TRANSMISSION PLANNING IN DEREGULATED ENVIRONMENTS

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Abstract A new market based approach for transmission expansion planning in deregulated environments is presented in this paper. In this approach, transmission-planning decisions are made based on the electric power market conditions. The main contribution of this research is 1) Introducing a new probabilistic tool for analyzing the electric market conditions, 2) Defining new criteria for ranking transmission expansion plans according to their effects on improving the competition and facilitating fairly access to cheap generation, and 3) Presenting a new algorithm for transmission expansion planning in deregulated environments using the above tool and criteria. The characteristics of this approach are 1) It encourages competition and provides fairly access to cheap generation, 2) It considers the uncertainties including uncertainty in loads, uncertainty in bid of generators, uncertainty in availability of IPPs, and uncertainty in wheeling transactions, 3) It is a value based approach instead of cost based.

Key Words Transmission Expansion Planning, Deregulation, Market Based Planning, Monte Carlo Simulation

چکیده در این مقاله، یک روش جدید برای طراحی توسعهٔ بازار- محوری شبکه‌های انتقال قدرت در محیط‌های مقررات زدایی شده ارائه شده است. در این روش، تصمیم‌گیری در مورد توسعه شبکه‌های انتقال بر اساس شرایط بازار انرژی الکتریکی انجام می‌شود. این تحقیق شامل مراحل ذیل می‌باشد. 1) معرفی یک ابزار احتمالی برای تحلیل موقعیت بازار انرژی الکتریکی. 2) تعریف معیارهای جدید برای رتبه بندی طرحهای توسعه انتقال از لحاظ تاثیر آنها در بهبود رقابت و تسهیل در دسترسی منصفانه همه مصرف کنندگان به تولید ارزان قیمت. 3) ارائه یک الگوریتم جدید برای توسعه انتقال در محیط‌های مقررات زدایی شده با استفاده از ابزار بند 1 و معیارهای بند 2. مشخصات این روش عبارت است از 1) باعث تشویق رقابت می‌شود و دسترسی منصفانه به تولید ارزان را برای همه مشتریان فراهم می‌نماید. 2) عدم قطعیتها (شامل عدم قطعیت در بار، عدم قطعیت در قیمت پیشنهادی ژنراتورها، عدم قطعیت در قابل دسترس بودن تولیدکنندگان توان مستقل و عدم قطعیت در قراردادهای انتقال توان) را در نظر می‌گیرد. 3) یک روش ارزش- محور می‌باشد.

1. INTRODUCTION

The main objective of power system planning in regulated power systems is to meet the demand of loads, while maintaining security, reliability and service quality of power system. In this environment uncertainty is low and planners have access to the required information for planning. In these systems location of loads and generations, size of loads and generating units, availability of units, load pattern, and dispatch pattern are known and therefore, planners can design the least cost transmission plan based on the certain reliability criteria. Transmission planning in regulated systems is modeled with a deterministic optimization. The objective function is cost of planning and operation, with technical, economical, and reliability constraints. In general this optimization is a nonlinear mixed-integer constraint optimization. Different mathematical and heuristic approaches have been proposed for solving this problem [1].

Restructuring and deregulation have increased the uncertainties in power systems [1-11]. In such environment:

- Players change their strategies frequently.
- Behavior of independent power producers (IPPs) is uncertain [10].
- Wheeling transactions are time variant [5,12].
- Transmission planning affects the interest of electric market participants in different ways [5,8-9].

These problems have made transmission planning difficult or impossible. Because of the uncertainties, most publications emphasize on probabilistic approaches for transmission planning in deregulated environments [6-7,13-18].

Characteristics of deregulated environments are different with regulated environments and therefore new approaches and criteria are needed for transmission planning in the deregulated power systems. Transmission planning in deregulated environments must consider the following points:

- Transmission planning must encourage competition [3,9-10,16,19].
- Transmission customers should have access to cheap generation equally and fairly [5,10].
- Transmission customers should be able to can utilize the network equally and fairly [10].
- Transmission planning must be robust against all power system uncertainties including uncertainty in loads, uncertainty in bid of generators, uncertainty in availability of IPPs, and uncertainty in wheeling transactions, [3-7, 9, 11, 17, 20-21].
- Justification of costs is very important in competitive environments. Therefore transmission planning must be value based instead of cost or reliability based [5-8, 12-14, 16-19].

In this paper a new method for transmission expansion planning for deregulated power systems is presented. In Section 2 a tool for analyzing electric market is presented. Market based criteria is presented in Section 3. In Section 4 a new algorithm for transmission expansion planning is presented. The presented method is applied to an eight-buses power system in Section 5.

2. PROBABILISTIC LOCATIONAL MARGINAL PRICE

One of the methods that are used for covering the uncertainties is probabilistic method. In regulated power systems, probabilistic load flow (PLF) is used for covering the uncertainties. The PLF is the same as load flow except its inputs are the probability density function (pdf) of loads and generation powers, and its outputs are the pdf of line flows and bus voltages. Technical criteria such as risk of violation line flow limits and bus voltage limits are computed using the outputs of PLF. Constructing a line parallel with the lines that their limits are violated frequently is a suit candidate for transmission expansion planning.

Transmission planning in deregulated environments must encourage the competition and provide fairly access to cheap generation for all customers. Therefore, moreover the technical criteria, market based criteria are needed for transmission planning in deregulated power systems.

Different market based criteria can be defined for transmission planning in deregulated power systems e.g. the probability of exceeding the LMP of a bus from a specified value, or the probability of exceeding the LMP difference of two buses from a specified value. pdf of LMPs have a principle role in computing the market based criteria. In this section a method for computing the pdf of bus LMPs is presented.

By definition "LMP is the cost of supplying next MW of load at a specific location, considering generation marginal cost, cost of transmission congestion, and losses" [22]. LMPs for a given operating point are computed using the optimization of appendix A. LMPs are the Lagrange multipliers (shadow prices) of the DC power flow constraints.

To compute the pdf of LMPs Monte Carlo simulation is used. The proposed algorithm can be summarized in the following steps:

1. Determining the probability density functions of

inputs.

1.1. Determining $f_d^i(p)$ for $i \in D$

where $f_d^i(p)$ is the pdf of ith load during the peak load of planning horizon, and D is the set of loads. A method for determining $f_d^i(p)$ described in [23].

1.2. Determining $f_b^i(c)$ for $i \in G$

where $f_b^i(c)$ is the pdf of bid of ith generating unit during the peak load of planning horizon, and G is the set of existing generating units. The method of [23] can also be used for determining $f_b^i(c)$.

1.3. Determining $f_{max}^i(p)$ and $f_b^i(c)$ for $i \in I$

where $f_{max}^i(p)$ is the pdf of maximum accessible power of ith IPP during the peak load of planning horizon, and $f_b^i(c)$ is the pdf of bid of ith IPP during the peak load of planning horizon, and I is the set of IPPs.

1.4. Determining $f_t^i(p)$ for $i \in T$

where $f_t^i(p)$ is the pdf of input power to the study area through the ith tie line due to transactions with neighboring areas and wheeling transactions during the peak load of planning horizon, and T is the set of tie lines. Note that these pdfs may be dependent.

In this paper, it is assumed that the pdf of inputs are specified for the planning horizon.

2. Selecting a magnitude for each input using a random generator with specified pdf. on the other hand determining a magnitude for:

   p_d^i for $i \in D$,

   c_b^i for $i \in G$,

   p_{max}^i for $i \in I$,

   c_b^i for $i \in I$,

   p_t^i for $i \in T$,

   according to their pdfs. Where p_d^i is the power of ith load, c_b^i is the bid of ith generating unit, p_{max}^i is the maximum accessible power of the ith IPP, and p_t^i is the power of ith tie line.

3. Running the optimization problem and saving the:

   p_g^i for $i \in G \cup I$,

   p_l^i for $i \in L$,

   lmp^i for $i \in B$,

   where p_g^i is power of ith generator, p_l^i is power of ith line, lmp^i is the locational marginal price of ith bus, L is the set of all transmission lines, and B is the set of all buses.

4. Repeating the steps 2, and 3 a great number and Computing:

   $f_g^i(p)$ for $i \in G \cup I$,

   $f_l^i(p)$ for $i \in L$, and

   $f_{lmp}^i(c)$ for $i \in B$.

   where $f_g^i(p)$ is the pdf of the generation power of ith generator, $f_l^i(p)$ is the pdf of power flow of ith line, and $f_{lmp}^i(c)$ is the pdf of locational marginal price of ith bus.

3. MARKET BASED CRITERIA

To have a perfect competitive electric market, consumers (or ISO) must have no constraint for purchasing the power from the cheap generation. Under transmission congestion condition, some consumer can't purchase power from the cheap generation and then competition defected. If LMP of all buses are equal, there is no congestion and consequently there is no constraint for consumer to purchase the power from the desired producer.

Under the congestion condition the flatter price profile throughout the network indicates the less congestion and consequently the more competitive conditions. In other words, having a flat price profile encourages competition. Therefore, price profile can be used as a criterion for distinguishing the degree of competitiveness.

What remains is definition of some indices for determining the flatness of a price profile. Consider an n buses network and suppose the pdf of LMPs have been computed for a given pdf for each input. Assume MLMP is a $1 \times n$ vector that its ith element is the mean of LMP of ith bus, and VLMP is a $1 \times n$ vector that its ith element is the variance of LMP of ith bus. The following indices can be defined for determining the flatness of price profile:

- Variance of MLMP: The less Variance of MLMP indicates the flatter price profile and consequently better field for competition.
- Mean of MLMP: The less mean of MLMP indicates that more cheap generation is dispatched. This means better condition for competition. Note that transmission planning may cause all cheap marginal generators are dispatched and therefore more expensive generators become marginal. In this case LMP of all buses and consequently mean of MLMP may increase. Therefore a high mean of MLMP doesn't necessarily indicate a bad condition for competition.
- Variance of VLMP: The less variance of VLMP indicates the more similar volatility of LMP in different buses and then the more similar risk in purchasing power from different buses.

Justification of costs is very important in competitive environments. Therefore, some criteria are also needed for comparing the value of plans. The following indices can be defined for comparing the value of each plan.

- The ratio of decrease in operation cost to transmission planning cost:
- $I_1 = \dfrac{AOCB - AOCA}{ATPC}$
- where AOCB and AOCA are annual operating cost before and after transmission planning respectively, and ATPC is the annual cost of transmission planning.
- The ratio of decrease in congestion cost to transmission planning cost:
- $I_2 = \dfrac{ACCB - ACCA}{ATPC}$
- where ACCB and ACCA are annual congestion cost before and after transmission planning respectively.
- The ratio of decrease in operation and congestion cost to transmission planning cost:
- $I_3 = I_1 + I_2$

4. TRANSMISSION PLANNING ALGORITHM

Now, there are required tool and criteria for transmission expansion planning. The presented algorithm for transmission expansion planning is as bellow:

1. Computing the pdf of LMPs for the given pdf of inputs for planning horizon using the algorithm of section 2.

2. Computing the following market based transmission planning indices:
   mean of MLMP
   variance of MLMP
   variance of VLMP
   indices I_1, I_2, I_3 (except for base case)

3. Determining the set of transmission line candidates:
   A high LMP at a bus indicates lack of access to cheap generation and a low LMP at a bus indicates probable excess cheap generation and not enough access to loads. Therefore, constructing a new line between a low LMP bus and a high LMP bus is an appropriate candidate for transmission planning. Transmission line candidates can be determined as bellow:

   3.1. Determining the set of buses that have the least mean of LMP and the least variance of LMP. These buses are called source terminals.

   3.2. Determining the set of buses that have the greatest mean of LMP and the least variance of LMP. These buses are called sink terminals.

   3.3. Determining the set of all new transmission line that can be built between each source terminal and each sink terminal.

4. Repeating steps 1, 2 with introducing each single transmission line candidate in the network.

5. Choosing the best plan according to the computed market based transmission-planning criteria.

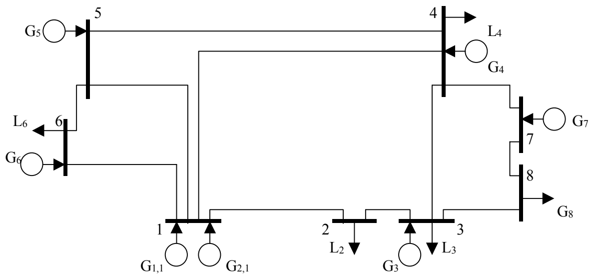

Figure 2. Eight bus network.

TABLE 1. Parameters of the 8-Bus Network.

Line	From	To	Reactance Ohm	Line limit MW
1	1	2	0.0300	280.0
2	1	4	0.0300	140.0
3	1	5	0.0065	380.0
4	2	3	0.0100	120.0
5	3	4	0.0300	230.0
6	4	5	0.0300	200.0
7	5	6	0.0200	300.0
8	6	1	0.0250	250.0
9	7	4	0.0150	250.0
10	7	8	0.0220	340.0
11	8	3	0.0180	240.0

TABLE 2. Generation Data for Transmission Planning Horizon.

Gen. No.	Bus No.	Min	Max	Bid
1	1	0	110	N~(14, 2.5)
2	1	0	100	N~(15, 1.8)
3	3	0	520	N~(30, 1.5)
4	4	0	250	N~(30, 2)
5	5	0	600	N~(10, 3)
6	6	0	400	N~(20, 2.1)
7	7	0	200	N~(20, 1.5)

TABLE 3. Load Data for transmission planning horizon.

Load No.	Bus No.	Load
1	2	N~(300, 10)
2	3	N~(300, 12)
3	4	N~(300, 15)
4	6	N~(300, 5)
5	8	N~(250, 9)

5. CASE STUDY

Consider the eight-bus network shown in Figure 2. System parameters are specified in the Tables 1. Pdfs of loads and pdfs of bid of generating units for the peak load of transmission planning horizon are estimated as Tables 2 and 3. In this example uncertainty on availability of IPPs, and uncertainty on wheeling transactions are ignored. For simplicity it is assumed that the loads are independent. It is also assumed that the bids of generators are independent.

In this example 500 samples are selected from the pdf of each input (load and bid).

The pdfs: $f_g^i(p)$ for $i \in G$, $f_l^i(p)$ for $i \in L$ and $f_{lmp}^i(c)$ for $i \in B$ are computed using Monte Carlo simulation. $f_{lmp}^i(c)$ for $i \in B$ for the base case are shown in appendix B.

The vectors MLMP and VLMP for the base case are:

MLMP =
[19.2326 30.1990 30.0616 29.7948 20.5637 19.9721 29.8675 29.9742]

VLMP =
[4.4711 5.8281 2.3032 3.3503 5.0405 4.5676 2.0319 1.4995]

In this system there are only two sets of buses, first the buses that their LMP is approximately equal to \$20/MWh, and second the buses that their LMP are approximately equal to \$30/MWh. Then, the set of source terminals and sink terminals are:

Source Terminals Set = $\{1, 5, 6\}$

Sink Terminals Set = $\{2, 3, 4, 7, 8\}$

Then the set of transmission line candidates is as follows:

Transmission Line Candidates Set = $\{$1-2, 1-3, 1-4, 1-7, 1-8, 5-2, 5-3, 5-4, 5-7, 5-8, 6-2, 6-3, 6-4, 6-7, 6-8 $\}$

Now, each single line candidate is introduced in the network and $f_g^i(p)$ for $i \in G$, $f_l^i(p)$ for $i \in L$, and $f_{lmp}^i(c)$ for $i \in B$ are computed again. The indices mean of MLMP, variance of MLMP,

TABLE 4. Market Base Criterions for the Example Network.

	Mean of MLMP $/MWh	Var of MLMP $/MWh	Var of VLMP $/MWh	I_1 M$/yeay	I2 M$/yeay	I2 M$/yeay
L1-2	25.2327	26.4557	5.8552	1.9677	0.9483	2.9160
L1-3	**24.6390**	**16.3959**	**1.9124**	**3.3255**	**0.6537**	**3.9792**
L1-4	25.4958	23.1414	8.0714	2.3400	-1.3009	1.0392
L1-7	26.0042	23.8213	3.3461	2.2349	-2.1309	0.1040
L1-8	26.0850	24.8550	3.7372	2.9149	-2.6882	0.2267
L5-2	25.0784	28.1989	4.1171	1.1826	2.0400	3.2226
L5-3	**24.2900**	**15.7641**	**1.2338**	**2.5601**	**2.1517**	**4.7118**
L5-4	25.0767	25.1621	2.1745	2.4462	-0.8541	1.5921
L5-7	25.7490	23.6951	6.9180	1.8308	-1.4804	0.3504
L5-8	26.0923	24.9851	3.0895	2.1451	-1.9732	0.1719
L6-2	25.0667	28.3437	3.3423	1.3534	1.9677	3.3211
L6-3	**24.2845**	**22.0086**	**42.1459**	**4.1752**	**-0.6209**	**3.5544**
L6-4	25.0127	30.8821	11.8928	3.5489	-2.6006	0.9483
L6-7	25.2806	33.7508	9.4688	3.7931	-3.7110	0.0821
L6-8	25.4616	33.9330	6.1980	4.2957	-4.1216	0.1741

variance of VLMP, I_1, I_2, and I_3 are computed for each plan. These indices are shown in table 4. It is assumed that the cost of transmission planning is equal to M$1/year for each plan.

As it shown in Table 4, plans L1-3, L5-3, and L6-3 create the smallest mean of MLMP and then these three plans are the best plans for electric energy consumers. These three plans also create the smallest variance of MLMP this means these plans create the flattest price profile and then the best field for competition. Note that the variance of MLMP in plans L1-3 and L5-3 are noticeable smaller than L6-3, and then these two plans create a flatter price profile.

The plans L1-3 and L5-3 also create the smallest variance of VLMP, i.e. with adding line 1-3 or 5-3 to the network, volatility of LMPs at different buses become more similar than other plans. In the other word, in these two plans the risk of purchasing power form the different buses is nearly the same. Note that the line 6-3 creates the greatest variance of VLMP and then is not a good plan.

Although the plan L6-8 has the smallest operation cost (greatest I_1), mean of MLMP is not small since congestion cost has the greatest value (smallest I_2) in this plan. The variance of MLMP and the variance of VLMP are also great in this case and then this plan don't provide good condition for competition.

The lines 1-3 and 5-3 create the smallest sum of operation cost and congestion cost (greatest I_3) and then these two plans are suitable choices for transmission planning. Between these two choices the cost of transmission planning determines the best one. $f_{lmp}^{i}(c)$ for $i \in B$ for the plan L5-3 are shown in appendix C.

6. CONCLUSION

The goal of transmission planning in deregulated environments is to expand and liquid electric markets and enhance their efficiency, while maintaining reliability of power systems. Therefore, new approaches and criteria are required for transmission planning in these environments. Uncertainty in these environments is very high and therefore probabilistic methods should be used for transmission planning. In this paper a new market based approach for transmission planning in deregulated environments is presented. This approach tries to fulfill the goal of transmission planning in deregulated environments. Case study shows the properties of this approach.

7. APPENDIX A: LOCATIONAL MARGINAL PRICE

By definition "LMP is the cost of supplying next MW of load at a specific location, considering generation marginal cost, cost of transmission congestion, and losses" [22]. LMPs for a given operating point are computed using the following optimization. LMPs are the Lagrange multipliers (shadow prices) of the DC power flow constraints.

$$\text{Min: } \sum_{j=1}^{Ng} C_{Gj}(P_{Gj}) + \sum_{j=1}^{Nl} C_{Dj}(P_{Dj})$$

$$\text{S.T.: } \mathbf{B\delta} = \mathbf{P}_G - \mathbf{P}_D$$

$$\mathbf{P}_\ell^{min} \le \mathbf{H}\,\boldsymbol{\delta} \le \mathbf{P}_\ell^{max}$$

$$\mathbf{P}_G^{min} \le \mathbf{P}_G \le \mathbf{P}_G^{max}$$

$$\mathbf{P}_D^{min} \le \mathbf{P}_D \le \mathbf{P}_D^{max}$$

where:

$C_{Dj}(P_{Dj})$ is the adjustment Price function of active load at bus j

$C_{Gj}(P_{Gj})$ is the adjustment Price function of active power generation at bus j

N_g is number of generators

N_l is number of loads

$\mathbf{B}$ is the linearized Jacobian matrix

$\mathbf{H}$ is the matrix of linearized line flows

$\boldsymbol{\delta}$ is the vector of voltage angles

$\mathbf{P}_G$ is the vector of active power generations

$\mathbf{P}_D$ is the vector of active loads

$\mathbf{P}_G^{min}, \mathbf{P}_G^{max}$ are the vectors of minimum and maximum active power generations limits

$\mathbf{P}_D^{min}, \mathbf{P}_D^{max}$ are the vectors of minimum and maximum loads limits

$\mathbf{P}_\ell^{min}, \mathbf{P}_\ell^{max}$ are the vectors of minimum and maximum limits of the lines. Note that losses are ignored in this method.

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