공급지장비를 포함한 송전계통계획

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Transmission System Expansion Planning Considering Outage Cost

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Abstract – This paper proposes a method for choosing the best transmission system expansion(TEP) plan considering an annual outage cost and a probabilistic transmission system reliability criterion ($_{R}LOLE_{TS}$). The objective method minimizes a total cost which are an investment budget for constructing new transmission lines and an annual outage cost, subject to the probabilistic transmission system reliability criterion, which consider the uncertainties of power system facilities. Test results on an existing 21-bus system are included in the paper. It demonstrated the suitability of the proposed method for solving the transmission system expansion planning problem subject to practical future uncertainties.

1. Introduction

The TEP problem can be classified in two models which are heuristic and mathematical optimization models. The firstly, the heuristic models describe all the plan scenarios such as techniques, economic (investment, operation cost), reliability, quality and etc. to search the best optimal solution. Various techniques including genetic algorithms (GAs), risk analysis (RA), game theory, simulated annealing (SA), expert system, fuzzy set theory, GRASP(Greedy Randomized Adaptive Search Procedure), tabu search, and etc. have been used to study this problem [1]-[9]. The secondly, the mathematical optimization models find an optimum solution by computing through a set of mathematical formulations which its variation parameters also describe a set of techniques, economic (investment, operation cost, reliability cost…), reliability, quality and etc. Several methods have been used a linear programming (LP), dynamic programming (DP), nonlinear programming, mixed integer programming and etc. The conventional TSEP problem is to minimize the total cost subject to a reliability level constraint [10]. This paper proposes an alternative method for choosing the best TSEP. The objective function is minimize total cost for constructing new transmission lines which are a investment cost and the annual outage cost, subject to probabilistic transmission system reliability criterion ($_{R}LOLE_{TS}$) which considers the uncertainties of transmission system elements. The annual outage cost of pure transmission system can be obtained by a yearly transmission system based outage energy *EENS*[MWh/year] times *IEAR*[$/kWh].

2. The Transmission System Expansion Planning Problem

A composite power system that includes generation and transmission facilities is shown in Fig.1 *TS* refers to the transmission system, NG is the number of generators, $_{k}F_{0}$ is the inverted load duration curve at load point k, and *NL* is the number of load points. In this paper, a composite power system is designated as HLII(HierarchicallevelII) and HLI(Hierarchical levelI) isused to designate generation and load components only. Table 1 shows two kinds of optimal model for transmission system expansion planning problem. Where, *IEAR*(*VOLL*) is an interrupted energy assessment rate [$/kWh].

<Table 1> Two kind of Optimal model for Transmission System Expansion Planning Problem

	Model I	Model II
Objective function	Minimize z = Investment cost + operating cost	Minimize z = Investment cost+ Outage cost
Main constraints	Reliability criterion (*LOLE*)	-
Method for assessing outage cost	-	$IEAR_{sys}$ × $EENS_{sys}$
Remarks	Optimal reliability criterion is necessary	Program assessing outage cost is necessary

2.1 The Objective Function

The conventional composite power system expansion planning problem is to minimize the total cost (C^T) and annual outage cost(*OTC*) as (1).

$$minimize\ C^T = \sum_{(x,y)\in B}\left[\sum_{i=1}^{m(x,y)} C^i_{(x,y)}U^i_{(x,y)} + OTC^i_{(x,y)}\right] \tag{1}$$

where,

r: the set of all branches (generators and transmission lines)

$m(x,y)$: the number of new candidate branches connecting nodes x and y.

$C^i_{(x,y)} = \sum_{j=1}^{i}\Delta C^j_{(x,y)}$: sum of the construction costs of the new generators and lines *1st* through *i-th* that connect buses x and y.

$C^i_{(x,y)}$: construction cost of the new *j-th* generator or line connecting nodes x and y

$OTC^i_{(x,y)}$: annual outage cost of the construction of the new generators and lines 1st through *i-th* that connect buses x and y.

$U^i_{(x,y)}$: the decision variable associated with the generator or line (1 if from 1st to *i-th* generators or lines are to be constructed, and 0 otherwise).

2.2 Constraints

The basic reliability criteria normally considered in a composite power system planning problem can be categorized as two types of constraints. One is a deterministic reliability criterion as (2) or (3) and the other is the probabilistic reliability criterion as (4).

$$P_c(S,T) \ge L_p \quad (s \in S,\ t \in T) \tag{2}$$

Where, is the capacity of the minimum cut-set of two subsets, S and T, containing source nodes s and terminal nodes t respectively when all nodes are separated by a minimum cut-set. The demand constraint (3) can be expressed by (4) with k being the cut-set number (k = 1 ,⋯,n), where, n is number of cut-set.

$$\sum_{(x,y)\in(S_k,T_k)}\left[P_{(x,y)} = P^0_{(x,y)} + \sum_{i=1}^{m(x,y)} P^i_{(x,y)}U^i_{(x,y)}\right] \geq L_p \qquad (3)$$

In the probabilistic approach, the probabilistic reliability criterion index, *LOLE* (Loss of Load Expectation), can be used as in (5).

$$LOLE_{TS}(P^i_{(x,y)},\Phi) \leq {}_R LOLE_{TS} \qquad (4)$$

Where, ${}_R LOLE_{TS}$ is the required transmission reliability criterion for the new system. Φ is a function of the load duration curve. A detailed discussion of Φ and *LOLE* is presented in [18].

3. Outage Cost Assessment of Composite Power System

3.1 Reliability indices of the load points

The load point reliability indices, $LOLE_k$ and $EENS_k$ can be calculated using (5) and (6) with the CMELDC, ${}_k\Phi_{NG}(x)$.

$$LOLE_k = {}_k\Phi_{NG}(x)\Big|_{x=AP_k} \qquad \text{[hours/year]} \qquad (5)$$

$$EENS_k = \int_{AP_k}^{AP_k+Lp_k} {}_k\Phi_{NG}(x)dx \qquad \text{[MWh/year]} \qquad (6)$$

where, L_{pk}: peak load at load point$k$ [MW]
AP_k: maximum arrival power at load point k[MW]

$$\begin{aligned} {}_k\Phi_i(x_e) &= {}_k\Phi_o(x_e) \otimes {}_k f_{osi}(x_{oi}) \\ &= \int {}_k\Phi_o(x_e - x_{oi})\, {}_k f_{osi}(x_{oi})dx_{oi} \end{aligned}$$

3.2 Reliability indices of the bulk system

While the $EENS_{HLII}$ of a bulk system is equal to the summation of the $EENS_k$ at the load points as shown in (7), the LOLE of a bulk system is entirely different from the summation of the $LOLE_k$ at the load points. The ELC_{HLII} (Expected load curtailed) of bulk system is equal to the summation of ELC_k at the load points. The $LOLE_{HLII}$ of the bulk system can be calculated using (9)[21].

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \qquad \text{[MWh/year]} \qquad (7)$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \qquad \text{[MW/cur.year]} \qquad (8)$$

$$LOLE_{HLII} = EENS_{HLII} / ELC_{HLII} \qquad \text{[hours/year]} \qquad (9)$$

$$EIR_k = 1 - EENS_k / DENG_k \qquad \text{[pu]} \qquad (10)$$

where, NL:number of load points
ELC_k = $EENS_k/LOLE_k$
$DENG_k$: demand energy at bus #k

3.3 Reliability Evaluation of Transmission System

The reliability indices of a transmission system can be expressed as the difference between the HLII and HLI reliability indices as shown in (11) and (12).

$$EENS_{TS} = EENS_{HLII} - EENS_{HLI} \qquad \text{[MWh/year]} \qquad (11)$$

$$LOLE_{TS} = LOLE_{HLII} - LOLE_{HLI} \qquad \text{[hours/year]} \qquad (12)$$

3.4 Outage Cost Assessment

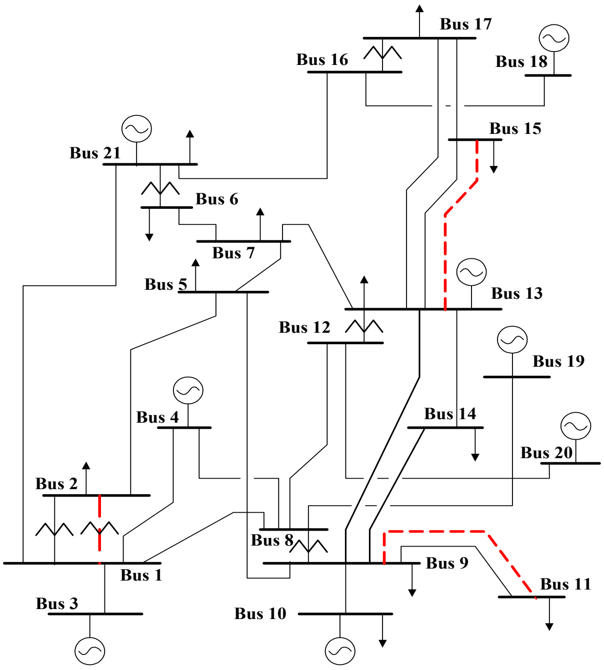
The annual outage cost assessment can be formulated by taking annual (Expected energy not served) of the construction element of the new generators and lines 1st through *i-th* that connect buses *x* and *y* multiplied with IEAR(Interrupted Energy Assessment Rate) system, that is sometime called *VOLL*(Value of Loss Load) as in (13).

$$OTC^i_{(x,y)} = IEAR \times \sum_{k=1}^{NL} EENS^i_{k(x,y)} \qquad \text{[M\$]} \qquad (13)$$

where, *IEAR*: interrupted energy assessment rate [$/kWh]

4. Case Studies

Fig.1 is an optimal solution of TSEP which considered both the probabilistic reliability criterion, ${}_R LOLE_{TS}$=50 [hours/year] and annual outage cost(*IEAR*=5[$/kWh]). A transformer and two transmission lines $TF^1_{1\text{-}2}$, $T^1_{13\text{-}15}$, $T^1_{9\text{-}11}$ were required to adding existed system, with total cost is 499.7[M$] which are the summation of the construction cost 279[M$] and annual outage cost 220.7[M$].

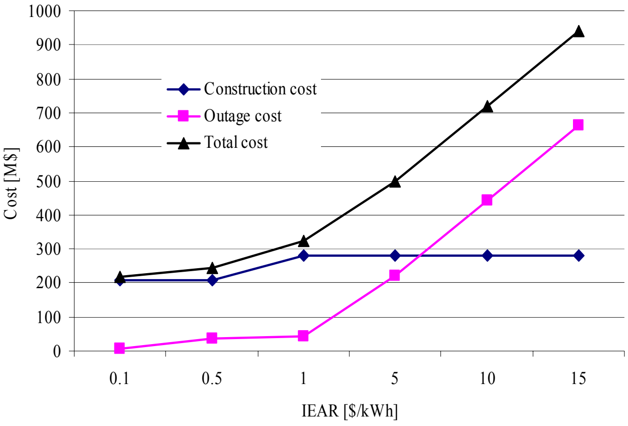


<Fig. 1> Optimal transmission system with considering outage cost (proposed method) (${}_R LOLE_{TS}$=50[hrs/yr],*IEAR*=5[$/kWh])

Table 2 and Fig.2 present characteristics of the optimal TEP results while *IEAR* was increasing. The general characteristic of the construction cost curve is increasing and saturate while *IEAR* still increase, because of the $C^i_{(x,y)}$ probabilistic transmission system reliability is satisfied for new system. In the presented study case, despite the cost of *EENS* is increased from 1 to 5[$/kWh], the investment in transmission does not increased. The reason is that reliability constraint (*LOLE*) should be still satisfied with ${}_R LOLE_{TS}$=50 [hrs/yr].

<Table 2> Various Optimal Solution of Transmission System Expansion Planning Due To Increase *IEAR*[$/kWh], (${}_R LOLE_{TS}$ =50[hrs/yr])

IEAR [$/kWh]	Optimal solution	Const. Cost [M$]	Out. Cost [M$]	Total cost [M$]
0.0	$T^1_{13-15}, T^1_{9-10}, T^1_{9-11}$	209	0.0	209
	$T^1_{13-15}, T^1_{9-10}, T^1_{9-11}$	209	7.3	216.3
0.5	$T^1_{13-15}, T^1_{9-10}, T^1_{9-11}$	209	36.7	245.7
1.0	$TF^1_{1-2}, T^1_{13-15}, T^1_{9-11}$	279	44.1	323.1
5.0	$TF^1_{1-2}, T^1_{13-15}, T^1_{9-11}$	279	220.7	499.7
10.0	$TF^1_{1-2}, T^1_{13-15}, T^1_{9-11}$	279	441.4	720.4
15.0	$TF^1_{1-2}, T^1_{13-15}, T^1_{9-11}$	279	662.1	941.1



<Fig. 2> Variation of the investment cost, outage cost and total cost due to increase *IEAR*[$/kWh], ($_{R}LOLE_{TS}$= 50[hrs/yr]).

6. Conclusions

This paper addresses TEP problem considering annual outage cost assessment (*OTC*) associated with construction cost (*C*), subject to the probabilistic transmission system reliability criterion ($_{R}LOLE_{TS}$). Optimal placements and the capacity of transformers as well as transmission lines can be determined using the proposed method. It presents a new alternative and practical approach that should serve as a useful guide for the decision maker to select a reasonable expansion plan. The proposed method finds the optimal TEP considering uncertainties associated with the forced outage rates of generators, transformers and transmission lines. It models the problem as a probabilistic integer programming one and considers problem uncertainties through probabilistic modeling. A proposed probabilistic branch and bound algorithm, which includes the network flow method, and the maximum flow-minimum cut set theorem is proposed to solve the problem. The 21-bus system analysis used to illustrate the method show that quite different expansion plans may be obtained from applying various *IEAR*. It is expected that the proposed methodology can be used to serve the TEP that includes the reliability index (*EENS*) in view point of economics. Furthermore, the method can be extended to CPSEP (composite power system expansion planning), which is handling transmission system and generation system together.

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