Economic Evaluation of Transmission Expansion for Investment Incentives in a Competitive Electricity Market

Robert Fischer and Sung-Kwan Joo*

Abstract: With the shift of the electric power industry from a regulated monopoly structure to a competitive market environment, the focus of the transmission expansion planning has been moving from reliability-driven transmission expansion to market-based transmission expansion. In market-based transmission expansion, however, a growing demand for electricity, an increasing number of transmission bottlenecks, and the falling levels of transmission investment have created the need for an incentive to motivate investors. The expectation of profit serves as a motivational factor for market participants to invest in transmission expansion in a competitive market. To promote investment in transmission expansion, there is an increasing need for a systematic method to examine transmission expansion for investment incentives from multiple perspectives. In this paper, the transmission expansion problem in a competitive market environment is formulated from ISO and investors' perspectives. The proposed method uses parametric analysis to analyze benefits for investors to identify the most profitable location and amount for transmission addition. Numerical results are presented to demonstrate the effectiveness of the proposed method.

Keywords: Electricity markets, parametric analysis, transmission expansion.

1. INTRODUCTION

Various optimization-based techniques [1-6] have been proposed for transmission expansion planning in a vertically integrated utility environment. With the shift of the electric power industry from a regulated monopoly structure to a competitive market environment, the focus of the transmission expansion planning has been moving from reliability-driven transmission expansion [7,8] to market-based transmission expansion [9-12]. Reference [13] provides an in-depth discussion of the issues and solutions methods in transmission expansion planning. In [9], the formulation of competition in decentralized transmission expansion based on Lagrangian Relaxation (LR) technique is presented to show transmission investment can be profitable in a competitive market. A procedure to identify optimal transmission upgrades is proposed in [10] by computing cost of upgrades and benefits. A technique of transmission planning using Bender's decomposition is presented in [11] to solve the complicated long-term network expansion problem by decomposing the investment cost and congestion cost minimization problem into network expansion problem (master problem) and operational problem (slave problem). Market-driven power flow patterns and decision analysis scheme based on the regret of plan are incorporated in the transmission expansion method [12] to find the best transmission expansion scenario. The economic value of transmission expansion is highly dependent on the accuracy of load forecast, fuel costs, and generation additions. Therefore, there is uncertainty in the economic assessment of transmission expansion associated with errors in load forecast fuel costs, and generation additions. Reference [14] describes a probabilistic approach to evaluate the economic value of transmission expansion considering those uncertainties about future market conditions.

In market-based transmission expansion, however, a growing demand for electricity, an increasing number of transmission bottlenecks, and the falling levels of transmission investment have created the need for an incentive to motivate investors. In a competitive market environment, the expectation of profit serves as a motivational factor for investors to invest in transmission expansion. To promote invest-

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ment in transmission expansion, therefore, there is an increasing need for a systematic method to examine transmission expansion for investment incentives.

The economics of transmission expansion needs to be evaluated from multiple perspectives: Independent System Operator (ISO)/Regional Transmission Organization (RTO) perspective or private investors' perspectives. In this paper, the transmission expansion problem in a competitive market environment is formulated from ISO and investors' perspectives. With a varying range of line capacities, the proposed method uses parametric analysis to compute benefits for investors to identify the most profitable location and amount for transmission addition.

The remaining of this paper is organized as follows. In Section 2, the transmission expansion problem in a competitive market environment is formulated from ISO and investors' perspectives. Next, the parametric analysis technique for transmission expansion is presented to identify the most profitable location and amount for transmission addition in Section 3. Finally, numerical results are presented to demonstrate the effectiveness of the proposed method in Section 4.

2. TRANSMISSION EXPANSION FROM ISO AND INVESTORS' PERSPECTIVES

Transmission expansion can significantly alter power flow patterns in power systems, thereby influencing market prices and welfare of market participants. To measure the overall benefits of transmission expansion, the benefits offered to different market participants need to be determined. The producer surplus (PS) of a generator is the difference between price times the amount of power generated and the variable production cost of generation for the amount of power produced. The total PS in a market is the summation of all generators' PS. The consumer surplus (CS) of a load is defined as the difference between the Value of Lost Load (VOLL) minus the price of the area times the demand of the area. Congestion revenue (CR) is defined as differential in source and sink LMPs times the amount of power transfer between source and sink. Therefore, the total surplus (TS) of the system is the sum of the total CS, the total PS, and the CR. The following equations describe these formulations.

$$PS = LMP_i \cdot P_i - MC_i \cdot P_i, \tag{1}$$

$$CS = VOLL \cdot D_i - LMP_i \cdot D_i, \tag{2}$$

$$CR = (LMP_i - LMP_j) \cdot F_{ij}, \tag{3}$$

$$TS = PS + CS + CR, \tag{4}$$

where $LMP_{i,j}$ is the LMP price for the area *i* or *j*, P_i is the amount of power produced at bus *i*, MC_i is the marginal cost of generation or producing the amount of power for bus *i*, D_i is the power demand of the area at bus *i*, and F_{ij} is the power that flows through the transmission line between buses *i* and *j*.

The economic benefits of the transmission expansion can be analyzed from multiple perspectives: ISO perspective and market players or private investors' perspective. From the ISO perspective, the objective of the transmission expansion is to maximize the social welfare. The cost of the transmission line is not accounted for when considering the social benefit of the transmission expansion from the ISO perspective. Therefore, from the ISO perspective, the optimal location and amount of transmission expansion can be described as the one that provides the largest social benefit to the entire market, as described in (5).

$$\overset{n}{\underset{k=1}{Max}} \{SB(\tau_k)\}, \tag{5}$$

where $SB(\tau_k)$ is the social benefit for a varying range of line capacity τ_k for the candidate site *k*.

On the other hand, from the market players or private investors' perspective, the increased revenue due to the transmission expansion must be greater than the investment cost of a transmission line. For a current transmission owner, there are two profitable transmission expansion scenarios. The first scenario is for a transmission owner that does not own one of the candidate sites for expansion. Suppose that the transmission owner intends to invest in a candidate site to gain increases in the revenues from the pre-existing lines that it does own. Since the new transmission line can alter LMPs and power flow patterns in the systems, the transmission owner needs to find the optimal location and amount of transmission addition to maximize the combined revenues from the new line and its own pre-existing lines. The following equation states that the optimal amount and location of transmission addition is the candidate scenario that maximizes the differences between the combined revenues from both new and pre-existing lines and the cost of the new transmission line:

$$\overset{n}{\underset{k=1}{Max}} \{(\Delta CR_{op}(\tau_k) + CR_{hj}(\tau_k) - C_T(\tau_k))\}, \tag{6}$$

where $\Delta CR_{op}(\tau_k)$ represents the change in the revenue from the pre-existing transmission line o to p due to the new line. $CR_{hj}(\tau_k)$ represents the revenue from the new transmission line *h* to *j*. $C_T(\tau_k)$ is the cost of a transmission line that is dependent on line capacity τ_k in candidate site k. The cost of a transmission line can be represented as an annualized cost where the total cost of the transmission line is allocated per year for a given time period [15]. If the revenues of transmission lines are greater than the cost of the new transmission line, then the new transmission line will be a profitable investment.

The second scenario for a transmission owner is similar to a private investor perspective. In this scenario, the new line will be added in a known congested line. For a current transmission owner of a congested line to add on to the pre-existing line, the optimal amount and location of transmission addition are described by the following equation:

$$\underset{k=1}{\overset{n}{Max}}\left\{\Delta CR_{hj}(\tau_k) - C_T(\tau_k)\right\}, \tag{7}$$

where $\Delta CR_{hj}(\tau_k)$ represents the change in the revenue from the enhanced transmission line h to j due to changes in the line capacity.

For the private investor, the predicted transmission revenue for a given amount of line addition has to be greater than the cost of the transmission line. However, due to the investors' need for profit, a profit margin, PM_{ij}, must be inserted into the location considerations as follows:

$$\underset{k=1}{\overset{n}{Max}}\left\{CR_{hj}(\tau_k) - C_T(\tau_k) - PM_{hj}\right\}. \tag{8}$$

Generators also have the opportunity and incentive to invest in transmission lines due to the possibility that their market shares and/or LMPs may increase with the transmission addition. For generators, the cost of building a transmission line has to be justified by an increase in PS. If the increased PS from the line addition is greater than the cost of the transmission line, then the investment in the transmission line is justified. The optimal location and amount of transmission addition from a generator's perspective are formulated as follows:

$$\underset{k=1}{\overset{n}{Max}}\left\{\Delta PS_j(\tau_k) - C_T(\tau_k)\right\}. \tag{9}$$

3. PARAMETRIC ANALYSIS FOR TRANSMISSION EXPANSION

LMP is becoming the standard in many competitive electricity markets for energy and congestion management. In an LMP-based market, generators are paid the LMP of the bus where they are located, while loads pay the LMP of the bus where they are located. LMP is defined as the cost of delivering the next MW of power without violating any system constraints [16]. The market optimization problem under LMP can be formulated as follows:

$$\text{Minimize } \sum_{i\in A} B_i \cdot P_i \tag{10}$$

subject to:

$$\sum_{i\in A} P_i - \sum_{i\in A} D_i = 0 \tag{11}$$

$$F_{ij} \le F_{ij}^{Max} \tag{12}$$

$$P_i^{\min} \le P_i \le P_i^{\max}, \tag{13}$$

where B_i is the supply bid function of generator i in area A, P_i is the supply quantity of generator i, D_i is the constant demand quantity at bus i, F_{ij}^{Max} is the maximum amount of power that can be transferred on the line between buses i and j, and $P_i^{\min}$ and $P_i^{\max}$ are the lower and upper limits of generator i, respectively.

The above optimization problem is solved for the optimal amount of power produced by generator i, i.e., the vector G_x. In this study, all the constraints are represented in terms of the vector G_x. The power balance constraint can be expressed in matrix form as follows:

$$\begin{bmatrix}1 & 1 & 1 & \cdots & 1\end{bmatrix} \cdot G_x = \sum_{i\in A} D_i, \tag{14}$$

where the matrix of ones is a $1\times n$ matrix where n is the number of generators.

Also, the inequality constraint can be re-written in terms of the vector G_x as follows:

$$\begin{bmatrix} A^T \cdot B^{-1} \\ -A^T \cdot B^{-1} \end{bmatrix} \cdot G_x \le \begin{bmatrix} \dfrac{P_{ij}^{\max}}{\left(1/x_{ij}\right)} + A^T \cdot B^{-1} \cdot D_x \\ \dfrac{P_{ij}^{\max}}{\left(1/x_{ij}\right)} - A^T \cdot B^{-1} \cdot D_x \end{bmatrix}, \tag{15}$$

$$A_0 \cdot G_x \le b_0. \tag{16}$$

In (16), x_{ij} represents the reactance of line between buses i and j. A_0 is an $n\times 2m$ matrix that represents the left-hand side of the inequality matrix. The upper half and lower half of A_0 represent the positive power flow and the negative power flow in the transmission line, respectively. b_0 represents the right-hand side of the inequality matrix.

In [16], the LMP at bus i is given by the following equation.

$$LMP_i = \lambda - \sum \mu_l \cdot \frac{dF_l}{dP_j}, \tag{17}$$

where LMP_i is LMP at bus i, λ is the marginal price at the reference bus, μ_l is the shadow price of line l, and $\frac{dF_l}{dP_j}$ is the shift factor for bus j on binding constraint l. The shift factors for the system correspond to the matrix A_0 due to the fact that A_0 is the Jacobian matrix with respect to $\frac{dF_l}{dP_i}$.

The dual variables represent the shadow prices of the primal problem. The shadow price represents the rate in change of the objective function with small changes in the right-hand side (RHS) variables. There are two forms of duality: canonical and standard. In the dual simplex method, the primal must be represented in canonical form. If the primal and dual are represented in standard form, the primal dual method must be used.

In this study, parametric analysis is used to find a direction for which the objective function changes along a certain direction based on perturbations to the system. Parametric analysis is performed on the RHS in the primal problem. The response of the shadow price values with response to changes in the line capacities is of interest. Therefore, parametric analysis in the dual problem is conducted with respect to changes in the objective function values.

In order to conduct the parametric analysis for the primal problem in equation (10), consider changes in the RHS variable in the following generic form of the optimization problem:

Minimize $c \cdot x$ (18)

subject to:

$$Ax \geq b + \Delta b \tag{19}$$

$$x \geq 0. \tag{20}$$

The changes in the RHS variable, i.e., Δb, can be solved for a given direction and range. In (19), $\Delta b_i = \alpha_i \cdot \tau$ is substituted for the changes in the RHS variable. α_i is the pre-specified direction and τ is the range of change for the change in b_i.

The procedure for application of the parametric analysis for systematic changes in the b_i parameters, described in [17], can be summarized as follows:

Step 1: Solve the initial primal problem in equation (10) using dual simplex method with $\tau = 0$.

Step 2: Introduce $\Delta b_i = \alpha_i \cdot \tau$ for changes in the RHS. Apply changes to the objective function to find how the objective function value changes with variations in τ.

Step 3: Increase τ as far as desired or until the right-side column value of any basic variable goes negative.

Step 4: Conduct an iteration using the dual simplex method to find the new optimal solution. Go back to step 3 and repeat the iteration process until none of the basic variables becomes negative for changes to τ.

Using the above procedure, the LMP at bus i can be represented with respect to the changes in the transmission capacity as follows.

$$LMP_i^{base} = \left(\lambda^{base} - \sum \mu_l^{base} \cdot \frac{dF_l}{dP_j} \right), \tag{21}$$

$$LMP_i(\tau) = \left(\lambda(\tau) - \sum \mu_l(\tau) \cdot \frac{dF_l}{dP_j} \right), \tag{22}$$

where $\lambda(\tau)$ is the change in the slack bus marginal cost with respect to change in the transmission capacity and $\mu_l(\tau)$ is the change in the shadow price with respect to the change in the transmission capacity.

For simplicity, the load curves can be represented as a step function where each step value is the average load for a given hour. The load curve can also be represented in peak load percentages. Using this type of load data, analysis can be formulated for four days and then extended to a one-year simulation to represent the changing loads for a year. The load changes influence prices and the supply quantities of generators. These changes can be properly represented by using parametric analysis for the RHS variables in the primal problem. The equality constraint is represented in (23) and (24), while the inequality constraint is represented in (25).

$$\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \cdot G_x \leq \sum_{i \in A} D_i \tag{23}$$

$$-\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \cdot G_x \leq -\sum_{i \in A} D_i \tag{24}$$

$$\begin{bmatrix} A^T \cdot B^{-1} \\ -A^T \cdot B^{-1} \end{bmatrix} \cdot G_x \leq \begin{bmatrix} \dfrac{P_{ij}^{\max}}{\left(1/x_{ij} \right)} + A^T \cdot B^{-1} \cdot D_x \\ \dfrac{P_{ij}^{\max}}{\left(1/x_{ij} \right)} - A^T \cdot B^{-1} \cdot D_x \end{bmatrix} \tag{25}$$

By combining these equations for use in the dual simplex method, every RHS variable is dependent on a value of the load, as shown in (26).

$$\begin{bmatrix} [1 \ \ 1 \ \ 1 \ \ \cdots \ \ 1] \\ -[1 \ \ 1 \ \ 1 \ \ \cdots \ \ 1] \\ A^T \cdot B^{-1} \\ -A^T \cdot B^{-1} \end{bmatrix} \cdot G_x \le \begin{bmatrix} \sum\limits_{i \in A} D_i \\ -\sum\limits_{i \in A} D_i \\ \dfrac{P_{ij}^{\max}}{\left({}^{1}\!/_{x_{ij}} \right)} + A^T \cdot B^{-1} \cdot D_x \\ \dfrac{P_{ij}^{\max}}{\left({}^{1}\!/_{x_{ij}} \right)} - A^T \cdot B^{-1} \cdot D_x \end{bmatrix} \tag{26}$$

In order to use parametric analysis, the loads are represented as peak load percentages. The percentages have to be represented with respect to the smallest percentage due to positive changes in the RHS. The starting point is at the smallest percentage or 1 and each point from the starting point is a percentage added on to this point. The load value is represented with respect to τ in terms of a tenth of a percent or any given percentage as follows:

$$D \cdot L_{\%} = \begin{bmatrix} D_1 + {}^{1}\!/_{\alpha} D_1 \cdot \alpha \cdot (L_{\%} - 1) \\ D_2 + {}^{1}\!/_{\alpha} D_2 \cdot \alpha \cdot (L_{\%} - 1) \\ D_3 + {}^{1}\!/_{\alpha} D_3 \cdot \alpha \cdot (L_{\%} - 1) \\ \vdots \\ D_m + {}^{1}\!/_{\alpha} D_m \cdot \alpha \cdot (L_{\%} - 1) \end{bmatrix}, \tag{27}$$

where ${}^{1}\!/_{\alpha}$ is the size of the percentage to be examined.

For a variety of percentages larger than one, the equation $\tau = \alpha \cdot (L_{\%} - 1)$ can be substituted in the RHS of (27). Now parametric analysis can be applied for the τ values to determine the ranges and how the additional transmission capacity affects the system by using the procedure for parametric analysis. Using the formulations presented in Section 2 and the parametric analysis, the following procedure is used for identifying the profitable location and amount of transmission addition:

Step 1: Solve both the primal optimization problem in (10) and its dual problem with τ equal to zero.

Step 2: Apply parametric analysis to the results of the optimization problem for increased load perturbations.

Table 1. Investment criteria using parametric analysis with varying range variable.

Market Players	Investment Criteria
ISO	$\underset{k=1}{\overset{n}{Max}} \left\{ \begin{aligned} & \sum_{i=1}^{m} \left(LMP_i(\tau_k) \cdot P_i(\tau_k) - LMP_i^{base} \cdot P_i^{base} \right) - MC_i(P_i(\tau_k)) \cdot \left(P_i(\tau_k) - P_i^{base} \right) \\ & + \sum_{i=1}^{m} \left(LMP_i(\tau_k) - LMP_i^{base} \right) \cdot D_i \\ & + \sum_{i,j \in A}^{L} \left(\left(LMP_i(\tau_k) - LMP_j(\tau_k) \right) \cdot H_x \cdot A^t \cdot B_{s}^{-1}{}_{*} \cdot P(\tau_k) \right) \\ & - \left(\left(LMP_i^{base} - LMP_j^{base} \right) \cdot H_x \cdot A^t \cdot B_{s}^{-1}{}_{*} \cdot P^{base} \right) \end{aligned} \right\}$
Generator	$\underset{k=1}{\overset{n}{Max}} \left\{ \sum_{i=1}^{m} \left(\lambda(\tau_k) - \sum_{l=1}^{L} \mu_l(\tau_k) \cdot \dfrac{dF_l}{dP_i} \right) \cdot P_i(\tau_k) - MC_i\left(P_i(\tau_k)\right) \cdot P_i(\tau_k) - C_T(\tau_k) \right\}$
Transmission Owner	$\underset{k=1}{\overset{n}{Max}} \left\{ \Delta CR_{hj}(\tau_k) - C_T(\tau_k) \right\}$
	$\underset{k=1}{\overset{n}{Max}} \left\{ \left(\Delta CR_{op}(\tau_k) + CR_{hj}(\tau_k) - C_T(\tau_k) \right) \right\}$
Private Investor	$\underset{k=1}{\overset{n}{Max}} \left\{ CR_{hj}(\tau_k) - C_T(\tau_k) - PM_{hj} \right\}$

Step 3: Apply parametric analysis for each candidate location.

Step 4: The candidate location and amount of τ that fulfills the equations listed in Table 1 describe the profitable location and amount of transmission expansion based on the investor's perspective.

Table 1 describes the optimal locations and amount of line addition. From an investor's point of view, these are the best locations for transmission expansion. However, there may be other locations that provide increased surpluses and revenues but not at the level described by the equations in Table 1. Nevertheless, these other locations and amounts can still be considered good locations to invest in as long as values in the equations remain positive.

4. NUMERICAL RESULTS

In this section, a 10-bus numerical example is presented to demonstrate the effectiveness of the proposed method. The test system is shown in Fig. 1 and the data values for the test system are listed in Tables A1-A4 in Appendix A. In order to analyze each time period for a ten-year duration, the percentages from the IEEE test system [18] were inserted into the load duration curve. With the load duration percentages and the times that that load percentage occurs in a year, generation levels, LMP, PS, SB, CR, and CS are computed to find the amount in question for a given year. Using the predicted loads for 2006-2016 from the California Energy Commission [19], the load increases for a ten-year period can be simulated.

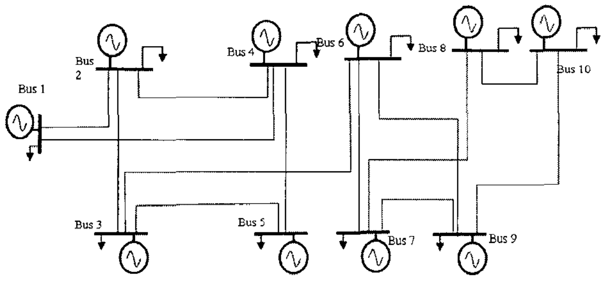

Fig. 1. 10-bus test system.

4.1. Best location and amount from ISO perspective

The 10-bus numerical example was analyzed for a ten-year time period starting in 2006. Once parametric analysis was performed for the load increases, lines 1, 4, 6, 7, 8, and 11 were identified as congested lines in the system for varying loads over a ten-year period. This system also displays interesting LMP characteristics. The majority of the LMP prices for the base case are below the marginal cost at the slack bus. Therefore, if the price of congestion decreases, then the LMP prices will increase. If the shadow prices decrease (or increase), then the LMP prices will increase (or decrease). This analogy is used in order to understand the changes to the system. Parametric analysis was applied to the six candidate locations for the increasing loads for a ten-year period. The generation levels, PS, SB, CR, CS, and LMP were recorded with respect to changes to the candidate locations.

Table 2 identifies the amount of transmission addition where the candidate locations have their highest social benefit. These values are listed in Table

Table 2. Social benefits for candidate lines.

(Mill $)	Line 1 at 49 MW	Line 4 at 96 MW	Line 6 at 151 MW	Line 7 at 68 MW	Line 8 at 241 MW	Line 11 at 41 MW
Year 2006	1.6736	17.766	1.7744	2.108	9.3064	6.3062
Year 2007	1.7713	18.448	5.7478	2.3006	8.8538	5.2683
Year 2008	2.6279	19.719	10.107	1.544	8.1723	3.8841
Year 2009	2.8831	21.334	13.178	1.3536	7.0169	3.1408
Year 2010	1.0632	14.748	0.40847	3.1551	10.437	7.0562
Year 2011	2.9755	23.17	26.21	1.2911	6.2874	2.3053
Year 2012	3.3171	23.254	30.376	1.4593	5.6407	1.4804
Year 2013	3.4528	22.522	35.244	1.3201	5.0985	1.1108
Year 2014	3.7991	21.615	38.805	0.65698	4.405	0.9927
Year 2015	4.1692	23.012	41.137	1.3961	4.1284	0.7123
Year 2016	4.8152	21.815	45.626	1.8095	3.6854	0.89178
Total	32.548	227.403	248.61367	18.39438	73.0318	33.14888

2, along with the corresponding social benefit for each year. As can be seen in Table 2, the optimal location and amount of transmission addition from a social perspective is line 6 at 151 MW of additional transmission capacity.

4.2. Profitable location and amount for transmission owner

For the cost formulation of the transmission line, the annualized cost and lengths of the transmission lines are arbitrarily chosen numbers in order to demonstrate the formulations. The annualized cost of the transmission line k is then chosen as 250 $/ (MW·km·year) and the line lengths are given in Table A-2 of Appendix A. The amount of power that the line carries per MW built is taken from the total amount of hours that the line is congested in the one-year simulation. Table A-4 in Appendix A shows these amounts for each year.

For lines 1, 4, 6, 7, 8, and 11 the line lengths are 325, 500, 175, 8, 125 and 40 miles, respectively. The average line cost is calculated as shown in Table A-7 in Appendix A. The locations to consider for profitable location from the investors' perspectives are the same as from the ISOs. However, the capacity value is different due to the loss of revenue from the transmission line cost. From the transmission owner's perspective, it is assumed that each line is owned by a different transmission owner and that it takes five years for each line to be built and put into service, i.e., 2010.

For case one, where the investor owns a separate location within the system, the new owner makes the congestion revenue from the new line and the increased transmission revenue, due to expansion, from the pre-existing line. Hence, the new revenue must be greater than the annual costs of the new line.

Table 3 shows the transmission owners that will receive increased revenue along with the amounts of capacity addition required for each candidate. It can be observed from Table 3 that the most profitable location and amount of transmission expansion for case 1 is line 4 with 101 MW of transmission addition.

These results confirm line 4 as being the most profitable location for the investment of the transmission addition for line 6 because line 4 has the highest LMP prices on its bordering bus. The high transmission revenue from line 4, along with line 6 being the only line with increased production revenue, elevated the transmission owner on line 6 to the best investment location. Line 4 is the location where the LMPs were most dramatically changed due to large changes in the shadow prices.

For the second case, the investor in the transmission line is the owner of the candidate line, indicating that the line addition is profitable when the addition increases the transmission revenue to more than the current value. For this numerical example, the only candidate location that had increased revenue was line 7. Table 4 shows the increased revenue and capacity amount. The candidate location on line 7 was the only location with a positive increase in transmission

Table 3. Transmission revenues for candidate locations and lines that have incentive to invest.

Candidate Line	Incentive Line	Cost of Candidate ($)	Max Revenue ($)	Capacity Addition (MW)	Profit Margin /MW /Year ($)	Profit over 6 years ($)
1	2	81,250	83,450	49	2,200	62,883,612
4	6	125,000	221,901	101	96,901	5,079,162,816
6	3	43,750	22,543	179	No profit	No profit
	8	43,750	68,158	143	24,408	856,467,444
	9	43,750	93,145	143	49,395	1,733,251,779
	11	43,750	31,969	142	No profit	No profit
	12	43,750	29,279	151	No profit	No profit
7	1	2,020	23,301	68	21,281	257,900,183
	2	2,020	23,593	68	21,573	261,438,872
	4	2,020	24,190	68	22,170	268,673,796
	6	2,020	22,984	36	20,964	254,058,523
8	6	31,250	38,093	29	6,843	19,645,824
	7	31,250	38,093	29	6,843	19,645,824
11	6	10,000	12,200	38	2,200	25,027,995
	8	10,000	12,200	38	2,200	25,027,995

revenue, because the decrease in shadow prices increased the nodal price at bus 5, a bordering bus of line 7, while the LMP at bus 4 stayed constant.

4.3. Profitable location and amount for generators

In order for a generator to have an incentive to invest in a transmission line, PS for the generator has to increase to an amount greater than or equal to the cost of the transmission line. Using the same technique used for finding the most profitable location and amount for transmission owners, one can identify the locations that increase PS. The candidate locations and each incentive generator with a positive increase in PS are described in Table 5. It can be observed

Table 4. Transmission revenues for candidate locations and lines that have incentive.

Candidate Line	Cost of Candidate ($)	Max revenue ($)	Capacity Addition	Profit Margin /MW/Year ($)	Profit over 6 years ($)
7	2,020	2,181	68 MW	161	1,951,126

Table 5. Producer surpluses of generators due to transmission line additions.

Candidate Line	Incentive Generator	Cost of Candidate ($)	Max revenue ($)	Capacity Addition	Profit Margin /MW /Year ($)	Profit over 6 years ($)
1	2	81,250	570,574	170	489,324	2,935,944
	3	81,250	626,857	170	545,607	3,273,642
	5	81,250	1,059,571	66	978,321	5,869,926
	6	81,250	57,143	105	No Profit	No Profit
4	1	125,000	4,392,686	75	4,267,686	25,606,116
	2	125,000	29,182,290	139	29,057,290	174,343,740
6	2	43,750	346,285	25	302,535	1,815,210
	3	43,750	2,836,714	29	2,792,964	16,757,784
	4	43,750	884,714	68	840,964	5,045,784
	5	43,750	3,002,167	99	2,958,417	17,750,502
7	1	2,020	278,977	99	276,957	1,661,742
	2	2,020	37,429	99	35,409	212,454
	4	2,020	220,976	339	218,956	1,313,736
8	3	31,250	179,571	20	148,321	889,926
	4	31,250	114,371	48	83,121	498,726
	5	31,250	254,429	48	223,179	1,339,074
	6	31,250	43,542,860	3	43,511,610	261,069,660
11	6	10,000	7,097,571	58	7,087,571	42,525,426
	9	10,000	7,594,743	58	7,584,743	45,508,458
	10	10,000	4,395,229	47	4,385,229	26,311,374

Table 6. Private investor's profit.

Candidate Line	Incentive Line	Cost of Candidate ($)	Max revenue ($)	Capacity Addition (MW)	Profit Margin /Year ($)	Profit over 6 years ($)
1	2	81,250	3,377,438	45	3,296,188	19,777,128
4	6	125,000	24,744,720	170	24,619,720	147,718,320
6	3	43,750	5,980,391	84	5,936,641	35,619,846
7	8	2,020	108,082,200	68	108,080,180	648,481,080
8	9	31,250	3,756,486	211	3,725,236	22,351,416
11	11	10,000	299,943	38	289,943	1,739,658

from Table 5 that generator 6 will gain the largest PS increase for an increase in line capacity on line 8.

4.4. Profitable location and amount for private investors

From the private investor perspective, the new transmission revenue gained by the increased line capacity must be greater than the cost of the transmission addition, in addition to a profit margin. Using parametric analysis, each of the candidate's transmission revenue can be examined. This analysis also includes the predicted amount of line flow on the line. For this numerical example, there must be an addition of at least 10 MW. There are two possibilities for the transmission revenue on a candidate location: the revenue is eliminated due to the LMPs rising to the same amount, and the revenue is reduced due to shadow prices in other parts of the system. The first case is examined for a point beyond the relief of congestion, while the numerical example of the second case only examines the addition through the relief of the congestion on the line. The candidate locations and each line for private investor revenue are described in Table 6.

Table 6 shows that the location for a private investor to make the greatest profit is line 7 with an addition of 68 MW. Line 7 results in the only positive increase in transmission revenue for an increase in line capacity. The positive increase, along with the addition of 68 MW, made line 7 the most profitable location for a private investor to make the most profit.

5. CONCLUSIONS

In this paper, the transmission expansion problem in a competitive market environment is formulated from ISO and investors' perspectives. The approach based on parametric analysis is proposed to compute benefits for investors to identify the profitable location and amount for transmission addition.

The parametric analysis results could be extended to include the changes to the marginal cost functions based on fluctuations in fuel costs, bilateral contracts, and gaming. Once the methodology for parametric analysis is configured for the changes in the system, the analysis can determine the changes to the shadow prices for ranges of the new values. With these ranges, both the extreme and the average case scenarios can easily be represented.

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APPENDIX A

Table A-1. Load data for 10-bus test system.

Bus	1	2	3	4	5	6	7	8	9	10
Load (MW)	800	500	1000	900	1200	1200	1000	1500	1000	800

Table A-2. Line data for 10-bus test system.

	From Bus	To Bus	Impedance (P.U.)	Capacity (MW)	Length (Miles)
Line 1	1	2	0.0139	550	325
Line 2	1	4	0.02112	100	50
Line 3	2	3	0.0845	450	10
Line 4	2	4	0.01267	600	500
Line 5	3	5	0.0192	450	250
Line 6	3	6	0.0119	6	175
Line 7	4	5	0.0839	250	8
Line 8	6	9	0.01037	450	125
Line 9	6	7	0.0883	450	325
Line 10	7	8	0.0605	300	95
Line 11	7	9	0.0165	600	40
Line 12	8	10	0.0476	400	200
Line 13	9	10	0.025	750	50

Table A-3. Generator bid data for 10-bus test system.

	Steps(MW)	Price($/MWh)		Steps(MW)	Price($/MWh)
Generator 1	0-100	15	Generator 6	0-100	8
	100-200	21		100-200	10
	200-300	24		200-300	12
	300-400	27		300-400	13
	400-500	32		400-500	14
	500-600	38		500-600	16
	600-700	45		600-700	17
	700-800	45		700-800	18
	800-900	45		800-900	20
	900-1000	50		900-1000	20
Generator 2	0-240	1.2	Generator 7	0-80	39
	240-480	1.6		80-160	41
	480-720	2		160-240	49
	720-960	2.6		240-320	52
	960-1200	3		320-400	54
	1200-1440	4.2		400-480	56
	1440-1680	5		480-560	58
	1680-1920	5.4		560-640	59
	1920-2160	6		640-720	61
	2160-2400	9		720-800	64
Generator 3	0-200	10	Generator 8	0-100	17
	200-400	12		100-200	18
	400-600	14		200-300	20
	600-800	20		300-400	22
	800-1000	27		400-500	24
	1000-1200	38		500-600	26
	1200-1400	42		600-700	28
	1400-1600	48		700-800	29
	1600-1800	51		800-900	30
	1800-2000	60		900-1000	32
Generator 4	0-80	22	Generator 9	0-100	26
	80-160	28		100-200	27
	160-240	34		200-300	27
	240-320	39		300-400	28
	320-400	41		400-500	29
	400-480	45		500-600	29
	480-560	45		600-700	31
	560-640	49		700-800	31
	640-720	55		800-900	31
	720-800	55		900-1000	31
Generator 5	0-140	5	Generator 10	0-100	26
	140-280	10		100-200	27
	280-420	14		200-300	28
	420-560	16		300-400	28
	560-700	18		400-500	29
	700-840	21		500-600	29
	840-980	24		600-700	29
	980-1120	25		700-800	29
	1120-1260	26		800-900	29
	1260-1400	28		900-1000	33

Table A-4. Hours per year that addition lines will carry power.

Year (H)	line 1	line 4	line 6	line 7	line 8	line 11
2006	3908	8736	4977	2050	6219	3914
2007	4438	8736	4962	2338	6030	3959
2008	4482	8736	5386	1833	5627	4014
2009	4730	8736	6086	1956	4828	3409
2010	2706	8736	3727	2714	7435	4482
2011	5117	8736	6496	1791	4254	2335
2012	5315	8736	6566	1988	4006	1871
2013	5315	8736	6589	1624	3774	1766
2014	5444	8736	6554	1217	3619	1236
2015	5444	8736	6472	2214	3421	1226
2016	5504	8736	6516	2493	3421	978
Average	4763.909	8736	5848.273	2019.818	4784.909	2653.636

Table A-5. Annualized cost of congested lines for 10-bus test system.

	Line 1	Line 4	Line 6	Line 7	Line 8	Line 11
COST($/MWh)	17.06	14.31	7.48	0.99	6.53	3.77
COST($/year)	81,250	125,000	43,750	2,000	31,250	10,000

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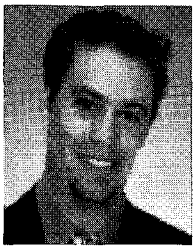

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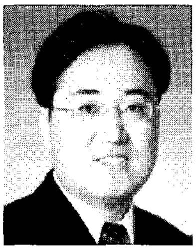

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