복합전력계통의 신뢰도와 혼잡비용과의 상관관계성에 관한 기초 연구

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A Basic Study on Relationship between Reliability and Congestion Cost of Composite Power System

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Abstract - This paper describes a probabilistic annual congestion cost assessment of a grid at a composite power system derived from a model. This probabilistic congestion cost assessment simulation model includes capacity limitation and uncertainties of the generators and transmission lines. In this paper, the proposed probabilistic congestion cost assessment model is focused on an annualized simulation methodology for solving long-term grid expansion planning issues. It emphasizes the questions of "how should the uncertainties of system elements (generators, lines and transformers, etc.) be considered for annual congestion cost assessment from the macro economic view point?". This simulation methodology comes essentially from a probabilistic production cost simulation model of composite power systems. This type of model comes from a nodal equivalent load duration curve based on a new effective load model at load points. The characteristics and effectiveness of this new simulation model are illustrated by several case studies of a test system.

1. Introduction

The main purpose of a transmission system is to delivery electrical energy economically and reliably from generation to load. But, an actual transmission system always has limited delivery capacity. The undesired situation of the limited delivery capacity of a transmission system results from congestion. With congestion, more trade or higher fuel cost generation is desired than what can be supported by the available transmission facilities[1,2]. Transmission congestion can happen in an actual situation. Transmission congestion or constraints can restrict not only the flow of power from low cost nodes to high value nodes creating supply-demand price imbalances in competitive markets but also results in higher production cost in regulated markets[2-12]. Eventually, there occurs a difference between the production cost for a practical actual system and that of the uncongested system. This difference is called the congestion cost. Additionally, an actual transmission system always has possibilities of outage accidents. The investment problem for long-term planning of transmission system needs for its solution of a probabilistic congestion cost assessment model which considers uncertainties of the transmission system facilities[13-18]. In order to assess the probabilistic approached congestion cost, an extended model based on the conventional ELDC (equivalent load duration curve) model, is necessary[19-22]. This model plays an important role in probabilistic operating/production cost simulation and reliability evaluation for power system planning, mainly generation system long term expansion planning [19-22].

This paper illustrates a probabilistic annual congestion cost assessment model of a grid at a composite power system. This probabilistic congestion cost assessment simulation model includes capacity limitation and the uncertainties of generators and transmission lines. The congestion of a grid may be defined as the differences between a practical actual system with limited delivery capacity and an uncongested system with unlimited delivery capacity. Therefore, transmission congestion cost means the difference between production cost at a practical actual system and that of an uncongested system. This simulation methodology basically comes from the probabilistic production cost simulation model of the composite power system. This, in turn, comes from an equivalent load duration curve based on a new effective load model at load points. The characteristics and effectiveness of this new simulation model are illustrated by case studies of a test system.

2. Probabilistic Annual Congestion Cost Assessment and Probalistic Production Cost Simulation At a Composite Power System

2.1 Probabilistic Annual Congestion Cost

Briefly, the congestion of a grid may be defined as the differences between a practical actual system with limited delivery capacity and an uncongested system with unlimited delivery capacity. Therefore, the transmission congestion cost can be defined as the difference between total production cost (TPC_{HLII}) of a practical actual system with a delivery limitation and that (TPC_{HLI}) of a perfect ideal system (uncongested and zero forced outage system) as expressed in Equation (1). In (1), CNC is the congestion cost.

$$CNC = TPC_{HLII} - TPC_{HLI} \quad [\$/year] \qquad (1)$$

Figure 1 shows the relationship between the congestion cost and production cost according to how strong the power system is. "Optimal PC" in Figure 1 means the optimal production cost assessed under the assumption of an uncongested system with zero forced outage. TPC_{HLII} will be decreased while TPC_{HLI} is flat. Therefore, as the system becomes stronger, TPC_{HLII} approaches TPC_{HLI}, Then the congestion cost is decreased.

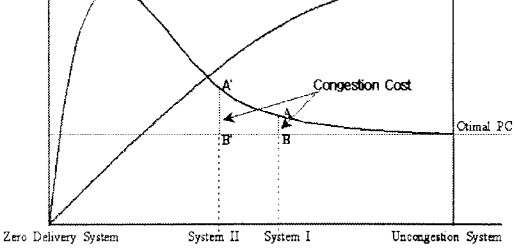

Fig. 1. Congestion cost concept diagram.

2.2 Probabilistic Production Cost (TPC_{HLII})

Figure 2 shows that ${}_k\Phi_i(x)$ at load point, #k, are obtained, after loading generators from #1 to #i, according to the merit order or bidding order of the electricity market, the reliability indices, and the nodal composite system equivalent load duration curve. It is called nodal CMELDC in this paper. In this Figure, L_{pk} and AP_{ik} on the horizontal axis express, respectively, the peak load and the maximum arrival power at load point #k with generators from #1 to #iloaded according to the merit order or the bidding order of the electricity market. In this Figure, the reliability indices, Loss of Load Expectation ($LOLE_{ik}$), and Expected Energy Not Supplied ($EENS_{ik}$) can be calculated using Equations (2) and (3) with ${}_k\Phi_i(x)$ [13-18]. It is important to note that AP_{ik} has non-coherence characteristics and that the nodal CMELDC can not be recursively obtained unlike that at HLI. This is because of capacity limitations of the transmission system[19-24].

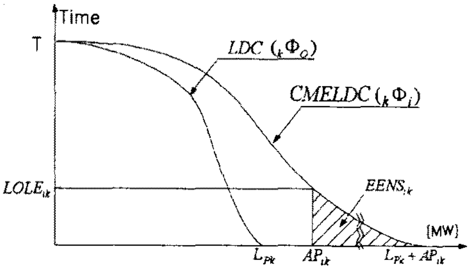

Fig. 2. Nodal reliability indices and nodal CMELDC at the load point #k.

$$LOLE_{ik} = {}_k\Phi_i(x)\ \Big|_{x=AP_{ik}} \tag{2}$$

$$EENS_{ik} = \int_{AP_{ik}}^{AP_{ik}+Lp_k} {}_k\Phi_i(x)dx \tag{3}$$

The nodal probabilistic production energy ΔE_i of a generator #i at the load point #k can be calculated as the difference between the $EENS_{i-1k}$ after loading the generator system without the generator and the $EENS_{ik}$ after loading the generator system with the generator as in Equation (4). The probabilistic production cost ΔPC_{ik} of generator #i at the load point #k can be also obtained from Equation (5). Please see the Appendix about the mathematical formulation of the relationship between LOLE and EENS and the nodal composite system equivalent load duration curve.

$$\Delta E_{ik} = EENS_{i-1k} - EENS_{ik} \qquad \text{[MWh]} \tag{4}$$

$$\Delta PC_{ik} = F_i\ (\Delta E_{ik},\ LOLE_{i-1k}) \qquad [\$] \tag{5}$$

where, F_i : operating cost function of generator #i [\$/h]

Finally, the total probabilistic annual production cost at the composite power systems, TPC_{HLII}, is calculated as Equation(6).

$$TPC_{HLII} = \sum_{i=1}^{NG}\sum_{k=1}^{NL} PC_{ik} \qquad [\$/\text{year}] \tag{6}$$

where,
PC_{ik} is the probabilistic annual production cost of the generator i delivered to the load point k [$/year]

3. Case Stduies

The program has been applied to the 8-bus test system shown in Figure 3 in order to demonstrate the effectiveness of the proposed method. Table I and Table II show the system conditions. The loads at the load points are peak values. Figure 4 shows the hourly chronological load variation curves of a standard day for this one year study. They were used for yearly load duration curves at the load points.

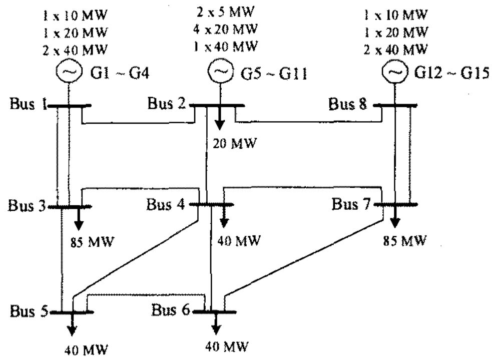

Fig. 3 An 8-bus system for the case study

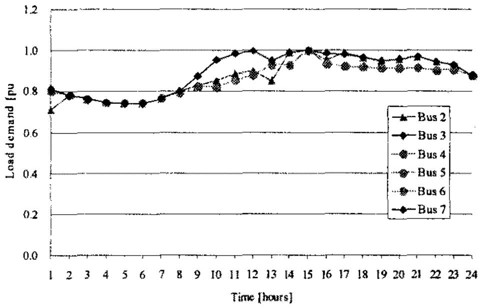

Fig. 4 Hourly load variation curves for standard days at the load buses

The following six scenarios were studied as shown in Table I. Case 0 assumed that the transmission system was an ideal system with unlimited delivery capacity and a zero forced outage rate. Case 1 was the base case. Case 2, 3, and 4 were contingencies of the lines. Case 5 assumed a new line addition from bus 2 to bus 3.

TABLE I System Conditions of the Cases

Cases	System conditions
Case 0	Uncongested system with unlimited delivery capacity
Case 1	**Non contingency (Base case)**
Case 2	$T_{1\text{-}3}^{1}$ Line contingency
Case 3	$T_{1\text{-}2}^{1}$ Line contingency
Case 4	$T_{2\text{-}4}^{1}$ Line contingency
Case 5	$T_{2\text{-}3}^{1}$ New line addition

Additionally, more case studies like that described in Table II were followed with the above detailed congestion cost assessment studies.

TABLE II System Conditions For Additional Cases and the Production Cost [103 $/year]

Cases	System condition (line contingencies)
Case 6	$T_{3\text{-}4}^{1}$
Case 7	$T_{3\text{-}5}^{1}$
Case 8	$T_{4\text{-}5}^{1}$
Case 9	$T_{5\text{-}6}^{1}$
Case 10	$T_{2\text{-}8}^{1}$
Case 11	$T_{4\text{-}7}^{1}$

Case 12	$T_{1\text{-}3}^{1}$ and $T_{2\text{-}4}^{1}$
Case 13	$T_{1\text{-}2}^{1}$ and $T_{2\text{-}4}^{1}$
Case 14	$T_{1\text{-}2}^{1}$, $T_{2\text{-}4}^{1}$ and $T_{2\text{-}8}^{1}$
Case 15	$T_{1\text{-}2}^{1}$, $T_{2\text{-}4}^{1}$, $T_{2\text{-}8}^{1}$, $T_{1\text{-}3}^{1}$ and $T_{7\text{-}8}^{1}$
Case 16	$T_{1\text{-}3}^{1}$, $T_{1\text{-}3}^{2}$, $T_{3\text{-}4}^{1}$, $T_{3\text{-}5}^{1}$, $T_{4\text{-}7}^{1}$ and $T_{7\text{-}8}^{1}$

Table III summarizes nodal congestion costs for all case s. Case 4 of the line contingency between bus 2 and bus 4 raises the most severe congestion costs for the grid. Ther efore, the line should be managed especially well in compa rison with other lines using this view point of congestion c ost management.

TABLE III The Bus/Nodal Congestion Cost For (N-1) Cont ingency Line of All Cases [103 $/year]

Gen #	Bus 2	Bus 3	Bus 4	Bus 5	Bus 7	Bus 6	Total
Case 1	2.30	5.00	2.70	2.70	5.00	2.70	20.6
Case 2	14.30	16.50	14.60	14.60	16.50	14.60	91.0
Case 3	13.9	26.7	17.3	17.3	26.7	17.3	119.5
Case 4	400.0	861.0	479.4	479.4	863.2	479.4	3,562.6
Case 5	0.10	0.10	0.00	0.00	0.10	0.00	0.40
Case 6	4.4	2.2	5.0	5.0	7.5	5.0	29.3
Case 7	4.4	2.2	5.0	5.0	7.5	5.0	29.3
Case 8	2.3	5.0	2.7	2.7	5.0	2.7	20.7
Case 9	2.3	5.0	2.7	2.7	5.0	2.7	20.7
Case 10	14.8	27.3	18.0	18.0	27.6	18.0	123.1
Case 11	3.1	4.0	3.2	2.4	5.3	3.2	21.2
L_{pk}	20	85	40	40	85	40	

(where, L_{pk} is peak load at k load point: MW])

TABLE IV The Annual Total Production Energy (TPE), The Tot al Production Cost (TPC) And Congestion Cost (CNC)

Cases	*TPE* [MWh/year]	TPC_{HLII} [10^3 $/year]	*CNC* [10^3 $/year]
Case 0	2,380,698	33,907.9	-
Case 1	2,380,691	33,928.5	20.6
Case 2	2,379,782	33,998.9	91.0
Case 3	2,380,499	33,976.6	68.7
Case 4	2,379,678	37,470.5	3,562.6
Case 5	2,380,696	33,908.3	0.4
Case 6	2,380,676	33,937.2	29.3
Case 7	2,380,663	33,937.2	29.3
Case 8	2,380,676	33,928.6	20.7
Case 9	2,380,686	33,928.5	20.7
Case 10	2,380,050	34,031.0	123.1
Case 11	2,380,674	33,929.6	21.2
Case 12	2,272,375	44,058.8	10,150.9
Case 13	2,346,765	49,343.1	15,435.2
Case 14	2,120,398	56,385.6	22,477.7
Case 15	1,828,974	53,144.5	19,236.6
Case 16	1,023,289	35,820.1	1,913.2

Table V compares the probabilistic reliability indices of all cases. As expected, the perfect delivery system (Case 0) always gives a higher reliability level than other cases considering delivery capacity limitation and uncertainty of the grid. While Case 4 become the most severe contingency case from the view points of congestion cost as shown in the previous Table III Case 2 become the most severe contingency case using the view points of reliability from Table V.

Figure 5 shows the trends of expected energy served (EES) and the total production cost (TPC) according to the levels of EENS, one of the kinds of reliability indices. As previously discussed with respect to Figure 2, this figure shows the characteristic that the stronger the system is, the lower is the probabilistic production cost. The non-smoothness of the decreased curve for the production cost comes from the non-coherency of the composite system.

TABLE V The Probabilistic Reliability Indices Of a Bulk System

Cases	LOLE [hrs/year]	EENS [MWh/year]	ELC [MW/Curt./year]	Remark
Case 0	0.794	28.955	36.477	
Case 1	1.099	35.808	32.589	Base case
Case 2	58.900	1,513.822	25.701	
Case 3	11.919	226.758	19.026	
Case 4	45.141	1,049.983	23.260	
Case 5	0.855	29.974	35.065	
Case 6	1.294	50.189	38.774	
Case 7	1.361	64.508	47.384	
Case 8	1.165	50.615	43.445	
Case 9	1.111	40.434	36.406	
Case 10	11.891	225.868	18.995	
Case 11	1.335	52.179	39.096	
Case 12	3,768.946	108,351.7	28.749	
Case 13	1,920.506	33,962.7	17.684	
Case 14	5,434.902	260,328.4	47.899	
Case 15	6,910.059	551,752.7	79.848	
Case 16	4,994.907	1,357,437	271.764	

(LOLE:[Hrs/year], EENS:[MWh/year], and ELC:[MW/curtailment/year])

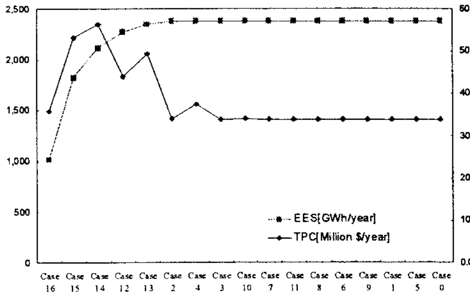

Fig. 5 The expected energy served (EES) and the total production cost (TPC) according to the levels of EENS

4. Conclusions

This paper illustrates a probabilistic annual congestion cost assessment of a grid at a composite power system. Specially, this paper proposes a methodology, using a simulation model, for nodal probabilistic annual congestion cost assessment where congestion costs at load points are able to be identified. This probabilistic congestion cost assessment simulation model includes capacities and uncertainties of the generators and transmission lines. The proposed probabilistic congestion cost assessment model focuses on an annualized simulation methodology for long-term grid expansion planning using a macroeconomics view point rather than a real time conventional congestion cost assessment on the detailed operation mode using optimal AC power/load flow and PTDF(power transfer distribution factors) [9]. The reason is that this paper focuses on the variable cost of the investment decision for solving the grid long term planning problem[1,2].

Therefore, the proposed model is different from a typical congestion cost assessment method by LMP methodology using a detailed load flow model. Instead, it emphasizes the development of a model and methodology about "how should the uncertainties of system elements (generators, lines and transformers, etc.) be handled in an annual congestion cost assessment?" This proposed simulation methodology essentially comes from a probabilistic production cost simulation model of a composite power system. This model, in turn, comes from an equivalent load duration curve based on the new effective load model at load points. This method will provide essential solutions for problems based on nodal and a decentralized operation and a control philosophy of electrical power systems under competition.

These case studies, described in this paper, demonstrated that the probabilistic annual congestion costs can be assessed by the proposed method. This method provides for a probabilistic production cost simulation for the generation related operating/variable cost assessment of objective function items in a composite power system expansion planning situation. It is expected that the simulation model will be useful for investment determinations that have to consider the uncertainties involved in grid expansion planning in the future.

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