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Economic Transmission Expansion Planning by using Von Neumann-Morgestern Criterion

M. Purushotham[1], Nandhyala Ramesh[2]
[1, 2]*Department of Electrical and Electronics Engineering, Shree Institute of Technical Education, Krishnapuram, Tirupati , A.P.*

***Abstract:** Restructuring and deregulation has exposed transmission planner to new objectives and uncertainties. Therefore, new criteria and approaches are needed for transmission planning in deregulated environments. A new market-based approach for transmission planning in deregulated environments is presented in this paper. The main contribution of this research is: i) introducing a new probabilistic tool, named probabilistic location marginal prices, for computing the probability density functions of nodal prices; ii) defining new market-based criteria for transmission expansion planning in deregulated environments; and iii) presenting a new approach for transmission expansion planning in deregulated environments using the above tool and criteria. The advantages of this approach are: i) it encourages and facilitates competition among all participants; ii) it provides nondiscriminatory access to cheap generation for all consumers; iii) it considers all random and nonrandom power system uncertainties and selects the final plan after risk assessment of all solutions; and iv) it is value based and considers investment cost, operation cost, congestion cost, load curtailment cost, and cost caused by system unreliability. The presented approach is applied to IEEE 30–bus test system.*

***Keywords:** Competitive electric markets, Monte Carlo methods, power transmission planning, price profile, risk analysis, Scenario techniques, uncertainty.*

I. INTRODUCTION

From the viewpoint of transmission planner, there are two major differences between planning in regulated and deregulated environments. • Objectives of transmission expansion planning in deregulated Power systems differ from those of the regulated ones [1]–[9]. Uncertainties in deregulated power systems are much more than in regulated ones [1], [2], [4], [5], [7], [10], [11]. The main objective of transmission planning in deregulated power systems is to provide a nondiscriminatory and competitive environment for all stakeholders, while maintaining power system reliability. Transmission expansion affects the interests of market participants unequally and this should be considered in transmission planning [3], [7]. Specifically, transmission planning follows the following objectives in deregulated power systems.

1) Encouraging and facilitating competition among electric market participants.
2) Providing nondiscriminatory access to cheap generation for all consumers.
3) Providing fair supply-side reserve for all generators and fair demand-side reserve for all consumers.
4) Providing a robust transmission network against all uncertainties.
5) Being value based instead of cost or reliability based.

Uncertainties can be classified in two categories: random and nonrandom uncertainties. Random uncertainties are deviation of those parameters which are repeatable and have a known probability distribution. Hence, their statistics can be derived from the past observations. Uncertainty in load is in this category. Nonrandom uncertainties are evolution of parameters which are not repeatable and hence their statistics cannot be derived from the past observations. Uncertainty in generation expansion is in this category. Since methods of modeling random and nonrandom uncertainties in planning are different, power system uncertainties must be identified and classified clearly before the planning process. In deregulated power systems, there is random uncertainty in:

a) Load;
b) Generation costs and consequently in bid of generators;
c) Power and bid of independent power producers (IPPs);
d) wheeling transactions;
e) Availability of generators, lines, and other system
f) Facilities;
g) And nonrandom uncertainty in
h) Generation expansion/closures;
i) Load expansion/closures;

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j) Installation/closure of other transmission facilities;
k) Replacement of transmission facilities;
l) Transmission expansion costs;
m) Market rules.

Because of these uncertainties, expansion of transmission system has been faced with great risks. Since risk assessment is characteristically based on probabilistic and stochastic methods, probabilistic methods should be developed for transmission planning in deregulated power systems [1], [4], [9], [11]–[14].

II. MODEL OVERVIEW

In this approach, first strategic scenarios are identified to model the nonrandom uncertainties. The identified scenarios must cover all nonrandom uncertainties. A degree of importance is assigned to each scenario. To model the random uncertainties, the probability distribution function (pdf) of each input with the random uncertainty is determined for the peak load of planning horizon. In each scenario, the pdfs of nodal prices are computed using Monte Carlo simulation. Then some expansion plans (candidates) are suggested for transmission planning by market analysis. Each of the candidates is introduced to the network and market-based criteria are computed in all scenarios. The final plan is selected by risk analysis of the solutions [1], [5], [10], [11], [15]–[17]. Market-based criteria are used as cost function of risk analysis.

The paper is organized as follows. In Section III, a probabilistic tool for computing the pdfs of nodal prices is introduced. Market-based criteria are defined in Section IV. A transmission expansion planning approach using above tool and criteria is presented in Section V. The approach is applied to the IEEE 30-bus test system in Section VI

III. PROBABILISTIC LOCATIONAL MARGINAL PRICES (LMPs)

In regulated power systems, probabilistic load flow (PLF) is used for modeling the uncertainties [18], [19]. The outputs of PLF are the pdfs of line flows and bus voltages. Transmission planning is performed based on technical criteria such as the probability of violation of line flow limits and/or bus voltage limits. In deregulated environments in addition to the technical criteria, market-based criteria are needed to achieve the objectives mentioned in Section I. Therefore, it is necessary to compute the pdfs of variables that show the performance of electric market. Performance of an electric market can be assessed by analyzing pdfs of nodal prices or LMPs.

By definition, “LMP is the cost of supplying nextMWof load at a specific location, considering generation marginal cost, cost of transmission congestion, and losses” [20]. LMPs for a given operating point are computed using optimal load flow (see the Appendix). LMPs are the Lagrange multipliers or shadow prices of the dc power flow constraints. To compute the pdfs of LMPs for a specified scenario Monte Carlo simulation is used. The algorithm of computing the pdfs of LMPs for a given scenario is as below.

1) Determine the unavailability of each transmission facility (line, generator, load,) and assign a standard uniform PDF to each one.
2) Determine the pdfs of all random inputs for the peak load of planning horizon including:
a) PDF of each load. A method for determining the pdfs of loads is described in [21].
b) pdf of bid of each generating unit.
c) pdf of maximum accessible power of each IPP.
d) Pdf of input/output power to/from the study area due to transactions with neighboring areas or wheeling transactions for each tie line. Note that the power of some tie lines may depend on the power of other tie lines. In this case, determine the dependent tie lines and the dependence relation.
3) Pick a number randomly from the standard uniform pdf of each transmission facility and compare it with its unavailability. If the number is greater than its unavailability, this transmission facility is on else it is off.
4) Pick a number from the pdf of each input randomly and compute the value of each dependent input.
5) Run the optimal load flow for the network configuration of step 3 and operating point of step 4 and save the outputs including LMPs.
6) Repeat steps 3, 4, and 5 a great number of times.
7) Fit a pdf to the samples of each output including LMPs.

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IV. MARKET-BASED CRITERIA

To achieve the objectives of transmission expansion plan- ning in deregulated environments, it is necessary to define some criteria to measure how competitive an electric market is and how much a specific expansion plan improves competition. In a stable perfect competitive market, all producers offer their prod- ucts at the same price and consumers have no limitation to buy from their favorite producer. Therefore, to have a competitive electric market LMPs must be made equal and congestion must be alleviated. Consider a network with N_b buses and N_l lines. Suppose some expansion plans were suggested for transmis- sion expansion. Assume the pdfs of LMPs were computed after adding each plan to the network using N_s samples.

A. Congestion Cost

Congestion cost of a line is defined as the opportunity cost of transmitting power through it

$$\mathrm{cc}_i = \left(\mathrm{lmp}_{i_2} - \mathrm{lmp}_{i_1}\right) \mathrm{P}_{i_1 i_2}$$

Total congestion cost of the network is equal to

$$\mathrm{cc} = \sum_{i=1}^{N_l} \mathrm{cc}_i. \qquad (2)$$

As more (less) transmission lines are congested, i.e., as con- straints for dispatching the cheapest undispatched generations increase (decrease), LMP differences among buses and conse- quently congestion costs increase (decrease). Therfore, conges- tion cost is a proper criterion for measuring price discrimina- tion and customer constraints. Consequently congestion cost is a proper criterion for measuring the degree of competitiveness of an electric market [22]. To consider the random uncertainties average congestion cost in the peak load of planning horizon is suggested for measuring the degree of competitiveness of elec- tric markets. Form the viewpoint of consumers, total payment for the elec- tric power, i.e., total congestion cost plus total payment to gen- erators, is important and hence it can be used as a criterion for transmission planning. This criterion, however, does not con- sider the competition.

B. Flatness of Price Profile

Suppose μ_i is mean of LMP of bus i over N_s samples. Con- sider a Cartesian coordinates for the network and assume x_i, and y_i are coordinates of bus i.

Definition: The surface which is fitted to the points (x_i, y_i, μ_i) for $i = 1, 2, \ldots, N_b$ using linear interpolation method is named price profile of the network.

In nodal pricing all participants purchase and sell electric en- ergy at the LMP of their buses. In order to provide a compet- itive environment for all participants to purchase and sell en- ergy at the same price, nodal prices must be made equal. In other words, price profile must become flat. As the price profile becomes flatter, differences among LMP's decrease. Therfore, customers purchase and sell energy at less discriminative prices and consequently competition is encouraged. As the price pro- file deviates from flatness, differences among LMP's increase, customers buy and sell at more discriminative prices, and con- sequently competition is discouraged. Therefore, the flatness of price profile is a proper criterion for measuring the degree of competitiveness of an electric market [23]. Standard deviation of the means of the LMPs is used to measure the flatness of price profile. Where mean of each LMP is taken over N_s samples and standard deviation of these means is taken over N_b buses.

Because of limitation in transmission expansion planning budget, for a given budget, it is logical to provide a competitive field for more participants or for more power. Hence, weighted standard deviation of mean of LMP is proposed for ranking the transmission plans. Generation power, load, and sum of genera- tion power and load are proposed to weight LMP of each bus. If generation power is used as weight, transmission planning tries to equalize LMPs at generation buses. Therefore, competition will be encouraged among producers. Due to congestion LMPs of load buses may be different. Hence, it does not necessarily provide a nondiscriminatory environment for consumers. This weight selects the plan which provides a competitive environ- ment for more generation power. If load is used as weight, transmission planning tries to equalize LMPs at load buses. Therefore, a nondiscriminatory environment will be provided for consumers. LMPs of generator buses may be different due to congestion. Thus, this weight does not necessarily encourage competition among generators. This weight selects the plan which provides a nondiscriminatory environment for more load. If sum of load and generation power is used as weight, transmission planning tries to equalize LMPs at all load and generator buses. Therefore, it encourages competition among producers and provides a nondiscriminatory environment for consumers. This weight puts more force on the buses with greater sum of load and generation and hence tries to provide a competitive and nondiscriminatory environment for more load and generation.

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C. Transmission Planning Costs

Justification of costs is very important in competitive environ- ments. Therefore transmission planning criteria must take into account transmission planning costs. In the following subsec- tion, presented criteria are developed in order to consider in- vestment and operation costs.

D. Investment Cost

From the viewpoint of value-based planning approaches, the plan which has the highest (lowest) value of planning criterion per unit of investment cost is the optimal plan. In order to have value-based criteria for trans- mission planning, the presented criteria are normalized on investment cost. Hence, the following normalized criteria are suggested for transmission planning.

1) *Decrease in Annual Congestion cost divided by Annual in- Vestment Cost:* This criterion shows how much annual congestion cost deceases per unit of investment cost. In other words, it shows how much competition is encouraged per unit of investment cost.
2) *Decrease in Weighted Standard Deviation of Mean of LMP Divided by Annual Investment Cost:* This criterion shows how much flatness of price profile improves per unit of investment cost. In other words, it shows how much competition is encouraged per unit of investment cost.
3) *Operation Cost:* Operation cost consists of cost of running generators, load curtailment cost, and reliability cost. When a new plan is added to the network operation cost changes. Thus, transmission planning criteria must consider operation cost. Flatter price profile (less congestion cost) means less constraint for dispatching cheap generations. Hence, the plan which provides flatter price profile (less congestion cost) has lower cost of running generators. Therefore, the presented criteria consider cost of running generators. The plan which provides more reliable network provides less constraint for transmitting power and hence has flatter price profile and lower congestion cost. Therefore, the presented criteria take into ac- count reliability of network too. Load curtailment is the result of network constraint and was considered in LMP's calculation. Therefore, the presented criteria also take into account load curtailment cost.

V. TRANSMISSION PLANNING PROCEDURE

Now, a new approach for transmission planning in dereg- ulated power systems is presented based on the probabilistic locational marginal prices introduced in Section III and the market-based criteria defined in Section IV. In this approach after identifying strategic scenarios and determining the pdfs of the inputs, pdfs of LMPs are computed for the peak load of each scenario. Then some candidates are suggested for transmission expansion planning. A high mean of LMP at a bus indicates no access to cheap generation and a low mean of LMP indicates access to excess cheap generation and no access to enough loads. Hence, constructing a new line between two buses with low and high mean of LMP will allow the dispatch of the excess cheap generation and flow of energy from low LMP bus to high LMP bus due to price potential difference. Con- sequently, the flatness of price profile is improved. Therefore, between each two buses that have LMP difference greater than a specified value (say SV), a new line is suggested as transmission expansion candidate. SV must be selected so that reasonable number of candidates is suggested. If SV is in- creased (decreased) the number of transmission candidates will be decreased (increased). If this method suggests many candi- dates, the ineffective candidates can be eliminated by increasing SV and determining the candidates again. After determination of transmission expansion candidates, each of them, with the highest possible capacity, is introduced to the network and the market-based criteria are computed for each scenario. The final plan is selected by risk analysis of the candidates. The presented market-based criteria are used as cost function of risk analysis. If the maximum desirable LMP difference among the buses is not achieved in the first stage of planning the process must be repeated. In the next stages of planning, SV must be reduced to have enough transmission candidates in each stage. Finally, the capacity of new transmission lines is determined so that the probability of violating their limits is less than 0.01 in each scenario during the peak load of planning horizon. The planning procedure is carried out in the following steps.

1) Determine strategic scenarios for modeling nonrandom uncertainties and assign a degree of importance to each one.
2) Compute the pdfs of LMPs for the existing network in each future scenario using the algorithm of Section III.
3) Select a value for SV.
4) Determine the set of transmission planning candidates. The set of candidates is equal to union of expansion candidates of all scenarios. If the selected value for SV doesn't suggest enough candidates, decrease SV and determine the set of transmission candidates again. If the selected value for SV suggests many candidates increase SV and determine the set of transmission candidates again to omit the ineffective candidates.

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5) Add each single transmission candidate with highest pos- sible capacity to the network and compute the pdfs of LMPs for all scenarios.
6) Compute the market-based criteria for each plan in each scenario.
7) Select the plan with minimax regret. The above men- tioned market-based criteria are used as cost functions for risk assessment.
8) If none of the candidates improve the price profile flat- ness, decrease the SV and go to Step 4.
9) If the price profile is not flat enough and if there is enough budget for more transmission planning go to step 4.
10) Compute the capacity of new transmission lines.

VI. CASE STUDY: IEEE 30-BUS TEST SYSTEM

The presented approach is applied to IEEE 30-bus test system [24]. Fig. 1 shows the single line diagram of IEEE 30-bus system. Characteristics of generators and loads for the peak load of planning horizon are given in Tables I and It is assumed that the unavailability of each transmission line is equal to 0.001. Standard deviation of mean of LMP and average congestion cost are equal to and for the existing network during the peak load of planning horizon. These values indicate that the network needs a few lines to have a flat price profile and zero congestion cost. To research which criterion leads to a flatter price profile and lower congestion cost, the presented planning approach is

$2.6351/MWhr
$2240.8/hr

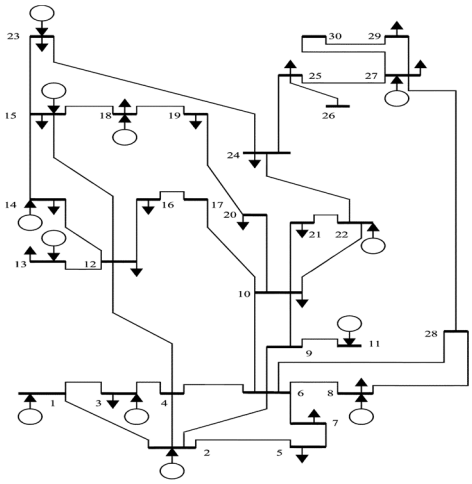


Fig. 1. Single line diagram of IEEE 30-bus system.

Repeated eight times (stages) under different criterion. In each planning stage, the minimax regret plan is selected and added to the network. Transmission planning is performed under two different assumptions: 1) there are not nonrandom uncertainties and 2) there are nonrandom uncertainties.

A. *There Are Not Nonrandom Uncertainties*

In this case, there is only one scenario, the scenario which is shown in Tables I and II. Therefore, the minimax regret plan is the optimal plan. Transmission planning was performed under the following market-based criteria.

1) Standard deviation of mean of LMP (SML).
2) Weighted standard deviation of mean of LMP with weights: Pg $\mathrm{Pg} + \mathrm{Pd}(\mathrm{WG}), \mathrm{W} = \mathrm{Pd}(\mathrm{WD}), \mathrm{W} =$ (WG).
3) Average congestion cost (ACC).
4) Average of load payment (ALP).

At the first stage between each two buses which have LMP dif- ference greater than a new line is suggested as transmission candidate. As new lines are added to the network, price profile becomes flatter. Therefore, number of candidates for the next planning stages decreases. In the stages that only a few candidates are suggested, SV is reduced to have reasonable number of candidates. SV and number of suggested expansion candidates (NC) for each criterion and planning stage are shown in Table III. In this table, smaller SV indicates flatter price pro- file. At a constant SV, smaller NC indicates flatter price

$SV = \$5/MWhr$

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Table I Characteristics Of Generators

Bus No.	Min	Max	pdf of Bid	Unavailability
1	0	2.0	N~(11.5, 1.2)	0.02
2	0	2.0	N~(11.0, 1.0)	0.02
3	0	0.5	N~(10.0, 1.0)	0.02
8	0	1.3	N~(11.5, 1.3)	0.02
11	0	1.2	N~(11.5, 1.1)	0.02
13	0	1.2	N~(16.0, 1.4)	0.02
14	0	1.6	N~(16.0, 1.5)	0.02
15	0	1.0	N~(17.0, 1.6)	0.02
18	0	1.0	N~(17.0, 1.6)	0.02
22	0	1.5	N~(16.0, 1.5)	0.02
23	0	1.5	N~(16.0, 1.4)	0.02
27	0	1.2	N~(22.0, 2.0)	0.02

Table II Characteristics Of Loads

Bus No	Min	pdf of load	Bid	Unavailability
3	0	N~(1.60, 0.120)	15	0.05
5	0	N~(0.85, 0.075)	14	0.05
7	0	N~(0.50, 0.050)	15	0.05
8	0	N~(0.25, 0.020)	17	0.05
10	0	N~(1.90, 0.150)	20	0.05
12	0	N~(0.50, 0.040)	18	0.05
13	0	N~(0.20, 0.020)	19	0.05
14	0	N~(0.50, 0.045)	17	0.05
15	0	N~(0.50, 0.050)	16	0.05
16	0	N~(0.09, 0.005)	20	0.05
8	0	N~(0.35, 0.020)	21	0.05
19	0	N~(0.17, 0.005)	23	0.05
20	0	N~(0.60, 0.045)	17	0.05
21	0	N~(0.34, 0.025)	19	0.05
23	0	N~(0.85, 0.075)	22	0.05
24	0	N~(0.09, 0.006)	25	0.05
25	0	N~(0.09, 0.002)	25	0.05
27	0	N~(0.27, 0.020)	23	0.05
29	0	N~(0.35, 0.025)	24	0.05

Since NC is number of pairs of buses which have LMP differ- ence greater than SV. Optimal expansion plan and its capacity in pu for each criterion and planning stage are shown in Table IV.

The presented criteria are dependent, i.e., when one of them is selected as planning criterion and we try to reduce it by ex- pansion planning other criteria will be reduced too. But the rela- tions are not linear and they have different effect on each other. In order to find out which criterion leads to a flatter price pro- file and lower congestion cost, a criterion is selected as plan- ning criterion and value of all criteria are computed in different stages of planning. The procedure is repeated for all planning criteria. Fig. 2(a) shows how SML changes in different stages of planning when SML, WG, WD, WGD, ACC, and ALP are used as planning criterion. Fig. 2(b)–(f) show how WG, WD, WGD, ACC, and ALP change in different stages of planning. The following conclusions can be deduced from Fig. 2:

1) ACC is the most effective criterion i.e., if ACC is used as planning criterion; we have the most decrease in SML, WG, WD, WGD, and ACC except for stages 1 and 2.

2) If ACC is used as planning criterion the smallest value of SML, or the flattest price profile, will be achieved after

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Table III
Values of SV in $/MWHR and number of suggested candidates for
Each criterion at different planning stages

	SML	WGD	WG	WD	ACC	ALP
Stage 1	5 (89)	5 (89)	5 (89)	5 (89)	5 (89)	5 (89)
Stage 2	5 (39)	5 (88)	5 (88)	5 (45)	5 (126)	5 (164)
Stage 3	5 (14)	5 (75)	5 (75)	5 (21)	5 (25)	5 (139)
Stage 4	5 (9)	5 (43)	5 (50)	3 (58)	4 (11)	5 (119)
Stage 5	3 (52)	5 (20)	5 (31)	3 (52)	3 (22)	5 (110)
Stage 6	3 (45)	3 (54)	4 (19)	3 (59)	2 (10)	5 (120)
Stage 7	2 (99)	2 (47)	2 (50)	1 (172)	1 (50)	4 (197)
Stage 8	1.5 (95)	1 (98)	1 (75)	1 (165)	1 (18)	4 (180)

* Number of candidates were specified inside the parentheses

Table IV
Optimal transmission plan and its capacity in pu for Each criterion at different planning stages

	SML	WGD	WG	WD	ACC	ALP
Stage 1	22-29 (0.56)	1-28 (3.05)	1-28 (2.98)	7-29 (0.68)	1-10 (3.67)	2-28 (0.74)
Stage 2	5-10 (1.48)	11-10 (1.81)	11-10 (1.97)	8-10 (3.22)	11-29 (0.72)	11-21 (1.27)
Stage 3	11-20 (1.70)	12-29 (2.33)	8-9 (1.61)	11-8 (1.64)	11-20 (1.17)	6-29 (0.82)
Stage 4	8-6 (1.12)	8-9 (1.43)	7-29 (0.67)	5-20 (1.13)	8-23 (1.79)	1-23 (3.03)
Stage 5	20-18 (0.74)	28-9 (2.81)	28-12 (2.51)	1-28 (0.92)	10-18 (1.02)	23-18 (1.68)
Stage 6	1-6 (2.54)	12-20 (1.22)	12-20 (1.21)	27-18 (0.60)	23-16 (0.51)	25-20 (0.22)
Stage 7	7-14 (1.41)	11-18 (0.92)	9-18 (0.94)	5-23 (1.56)	10-15 (1.22)	18-14 (1.11)
Stage 8	5-21 (1.06)	5-23 (1.82)	5-23 (1.58)	17-25 (0.35)	5-14 (1.35)	22-30 (0.26)

* Optimal transmission plans were specified with number of their end buses.
Capacities of optimal plans were specified inside the parentheses

Three planning stage. Note that after one stage of plan- ning, the network configuration may be different under different criteria. Therefore, using SML as planning cri- terion doesn't lead to the flattest price profile necessarily.

1) If ACC is used as planning criterion, SML and WD over- shoot in stage 1.
2) If ALP is used as planning criterion, price profile will de- viate from flatness and congestion cost will decrease just a little. Hence, ALP is not a proper criterion for expansion planning in deregulated power system.
3) WGD and WG cause acceptable decrease in other cri- teria if are used as planning criteria and hence are suitable criteria for transmission planning in deregulated power systems.

B. There Are Nonrandom Uncertainties

In this case, it is assumed that a generator and an IPP may be added to the network. Characteristics of the new generator and IPP are given in Table V. It is also assumed that the load of bus no. 24 may be extended. Characteristics of the new load are given in Table VI. To take into account the risk of these nonrandom uncertainties the following scenarios are defined:

1) Base case (scenario which is shown in Tables I and II)
2) Base case plus the new generator
3) Base case plus the load change
4) Base case plus the IPP
5) Base case plus the new generator and load change
6) Base case plus the new generator and IPP
7) Base case plus the load change and IPP
8) Base case plus the new generator, load change, and IPP

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It is assumed that all above scenarios have the same degree of importance. SML, WGD, and ACC are used as cost function of risk analysis. SV and number of suggested candidates are shown in Table VII at different stages of planning for each criterion. The minimax regret plan and its capacity in pu are shown in Table VIII at different stages of planning for each criterion.

Fig. 3(a)–(c) shows values of SML, WGD, and ACC in dif- ferent scenarios and different stages of planning. In each stage there are three bars. These bars, from left to right, show the maximum values of the criteria over different scenarios when SML, WGD, and ACC are used as planning criterion respec- tively. There are eight signs over each bar which show values of the criteria in different scenarios. The following results can be deduced from Fig. 3.

Table VI Characteristics Of New Load

Type	Bus No.	Min	Max	pdf of Bid	Unavailability
Gen.	10	0	1.5	N∼(11, 1.2)	0.02
IPP	16	0	N∼(0.8, 0.2)	*N*∼(13, 1.5)	0.02.

TABLE VII
Values of SV in $/MWHR and number of suggested candidates for
Each criterion at different planning stages

	SML	WGD	ACC
Stage 1	5 (113)	5 (113)	5 (113)
Stage 2	5 (58)	5 (64)	5 (170)
Stage 3	5 (43)	5 (50)	5 (62)
Stage 4	4 (70)	4 (76)	5 (69)
Stage 5	4 (63)	4 (70)	5 (32)
Stage 6	3 (76)	3 (52)	5 (21)
Stage 7	2.5 (102)	3 (18)	3 (80)
Stage 8	2.5 (88)	3 (18)	3 (19)

* Number of candidates were specified inside the parentheses

TABLE VIII
Minimax Regret Transmission Plan And Its Capacity In Pu For Each Criterion At Different Planning Stages

	SML	WGD	ACC
Stage 1	12-29 (0.71)	5-29 (0.68)	1-10 (3.95)
Stage 2	5-20 (1.38)	8-10 (2.12)	11-29 (1.74)
Stage 3	11-9 (1.72)	11-20 (1.52)	29-24 (1.21)
Stage 4	10-18 (0.99)	2-12 (2.69)	8-20 (1.44)
Stage 5	8-12 (2.08)	12-18 (0.96)	10-18 (0.96)
Stage 6	20-24 (0.76)	8-23 (1.42)	24-16 (0.90)
Stage 7	5-21 (0.92)	16-23 (1.40)	10-14 (1.76)
Stage 8	13-17 (0.55)	3-24 (1.31)	8-15 (0.14)

* Minimax regret transmission plans were specified with number of their end buses. Capacities of transmission plans were specified inside the parentheses

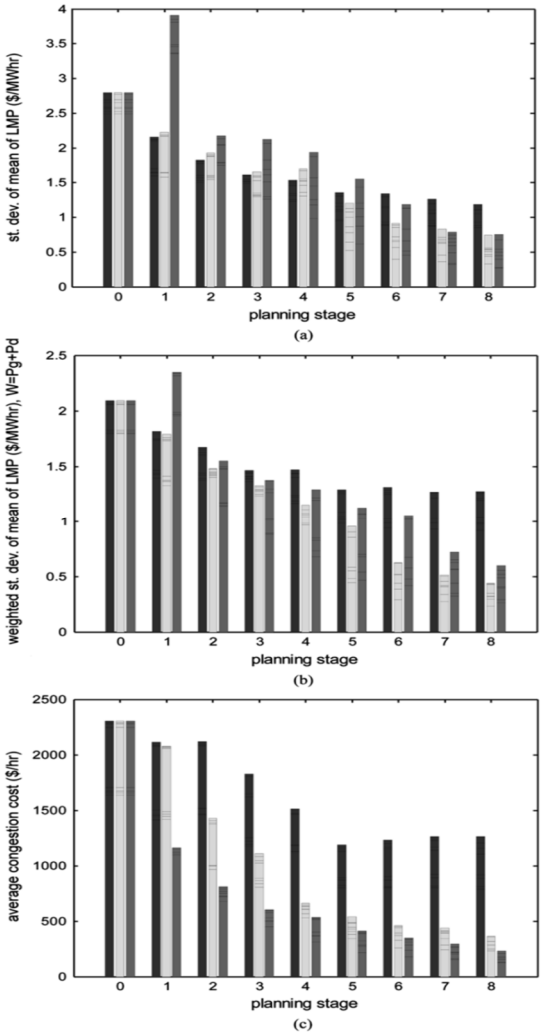
a) If WGD is used as planning criterion the smallest value of SML, or the flattest price profile, will be achieved after five stages of planning.
b) If ACC is used as planning criterion, SML overshoots in stage 1.
c) ACC causes acceptable decrease in other criteria if it is used as planning criterion.

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Finally the following conclusions can be drawn from this example

1) Transmission planning with ACC criterion tries to alle- viate the congestion and transmission planning with SML, WG, WD, or WGD criterion tries to reduce the LMP dif- ferences. Since LMP differences appear due to congestion, as congestion is alleviated LMP differences vanish. There- fore, ACC is a more effective criterion than other criteria in single scenario cases.

2) In multiscenario cases, different lines may be congested in identified scenarios. That is, the cause of LMP differences is not the same in different scenarios. Hence, the ACC



Criterion in multiscenario cases is not as effective as in single scenario cases in providing a flat price profile.
WGD is an effective criterion for providing flat price pro- file and reducing congestion cost both in single and mul- tiscenario cases. In this example, WGD provides flatter price profile than ACC in multiscenario case.

VII. CONCLUSION

In this research work, a new probabilistic tool for computing the probability density functions of nodal prices was introduced. New market-based criteria were defined for transmission plan- ning in deregulated environments. A new approach for trans- mission expansion planning in deregulated environments using the above tool and criteria was presented. All random and non- random power system uncertainties are considered by this ap- proach and the final plan is selected after risk assessment of all solutions. This approach tries to facilitate competition and provides nondiscriminatory access to cheap generation by pro- viding a flat price profile throughout the network. It is value based and considers investment cost, operation cost, congestion cost, load curtailment cost, and cost caused by system unrelia- bility. The presented approach was applied to IEEE 30-bus test system and the effectiveness of presented market-based criteria was demonstrated for the single and multiple scenario cases

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A. Appendix Optimal Load Flow

LMPs for a given operating point are computed using the following optimization. LMPs are the Lagrange multipliers or shadow prices of dc power flow constraints.

$$\text{Min:} \quad \mathbf{C}_G^T \mathbf{P}_G - \mathbf{C}_D^T \mathbf{P}_D$$

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

$$-\overset{\max}{\mathbf{P}_\ell} \le \mathbf{H}\delta \le \overset{\max}{\mathbf{P}_\ell}$$

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

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

where

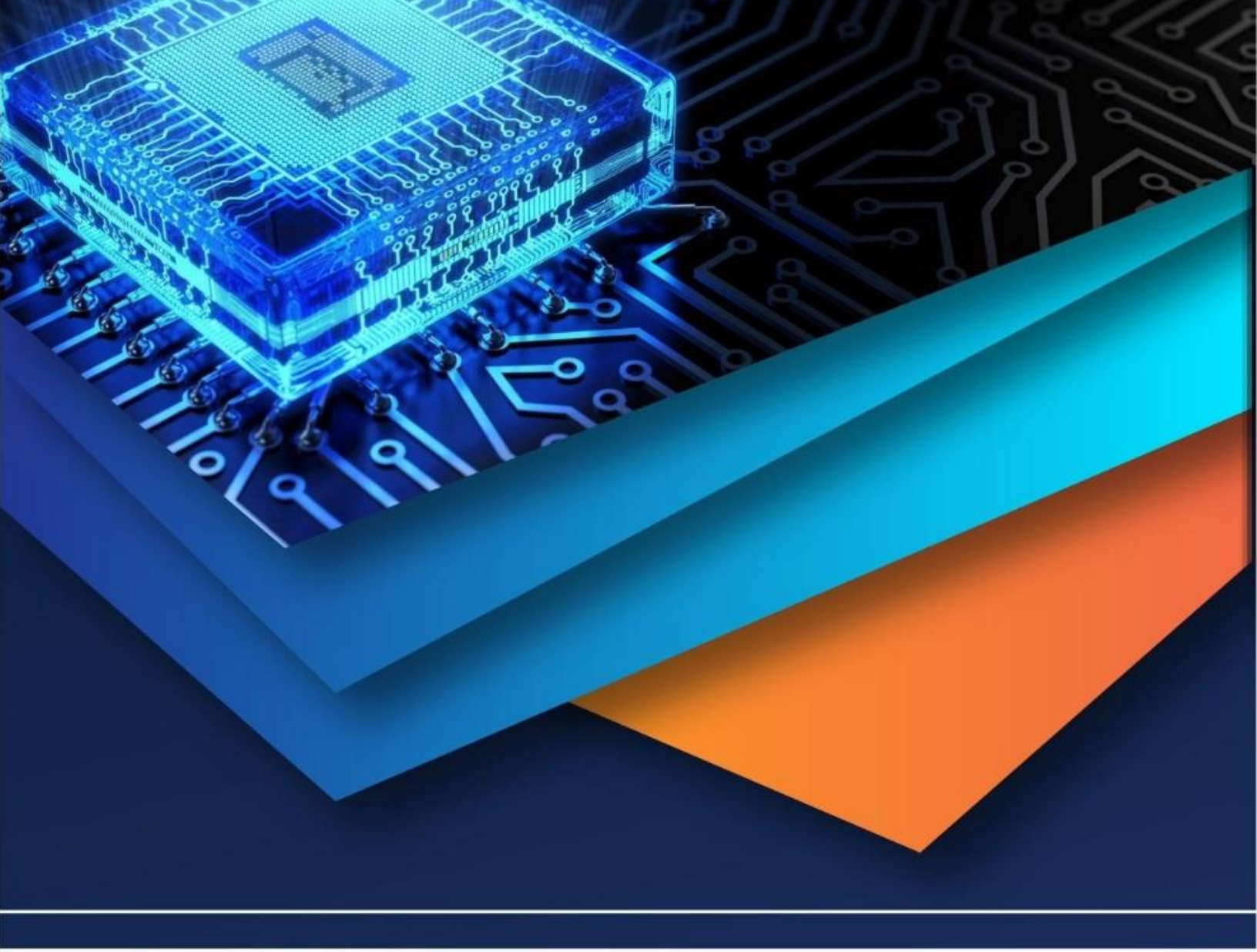
$\mathbf{C}_G$	vector of bid of generators; vector of bid of loads;
$\mathbf{P}_G$	vector of active power generations; vector of active loads;
$\mathbf{B}$	linearized Jacobian matrix; matrix of linearized line flows; vector of voltage angles;
$\mathbf{H}$	vectors of minimum and maximum power generation limits;
$\mathbf{P}_D^{\min}, \mathbf{P}_D^{\max}$	ectors of minimum and maximum load limits;
$\mathbf{P}_\ell^{\max}$	vector of maximum line flow limits.

Losses are ignored.

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