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A Basic Study on Composite Power System Expansion Planning Considering Probabilistic Reliability Criteria

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Abstract – This paper proposes a method for choosing the best composite power system expansion plan considering probabilistic reliability criterion. The proposed method was modeled as the minimization of the investment budget (economics) for constructing new transmission lines subject to not only deterministic(demand constraint) but also probabilistic reliability criterion(LOLE) with considering the uncertainties of the system elements. This is achieved by modeling the power system expansion problem as an integer programming one. The method solves for the optimal strategy using a probabilistic theory based branch and bound method that utilizes a network flow approach and the maximum flow-minimum cut set theorem. Although the proposed method is applied to a simple sample study, the testresults demonstrate a fact that the proposed method is suitable for solving the power system expansion planning problem subject to practical uncertainties for future.

1. INTRODUCTION

Power system expansion planning with open access to the transmission system has become a hot issue in electricity energy industries in recent. Electric market environment access has moved the industry from conventional monopolistic electricity markets to competitive markets. In a competitive market, the price of the delivered energy and the quality of electrical energy including voltage quality and reliability of service are the main factors for business success. A key factor in today's competitive environment is an orientation toward customer's needs and willingness to pay for quality. Compote power system expansion planning addresses the problem of broadening and strengthening an existing generators and transmission network to optimally serve a growing electricity market while satisfying a set of economic and technical constraints [1], [2]. The problem is to minimize cost subject to a reliability level constraint. Various techniques including branch and bound, sensitivityanalysis, Bender decomposition, simulated annealing, genetic algorithms, tabu search, and GRASP were used to study the problem [2]-[13]. Because it is very difficult to obtain the optimal solution of composite power systems considering generators and transmission lines simultaneously, transmission system expansion planning is performed following generation expansion planning. System planners and owners are expected to evaluate the reliability and economics parameters in grid planning when the problem involves many uncertainties including those of the investment budget, reliability criterion, load forecasting and system characteristics, etc. [16], [17]. It is a challenging task to develop an expansion plan that considers all these items in an effective and practical manner. When the database available for evaluating reliability indices and the investment budget for constructing new equipmentsis limited in size, it becomes difficult if not impossible to use general probabilistic methods to solve the problem [1], [16]. Under such circumstances, methodologies that are based on fuzzy set theory or probabilisticapproach become attractive and useful to accomplish the task. The former is very attractive because experience and knowledge of experts and decision makers can be very helpful in dealing with subjective uncertainties and ambiguity in planning problems. The latter is also valuable for considering the objective uncertainties of power system elements.

This paper proposes a method a method for choosing the best expansion plan of composite power system which is including generation as well as transmission systems together with considering probabilistic reliability criterion based on probabilistic reliability evaluation of composite power system.

2. THE COMPOSITE SYSTEM EXPANSION PLANNING PROBLEM

2.1 Objective function

The objective in the conventional composite power system expansion planning is to minimize total construction cost *CT* for investing in new generators and transmission lines as in (1)[23], [24].

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

where,

ρ : 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 of construction costs of the new generators and lines 1st through *i-th* that connect buses *x* and *y*

$C^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta C^{(j)}_{(x,y)}$

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

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

with

$$U^{(i)}_{(x,y)} = \begin{cases} 1 & P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0 & P_{(x,y)} \neq P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{cases}$$

$P^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta P^{(j)}_{(x,y)}$

with $P^{(i)}_{(x,y)}$: sum of capacities of branches (generators and transmission lines) between nodes *x* and *y*

$\Delta P^{(j)}_{(x,y)}$: capacity of the *j-th* element of candidate branches connecting nodes *x* and *y*

$P^{(0)}_{(x,y)}$: capacity of existing generators and lines that connect nodes *x* and *y*.

2.2 Constraints

This problem can consider two constrains, which are deterministic and probabilistic reliability criterion. First, no shortage of power supply requires that the total capacity of branches involved in the minimum cut-set should be greater than or equal to the system peak load demand, L_p. This is also referred to as the bottleneck capacity. Therefore, a no shortage power supply constraint can be expressed by (3)

$$P_c\left(X,\overline{X}\right)\geq L \qquad \left(s\in X, t\in \overline{X}\right) \tag{3}$$

where, $P_c\left(X,\overline{X}\right)$ is the capacity of minimum cut-set of two subsets, X and $\overline{X}$,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.

$$\sum_{(x,y)\in(X_k,\overline{X}_k)}\left[P_{(x,y)} = P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)}U^{(i)}_{(x,y)}\right]\geq L_p \tag{4}$$

Second, the probabilistic reliability criterion called *LOLE*(Loss of Load Expectation), which will be commented in detail in Section III, can be used as (5). Where, *RLOLE** is required reliability criterion which reliability level of the new system should be satisfied with and Φ is function of load duration curve commented in detail, section 3.

$$LOLE(P^{(i)}_{(x,y)},\Phi) = RLOLE^{*} \tag{5}$$

3. THE COMPOSITE SYSTEM RELIABILITY EVALUATION

The indices of HLII can be classified mainly for two kinds as load point indices and bulk system indices according to object of evaluation. And the reliability indices can be evaluated using a Synthesized Fictitious Equivalent Generator (SFEG) model of Fig. 2 which is introducing CoMposite power system Equivalent Load Duration Curve (CMELDC) of HLII.[5]-[19].

3.1 Reliability indices at load points

Reliability indices and CMELDC at load point #*k* is shown as in Fig. 2. Where, *Lpk* and *APk*of the horizontal axis expresses peak load and arrival power at load point #k respectively. In this figure, the load point reliability indices, *LOLEk* and *EENSk* can be calculated using Eq. (9) and Eq. (10) with ${}_k\Phi_{NG}(x)$.

$$LOLE_k = {}_k\Phi_{NG}(x)\,\Big|_{x=AP_k} \quad \text{[day]} \tag{9}$$

$$EENS_k = \int_{AP_k}^{AP_k+Lp_k} {}_k\Phi_{NG}(x)dx \quad \text{[MWh]} \tag{10}$$

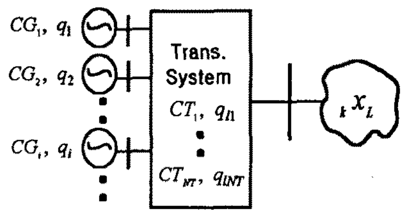
Where, AP_k *: maximum arrival power at load point # k [MW]*

$$\begin{aligned}{}_k\Phi_i(x_e) &= {}_k\Phi_o(x_e)\otimes_k f_{osi}(x_{oi})\\ &= \int {}_k\Phi_o(x_e - x_{oi})\,{}_k f_{osi}(x_{oi})dx_{oi}\end{aligned} \tag{11}$$

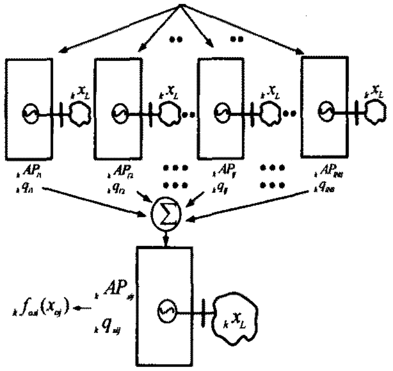
Where, : the operator meaning convolution integral

k_0 = original load duration curve at load point #*k*

${}_kf_{osi}$: outage capacity *pdf* of synthesis fictitious generator operated by generators from #*1* to #*i* at load point #*k*.



(a) Actual system



(b) Synthesized fictitious equivalent generator

Fig. 2 Synthesized Fictitious Equivalent Generator Model at HLII

3.2 Reliability indices of bulk system

While the $EENS_{HLII}$ of bulk system is equal to summation of $EENS_k$ at load points as Eq.(12), *LOLE* of bulk system is entirely different from summation of $LOLE_k$ at load points. But, as the ELC_{HLII} of bulk system is equal to summation of ELC_k at load points, $LOLE_{HLII}$ of bulk system can be calculated the divided by ELC_{HLII} as Eq.(14).

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \qquad \text{[MWh]} \tag{12}$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \qquad \text{[MW/cur.yr]} \tag{13}$$

$$LOLE_{HLII} = EENS_{HLII} \,/\, ELC_{HLII} \qquad \text{[pu]} \tag{14}$$

Where, *NL* : number of load point

R : set of states of not suppiled powers

$ELC_k = EENS_k \,/\, LOLE_k$ [MW/cur.yr]

These conventional formulates was calculated by a computer program which is ComRel.For version 3.2. It can calculate about 100 buses, 150 transmission lines, eight contingencies depth with four generators and four circuits and 10^{-9} cut offfor state probability of a contingency. This program has developed at power system laboratory of GSNU.

4. SAMPLE TEST

The proposed method was tested on the two-buses sample system shown in Fig. 3. Considering a forecasted future system load, the only deterministic approach and the other probabilistic approach were studied. The probabilistic approach isconsidering both the deterministic reliability criterion and the probabilistic reliability criterion.

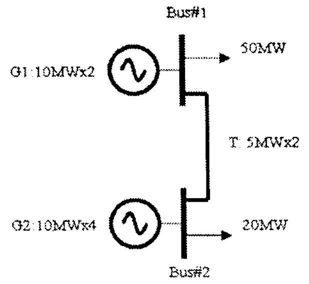


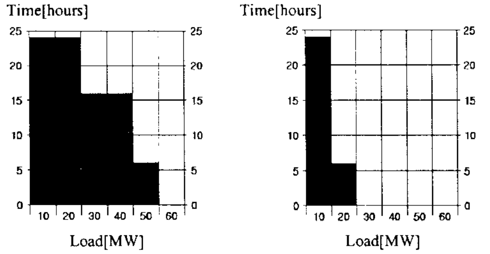
Fig. 3 Two- buses sample system

Table 1 shows the system data with GN, TL and LD representing generators, transmission lines, and loads respectively. SB and EB are start and end buses of the line, respectively. $P_{(x,y)}^{(0)}$ and $C_{(x,y)}^{(0)}$ are respectively, the capacities and costs of existing lines that connect nodes *x* and *y*. In this study, four candidate generators and lines are considered (or *m(x,y)* = 4 in (1) and (4)). Parentheses in $P_{(x,y)}^{(i)}$ and $C_{(x,y)}^{(i)}$ are omitted for convenience in Table 1. In this study, the required probabilistic reliability criterion level, *RLOLE**=100[hrs/yr] is assumed. The *FORs*(forced outage rates) of elements are assumed with 0.015 at generator site #1, 0.005 at generator site #2, and 0.00457 for lines.

TABLE 1
System Capacity and Cost Data P(*): (MW) and C(*): (M$)

NL	SB	EB	ID	ΔP_{xy}^0	ΔP_{xy}^1	ΔP_{xy}^2	ΔP_{xy}^3	ΔP_{xy}^4	ΔC_{xy}^0	ΔC_{xy}^1	ΔC_{xy}^2	ΔC_{xy}^3	ΔC_{xy}^4
1	0	1	GN	20	10	10	10	0	0	10	10	10	10
2	0	2	GN	40	10	10	10	0	0	8	8	8	8
3	1	2	TL	10	5	5	5	5	0	2	2	2	2
4	2	4	LD	50	0	0	0	0	0	0	0	0	0
5	3	4	LD	20	0	0	0	0	0	0	0	0	0

(#0 and #4 mean source and terminal nodes, respectively)



(a) ILDC at Bus 1 (b) ILDC at Bus 2

Fig. 4 Inverted load duration curves at buses

Table 2 shows processing for searching optimal solution, which is called as solution graph. Where, NF, DF, DFO, NPF, PF and PFO mean non deterministic and probabilisticfeasible solution, deterministic feasible solution, deterministic feasible and optimal solution, non probabilistic feasible solution probabilistic feasible solution and probabilistic feasible and optimal solution respectively. For example, systems 2 and 3 branched from system 1. The new generators or lines of systems 2 and 3 come from candidate generators and lines on bottle neck of system 1. System 7*, which has 14[M$] for construction cost and G_1^1, $T_{1-2}^1$and T_{1-2}^2 for new construction is obtained asoptimal solution of deterministic reliability criterion approach (demand balance constraint). But, the reliability index, *LOLE* of the system 7* is 106[hrs/yr] over required probabilistic reliability criterion level, *RLOLE**=100[hrs/yr]. System 11*, which cost has 16[M$] for construction cost and G_2^1, T_{1-2}^1, T_{1-2}^2, T_{1-2}^3,and T_{1-2}^4 for new construction is obtained as optimal solution of probabilistic and deterministic reliability criterion approach. The reliability index, *LOLE* of the optimal system 11* is 95[hrs/yr] and it is satisfied with a required probabilistic reliability criterion level, *RLOLE**=100[hrs/yr]. Optimal new systems using deterministic and probabilistic approach are shown in Fig. 4 and Fig.5 respectively.

TABLE 2
Processing For Searching Optimal Expansion Plans

System #	Con. Gens & Lines	Cost [M$]	LOLE [hrs/yr]	EENS [MWh/yr]	Connected #	Remarks
1	-	0	4,160	100555	2, 3	NF
2	G_1^1	10	1,661	34,002	4, 5	NF
3	T_{1-2}^1	2	2,900	66,736	5, 6	NF
4	G_1^1, G_1^2	20	101	2,042	9	DF, NPF
5	G_1^1, T_{1-2}^1	12	876	17,894	7	NF
6	T_{1-2}^1, T_{1-2}^2	4	1,655	33,849	7, 8	NF
7*	G_1^1,T_{1-2}^1, T_{1-2}^2	14	106	2,140	-	DFO,NPF
8	G_2^1, T_{1-2}^1, T_{1-2}^2	12	1,634	33,298	10	NPF
9	G_1^1, G_1^2, T_{1-2}^1	22	49	989	END	PF
10	G_2^1,T_{1-2}^1,T_{1-2}^2, T_{1-2}^3	14	854	17331	11	NPF
11*	G_2^1,T_{1-2}^1,T_{1-2}^2, T_{1-2}^3,T_{1-2}^4	16	95	1,909	END	PFO

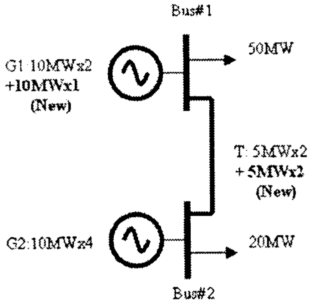


Fig. 4 Optimal system by deterministic approach

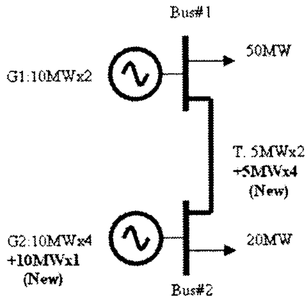


Fig. 5 Optimal system by probabilistic approach

5. CONCLUSIONS

This paper addresses the composite power system expansion planning problem considering generation and transmission system together by using probabilistic reliability criterion. Optimal sites and capacity of generators as well as transmission lines can be determined using the proposed method. It presents a new and practical approach that should serve as a useful guide for the decision maker to select a reasonable expansion plan prior to checking system stabilityand dynamics in detail. The proposed method finds the optimal composite power system expansion plan considering uncertainties associated with the forced outage rates of generators and lines, as it is, probabilistic reliability criterion. 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. Vivid test of the proposed method on two buses sample system including comparison between determine and probabilistic approaches shows that the proposed method will be suitable for application to perform practical expansion planning of composite power systems and transmission systemsin near future, although it is very simple system application.

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