nodal prices will be the same. But, adding MWs incrementally to the new line would pay the investor for the cost of the new line up to a limit.

The expression for the investor *FTR* allocation is:

$$\begin{aligned}&(p_2-p_1)|_{new}*(flow|_{1-2\ new}-flow|_{1-2\ old})+\\&(p_3-p_1)|_{new}*(flow|_{1-3\ new}-flow|_{1-3\ old})\end{aligned} \tag{20}$$

(20) can also be obtained from the following expression:

$$\Delta MS-\Delta FTR=(MS|_{new}-MS|_{old})-(FTR|_{new}-FTR|_{old}) \tag{21}$$

where *MS* is the merchandising surplus and *FTR* are the rights allocated to generator 1 in this case. Table 4 shows the values of the incremental *FTR* for the investor from (20) or (21). As it can be seen, the value of 36 MW marks the peak with a corresponding amount of $36.92. Compared to the value of 62.78 MW, minimum line addition of the previous case without *FTR*, it means that private investment would lead to underinvestment in this case. That also means that incremental transmission rights may send wrong signals to possible private investors. In addition, the investor should compare the results from Table 4 with his own line construction cost to analyze the profitability of his investment.

Table 4. Private investor *FTR* allocation.

Δ MW added to line 2-3	Δ *FTR* awarded to investor
0	0
5	9.65
10	20.36
15	26.13
25	34.83
35	35.75
36	36.92
37	32.01
62.78	0
100	0

Conclusions

This paper has studied the problem of transmission investment in the new competitive arena. We have shown a multi-layered analytic framework that includes specifically an investment layer to analyze the problem. Our framework allows for sequential decomposition of the problem and scenario analysis, making it a powerful policy analysis tool. We have considered the existence of *FTR* in the model and also the presence of private investors. From the results of our case studies, we have obtained the minimum line addition that optimizes social welfare and compared it to the results with *FTR*. If the investor and the *FTR* holder were the same, we concluded that the investment would be only possible under several conditions related to the initial and final values of *FTR*, *MS*, *MCP* and nodal prices. In case of external investment, we found that there may be underinvestment, as compared to the standard case that maximizes social welfare.

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