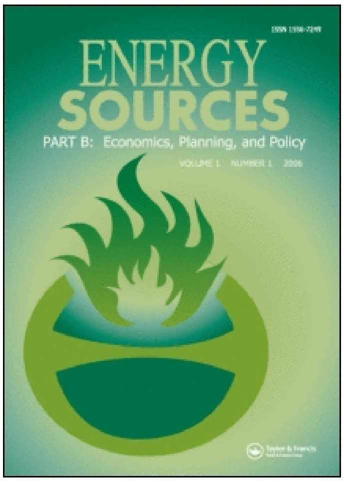

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Transmission Expansion Planning and Cost Allocation Under Market Environments

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Abstract *An important component to be considered in electric power system expansion planning is the security of service that the system is able to provide. Under the market environment the effect of expansion on the market conditions also has to be regarded during the planning. This article proposes a new method for transmission expansion planning under market environments which considers global welfare, construction, and security enhancement cost. Finally, a proper method to share the cost of expansion fairly between all network agents is suggested. To investigate the validity of the method, it is applied to the modified Garver 6-bus test system for expansion.*

Keywords cost allocation, cost of security enhancement, electricity market, expansion planning, transmission expansion

1. Introduction

Power system expansion planning, including transmission expansion planning, is normally carried out by one authority and therefore known as centralized planning. The task is to determine when and where the new transmission facilities should be installed such that they will operate in an optimal manner, subject to technical, financial and environmental constraints (Xu et al., 2006).

Starting from Garver's article in 1970, a variety of techniques such as branch-and-bound algorithm, sensitivity analysis, Benders decomposition, simulated annealing, genetic algorithm (GA), tabu search algorithm, and greedy randomized adaptive search algorithm (GRASP) were used to study the transmission network expansion planning problem. However, the mathematical models presented in the technical literature for the transmission planning problem have been mainly developed for traditional regulated monopoly power system paradigms. These are not strictly suitable for the competitive

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market environment and new approaches should be investigated (Fang and Hill, 2003). Furthermore, the uncertainty associated with generator sitting and timing will inevitably increase the uncertainty in future power-flow patterns. This brings a new challenge to the transmission planning problem (Fang and Hill, 2003).

In vertically integrated systems, the cost of expansion and the security of service as well as expansion benefits for networks are taken into account. In restructured cases, researchers have considered other variables such as agents' profit (Xu et al., 2006; Ruiz and Contreras, 2007; Shrestha and Fonseka, 2004), or locational marginal pricing (LMP) variances (Buygi et al., 2004; Buygi et al., 2006) through transmission expansion planning under market environments in their studies and finally refined their plan to have an $(N-1)$ secure network (Silva et al., 2005). In these articles the security of service has not been included in the objective function for expansion planning.

Different investigations have been carried out to obtain security cost of networks based on the customers' interruption costs (Neudorf et al., 1995; Moya, 1997; 2002). The articles have considered load reduction costs to save systems stable in abnormal situations as the security cost of the system. Considering the security cost during network planning, it is possible to lead the planning of a network to a more secure situation.

A new method for transmission expansion planning under a market environment considering the cost of security enhancement based on a presented paper by the authors of this article (Shariati et al., 2008) is discussed and an expansion cost allocation scheme is proposed to define the share of each participant in the expansion cost.

2. Planning Components

Transmission line construction is considered to be one of the most expensive and time consuming projects in power systems. This matter intensifies the importance of optimal planning.

There are three factors dealing with expansion planning under a market environment: global welfare (GW), the construction cost (CC), and the security enhancement cost. These components are explained in the following sections.

2.1. Global Welfare

The power exchange gets the producers' bids and buyers' offers and sorts them to perform a supply-demand diagram and extracts the market equilibrium point. In reality, due to the congestion and loss in lines, it is not possible to operate the network just due to the market mechanism. Therefore, the market would be cleared according to the locational marginal prices (LMP) and final revenue of the agents would be different. For instance, a seller would benefit according to:

$$S_n^S = LMP_n \times P_n^S - \pi_n^S \times P_n^S \tag{1}$$

GW is defined as the area between supply and demand curves in the supply-demand diagram (for accepted offers and bids). To maximize market profit of all agents or GW, the market pperator (MO) runs an optimal power flow (OPF) in each hour to obtain LMP, GW and each agent's profit.

$$
\begin{aligned}
&MaxS = \sum_{h \in H} \sum_{n=1}^{N} [\pi_n^b(p_n^b) - \pi_n^S(p_n^S)] \\
&\text{S.t.} \\
&g_{i\,\min} \leq g_i \leq g_{i\,\max} \\
&Qi_{\min} \leq Qi \leq Qi_{\max} \\
&\sum_j d_j(t_h) + D_h - \sum_i g_i(t_h) = 0 \\
&Zi_{\min} \leq Zi(t_h) \leq Zi_{\max} \\
&f_{\min} \leq f \leq f_{\max}
\end{aligned}
\tag{2}
$$

S represents the global welfare for all planning periods; π_n^b, p_n^b, π_n^s and p_n^s are bidding and offering price and power of agents. Network constraints, generation power (g), reactive power (Q), load (d) and loss (D) and generation balance, transmission lines limits (Zi) and frequency (f) should be respected during this optimization.

2.1.1. Construction cost. The construction cost is the sum of investment costs IC_p, along the np periods in the horizon, adequately adjusted using a return rate r (2) (Silvestre et al., 2005).

$$CC = \sum_{p=0}^{np-1} \frac{IC_p}{(1+r)^p} \tag{3}$$

2.1.2. Cost of security enhancement. Contingencies don't follow a regular structure, however, they can be categorized and be responded to with prepared responses. A network usually operates while it is $(N-1)$ secure. This means that the network can overcome a single contingency and avoid any potential harm. Therefore, during the planning period, it is necessary to consider the security of service and find the most reliable plan.

Generation reserves (for small networks equal to the largest generator) will be provided through ancillary service markets and agents having the ability of providing these services participate in the competition. These extra costs for generation reliability will be recovered through added costs to customers' bills.

Transmission contingencies should be resolved by load shedding to make the network safe and stable. Different types of loads result in different load shedding costs; for instance, the cost of an interruption in the supply of an industrial customer is much higher than a residential one. Therefore, for the load shedding, optimal weighted load shedding (OWLS) should be carried out to keep the network stable with the minimum necessary cost.

Transmission line outages split to permanent outages and transient outages. Permanent outages are those which require component repair in order to restore the component to service (Xiao et al., 2006). For a permanent outage, both the outage rate (OR) and the outage duration (OD) must be observed. Transient outages are not permanent, including both automatic and manual reclosing. For a transient outage, the OR is important to be considered and the OD is usually short.

Line outage probability calculation is the reliability subject and is related to operation condition, equipment maintenance and facility planning. The operation conditions are factors such as line length, weather condition, wind speed, voltage level, and geographic location. Analysis requires a great deal of historical data on the failures in order to obtain meaningful failure rates to represent the elements which may fail (Xiao et al., 2006).

Important research that should be carried out through the network is the observation of customers' interruption cost (IC). Customers can be divided to residential, commercial, and industrial. Subtle observation among customers, as shown by Subramaniam et al. (1993a, b) could clarify these interruption costs. IC is defined by the effect that contingencies may have on operating conditions, leading to the possible need for interrupting part of the system demand. IC relation with the interruption duration is not linear. For simplicity the average IC per hour of interruption ($/MWh) is considered for each type of customer.

To obtain the loss of load cost (LLC) for a contingency event, the sum of its effects on loads should be considered. Therefore, LLC for the line k (*LLCk*) is calculated as:

$$LLC_k = OR \times OD \times \sum_u ICu \times LDuk \tag{4}$$

LLCk is the LLC for the line k in a year. It is equal to the cost of all necessary load shedding during the contingency on the line k. OR and OD are the outage rate (per year) and outage duration (per hour) of line k. *LDuk* is the necessary load decrease for the user u during the contingency k. To minimize the *LLCk* instead of LD, OWLS is computed through GA. This optimization is used to attain the minimum necessary cost to save the network and respect all network boundaries.

$$\begin{aligned} & MinLLC_k = OR \times OD \times \sum_{u=1}^{n} IC_u \times OWLS_u \\ & \text{S.t.} \\ & V_{\min} \le V_l \le V_{\max} \qquad l = 1 \ldots m \\ & g_{i\,\min} \le g_i \le g_{i\,\max} \\ & z_{m\,\min} \le z_m \le z_{m\,\max} \end{aligned} \tag{5}$$

The LLC for contingency k is the sum of necessary OWLS costs multiplied by OR and OD. Each planning measure leads the network to a unique level of security. Therefore, the LLC during network contingencies is different for each planning measure. This difference is an adequate measure to rank expansion candidates. The total loss of load cost for an expansion will be achieved by:

$$LLC = \left(\sum_{k=1}^{n} LLC_k\right) \times y \times ac \tag{6}$$

For the expansion plan i, the sum of all LLCs multiplied by the operating period (year) identifies the LLC for the expansion i. The security enhancement cost for expansion i is defined to be the decrease in LLC after the expansion. For simplicity a permanent IC is specified for each type of user (industrial, commercial, or residential). However, in practice, IC depends on more factors such as backup systems and specially outage time (from no load to full load time). Usually lines outages for repair don't happen during the full load periods. Therefore, *ac* is a coefficient less than 1 to refine assumed IC.

3. Final Objective Function of Planning

There are three factors dealing with expansion planning under the market environment: the GW, the construction cost, and the security cost.

The final development (FD) of objective function is considered as:

$$\begin{aligned} \Delta S &= S_f - S_0 \\ \Delta SC &= LLC_0 - LLC_f \\ FD &= \Delta S + \Delta SC - CC \end{aligned} \tag{7}$$

ΔS is the market revenue of expansion, LLC_0 and LLC_f are the minimum LLC before and after expansion. Thus, ΔSC is the security enhancement cost for each planning scenario and CC is the construction cost.

This would be calculated for each expansion candidate to extricate the optimum candidate.

4. Transmission Expansion Cost Allocation

The expansion plan is chosen according to (5) and the entire network will benefit the expansion; however, who will be responsible for the expansion cost? The measure of a network owner in a cost allocation mechanism should be fair to all agents, therefore, whoever benefits more from expansion should pay more for it. Transmission expansion cost allocation is dependent on the strategy taken to evaluate the cost of transmission. In this article it is assumed that transmission cost includes a fixed part (C_F) and a variable part (C_V).

$$C_T = C_F + C_V \tag{8}$$

C_T is the total cost function of a transmission line. The variable part of this cost is covered through normal operation cost (merchandising surplus) and the fixed part, which recovers CC, should be covered in a specified time period by agents. Different strategies could be suggested for this part of the transmission cost, such as equal sharing or covering through additional price to C_V. In this article a new strategy which shares this cost fairly among network agents is considered. Therefore, expansion cost has to be split according to agents' profit from expansion. The buyer i connected to bus N, would benefit from the expansion according to the price drop in bus N (because of congestion relief in the network) and security enhancement during contingency situations.

$$X_{bi} = \Delta S_{bi} \tag{9}$$

X_{bi} is the total profit gained by buyer i, ΔS_{bi} is market revenue change for i after expansion, ΔSC_{bi} is the total profit gained from security enhancement for i. Respectively we have for seller j:

$$X_{sj} = \Delta S_{sj} \tag{10}$$

The share of each agent from total payment is defined as:

$$SX_{bi} = \frac{X_{bi}}{\Delta S}$$
$$SX_{sj} = \frac{X_{sj}}{\Delta S} \tag{11}$$

SX_{bi} is the share of buyer i from total expansion cost and similarly SX_{sj} is the share of seller j. Usually the cost of expansion is provided by grid owner (GO) and then covered in a predefined period of time. Therefore regardless of the strategy of payment, the share of each agent is defined.

Implementation results on the modified Garver 6-bus test system illustrate the mentioned strategy.

5. Case Study

The modified Garver (1970) 6-bus test system is used to illustrate the described method. The one line diagram of this network is shown in Figure 1 Predicted information of generators, lines and loading condition for the operation period is given in Tables 1 and 2.

The market structure of the system consists of 3 generating units and 5 loads. Two of the loads (D2 and D4) are industrial customers and their loads' interruption leads to high losses. Their demand is assumed to be performed through long-term contracts. However, for simplicity we assume that they should pay according to the nodal prices. Agents' average offers and bids are shown in Table 1.

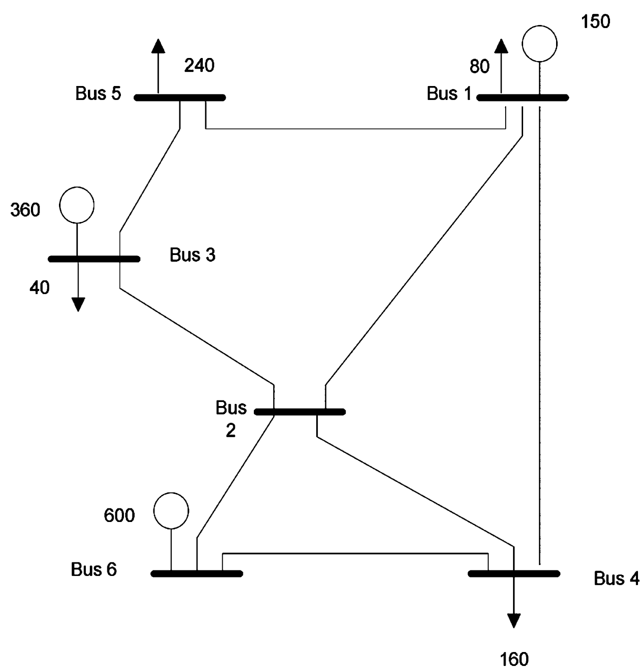

Figure 1. Schematic of the modified 6-bus test system.

Table 1
Generators and load information

	Generator			Load			
		MWh offer	Offer price [$/MWh]		MWh bid	Bid price [$/MWh]	IC [$/MWh]
1	G1	150	10	D1	80	30,28,26,20	280
2	—	—	—	D2	240	—	4,800
3	G2	360	15,19,20	D3	40	28,26,24,22	280
4	—	—	—	D4	160	—	4,800
5	—	—	—	D5	240	34,30,26,24,18	280
6	G3	600	8,12,15,17,19,21	—	—	—	280

Table 2 shows the line information of the system. The first two columns provide the nodes of origin and destination of the lines, the third and fourth columns show the electric parameters of the lines and the fifth column shows the transmission lines capacities. The construction costs for all lines are shown in the sixth column. Status of a line (already built or not) is shown in the seventh column, 0 value defines the possibility of building a new line.

Table 2
Line information

F	t	R, p.u.	X, p.u.	Limit	CC, M$	Already built	OR, 1/yr	OD, h
1	2	0.1	0.4	100	40	1	0.2	15
1	3	0.09	0.38	100	38	0	0.2	15
1	4	0.15	0.60	80	60	1	0.2	15
1	5	0.05	0.20	100	20	1	0.2	15
1	6	0.17	0.68	70	68	0	0.2	15
2	3	0.05	0.20	100	20	1	0.2	15
2	4	0.1	0.40	100	40	1	0.2	15
2	5	0.08	0.31	100	31	0	0.2	15
2	6	0.08	0.30	200	30	1	0.2	15
2	6	0.08	0.30	200	30	0	0.2	15
3	4	0.15	0.59	82	59	0	0.2	15
3	5	0.05	0.20	150	20	1	0.2	15
3	5	0.05	0.20	150	20	0	0.2	15
3	6	0.12	0.48	100	48	0	0.2	15
4	5	0.16	0.63	75	63	0	0.2	15
4	6	0.08	0.30	200	30	1	0.2	15
4	6	0.08	0.30	200	30	0	0.2	15
5	6	0.15	0.61	78	61	0	0.2	15

Table 3
Implementation results

	f	*t*	ΔGW	ΔSC, M$	CC, M$	FD
1	1	3	2.18E+06	0.383	38	−3.54E+07
2	1	6	2.91E+07	6.863	68	−3.20E+07
3	2	5	7.94E+05	9.739	31	−2.05E+07
4	2	6	6.43E+07	17.647	30	5.20E+07
5	3	4	5.54E+06	13.283	59	−4.02E+07
6	3	5	1.48E+07	7.312	20	2.15E+06
7	3	6	3.07E+07	−0.197	48	−1.75E+07
8	4	5	1.59E+06	11.758	63	−4.97E+07
9	4	6	5.92E+07	23.026	30	5.22E+07
10	5	6	4.91E+07	2.376	61	−9.48E+06

For a real network the contingency rates should be performed through reliability analyses like what is done by the Reliability Test System Task Force (1979). Reliability analysis are not given for the L. L. Garver test system, hence, the outage rates and outage duration shown in Table 2 are assumed according to the data given in Reliability Test System Task Force (1979) for the IEEE 30-bus test system.

Interruption costs were considered 4800 ($US/MW) for industrial customers and 280 ($US/MW) for residential users for an hour of interruption. These values are based on the data given in Moya (1997) and Subramaniam et al. (1993a, b).

Expansion candidates are 0 in seventh column in Table 2 and study results of the method are shown in Table 3.

Security cost (SC) is performed due to the given data and Eq. (5) for 25 years of operation and adjusting coefficient (ac) of 0.5. If no expansion measure takes place, the cost of security enhancement will be 28.5 million dollars. The enhancement of global welfare and the cost of security enhancement for each candidate are shown in the third and fourth columns of Table 3. The fifth column is the construction cost and the last column shows the final development of objective function for each candidate.

Objective function shows the triumph of the ninth candidate among other expansion candidates. It means that construction of a new line between buses 4 and 6 refines the competition level in the market more than other candidates according to the CC and SC for each planning.

An important point to be considered is the amount of SC obtained for each plan. It is interesting that these costs are really close to the construction costs. Therefore, this matter intensifies the necessity of their consideration during planning periods.

Expansion cost has to be split regarding to agents' profit from expansion. The surplus of each agent from expansion plan 9 is shown in the fourth column and the share of expansion cost is calculated in the last column of Table 4.

6. Summary and Conclusion

A new strategy for transmission expansion planning under the market environment is discussed in this article. In this method, further to other effective components of the expansion planning under the market environment, the cost of security enhancement has

Table 4
Implementation results

	S1	S2	ΔS	X
D1	102,300,608	1.09E+08	6.66E+06	0.113
D2	1.472E+09	1.489E+09	1.69E+07	0.286
D3	41,749,005	4.41E+07	2.33E+06	0.039
D4	985,162,145	1.012E+09	2.68E+07	0.454
D5	319,784,930	3.35E+08	1.48E+07	0.251
G1	237,401,299	219,742,630	−1.77E+07	−0.298
G2	59,488,055	49,331,389	−1.02E+07	−0.172
G3	195,592,786	215,009,140	1.94E+07	0.328

also been considered. The security enhancement cost is considered to be equal to the minimum total loss of the load costs due to the all network contingencies.

The construction cost of the network expansion is considered to be supplied by all network participants (customers and sellers). A new strategy, regarding the advantage of each agent from the expansion project, is presented in this article to assess the share of each network participant from the construction cost. The attained results of applying the method to the test system illustrate the described method.

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Nomenclature

GO	Grid owner
CC	Construction cost
LMP	Locational marginal pricing
S_n^s	Surplus of seller n
P_n^s	Seller's (n) energy bid block for the hour [MW]
π_n^s	Seller's (n) offer price [US$/MW]
π_n^b	Customer's (n) bid price [US$/MW]
p_n^b	Customer's (n) energy bid block for the hour [MW]
g_i	The generation of generator i
$g_{i\,\max}, g_{i\,\min}$	Upper and lower bound for the generator i
d_j	Demand on bus j [MW]
Qi	Reactive power in bus i
D_h	Loss of power in hour h
$Zi(t_h)$	MVA transmitted in line i in hour t_h
f	Voltage frequency
LLC_k	Loss of load cost for line k
ICu	Interruption cost for customer u [US$/MW]
LDuk	Load decrease at node u during contingency k [MW]
OWLS	Optimum weighted load shedding
LD	Load decrease [MW]
OR	Outage rate of a contingency [times/y]
OD	Outage duration of a contingency [h]
LLC	Loss of load cost
ΔS	Market revenue of expansion
ΔSC	Security enhancement cost
GA	Genetic algorithm
ac	Adjusting coefficient for interruption cost
y	Operation period designed during planning [y]
X_{bi}	the total profit gained by buyer i
SX_{bi}	the share of buyer i from total expansion cost
SX_{sj}	the share of seller i from total expansion cost