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A profit-maximizing approach for transmission expansion planning using a revenue-cap incentive mechanism

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Abstract: This paper proposes an incentive mechansim for transmission expansion planning. The mechansim is a bilevel program. The upper level is a profit-maximizing transmission company (Transco) which expands its transmission system while endogenously predicts and influences the generation investment. The lower level is the optimal generation dispatch and investment. The Transco funds its transmission investment costs by collecting merchandising surplus and charging a fixed fee to consumers. The Transco is subject to a revenue cap set by the regulator. This mechansim is formulated as a mixed-integer, quadratically-constrained program (MIQCP) and applied to modified Garver and IEEE 24-node systems. The results of proposed approach have been compared with the welfare-maximum benchmark and cases of Transco with cost-plus regulation and no regulation. In all tested cases, the proposed approach results in welfare-maximum outcomes while the other regulatory approaches fail to produce welfare-maximum outcomes. The profit-maximizing approach has also been successful in cases where transmission investment is driven by demand growth and reactive Transco.

Key Words: Transmission expansion planning, incentive mechanism.

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1 Nomenclature

Indices

t	Planning period
n	Node
i	Demand
j	Existing generator
k	Candidate generator
l	Existing transmission line
m	Candidate transmission line

Parameters

$\alpha_i > 0$	Intercept of linear utility i (\$/MWh)
$\beta_i < 0$	Slope of linear utility i (\$/MW^{2}h)
c_j	Marginal cost of generator j (\$/MWh)
$\widehat{c}_k$	Marginal cost of generator k (\$/MWh)
$\overline{C}_m$	Investment cost of line m (\$)
$\underline{C}_k$	Investment cost of generator k (\$)
$J_{n,j}, K_{n,k}$	Incidence matrix for generators
$I_{n,i}$	Incidence matrix for demands
$S_{n,l}, \overline{S}_{n,m}$	Matrix of sending nodes of lines
$R_{n,l}, \overline{R}_{n,m}$	Matrix of receiving nodes of lines
$F_l(\widehat{F}_m)$	Maximum capacity of line $l(m)$ (MW)
$X_l(X_m)$	Reactance of line $l(m)$ (p.u.)
G_j	Maximum production of generator j (MW)
D_i	Maximum consumption of demand i (MW)
Ξ_1, Ξ_2	Suitably large numbers
$\Upsilon(*)$	1 if $*$ is true and 0 otherwise

Continuous variables

$d_{i,t}$	Consumption of unit i in period t (MW)
$g_{j,t}$	Production of unit j in period t (MW)
$\widehat{g}_{k,t}$	Production of unit k in period t (MW)
$f_{l,t}(\widehat{f}_{m,t})$	Flow of line $l(m)$ in period t (MW)
$\theta_{n,t}$	Voltage angle at node n in period t (p.u.)
$\widehat{G}_{k,t}$	Investment for unit k in period t (MW)
Φ_t	Fixed charge of Transco to consumers (\$)
$\lambda_{n,t}$	Price at node n in period t (\$/MW)
	Lagrange multiplier (\$/MW) for:
$\tau 0_k$	no generation investment in period 1
$\xi 0_t$	slack bus constraint
$\underline{\mu}_{l,t}, \overline{\mu}_{l,t}, \sigma_{l,t}$	line l constraints
$\overline{\sigma}_{m,t}, \underline{\sigma}_{m,t}$	line m constraints
$\underline{\nu}_{j,t}, \overline{\nu}_{j,t}$	generator j constraints
$\underline{\phi}_{k,t}, \overline{\phi}_{k,t}$	generator k constraints
$\underline{\omega}_{i,t}, \overline{\omega}_{i,t}$	demand i constraints

Binary variable

$z_{m,t}$	Investment option for line m at period t

2 Introduction

Optimal expansion of the transmission network is a major concern in electricity markets around the world. While generation and retail sectors have flourished under the forces of competition, the transmission sector has experienced a shortfall in necessary investment mainly because of lack of incentive mechanisms [1]. This has increased congestion in the transmission network [2]. The large-scale integration of renewable energy sources requires significant transmission expansion planning. Lack of investment incentives in the transmission sector exacerbates the situation and further increases transmission congestion costs [3]. Transmission congestion may increase market power in certain areas [4], and create entry barriers for new competitive generators. Accordingly, a well-functioning transmission network is a critical part of the wholesale and retail markets for electricity. The incentive problem for transmission expansion planning has been addressed in the relevant literature. Physical characteristics of electricity (such as loop flows), economies of scale, and dynamics between the forward transmission market and other markets are mentioned as complicating factors in analysis of incentives for transmission expansion planning [5], [6]. To tackle the incentive problem, the incremental surplus subsidy scheme (ISS) is proposed in [7]. References [8] and [9] propose price-cap mechanisms for incentivizing transmission expansion planning by a transmission company (Transco). Under certain conditions, these mechanisms lead to a transmission expansion plan which maximizes social welfare [10]. Reference [11] proposes a reward/penalty mechanism. In this mechanism, the regulator rewards the Transco when the transmission network is expanded and the congestion rents are decreased. Reference [12] proposes an out-turn mechanism. The out-turn is defined as the difference between actual electricity prices and prices without transmission congestion. The Transco is responsible for total out-turn cost and any transmission losses. The merchant mechanism proposed in [13] aims to bring competition into transmission expansion planning using the concept of financial transmission rights (FTR) [14]. References [10] and [15] extend the work in [8] and propose the HRV mechanism for transmission expansion planning. In the HRV mechanism, Transco maximizes its profit (sum of merchandising surplus and a fixed charge) subject to the price-cap constraint introduced in [8]. The HRV mechanism has been tested on simplified models of Northwestern Europe and the Northeast U.S. [10], [16]. Mathematically, the HRV model is a non-linear program with equilibrium constraints (NLPEC) and local optimizers have been used to solve the related model but with no guarantee of global optimality. Nevertheless, finding an optimal incentive mechanism for transmission expansion planning is an open question both in thory and in practice. The current paper contributes to the literature by proposing an alternative incentive mechanism for transmission expansion planning following the mechanisms in [8] and [10]. The revenue of the Transco consists of its network merchandising surplus and a fixed charge to consumers. The Transco maximizes its profit by expanding its transmission network. The profit-maximizing Transco is subject to a proposed revenue-cap constraint which is set by the regulator. The Transco also anticipates and influences optimal generation dispatch and investment (we disregard strategic behavior in the generation sector). The proposed revenue-cap regulatory constraint is linearized while the price-cap regulatory constraint in [8] has bilinear terms and cannot be linearized. Subsequently, the whole mechanism is reformulated as a mixed-integer, quadratically-constrained program (MIQCP) which can be solved to global optimality (contrary to the NLPEC of HRV model with no guarantee of global optimality). In all previous incentive models the discrete nature of transmission expansion[1] and potential substitution between generation expansion and transmission expansion are ignored. In our proposed model, the transmission expansion is a discrete decision and the generation investment decisions are decided endogenously by the anticipatory, profit-maximizing Transco. We have also tested our proposed incentive mechanism when transmission expansion planning is driven by demand growth and when the generation expansion planning decisions are exogenous to the model (reactive Transco). The numerical results in this paper show that in all studied cases, the proposed mechanism incentivizes the Transco to expand the transmission network in a welfare-maximizing way. The rest of this paper is organized as follows. Section 3 presents the benchmark model for the proposed incentive mechanism. The proposed approach for transmission expansion planning is detailed in Section 4. To show the operation of the incentive mechanism an illustrative example is used in Section 5. The modified Garver and IEEE 24-node system are studied in Section 6. Two cases of transmis-

[1] Modeling marginal changes in transmission capacity is a poor representation of real transmission expansion which is charactrized by lumpiness and non-convexities [17].

sion expansion planning driven by demand growth and a reactive Transco are studied in Section 7. Section 8 concludes.

3 The welfare-maximizing benchmark

We assume a welfare-maximizing utility owning both generation and transmission assets. The welfare-maximizing expansion planning of joint generation and transmission system is set out in (1).

$$\begin{aligned}
&\underset{\Omega_s}{Maximize} \sum_t \langle \psi(\sum_i (\frac{1}{2}\beta_i d_{i,t}^2 + \alpha_i d_{i,t}) - \sum_j c_j\ g_{j,t} - \sum_k \widehat{c}_k\ \widehat{g}_{k,t}) - \sum_m \overline{C}_m (z_{m,t} - z_{m,t-1}) - \\
&\quad \sum_k \underline{C}_k (\widehat{G}_{k,t} - \widehat{G}_{k,t-1}) \rangle \qquad (1a)\\
&Subject\ to\\
&z_{m,t} \geq z_{m,t-1}\ \forall m, \forall t \geq 2, z_{m,t=1} = 0\ \forall m \qquad (1b)\\
&\widehat{G}_{k,t} \geq \widehat{G}_{k,t-1}\ (\tau_{k,t})\ \forall k, \forall t \geq 2, \widehat{G}_{k,t=1} = 0\ (\tau 0_k)\ \forall k \qquad (1c)\\
&\sum_j J_{n,j} g_{j,t} + \sum_k K_{n,k} \widehat{g}_{k,t} - \sum_i I_{n,i} d_{i,t} - \sum_l S_{n,l} f_{l,t} + \sum_l R_{n,l} f_{l,t} - \sum_m \overline{S}_{n,m} \widehat{f}_{m,t}\\
&\quad + \sum_m \overline{R}_{n,m} \widehat{f}_{m,t} = 0\ (\lambda_{n,t})\ \forall n, t \qquad (1d)\\
&f_{l,t} - \frac{100}{X_l} (\sum_n S_{n,l} \theta_{n,t} - \sum_n R_{n,l} \theta_{n,t}) = 0\ (\sigma_{l,t})\ \forall l, t \qquad (1e)\\
&- F_l \leq f_{l,t} \leq F_l\ (\underline{\mu}_{l,t}, \overline{\mu}_{l,t})\ \forall l, t \qquad (1f)\\
&\widehat{f}_{m,t} - \frac{100}{X_m} (\sum_n \overline{S}_{n,m} \theta_{n,t} - \sum_n \overline{R}_{n,m} \theta_{n,t}) \leq \Xi_1 (1 - z_{m,t})\ (\overline{\sigma}_{m,t})\ \forall m, t \qquad (1g)\\
&\widehat{f}_{m,t} - \frac{100}{X_m} (\sum_n \overline{S}_{n,m} \theta_{n,t} - \sum_n \overline{R}_{n,m} \theta_{n,t}) \geq -\Xi_1 (1 - z_{m,t})\ (\underline{\sigma}_{m,t})\ \forall m, t \qquad (1h)\\
&- z_{m,t} \widehat{F}_m \leq \widehat{f}_{m,t} \leq z_{m,t} \widehat{F}_m\ (\underline{\gamma}_{m,t}, \overline{\gamma}_{m,t})\ \forall m, t \qquad (1i)\\
&0 \leq g_{j,t} \leq G_j\ (\underline{\nu}_{j,t}, \overline{\nu}_{j,t})\ \forall j, t \qquad (1j)\\
&0 \leq g_{k,t} \leq \widehat{G}_{k,t} (\underline{\phi}_{j,t}, \overline{\phi}_{j,t})\ \forall k, t \qquad (1k)\\
&0 \leq d_{i,t} \leq D_{i,t}\ (\underline{\omega}_{i,t}, \overline{\omega}_{i,t})\ \forall i, t \qquad (1l)\\
&\theta_{n=1,t} = 0\ (\xi 0_t)\ \forall t \qquad (1m)
\end{aligned}$$

The optimization problem (1) is a dynamic, mixed-integer, quadratic program (MIQP) over planning periods (t). We assume a quadratic utility function for demand, linear generation operation and investment costs, and linear transmission investment costs in the objective function (1a). The objective function is to maximize the sum of social welfare over different planning periods. ψ is the discount factor which makes the short-term social welfare and long-term investment costs comparable. By constraints (1b) and (1c), the first period is assumed to have no generation-transmission investment and investments are understood to be cumulative. Energy balance at each node is modeled in (1d). Constraints (1e) and (1f) calculate the power flows through existing transmission lines and bound the calculated power flows by thermal limits of the lines (base of 100 MVA is used to change the p.u. power flow values to actual MW values). Constraints (1g), (1h), and (1i) model the investment in new transmission lines and bound their power flows by thermal capacities of these new lines. The Ξ_1 is a suitably large constant. The maximum generation capacities of existing and new generators are modeled in constraints (1j) and (1k). The maximum consumption for each demand point in each planning period is modeled in (1l). Constraint (1m) sets node 1 as the reference node. $\Omega_s = \left\{z_{m,t}, \widehat{G}_{k,t}, d_{i,t}, g_{j,t}, \widehat{g}_{k,t}, f_{l,t}, \widehat{f}_{m,t}, \theta_{n,t}\right\}$ is the set of decision variables considered. As it is commonly assumed in the engineering literature ([18], [19]) a single load scenario corresponding to forecasted peak load in each planning period ($D_{i,t}$) is considered. The results of the optimization problem (1) are used as the benchmark for measuring the economic efficiency of our proposed transmission expansion planning approach.

4 The profit-maximizing transmission expansion planning

We assume an independent regional transmission company (Transco) who owns the transmission network. The Transco does the transmission expansion planning, bears the costs, and collects the revenues. The Transco revenue consists of its network merchandising surplus (total payoff from demand minus total payment to generators) and a fixed charge (Φ_t) per planning period t. The fixed charge is a charge to consumers to fund the transmission expansion costs. This profit-maximizing Transco can be modeled via a bilevel program shown in (2).

$$\underset{z_{m,t},\Phi_t}{Maximize} \sum_t \langle \sum_{n,i} I_{n,i}\lambda_{n,t}d_{i,t} - \sum_{n,j} J_{n,j}\lambda_{n,t}g_{j,t} - \sum_{n,k} K_{n,k}\lambda_{n,t}\widehat{g}_{k,t}) + \Phi_t - \sum_m \overline{C}_m(z_{m,t} - z_{m,t-1})\rangle \tag{2a}$$

$$Subject\ to$$

$$z_{m,t} \geq z_{m,t-1}\ \forall m, \forall t \geq 2, z_{m,t=1} = 0\ \forall m \tag{2b}$$

$$\Phi_t - \langle \sum_i (\frac{\psi}{2}\beta_i d_{i,t}^2 + \psi\alpha_i d_{i,t}) - \sum_{n,i} I_{n,i}\lambda_{n,t}d_{i,t}\rangle \leq (1+R+Y)\{\Phi_{t-1} - \langle \sum_i (\frac{\psi}{2}\beta_i d_{i,t-1}^2 + \psi\alpha_i d_{i,t-1}) - \sum_{n,i} I_{n,i}\lambda_{n,t-1}d_{i,t-1}\rangle\}\ (\forall t \geq 2), \Phi_{t=1} = 0 \tag{2c}$$

$$Where\ \{d_{i,t}, g_{j,t}, \widehat{g}_{k,t}, \lambda_{n,t}\} \in \arg \underset{\Omega_s/z_{m,t}}{Maximize} \sum_t \langle \psi(\sum_i (\frac{1}{2}\beta_i d_{i,t}^2 + \alpha_i d_{i,t}) - \sum_j c_j\ g_{j,t} - \sum_k \widehat{c}_k\ \widehat{g}_{k,t}) - \sum_k \underline{C}_k(\widehat{G}_{k,t} - \widehat{G}_{k,t-1})\rangle \tag{2d}$$

$$Subject\ to\ (1c) - (1m) \tag{2e}$$

The Transco maximizes its profit over planning periods (t) subject to a regulatory constraint on its fixed-charge component (Φ_t) of its revenue. The regulatory constraint sets an upper bound on the fixed charge. The upper bound is the sum of the fixed charge in the previous planning period and change in consumer surplus between current planning period and the previous one. Under the proposed structure, the profit-maximizing Transco is willing to cede some merchandising surpluses in exchnage of an increase in the fixed charge. Mathematically, this revenue-cap regulatory constraint can be written as (2c) where R and Y are inflation and efficiency factors set by the regulator (in this paper they are set to 0 for sake of mathematical brevity), respectively. The Transco anticipates and influences the generation dispatch and investment resulting from its transmission planning decisions. In an environment of price-taking generators and loads, the optimal generation dispatch and investment can be modeled as optimization problem (2d)–(2e). This optimization problem is a convex quadratic program (QP) in minimization where the transmission planning decisions are exogenously set by the Transco. Accordingly, the interaction between the profit-maximizing Transco with revenue-cap regulation and optimal generation dispatch and investment can be modeled as the bilevel program (2). The upper level is the profit-maximizing Transco (2a)–(2b)–(2c) and the lower level is a convex QP (in minimization) for the generation dispatch and investment decisions (2d)–(2e). Since the lower level is a convex QP (in minimization), the Karush-Kuhn-Tucker (KKT) optimality conditions [20] are both necessary and sufficient. Hence, the lower-level optimization can be replaced by its KKT conditions.[2] Following [22] and [23], the complementary slackness conditions are replaced by the strong duality condition. This leads

[2]We have assumed that when the lower-level problem has multiple optimal solutions, that the one that is selected, related to the upper level is "optimistic" [21]. That is to say, the lower-level problem does not strive to make the upper-level problem worse.

to less number of constraints and binary variables in the final model. The stationary conditions for the lower-level QP (2d)–(2e) are derived in (3).

$$\psi\beta_i d_{i,t} + \psi\alpha_i - \sum_n I_{n,i}\lambda_{n,t} + \underline{\omega}_{i,t} - \overline{\omega}_{i,t} = 0 \ \forall i,t \tag{3a}$$

$$-\psi c_j + \sum_n J_{n,j}\lambda_{n,t} + \underline{\nu}_{j,t} - \overline{\nu}_{j,t} = 0 \ \forall j,t \tag{3b}$$

$$-\psi\widehat{c}_k + \sum_n K_{n,k}\lambda_{n,t} + \underline{\phi}_{k,t} - \overline{\phi}_{k,t} = 0 \ \forall k,t \tag{3c}$$

$$\underline{C}_k + \tau 0_k - \tau_{k,2} + \overline{\phi}_{k,1} = 0 \ (t=1) \ \forall k \tag{3d}$$

$$\tau_{k,t} - \tau_{k,t+1} + \overline{\phi}_{k,t} = 0 \ (1 < t < T) \ \forall k,t \tag{3e}$$

$$-\underline{C}_k + \tau_{k,T} + \overline{\phi}_{k,T} = 0 \ (t=T) \ \forall k \tag{3f}$$

$$-\sum_n S_{n,l}\lambda_{n,t} + \sum_n R_{n,l}\lambda_{n,t} + \sigma_{l,t} + \underline{\mu}_{l,t} - \overline{\mu}_{l,t} = 0 \ \forall l,t \tag{3g}$$

$$-\sum_n \overline{S}_{n,m}\lambda_{n,t} + \sum_n \overline{R}_{n,m}\lambda_{n,t} + \underline{\sigma}_{m,t} - \overline{\sigma}_{m,t} + \underline{\gamma}_{m,t} - \overline{\gamma}_{m,t} = 0 \ \forall m,t \tag{3h}$$

$$\begin{aligned}&-\frac{100}{X_l}\sum_l S_{n,l}\sigma_{l,t} + \frac{100}{X_l}\sum_l R_{n,l}\sigma_{l,t} + \xi 0_t \Upsilon(n=1) - \frac{100}{X_m}\sum_m \overline{S}_{n,m}\underline{\sigma}_{m,t} + \frac{100}{X_m}\sum_m \overline{R}_{n,m}\underline{\sigma}_{m,t}\\ &\quad + \frac{100}{X_m}\sum_m \overline{S}_{n,m}\overline{\sigma}_{m,t} - \frac{100}{X_m}\sum_m \overline{R}_{n,m}\overline{\sigma}_{m,t} = 0 \ \forall n,t\end{aligned} \tag{3i}$$

Let $A_{i,t} = -\frac{1}{\psi\beta_i}(\psi\alpha_i - \sum_n I_{n,i}\lambda_{n,t} + \underline{\omega}_{i,t} - \overline{\omega}_{i,t})$, then the strong-duality condition is:

$$\begin{aligned}&-\sum_i \frac{1}{2}\psi\beta_i A_{i,t}^2 + \sum_i D_{i,t}\overline{\omega}_{i,t} + \sum_j G_j\overline{\nu}_{j,t} + \sum_l F_l(\underline{\mu}_{l,t} + \overline{\mu}_{l,t})\\ &+ \sum_m z_{m,t}\widehat{F}_m(\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t}) + \sum_m \Xi_1(1 - z_{m,t})(\overline{\sigma}_{m,t} + \underline{\sigma}_{m,t})\\ &\qquad = \sum_i(\frac{1}{2}\psi\beta_i d_{i,t}^2 + \psi\alpha_i d_{i,t}) - \sum_j \psi c_j g_{j,t} - \sum_k \psi\widehat{c}_k\widehat{g}_{k,t} - \sum_k \underline{C}_k(\widehat{G}_{k,t} - \widehat{G}_{k,t-1})\rangle \ \forall t\end{aligned} \tag{4}$$

Doing this, the initial bilevel model (2) is transformed into a mixed-integer, non-linear program (MINLP). The nonlinearities in the resulting MINLP model are: (a) the bilinear terms $\lambda_{n,t}d_{i,t}$, $\lambda_{n,t}g_{j,t}$, $\lambda_{n,t}\widehat{g}_{k,t}$ in the Transco profit function. (b) the bilinear terms $\Xi_1(1-z_{m,t})(\overline{\sigma}_{m,t} + \underline{\sigma}_{m,t})$ and $z_{m,t}\widehat{F}_m$ $(\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t})$, (c) the terms $A_{i,t}^2$ and $d_{i,t}^2$ in the strong-duality condition, and (d) the non-convex regulatory constraint (2c). Regarding the bilinear terms in (a), we have:

$$\begin{aligned}&\sum_{n,i} I_{n,i}\lambda_{n,t}d_{i,t} - \sum_{n,j} J_{n,j}\lambda_{n,t}g_{j,t} - \sum_{n,k} K_{n,k}\lambda_{n,t}\widehat{g}_{k,t}\\ &= \sum_n \lambda_{n,t}\Big(\sum_i I_{n,i}d_{i,t} - \sum_j J_{n,j}g_{j,t} - \sum_k K_{n,k}\widehat{g}_{k,t}\Big) \overset{(1d)}{=} \sum_l f_{l,t}\Big(-\sum_n S_{n,l}\lambda_{n,t} + \sum_n R_{n,l}\lambda_{n,t}\Big)\\ &+ \sum_m \widehat{f}_{m,t}\Big(-\sum_n \overline{S}_{n,m}\lambda_{n,t} + \sum_n \overline{R}_{n,m}\lambda_{n,t}\Big) \overset{(3g)(3h)}{=} \sum_l f_{l,t}(\overline{\mu}_{l,t} - \underline{\mu}_{l,t} - \sigma_{l,t})\\ &\qquad + \sum_m \widehat{f}_{m,t}(\overline{\gamma}_{m,t} - \underline{\gamma}_{m,t} + \overline{\sigma}_{m,t} - \underline{\sigma}_{m,t})\end{aligned} \tag{5}$$

From (1e) and the complementary conditions for constraints (1f), (1g), (1h), and (1i), we have

$$(5) = \sum_l F_l(\overline{\mu}_{l,t} + \underline{\mu}_{l,t}) + \sum_m \widehat{F}_m z_{m,t}(\overline{\gamma}_{m,t} + \underline{\gamma}_{m,t}) + \underbrace{\Xi_1(1 - z_{m,t})\,(\overline{\sigma}_{m,t} + \underline{\sigma}_{m,t})}_{T1} + \underbrace{\theta_{n,t}(3i)}_{T2} \tag{6}$$

If $z_{m,t} = 1$, then term $T1$ is zero. If $z_{m,t} = 0$, then both constraints (1g) and (1h) are slack which means $\overline{\sigma}_{m,t} = \underline{\sigma}_{m,t} = 0$ and accordingly $T1 = 0$. Hence, $T1$ is always zero. From (1m) and (3i), it is obvious that $T2$ is zero. By introducing $\widehat{\gamma}_{m,t} = z_{m,t}(\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t})$ and $\widehat{\gamma}_{m,t} - (\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t}) \leq \Xi_2(1 - z_{m,t})$, $\widehat{\gamma}_{m,t} - (\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t}) \geq -\Xi_2(1 - z_{m,t})$, $\widehat{\gamma}_{m,t} \leq \Xi_2 z_{m,t}$, $\widehat{\gamma}_{m,t} \geq -\Xi_2 z_{m,t}$, the non-linear term $z_{m,t}(\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t})$ can be removed [24]. For quadratic terms, $A^2_{i,t}$ and $d^2_{i,t}$, we replace them with new variables $A2_{i,t}$ and $d2_{i,t}$ and add two constraints $A2_{i,t} \geq A^2_{i,t}$ and $d2_{i,t} \geq d^2_{i,t}$ to the formulation. For the non-convex regulatory constraint (2c), from stationary condition (3a) and complementary slackness conditions for (1l), we have: $(\frac{\psi}{2}\beta_i d^2_{i,t} + \psi\alpha_i d_{i,t}) - \sum_n I_{n,i}\lambda_{n,t} d_{i,t} = -\frac{\psi}{2}\beta_i A^2_{i,t} + D_{i,t}\ (\underline{\omega}_{i,t} + \overline{\omega}_{i,t}) = -\frac{\psi}{2}\beta_i A2_{i,t} + D_{i,t}\ \overline{\omega}_{i,t}$. Now we can write the whole formulation of the profit-maximizing Transco as a dynamic and mixed-integer quadratically-constrained program (MIQCP). This MIQCP is shown in (7).

$$\underset{\Omega_p}{Maximize} \sum_t \langle \sum_l F_l(\overline{\mu}_{l,t} + \underline{\mu}_{l,t}) + \sum_m \widehat{F}_m \widehat{\gamma}_{m,t} + \Phi_t - \sum_m \overline{C}_m (z_{m,t} - z_{m,t-1}) \rangle \tag{7a}$$

Subject to

$$\Phi_t + \frac{\psi}{2}\beta_i A2_{i,t} - D_{i,t}\ \overline{\omega}_{i,t} \leq \Phi_{t-1} + \frac{\psi}{2}\beta_i A2_{i,t-1} - D_{i,t}\ \overline{\omega}_{i,t-1}\ (\forall t \geq 2), \Phi_{t=1} = 0 \tag{7b}$$

$$(1b) - (1m) - (3a) - (3i) \tag{7c}$$

$$-\sum_i \frac{1}{2}\psi\beta_i A2_{i,t} + \sum_i D_{i,t}\overline{\omega}_{i,t} + \sum_j G_j \overline{\nu}_{j,t} + \sum_l F_l(\underline{\mu}_{l,t} + \overline{\mu}_{l,t}) + \sum_m \widehat{\gamma}_{m,t}\widehat{F}_m = \sum_i (\frac{1}{2}\psi\beta_i d2_{i,t} + \psi\alpha_i d_{i,t}) - \sum_j \psi c_j g_{j,t} - \sum_k \psi\widehat{c}_k \widehat{g}_{k,t} - \sum_k \underline{C}_k(\widehat{G}_{k,t} - \widehat{G}_{k,t-1})\rangle\ \forall t \tag{7d}$$

$$\widehat{\gamma}_{m,t} - (\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t}) \leq \Xi_2(1 - z_{m,t})\ \forall m, t \tag{7e}$$

$$\widehat{\gamma}_{m,t} - (\underline{\gamma}_{m,t} + \overline{\gamma}_{m,t}) \geq -\Xi_2(1 - z_{m,t})\ \forall m, t \tag{7f}$$

$$-\Xi_2 z_{m,t} \leq \widehat{\gamma}_{m,t} \leq \Xi_2 z_{m,t}\ \forall m, t \tag{7g}$$

$$A2_{i,t} \geq A^2_{i,t}, d2_{i,t} \geq d^2_{i,t}\ \forall i, t \tag{7h}$$

where $\Omega_p = \Omega_s \cup \Big\{ A_{i,t}, A2_{i,t}, d2_{i,t}, \lambda_{n,t}, \underline{\omega}_{i,t}, \overline{\omega}_{i,t}, \underline{\nu}_{j,t}, \overline{\nu}_{j,t},\ \underline{\phi}_{k,t}, \overline{\phi}_{k,t}, \tau_{k,t}, \tau 0_k, \sigma_{l,t}, \underline{\mu}_{l,t}, \overline{\mu}_{l,t}, \underline{\sigma}_{m,t}, \overline{\sigma}_{m,t}, \underline{\gamma}_{l,t}, \overline{\gamma}_{l,t}, \xi 0_t \Big\}$ is the set of decision variables of the optimization problem (7). The values Ξ_1 and Ξ_2 are suitably large constants. These constants must be selected carefully such that they do not impose extra bounds on variables (if they are selected too small) or result in ill-conditioning in the optimization problem (7) (if they are selected very large). The optimization program (7) is a MIQCP and can be solved using commercial solvers. The proposed approach for transmission expansion planning has the following sequence of actions:

1. The regulator sets the parameters R and Y in the regulatory constraint (2c). It also estimates the parameters α_i, β_i of linear demand functions using historic market prices [25], [7].
2. The Transco maximizes its profit over the planning periods taking regulatory constraint into account.
3. The Transco auctions off its (existing and expanded) transmission capacity as the point-to-point FTRs to market participants.
4. The Transco collects the merchandising surplus using the FTR auction in step 3 and sets the fixed charges according to the regulatory constraint.
5. The market operator distributes the merchandising surplus between FTR holders.

For sake of comparison, two existing approaches for regulating a Transco are also modeled.

1. *Transco without regulation*: In this case, the Transco is unregulated in terms of transmission expansion planning decisions. This case can be modeled by removing the revenue-cap regulatory constraint (7b) from optimization problem (7) and setting $\Phi_t = 0$. In the no-regulation case, the cost of transmission

expansion planning has to be fully recovered by congestion rents. Accordingly, the Transco will only expand such lines that increase congestion rent.

2. *Transco with cost-plus regulation*: In this case, the Transco receives not only the merchandising surplus but it can charge an extra fixed fee based on its cost of transmission expansion planning. This case can be modeled by replacing the regulatory constraint (7b) by $\Phi_t = \Phi_{t-1} + (1+r)\sum_m \overline{C}_m(z_{m,t} - z_{m,t-1})$ where $r \in \mathbb{R}_+$ is set by the regulator.

5 Illustrative example

The proposed mechanism for transmission expansion planning is applied to an illustrative two-node system. The single-line diagram and data of this example system is shown in Figure 1. Four planning periods (t_1,t_2,t_3,t_4) are considered and peak demand at each planning period is increased by 10% as compared to the previous period peak demand. Peak demand at first period (t_1) is 200 MW. Each planning year is represented by 500 identical hours ($\psi = 500$). The parameters α_i and β_i are calculated using $\alpha_i = \lambda_{ref} - D_i\beta_i$ and $\beta_i = \frac{\lambda_{ref}}{\epsilon D_i}$ where λ_{ref} is the reference price for the demand utility function and ϵ is the demand elasticity For all numerical examples $\lambda_{ref} = 30\$/MWh$ and $\epsilon = -0.25$. The reported prices are nodal prices per planning year ($\lambda_{n,t}$ in optimization (2d)–(2e)).

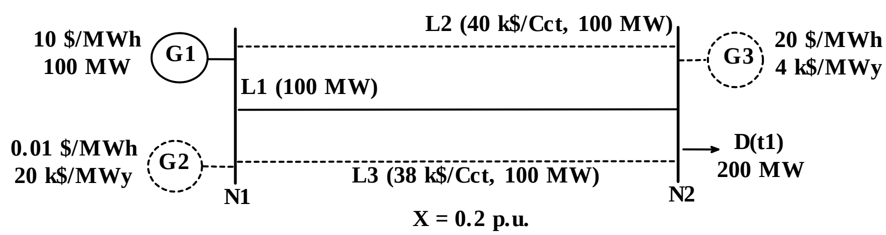

Figure 1: The illustrative 2-node system: Marginal costs in $/MWh, generation investment cost in k$/MWy, transmission investment cost in k$/Cct, capacities in MW, existing assets in solid lines, and candidate assets in dashed lines, Cct: Circuit

As it is shown in Figure 2, the Transco with revenue-cap regulation is incentivized to produce the results of the welfare-maximizing benchmark. The Transco without regulation invests in L3 and generators G2 and G3 react by expanding their generation capacities to 100 MW and 12.22 MW, respectively. The Transco with cost-plus regulation invests in L2 and this results in 100 MW and 12.22 MW generation capacities for G2 and G3, respectively. In both the no-regulation, and cost-plus regulation cases, existing and new lines are still congested and the served demand (212.22 MW) is less than the served demand in the revenue-cap regulation case (225 MW). The Transco with cost-plus regulation selects the expensive candidate line (L2) for investment as compared to L3 selected in the no-regulation case. This is because the cost-plus

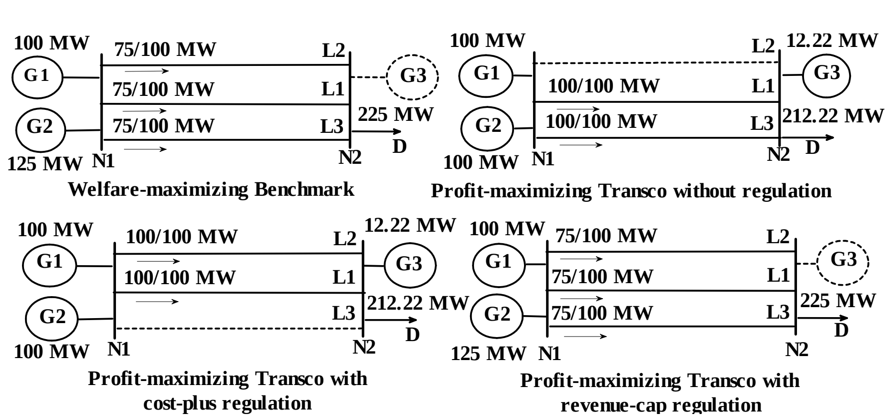

Figure 2: The power-flow results in period 4 under different regulatory regimes for two-node example system

regulated Transco is rewarded a portion of its investment cost. The expansion results over regulatory periods (t_1,t_2,t_3,t_4) are set out in Table 1 for benchmark and revenue-cap cases, and in Table 2 for cost-plus and no-regulation cases. For the rest of the tables in this paper, BI, N-REG, CP-REG, and RC-REG stand for benchmark investment, no-regulation, cost-plus regulation, and revenue-cap regulation. Also, G-Plan, T-Plan, FC, TIC, GIC, TP, and SW stand for generation expansion plan, transmission expansion plan, fixed charge, transmission investment cost, generation investment cost, Transco profit, and social welfare, respectively. As we can see, the prices at nodes 1 and 2 converge to 7,505 $/MW in revenue-cap regulation while in the no-regulation or cost-plus regulation, there is a price difference of 4708 $/MW (11333 − 6625) between nodes 1 and 2. The social welfare at period 4 for revenue-cap regulation is $8,780,437 which is $242,234 (8780437 − 8538203) higher than the social welfares for no-regulation and cost-plus regulation.

Table 1: Dispatch and Investment results for BI and RC-REG (values inside []) over different regulatory periods for two-node system

Periods	t_1	t_2	t_3	t_4
G1(MW)	100	95	100	100
G2(MW)	0	125	125	125
G3(MW)	0	0	0	0
L1(MW)	100	73.33	75	75
L2(MW)	0	73.33	75	75
L3(MW)	0	73.33	75	75
N1($/MW)	37,341	5,003	7,505	7,505
N2($/MW)	46,182	5,004	7,505	7,505
FC(k$)	[0]	[6,754]	[6,207]	[6,207]
TIC(k$)	0	78	0	0
GIC(M$)	0	2.4995	0	0
SW($)	5,499,999	6,186,750	8,780,437	8,780,437

Table 2: Dispatch and Investment results for N-REG and CP-REG (values inside []) over different regulatory periods for two-node system

Periods	t_1	t_2	t_3	t_4
G1(MW)	100	100	100	100
G2(MW)	0	100	100	100
G3(MW)	0	12.22	12.22	12.22
L1(MW)	100	100	100	100
L2(MW)	0[0]	0[100]	0[100]	0[100]
L3(MW)	0[0]	100[0]	100[0]	100[0]
N1($/MW)	36,112	6,716	6,673	6,625
N2($/MW)	45,000	11,333	11,333	11,333
FC(k$)	[0]	[48]	[48]	[48]
TIC(k$)	0	38[40]	0	0
GIC(M$)	0	2.0489	0	0
SW($)	5,499,999	6,451,314 [6,449,314]	8,538,203	8,538,203

6 Numerical results

To further investigate the proposed model, the Garver's 6-node and IEEE 24-node systems are studied. The mathematical models are coded in GAMS and solved using CPLEX 12.6 solver. The simulations are run on a computer with a 2.7 GHz processor and 16 GB of RAM.

6.1 Modified Garver's 6-node example system

This system has 6 nodes, and 7 existing transmission lines. In the modified system, line between nodes 4 and 6 is added to the existing transmission lines. The profit-maximizing Transco has 10 candidate transmission lines located between nodes (2,3), (2,4), (2,5), (2,6), (3,4), (3,5), (3,6), (4,5), (4,6), and (5,6) where pair (x,y)

means line from node x to node y. There are two candidate generators at nodes 2 and 4. The marginal costs for these generators are 0.01 and 0.02 \$/MWh with the investment cost of 20,000 and 4000 \$/MWy. The ψ is taken as 50. The rest of system data is the same as the one reported in [26]. Different regulatory regimes lead to different transmission expansion planning strategies. This in turn results in different investment reactions by generators. These investment strategies are reported in Table 3.

Table 3: Investment results under different regulatory regimes for modified Garvers's system

	BI	N-REG	CP-REG	RC-REG
G-plan	G4 305MW	G4 306MW	G4 376MW	G4 293MW
T-plan	(3,5)	(2,5)	(2,5),(3,4) (3,6),(4,6)	(2,6),(3,5) (3,6)
FC(k\$)	0	0	950.4	4565.9
TIC(k\$)	20	60	198	80
GIC(M\$)	1.2225	1.2245	1.5064	1.1736
TP(M\$)	–	1.9373	2.4137	5.4787
SW(M\$)	10.146	9.857981	9.648374	10.10564

As in Table 3, the Transco with revenue-cap regulation while maximizing its own profit achieves the closest system social welfare (10.10564 M\$) to the benchmark social welfare (10.146 M\$). For this system, the Transco with no-regulation is the second best (with social welfare of 9.857981 M\$), and the Transco with cost-plus regulation is the third best (with social welfare of 9.648374 M\$). The nodal prices in period t_4 are shown in Table 4. As this table shows the average of nodal prices ($\frac{\sum_n \lambda_n}{N}$) under the proposed approach for transmission expansion planning is closest to the benchmark nodal prices.

Table 4: Nodal prices (\$/MW) in period 4 under different regulatory regimes for modified Garvers' system

Approach	BI	N-REG	CP-REG	RC-REG
N1	1256	2292	2299	1187
N2	1545	1982	1898	1377
N3	1000	1000	1000	1000
N4	1334	1334	1334	1278
N5	1085	2767	2821	1063
N6	1334	1334	1254	1250
Avg.	1888	2677	2651	1788

6.2 Modified IEEE 24-node example system

The initial network topology is the one reported in [27] and 10 candidate transmission lines as specified in Table 5 are considered. The generation system is modified as reported in Table 6 and 7. The rest of data is the one reported in [19]. The ψ is set at 5000.

The total load is 2850 MW, which corresponds to the Tuesday of week 51 from 5 to 6 pm. The Transco plans under different regulatory regimes and the various generation investment choices are reported in Table 8.

The results for the profit-maximizing Transco with revenue-cap regulation are the same as the benchmark results. The case without regulation is the second best and the case with the cost-plus regulation is in the third place in terms of social welfare. The Transco with cost-plus regulation has the highest cost of transmission expansion planning and the one without regulation has the lowest transmission expansion cost. These results are expected. In the case of cost-plus regulation, the Transco is rewarded based on its transmission investment cost, and in the no-regulation case, the Transco invests in lines which increases congestion rent and it does not relieve congestion from system. The profile of nodal prices at period t_4 for different nodes under different regulatory regimes are plotted in Figure 3.

Table 5: Candidate transmission lines for modified IEEE 24-node system, Cct: Circuit

(from-to)	X (pu)	$\overline{C}_m$(M$/Cct)	$\widehat{F}_m$(MW)
(15,21)	0.049	24.81	166
(15,24)	0.0519	26.27	166
(16,17)	0.0259	13.11	166
(16,19)	0.0231	11.70	166
(17,18)	0.0144	7.29	166
(17,22)	0.1053	53.31	166
(18,21)	0.0259	13.11	166
(19,20)	0.0396	20.05	166
(20,23)	0.0216	10.93	166
(21,22)	0.0678	34.32	166

Table 6: Generators' data for modified IEEE 24-node system

Gen.	Node	c_j ($/MWh)	G_j (MW)	Gen.	Node	c_j ($/MWh)	G_j (MW)
G1	1	130	40	G8	8	12	310
G2	1	16	152	G9	9	4	800
G3	2	130	40	G10	22	0.001	300
G4	2	16.2	152	G11	23	12	310
G5	7	43	300	G12	23	11	350
G6	6	48.1	591	G13	15	0.001	100
G7	7	56.1	60	G14	16	0.002	100

Table 7: Candidate Generators for modified IEEE 24-node system

Gen.	Node	$\widehat{c}_k$($/MWh)	$\underline{C}_k$ (k$/MW)
G15	3	0.001	700
G16	5	0.002	300
G17	10	0.003	20,000
G18	15	0.004	30,000
G19	20	0.005	15,000

Table 8: Investment results under different regulatory regimes for the modified IEEE 24-node system

	BI	N-REG	CP-REG	RC-REG
G-plan	G15 123.1MW G16 93.5MW	G15 116.5MW G16 93.2MW	G15 119.6MW G16 97MW	G15 123.1MW G16 93.5MW
T-plan	(19,20) (20,23)	(16,19)	(15,21)(15,24) (16,17)(16,19) (18,21)(19,20)	(19,20) (20,23)
FC(M$)	–	–	418.83	406.92
TIC(M$)	30.980	11.700	116.34	30.980
GIC(M$)	114.27	109.49	112.86	114.27
TP(M$)	–	1197.5	1498.0	1530.8
SW(M$)	4125.455	3979.628	3855.140	4125.455

As it is clear from Figure 3, the Transco with revenue-cap regulation achieves the lowest electricity prices. The average of nodal prices for revenue-cap regulation is 201 k$/MW while for cost-plus regulation and no-regulation, it is 240 k$/MW. This is equivalent to a 20% increase in average prices.

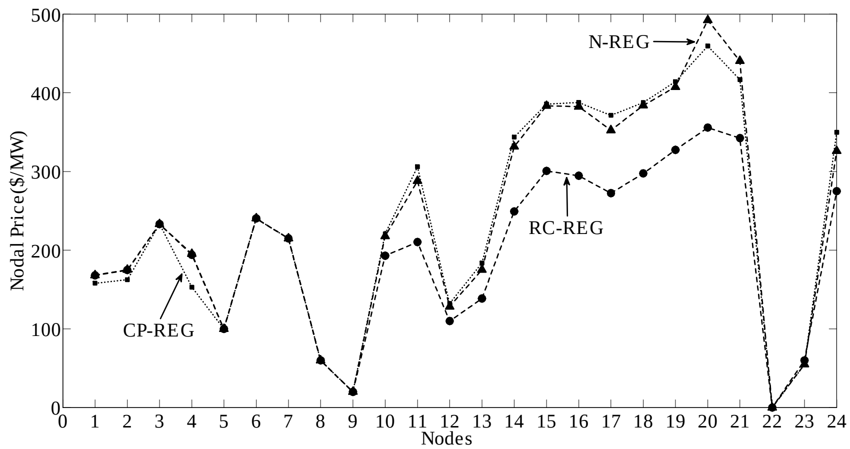

Figure 3: The nodal prices under different regulatory regimes in planning period 4 for the modified IEEE 24-node system

7 Further Discussions

The proposed approach for transmission expansion planning is analyzed under two other realistic situations. First, it is assumed that the generation system is static and transmission expansion planning is only driven by demand growth. Second, we take the view of a reactive Transco where the generation investments are exogenous parameters.

7.1 Case 1: Transmission expansion planning driven by demand growth

For this study, only existing generators of the modified Garver's system are considered. The rest of the system data are those specified in Section 6. The results of transmission expansion planning under different regulatory regimes are reported in Table 9.

Table 9: Transmission investment under different regulatory regimes for modified Garver's example system – case 1

	BI	N-REG	CP-REG	RC-REG
T-plan	(2,6) (3,5) (4,6)	– – –	(2,4)(2,5) (3,4)(3,6) (4,5)	(2,6) (3,5) (4,6)
FC(k$)	–	–	853.2	3877.2
TIC(k$)	70	0	237	70
TP(M$)	–	3.1379	3.6930	5.1022
SW(M$)	9.975325	8.980316	8.912756	9.975325
Avg($/MW)	1435	2925	2755	1435

The Transco without regulation does not invest in any new transmission lines. This is because investing in any transmission line reduces the overall system congestion rent. The profit of the Transco is 3.1379 M$ and the social welfare is 8.980316 M$. The Transco with cost-plus regulation invests in five new lines as reported in Table 9 with investment cost of 237 M$. The Transco profit with cost-plus regulation is higher than one for the case with no-regulation but at the cost of decreased social welfare. However, the revenue-cap regulation approach results in the benchmark solution. In terms of nodal prices, the average price for Transco with revenue-cap regulation is the cheapest as compared to ones for no-regulation and cost-plus regulation cases (1435 $/MW as compared to 2925 $/MW and 2755 $/MW). Table 10 reports the results for the modified IEEE 24-node system.

Table 10: Transmission investment under different regulatory regimes for the modified IEEE 24-node system – case 1

	BI	N-REG	CP-REG	RC-REG
T-plan	(19,20) (20,23)	(19,20) (20,23) (17,18)	(15,21)(15,24)(16,17) (16,19)(17,18)(18,21) (19,20)(20,23)	(19,20) (20,23)
FC(M\$)	–	–	458.16	148.15
TIC(M\$)	30.98	38.270	127.27	30.98
TP(M\$)	–	1233.4	1614.4	1389.3
SW(M\$)	4016.828	4015.358	3911.275	4016.828
Avg(\$/MW)	243	243	246	243

The proposed Transco invests 30.98 M\$ in transmission system expansion and collects a profit of 1389.3 M\$ which includes a total fixed charge of 148.15 M\$. The social welfare is 4016.828 M\$ which is the benchmark social welfare. Average price in this case is 243 \$/MW. In cases of no-regulation and cost-plus regulation, the Transco invests 38.27 M\$ and 127.27 M\$ in transmission system which are higher than the benchmark cost. Accordingly the social welfare in these cases are less than the benchmark social welfare.

7.2 Case 2: Reactive Transco with exogenous generation investments

In this case, the capacity of existing generators for the modified Garver's system and modified IEEE 24-node system are increased by 15% in each planning year. The results are reported in Tables 11 and 12. For this case, the proposed model has the closest social welfare to the benchmark welfare. In terms of average nodal prices for period t_4, both revenue-cap and cost-plus regulation prices (208 k\$/MW) are closest to the benchmark price (192 k\$/MW).

Table 11: Transmission investment under different regulatory regimes for the modified Garvers' system – case 2

	BI	N-REG	CP-REG	RC-REG
T-plan	(2,3) (2,6) (3,5)	(2,4)	(2,4)(2,5) (3,4)(3,6) (4,5)	(2,3) (2,6) (3,5)(4,6)
FC(k\$)	-	-	853.2	4249.2
TIC(k\$)	80	38	237	110
TP(M\$)	-	2.7787	3.3304	5.2680
SW(M\$)	10.23066	9.344380	9.285405	10.15882
Avg(\$/MW)	1312	2554	2375	1317

8 Conclusions

This paper proposes a profit-maximizing approach for transmission expansion planning. The Transco expands the transmission network over planning periods, collects merchandising surplus, and charges fixed fees to consumers. This is subject to a proposed revenue-cap constraint set by the regulator. The proposed approach is a bilevel program with a profit-maximizing Transco at the upper level and optimal generation dispatch and investment at the lower level. The whole proposed mechanism is reformulated as a mixed-integer, quadratically-constrained program (MIQCP) which can be solved to global optimality. Also, the model considers the discrete nature of transmission planning decisions and potential substitution between transmission expansion and generation expansion. The mechanism has been applied and tested on a modified Garvers'

Table 12: Transmission investment under different regulatory regimes for the modified IEEE 24-node system – case 2

	BI	N-REG	CP-REG	RC-REG
T-plan	(19,20) (20,23) (21,22)	- – –	(15,21)(15,24)(16,17) (16,19)(17,18)(17,22) (18,21)(19,20)(20,23)	(19,20) (20,23) (17,22)
FC(M$)	–	–	570.39	331.23
TIC(M$)	65.300	0	180.58	84.29
TP(M$)	–	1223.3	1667.7	1512.6
SW(M$)	4136.749	3958.543	3993.819	4091.041
Avg(k$/MW)	192	253	208	208

system as well as a modified IEEE 24-node system. In all tests, the proposed mechanism incentivizes Transco to produce welfare-maximum outcomes. We further have tested the proposed mechanism under cases where transmission expansion planning is driven by demand growth and reactive Tranco. The welafre-maximum outcomes are also achieved under these two cases. The results imply that the proposed mechanism can tackle the incentive problem for investment in transmission sector. Application of the stochastic programming models to the proposed approach in the paper is a good extension of this work.

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