Transmission Augmentation in an Oligopoly Electricity Market – Part II (Numerical Studies)

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Abstract- **This paper proposes a Three-Stage Model for transmission augmentation in restructured electricity markets. The mathematical formulation of the model is developed based on the game theory. Transmission Network Service Provider, TNSP, Generating Companies, GenCos, and Market Management Company, MMC, are placed in different stages of the model. These stages are linked to each other using the Leader-followers game and the concept of Nash equilibriums. An increase in transmission capacity can have two benefits for the electricity market; firstly, efficiency benefit in terms of improving the social surplus of the electricity industry, and, secondly, competition benefit which leads to increasing competition among generating companies. The introduced Three-Stage Model can capture both benefits of transmission projects in electricity markets. An effective numerical method is designed for solving the developed Three-Stage Model. A modified IEEE 14 example system is employed to show the effectiveness of the methodology. This paper has been organized in two parts. First part deals with the mathematical formulation of the algorithm and second part deals with the numerical studies. What follows is the second part of the paper.**

I. Introduction to part II

The part I of the paper explained the developed mathematical framework for augmenting of the transmission system. The developed mathematical framework employs the leader-followers ‘concept in its formulation. The final formulation is a equilibrium problem with equilibrium constraints which accommodates all engaged parties in transmission planning problem. The mathematical framework and the developed numerical solution are detailed in the part I of the paper. To show the effectiveness of the framework IEEE 14 bus test system is used. The test system has been modified so that it can show different aspects of the developed framework. The rest of paper has organized as follows; section 2 deals with the application of the method to the modified IEEE 14 bus test system. Further discussion on the model has been provided in section 3. Finally, the concluding remarks will close the paper.

II. Application to the Modified IEEE 14-bus Example System

The modified IEEE 14 bus test system depicted in figure 1 has been employed to show the effectiveness of the proposed algorithm.

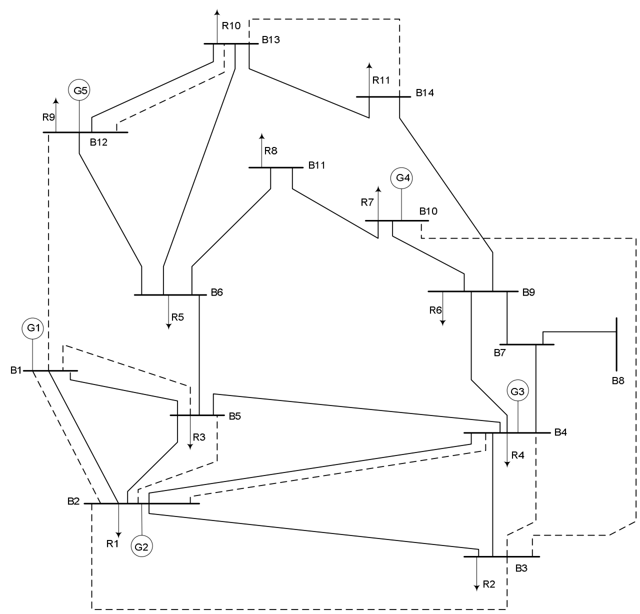

Fig. 1, Modified IEEE 14 bus test system

There are five competing generators labelled as G1 to G5, and eleven competing retailers labelled as R1 to R11 in the 14-bus example system. The TNSP is responsible for the market-based augmentation of the system. The information of the generators, retailers, and transmission network are shown in tables I, II, and III respectively. The upgrade or expansion projects for the existing transmission system are collected in table IV.

TABLE I GENERATORS ‘DATA

Generator	(MW)	(MW)	($/MWh)
G1	0.0	132.4	39.2
G2	0.0	80	25.2
G3	0.0	120	6.7
G4	0.0	70	21.5
G5	0.0	140	12.7

TABLE II RETAILERS ‘DATA

Retailer	$\underline{d}$(MW)	$\overline{d}$(MW)	$VOLL$($/MWh)
R1	0	41.7	151
R2	0	184.2	177
R3	0	87.8	154
R4	0	14.6	157
R5	0	21.2	153
R6	0	49.5	165
R7	0	9	169
R8	0	6.5	153
R9	0	12.1	166
R10	0	26.5	156
R11	0	28.9	158

TABLE III TRANSMISSION NETWORK DATA

Line#	From	To	Reactance(p.u.)	Limit(MW)
1	B1	B2	0.05917	50
2	B1	B5	0.22304	50
3	B2	B3	0.19797	50
4	B2	B4	0.17632	50
5	B2	B5	0.17388	50
6	B3	B4	0.17103	50
7	B4	B5	0.04211	50
8	B4	B7	0.20912	50
9	B4	B9	0.55618	50
10	B5	B6	0.25202	50
11	B6	B11	0.19890	50
12	B6	B12	0.25581	50
13	B6	B13	0.13027	50
14	B7	B8	0.17615	50
15	B7	B9	0.11001	50
16	B9	B10	0.08450	50
17	B9	B14	0.27038	50
18	B10	B11	0.19207	50
19	B12	B13	0.19988	50
20	B13	B14	0.34802	50

TABLE IV TRANSMISSION NETWORK UPGRADE OR EXPANSION DATA

Project #	Type of project	From	To	Max Capacity per circuit (MW)/ maximum no. of circuits	Investment cost($)
0	No upgrade or expansion	-	-	-	-
1	Upgrade	B1	B2	100/4	5000
2	Upgrade	B1	B5	100/4	7500
3	Upgrade	B2	B3	100/4	2250
4	Upgrade	B2	B4	100/4	1750
5	Upgrade	B2	B5	100/4	3750
6	Upgrade	B3	B4	100/4	6250
7	Upgrade	B12	B13	100/4	5500
8	Upgrade	B13	B14	100/4	1120
9	Expansion	B1	B12	100/4	2500
10	Expansion	B10	B3	100/4	2000

For demonstration purposes, the reactances of transmission upgrade projects in table IV are considered the same as the reactances of transmission lines established in their parallel corridors. The reactnces of lines 21 and 22 which are the expansion projects in table IV are taken as 0.02p.u .

In applying Three-stage Model on the modified IEEE 14-bus example system, the maximum number of iterations in Gauss-Seidel method has set to be 5 with an accuracy limit of 0.001. Regarding the bid specifications of the GenCos, the s_i^{min} is 0.8 times of true marginal cost and s_i^{max} is 3.0 times of true marginal cost and this setting is the same for all GenCos. 50 iterations, a step factor of 0.01 and accuracy limit of 0.001 have been used for solving the revenue maximisation of GenCos. Two cases of without monopoly rent and with monopoly rent have been studied and compared.

Case 1: Without monopoly rent ($\alpha = 1.0$)

Table V and VI show the strategic bidding of each GenCo to different transmission projects, monopoly rent of each GenCo, total monopoly rent of the system, *MR*, and social surplus, *SS* in the first iteration of Three-stage Model.

TABLE V STRATEGIC BIDDINGS OF GENCOS, MR, SS, AND INVESTMENT COST IN THE FIRST ITERATION OF THREE-STAGE MODEL

	No. of Transmission Upgrade or Expansion Project				
	0	1	2	3	4
Bid of GenCo1 with MC = 39.2 ($/MW)	109.55	109.55	109.55	39.2	109.55
Bid of GenCo2 with MC = 25.2 ($/MW)	40.95	40.95	40.95	20.16	40.95
Bid of GenCo3 with MC = 6.7 ($/MW)	5.36	5.36	5.36	5.36	5.36
Bid of GenCo4 with MC = 21.5 ($/MW)	59.95	59.95	59.95	59.34	59.95
Bid of GenCo5 with MC = 12.7 ($/MW)	35.43	35.43	35.43	35.42	35.43
MR of GenCo1($)	2501	2501	2501	**0**	2501
MR of GenCo2($)	5925	5925	5925	**2755**	5925
MR of GenCo3($)	6090	6090	6090	**4736**	6090
MR of GenCo4($)	2269	2269	2269	**1230**	2269
MR of GenCo5($)	2321	2321	2321	**2300**	2321
Total MR ($)	19107	19107	19107	11021	19107
SS ($)	49283	49283	49283	55342	49283
Investment Cost ($)	0	500	750	2250	1750
SS-MR-Cost($)	30176	29676	29426	42071	28426

TABLE VI STRATEGIC BIDDINGS OF GENCOS, MR, SS, AND INVESTMENT COST IN THE FIRST ITERATION OF THREE-STAGE MODEL (CONTINUED)

	No. of Transmission Upgrade or Expansion Project					
	5	6	7	8	9	10
Bid of GenCo1 with MC = 39.2 ($/MW)	109.55	109.55	78.4	109.55	74.73	110.43
Bid of GenCo2 with MC = 25.2 ($/MW)	40.95	40.95	47.88	40.95	70.68	40.95
Bid of GenCo3 with MC = 6.7 ($/MW)	5.36	5.36	5.36	5.36	5.36	5.36
Bid of GenCo4 with MC = 21.5 ($/MW)	59.95	59.95	59.62	59.95	60.12	17.2
Bid of GenCo5 with MC = 12.7 ($/MW)	35.43	35.43	35.59	35.43	10.16	35.51
MR of GenCo1($)	2501	2501	**1219**	2501	**114**	**3346**
MR of GenCo2($)	5925	5925	**3145**	5925	**2877**	**6174**
MR of GenCo3($)	6090	6090	**4613**	6090	**3727**	**4843**
MR of GenCo4($)	2269	2269	**1702**	2269	**2557**	**-16**
MR of GenCo5($)	2321	2321	**2787**	2321	**5553**	**2557**
Total MR ($)	19107	19107	13466	19107	14828	16920
SS ($)	49283	49283	50492	49283	52789	56765
Investment Cost ($)	3750	6250	5500	1120	2500	2000
SS-MR-Cost($)	29801	29551	36476	29056	35461	37845

As in tables V and VI, positive effect of transmission capacity on MR has been indicated by underlined and bold figures. Bold figures show the negative effect of transmission capacity on MR in term of increasing the MR compared with no action case. When transmission capacity does not have any effect on MR, it has been shown by usual figures. Transmission upgrades 1, 2, 4, 5, 6, and 8 do not have any effect on MRs of GenCos. Upgrade of transmission corridor 3 by 100MW would decrease the GenCo 1's MR from $2501 to $0. Similarly, transmission project 3 has a positive effect of 53%, 22.23%, 45.79%, and 0.9% in decreasing the monopoly rents of GenCos 2 to 5. Hence, transmission upgrade 3 could be evaluated as a very good upgrade in terms of MRs of GenCos. Going to transmission project 7, it has positive effects of 51.26%, 46.91%, 24.25%, and 24.98% in decreasing the monopoly rents of GenCos 1 to 4. However, upgrading of transmission corridor 7 increases the monopoly rent of GenCo 5 from $2321 to $2787 which is about -20%. The same effect can be observed in the monopoly rent of GenCo 5 for transmission project 9. In this case, the GenCo 5 enjoys from a 139.25% increase in his monopoly rent. Accordingly, GenCo 5 would advocate transmission project 9 instead of transmission project 3 in which he loses $21 of his monopoly rent. Obviously, TNSPs owned and operated by GenCos may not advocate optimal transmission expansion strategy.

Figure 3 shows the objective function of TNSP (partition 3 of equation (8)) versus the transmission projects. TNSP would select transmission project 3 with the total benefit of $42071.

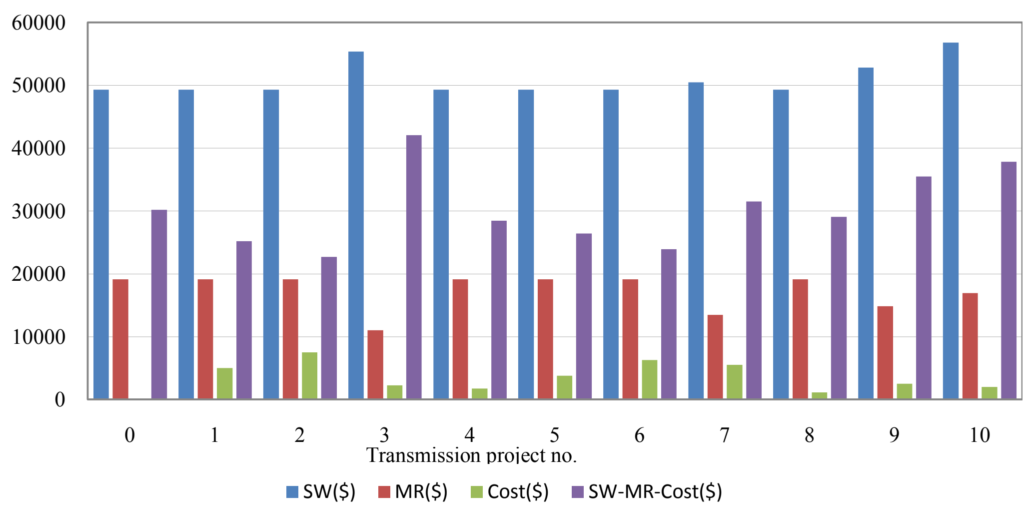

Figure 3, First iteration of Three-stage Model

In the next iteration, the Three-stage Model upgrades the transmission corridor B1-B2 by 100MW. This results to the social surplus of $59731 and monopoly rent of -$133, -$76, and $-144 for GenCos 1 to 3 and $0 for GenCos 4 and 5. The cost-benefit analysis introduced in Three-stage Model approves transmission projects of 3 and 1 and the rests can not get approved. Based on the Three-stage Model, the approval is based on the capturing the competition benefit and efficiency benefit of transmission projects. This has been shown in figure 4 by calculating the change in SS, MR as a result of transmission projects.

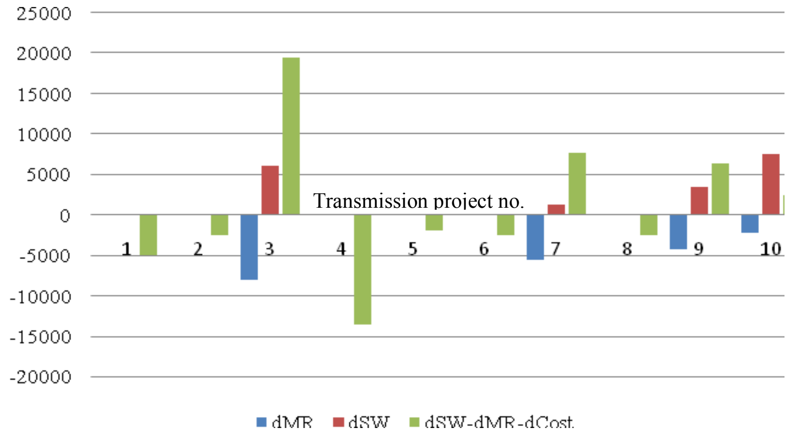

Figure 4, Effect of transmission projects on SS and MR during iteration 1 of the Three-stage Model

As in figure 4, during iteration 1 of Three-stage Model, transmission project 3 has high efficiency effect and highest competition effect.

Case 2: Comparing the case of without monopoly rent ($\alpha = 1.0$) with full modeling of monopoly rent ($\alpha = 0$)
Figure 5 shows both cases of without monopoly rent effect and full modeling of monopoly rent in one diagram.

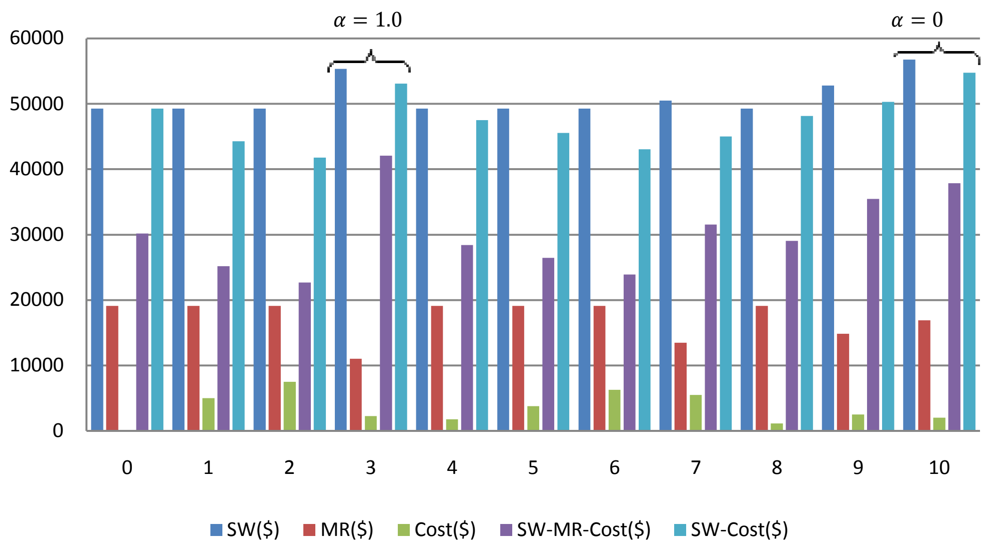

Figure 5 comparing the without monopoly rent and with monopoly rent scenarios

As it is clear from figure 5, the TNSP would select the transmission project 10 when it is neutral to the GenCos' monopoly rent. In the second case, $\alpha = 1.0$, monopoly rent is implicitly cancelled from the TNSP objective function. In the second case, transmission project 3 would be selected. Comparing transmission project 10 and 3, one can concludes that in terms of social surplus both have almost the same effect on the electricity market while the competition effect of transmission project 3 is much better than transmission project 10. The planning schedule of TNSP with no competition effect is expansion of transmission corridor B10 to B3 by 100MW and B1 to B12 by 100MW. The SS after expansion is $63270 with total MR of $21873. Table VII compares the two cases of without monopoly rent and no competition modelling in terms of SS and MR.

TABLE VII SS AND MR IN TWO CASES OF WITHOUT MONOPOLY RENT AND NO COMPETITION MODELLING IN TRANSMISSION AUGMENTATION

		Three-stage Model expansion	
	Base case	$\alpha = 1.0$	$\alpha = 0$
Social surplus ($)	49283	59731 (**%21.2 INC**)	63270(**%28.38 INC**)
Monopoly Rent ($)	19107	11021(**%42.32 DEC**)	21906(**%14.65 INC**)
		INC DEC	Increase Decrease

As in table VII, using the Three-stage Model, with modelling the without monopoly rent effect of transmission capacity, the transmission planning schedule results in %21.2 increase in social surplus of the electricity industry and simultaneously %42.32 decrease in monopoly rent and consequently increase of competition among GenCos. In case of $\alpha = 0$ or without modelling competition effect of transmission capacity, we have an increase of %28.38 in social surplus which is only %7.18 more than social surplus of without monopoly rent case. While, monopoly rent has an increase of %14.65 with respect to state of electricity market before expansion or in other words decreasing competition among GenCos. Results of table VII clearly show that ,firstly, transmission capacity has a significant effect on promoting competition among GenCos and ,secondly, the proposed Three-stage Model can augment transmission system not only in terms of increasing the social surplus of the electricity industry but also in terms of promoting competition among GenCos. Accordingly, Three-stage Model can capture both efficient effect and competition effect of transmission capacity in an integrated mathematical framework for optimum augmentation of the transmission system.

III. FURTHER DISCUSSIONS ON THREE-STAGE MODEL

In the proposed Three-stage Model, it is also possible to consider the retailers bidding strategy. The retailers would be treated as individual players in the game formulates as the partition 2 of (8). Mathematically speaking the equation (6) would be modified as (15).

$$\begin{matrix} Max_{s_p}\,\Omega'_p(s_p) \\ s.t. \\ s_p^{min} \le s_p \le s_p^{max} \end{matrix} \;\perp \cdots \perp\; \begin{matrix} Max_{s_q}\,\Omega'_q(s_q) \\ s.t. \\ s_q^{min} \le s_q \le s_q^{max} \end{matrix} \qquad p = 1, \dots, N_G \text{ and } q = 1, \dots, N_R \quad (15)$$

Where in (15), the first maximisation problem iterates over all GenCos and the second one iterates over all retailers.

Also, for considering the dynamic nature of the load, one can divide the horizon year period into different segments, like 12 months, 48 weeks, or if necessary 8064 hours per year, and runs the Three-stage Model in each segment of horizon year period. After comparing the results of expansion, the more robust transmission lines which have the highest effect over all segments can be chosen.

IV. CONCLUSION OF PART I AND II

It is critical for a TNSP to have a good planning framework in order to (1) capture the real value of transmission projects in terms of efficiency benefit and competition benefit, (2) model the interaction of market participants in a proper and integrated mathematical framework and (3) produce the best transmission planning schedule in terms of the investment cost of expansions. Addressing these issues, a Three-stage Model is introduced. The first phase models the TNSP's objective function. TNSP finds the optimum expansion schedule through a step-by-step expansion methodology. In phase two, the competition among GenCos is modelled through Nash equilibriums. The revenue maximisation problem of each GenCo is modelled using a bilevel programming problem. Gradient search method with the proper partitioning of GenCo's bidding space is used for solving the introduced bilevel problem. The Nash equilibrium point is found using the iterative Gauss-Seidel method. Finally, phase three deals with the Market Management Company, MMC. MMC clears the market using a security-constrained economic dispatch. A revised simplex method is used for solving the MMC optimisation problem.

The three phases of the Three-stage Model are linked through the static version of Leader-followers game. TNSP moves first and makes its decision taking into account all possible responses from GenCos, MMC and considering the efficiency benefit, competition benefit, and associate costs of each transmission project. GenCos take the final decision of the TNSP and compete for gaining the highest revenue from the electricity market. In doing so, they consider all possible responses from other GenCos and MMC. The final bidding strategy is submitted to the MMC and MMC clears the market in the third phase. A modified 14-bus example system is employed to show the proposed method.

The numerical results show that (1) transmission capacity has obvious effects on both efficiency and competitiveness of electricity markets (2) expansion of one transmission corridor can increase or decrease market power and consequently can have negative and positive competitiveness effect (3) TNSPs owned and operated by GenCos may not advocate optimal transmission expansion and (4) considering the strategic behaviours of GenCos the congestion-driven transmission expansion can not be a proper transmission expansion scheme.

APPENDICES

Appendix I:

The introduced vectors and matrices in (9) in terms of vectors and matrices in (8) are defined as follows;

$$\boldsymbol{C^T} = [\boldsymbol{C'^T} \quad \boldsymbol{VOLL^T} \quad \boldsymbol{0^T}]$$

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{g} \\ \boldsymbol{d} \\ \boldsymbol{\theta} \end{bmatrix}$$

$$[\boldsymbol{B}] = \begin{pmatrix} [\boldsymbol{0}] & [\boldsymbol{0}] & [\boldsymbol{\mathcal{H}}'_l] \\ [\boldsymbol{0}] & [\boldsymbol{0}] & -[\boldsymbol{\mathcal{H}}'_l] \\ [\boldsymbol{I}] & [\boldsymbol{0}] & [\boldsymbol{0}] \\ -[\boldsymbol{I}] & [\boldsymbol{0}] & [\boldsymbol{0}] \\ [\boldsymbol{0}] & [\boldsymbol{I}] & [\boldsymbol{0}] \\ [\boldsymbol{0}] & -[\boldsymbol{I}] & [\boldsymbol{0}] \end{pmatrix} \boldsymbol{D} = \begin{bmatrix} \boldsymbol{f}'^{u}_{l} \\ \boldsymbol{f}'^{u}_{l} \\ \overline{\boldsymbol{g}} \\ -\underline{\boldsymbol{g}} \\ \overline{\boldsymbol{d}} \\ -\underline{\boldsymbol{d}} \end{bmatrix}$$

$$\boldsymbol{A} = [\boldsymbol{G} \quad \boldsymbol{D} \quad -[\boldsymbol{\mathcal{B}}'_x]]$$

$[\boldsymbol{G}]$ *and* $[\boldsymbol{D}]$ *are the matrices which determine the transmission connection buses of the registered generators and retailers in the electricity market.*

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