THE EFFECT OF GENERATION CAPACITY EXPANSION ON THE RELIABILITY INDICES

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ABSTRACT

The main function of a power system is to supply the customer load demands as economically as possible and with an acceptable degree of reliability. A Power system is complex, highly integrated, and very large and includes a number of different factors affecting the required functions. The major parts of an electric power system are the generation, transmission, and distribution system. At the present state, power system reliability evaluations are generally conducted separately for each major part of the system according to the system functional zones. This also ensures more flexibility in selecting failure criteria and making appropriate assumption. In this paper it is only considered the issue of generation capacity reserve assessment and, the relation between system reliability level and the load growth is analyzed. The concept of capacity expansion analysis is illustrated using a simple test system. The impact on the system reliability of adding a unit to the overall system can be seen in terms of the increased system peak load-carrying capability.

I. INTRODUCTION

Electrical power system reliability assessment has a very wide range of meaning and it indicates, in a general sense, overall ability of the system to perform its function. Power system reliability studies generally are performed for two purposes [1,2].

(a) Long-term reliability evaluation may be conducted to assist in long-range system planning;

(b) Short-term reliability evaluation may be assisted in day-to-day operation decisions.

For this reason power system reliability assessment is divided into two basic aspects [2-4]:

–*System adequacy* relates to the ability of installed generation and transmission facilities to serve the total system-load requirements. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required transporting the energy actual load points.

–*System security* relates to the ability of system to respond to the disturbances arising within the system. Security is therefore associated with the response of the system to whatever perturbations it is subject.

Adequacy is therefore associated with static conditions, which do not include system disturbances. The adequacy studies of power supply system are conducted individually in three functional zones: generation, transmission, and distribution. The functional zones can be combined to give the hierarchical levels [2,3].

II. RELIABILITY OF GENERATION SYSTEM

The model of generating capacity reliability evaluation does not represent the entire power system. Only generating units included and the rest of the system is assumed to be perfectly reliable. The power system under consideration is a single system in which all the generating units and system load are connected to a single busbar.

The system is considered to operate successfully as long as there is sufficient generation capacity to supply the load. The basic elements used to evaluate generation adequacy are shown in Fig.1. First, mathematical representations of generation and load are combined to form the appropriate risk model of supply shortages in the system. Secondly, probabilistic estimates of shortage risk are used as indices of bulk power generation reliability for the considered configuration. This approach only considers bulk generation and the aggregate load in the system. Evidently, the transmission and distribution grids are very important to evaluate the reliability offered to single customers. However, the model is sufficient for the purpose of comparing the adequacy of different generation configurations. Accordingly, the calculated indices do not reflect generation deficiencies at any particular load point but measure the overall adequacy of generating system.

2.1 Risk of supply shortages

In power system analysis, boiler, steam (water) turbines and generators are often treated as an entity, called the generating unit. A model of bulk generation must consider the size of generation units and the two main processes involved in their operation, namely the failure and the restoration processes. A failure in a generating unit results in the unit being removed from service in order to be repaired or replaced, this event is known as an *outage*. Such outages can compromise the ability of the system to supply the load and affect system reliability.

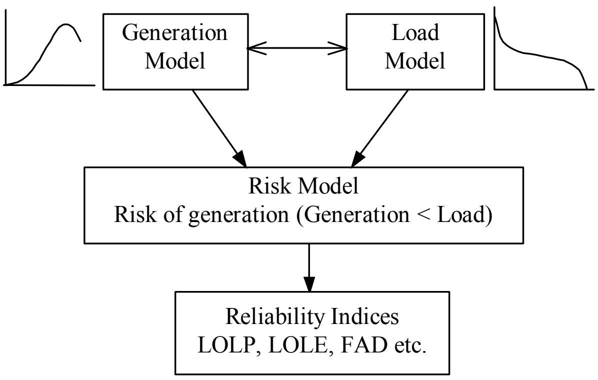

Figure 1. Conceptual tasks for generating capacity reliability evaluation.

An outage may or may not cause an interruption of service depending on the margins of generation provided. Outages also occur when the unit undergoes maintenance or other scheduled work necessary to keep it operating in good condition [5].

- A *forced outage* is an outage that results from emergency conditions, requiring that the component be taken out of service immediately.
- A *scheduled outage* is an outage that results when a component is deliberately taken out of service, usually for purposes of preventive maintenance or repair.

The status of a generating unit is conveniently described as residing in one of several possible states [1- 7]. A hierarchical representation of said states is shown in Fig.2.

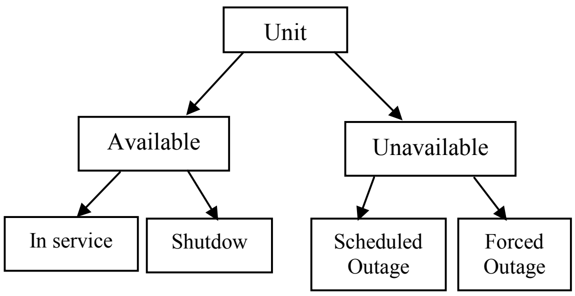

Figure 2. Generating unit states

2.2 State space representation and reliability data of a generating unit

To investigate the effect of a unit on system generation reliability, it is sufficient to know its capacity and the probability of residing in each state.

A simple two-state can represent the operating life of a generation unit model in a "service-repair" process as shown in Fig. 3, where λ and μ are the unit failure and repair rate respectively. The most important quantity for generation reliability analysis is the probability of unit failure.

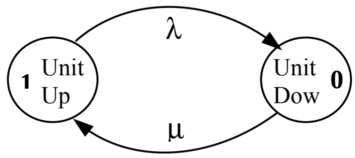

Figure 3. Sate Space Model of a two-state unit

The long-run failure probability, known as the unavailability of a unit, *U* and the long-run success probability, known as the availability of a unit, *A* can be expressed in terms of unit's failure and repair rates as follows.

$$U = \frac{\sum(down\ time)}{\sum(down\ time + Up\ time)} \quad (1)$$

$$A = \frac{\sum(Up\ time)}{\sum(down\ time + Up\ time)} \quad (2)$$

$$U = \frac{\lambda}{\lambda+\mu} = \frac{r}{r+m} \quad (3)$$

$$A = \frac{\mu}{\lambda+\mu} = \frac{m}{r+m} \quad (4)$$

Where λ = unit failure rate, μ = unit repair rate.

m = mean time to failure (MTTF)
r = mean time to repair (MTTR)
$T = m+r$ = mean cycle time,
f = cycle frequency = $1/T$

$$MTTF = \frac{1}{\lambda},\ MTTR = \frac{1}{\mu},\ f = \lambda \cdot U$$

The data given above and generating unit's effective capacity *C* form together the generating unit reliability data. The parameter *U* is a good approximation of a unit failure probability even when preventive maintenance is considered, provided that maintenance is scheduled during low demand periods. The unavailability is then an adequate estimator of the probability of finding a unit out of service at some point in the future. The unit unavailability is commonly referred to as the 'forced outage rate', *FOR*, which in fact is not a rate but the ratio of eq. (5).

$$FOR = \frac{forced\ outage\ hours}{in\ service\ hours +\ forced\ outage\ hours} \quad (5)$$

If computed over a long period of time, the *FOR* is equivalent to unit unavailability. Models with multiple states can be used to represent partial outages as derated states. Multistate models are also useful to accommodate intermittent operation and start-up failure rates. The most critical period of in the operation of a unit is the start-up period, and it comparison with base load unit, a peaking unit have fewer operating hours and many most start-ups and shutdowns. These aspects must also be included in arriving at an estimate of unit unavailability at some time in the future. A working group of the IEEE Subcommittee on the Application of Probability Methods proposed the four-state model and developed an equation, which permitted more factors to be considered [6]. Another improved model given in ref. [7]

2.3 Capacity outage probability model

The final step in building a generation model is to combine the capacity and availability of the individual units to estimate available generation in the system. The result is a capacity model; in which each generating unit is represented by its nominal capacity $\boldsymbol{c_i}$ and its unavailability index $\boldsymbol{U_i}$ (or forced outage rate).

For each of the N generators in the system, the available capacity $\boldsymbol{c_i}$, i =1…N, is a random variable that can take the value **0** with probability $\boldsymbol{U_i}$ and the value $\boldsymbol{c_i}$ with probability $\boldsymbol{A_i} = \mathbf{1} - \boldsymbol{U_i}$. [5]

In most reserve studies the two-state representation is sufficient. The individual state probability is

$$P(X = x_i) = \begin{cases} A & x_i = c_i \\ U & x_i = 0 \end{cases} \tag{6}$$

The cumulative state probability (or the distribution function) is

$$P(X \le x_i) = \begin{cases} 0 & x_i < 0 \\ U & 0 \le x_i < c_i \\ 1 & x_i \ge c_i \end{cases} \tag{7}$$

The total generating capacity available (effective capacity) in the system is:

$$C_A = \sum_{i=1}^{N} c_i \tag{8}$$

C_A is a random variable itself. We assume that all units can fail and be repaired independently of failures and repairs of other units. Under these conditions, the probability distribution of C_A can be obtained combining the single probabilities of the different $\boldsymbol{c_i}$. The result is a discrete capacity distribution $C_A = \{C_j, p_j\}$, j = 1…2^N, with a sample space of 2^N capacity states. Each capacity state represents an outage event with one or several units out of service. The capacity of the j^{th} state, C_j, with k available units and $N-k$ failed units is the sum of the capacities of the k available units, or

$$C_j = c_1 + \ldots + c_k \tag{9}$$

The probability of finding the j^{th} state is equal to the product of the probabilities A_i of the k available units and the probabilities U_i of the $N-k$ out-of-service units, that is:

$$P_i = A_1 A_2 \ldots A_k . \; U_1 U_2 \ldots U_{N-k} \tag{10}$$

There are 2^N possible different capacity states. In practice, several states have the same capacity so they can be grouped in a single state with the same capacity and probability equal to the sum of the single probabilities. This capacity probability distribution is usually tabulated and referred to as the *capacity outage probability table*.

For Example: Consider a power system consisting of three generating units. The capacity of unit 1 is C_1 MW; units 2 and 3 are C_2 and C_3 MW each. The forced outage rates of the units are U_1, U_2 and U_3 respectively. There are $2^3 = 8$ capacity states. The individual states probabilities as follows:

$p_{111} = P(C_1 + C_2 + C_3) = A_1 A_2 A_3$ (No outage capacity)

$p_{011} = P(0 + C_2 + C_3) = U_1 A_2 A_3$ (Outage capacity #1)

$p_{101} = P(C_1 + 0 + C_3) = A_1 U_2 A_3$ (Outage capacity # 2)

$p_{110} = P(C_1 + C_2 + 0) = A_1 A_2 U_3$ (Outage capacity # 3)

$p_{001} = P(0 + 0 + C_3) = U_1 U_2 A_3$ (Outage caps. #1 and #2)

$p_{010} = P(0 + C_2 + 0) = U_1 A_2 U_3$ (Outage caps. #1 and #3)

$p_{100} = P(C_1 + 0 + 0) = A_1 U_2 U_3$ (Outage caps. #2 and #3)

$p_{000} = P(0 + 0 + 0) = U_1 U_2 U_3$ (Full outage capacity)

These probabilities can be organize to give the capacity outage probability tables as shown in Tab. 1

Table 1. The capacity outage probability table for 3 generating unit with two-state.

Outage Capacity (MW)	Individual probability	Cumulative Probability
0	p_{111}	$p_{000}+p_{010}+p_{100}+p_{001}+p_{110}+p_{101}+p_{010}+p_{111}= 1$
C_1	p_{011}	$p_{000}+p_{100}+p_{010}+p_{001}+p_{110}+p_{101}+p_{001}$
C_2	p_{101}	$p_{000}+p_{100}+p_{010}+p_{001}+p_{110}+p_{101}$
C_3	p_{110}	$p_{000}+p_{100}+p_{010}+p_{001}+p_{110}$
C_1+C_2	p_{001}	$p_{000}+p_{100}+p_{010}+p_{001}$
C_1+C_3	p_{010}	$p_{000}+p_{100}+p_{010}$
C_2+C_3	p_{100}	$p_{000}+p_{100}$
$C_1+C_2+C_3$	p_{000}	p_{000}

2.3.1 Recursive Algorithm for capacity model building

A computer programming software is realized for computing the capacity outage probabilities using the recursive algorithm [1-4]. After adding new units, the software enables to compute the new capacity states and their probabilities depending on the existing states with few computational procedures. The capacity model can be created using a simple recursive algorithm, which can also be used to remove a unit from the model. This approach can also be used for a multi-state unit, i.e. a unit that can exist in one or more derated states or partial output states as well as in the fully up and down states. In the recursive algorithm, it assumed that $\boldsymbol{X}$ a discrete random variable and it is created the capacity outage tables for (n-1) units with the cumulative probability of a particular capacity outage state of $\boldsymbol{X}$ MW, $P_{n-1}(X)$. Therefore, the cumulative probability after adding a unit having (a) capacity C_n and (b) forced outage rate U_n, is given by

$$P_n(X) = (1 - U_n) \cdot P_{n-1}(X) + U_n \cdot P_{n-1}(X - C_n) . \tag{11}$$

Where $P_{n-1}(X)$ and $P_n(X)$ denote the cumulative probabilities of the capacity outage state of ***X*** MW before and after the unit is added. Setting initializes the above expression with

$$P_{n-1}(X) = \begin{cases} 1 & X \le 0 \\ 0 & otherwise. \end{cases}$$

Equation (11) can be modified as follows to include multi-state unit representations.

$$P_n(X) = \sum_{i=1}^{n} p_i P_{n-1}(X - C_i) \qquad (12)$$

Where n = number of unit states, C_i = Capacity outage of state *i* for the unit being added, p_i = probability of existence of the unit state *i*. Setting same as above condition initializes this expression.

2.4 Load Model

The load demand in a power system in any time period (a year, a month, a season, a week, a day or an hour) is a stochastic process, which is difficult to describe with a simple mathematical formula [3,4,9]. Depending upon the objective of the analysis, different load models can be established from primary load data. The simplest load duration model is one in which each day is represented by its daily peak load. The individual peak loads are arranged in descending order to form a cumulative load model known as the *daily peak load variation* curve. Another method uses hourly load values in a given period and organizes them in descending order to produce the *load duration* curve. The advantage of this representation is that the area under the duration curve is the energy required in the period considered. Fig. 4 shows the typical shape of a load duration curve.

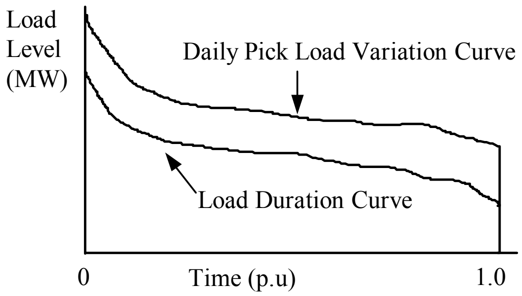

Figure 4. Load Models

The probability of a load increase from every level is

$$P(L_i) = \sum_j (t_{ij} / T) \qquad (13)$$

in which t_{ij} is the pause time of load level L_i inside the time interval t_j (0 or t_j); *T* is the exmination period ($\sum t_j$). Therefore the cumulative load level L_i is

$$P(l \ge L_i) = \sum_{k \ge i} p(L_k) \qquad (14)$$

As for the load cumulative frequency function, suppose that the load is L_i inside the time interval of t_j and load changes to L_{i+1} or L_{i-1} at the end of t_j. Then the load goes increases and corresponding probability that generation capacity decreases is

$$P(Lij) = \frac{t_{ij}}{T}. \qquad (15)$$

The transition rate is $\lambda'_{ij} = 0 \quad \lambda''_{ij} = \frac{1}{t_{ij}}$.

The upward depardure frequency of the load is

$$f(L_{ij}) = p(L_{ij})(\lambda'_{ij} - \lambda''_{ij}) = -\frac{1}{T} \qquad (16)$$

The probability that the load decreases is the same.

2.5 Generation Shortages

The applicable capacity outage distribution needs to be combined with an appropriate system load model to produce a generation shortage risk index. A supply shortage will occur whenever the system load exceeds the generating capacity remaining in service. If ***L*** is the system load, the probability of having power shortages will be the probability of all the outage events for which $\boldsymbol{C_A}$ is less than ***L***, or $\boldsymbol{P(C_A \le L)}$. [1-5]

2.6 Generation Reliability Indices

The application of probability models to the evaluation of generation reliability allows the integration of different unit sizes and types, the effects of maintenance, the capacity of interconnections and other factors. In addition, economic aspects can be better accommodated. The analytical methods commonly employed are the “loss of load” and the “frequency and duration” approaches [1-5, 9,10].

Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE)

LOLP is defined as the probability of the effective system capacity not meeting load demand, which can be written as

$$\text{LOLP} = P(X > R) \qquad (17)$$

Where *X* system outage capacity,
$R = C_A - L$ **:** System reserve capacity,
L: maximum load level.
Usually it is not the probability indices but expectations that are used in engineering application. The latter means the expected number of days or number of hours in the period of investigated when the maximum load exceeds the system effective capacity:

$$\text{LOLE} = \text{LOLP}.\ \text{T} \qquad (18)$$

In the much of the literature, strict distinctions are not made and LOLP index referred to is actually the LOLE index [3]. Here if the load model is an annual continuous load curve (day maximum load), then T is 365 days and the unite of LOLE is days per year; if the load model is a day load curve (hour), then T is 8760 hours and the unite of LOLE is hours per year [3].

Expected Energy not served (ENNS)

EENS is the expectation of the energy loss caused to customers by insufficient power supply.

$$\text{EENS} = \sum_{R-X>0} p(R)\cdot(X-R)\cdot t \qquad \text{MWh} \qquad (19)$$

If the load model is based on hours, then *p(R)* =1/8760, t=8760 hours. The cost of power interruption can be further calculated from EENS.

Frequency and Duration (FAD)

The cumulative system interruption frequency can be obtained from the cumulative state frequency [3].

$$F = F(X > R) \text{ times / year} \qquad (20)$$

FAD is very important if the cost to customers is influenced by the frequency of power interruption over a certain period of time, for instance to customers in the chemical industry.

III. GENERATION EXPANSION PLANING

An important application of generation reserve studies is the planning for unit additions in the future. The determination of such a schedule is based on an acceptable level of risk expressed in one of the reliability indices, and on the rate of load growth expected for a number of years ahead. Here we will use the LOLE technique for generation additions planning. Using the LOLE (or LOLP), it can be determined how much capacity is required to obtain a specified level of risk. As demand grows over time, generation additions are timed such that the LOLP does not exceed the design criterion. LOLP varies exponentially with load changes. The graph is almost straight line on semi-log scale as shown in Fig.5, which plots LOLE versus annual peak load [2,3,4,10].

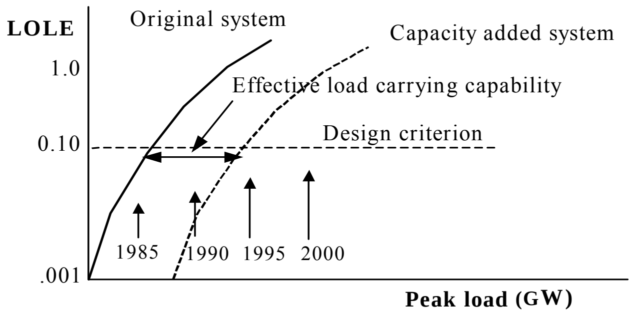

Figure 5. The effect of the capacity adding on picks load-carrying capability

The design criterion in this example case is 0.001 days/year. It can be concluded from this figure that the capacity expansion is needed to assure required reliability level depending on the load growth over the years.

The concept of Effective Peak Load Carrying Capacity (EPLCC) of a generating unit is defined as the amount of additional peak load that a generating unit permits a power system to carry at same LOLE index. In the case study of this paper, we determined the effective load carrying capability using computer programming, but it is also possible to derive an approximate formula regarding the character of LOLE in the vicinity of the target value is a quite linear on semi-log scale [2,10].

IV. CASE STUDY

Using data of the example system given in Tab. 2, the capacity outages and its relevant probabilities are computed and the results are given in Tab.3.

Table 2. Generating system data

Unite #	Capacity (MW)	FOR
4	20	0.015
7	5	0.005
1	15	0.005
4	20	0.005

Table 3. Generating system capacity outage probability table

Capacity out of service (MW)	Individual probability	Cumulative probability
0	0.88638397	1.00000000
5	0.03117934	0.11361603
10	0.00047004	0.08243670
15	0.00445813	0.08196666
20	0.07196639	0.07750853
25	0.00252833	0.00554214
30	0.00003810	0.00301381
35	0.00036117	0.00297571
40	0.00246562	0.00261453
45	0.00008648	0.00014892
50	0.00000130	0.00006244
55	0.00001234	0.00006114
60	0.00004638	0.00004880
65	0.00000162	0.00000243
70	0.00000002	0.00000080
75	0.00000023	0.00000078
80	0.00000052	0.00000055
85	0.00000002	0.00000002
90	0.00000000	0.00000001
95	0.00000000	0.00000001

Peak Load is 155 MW in this example case. The load duration curve is depicted in Fig. 6. In this figure, the coordinates are normalized taking the 365 days as a unity i.e. 1.0 and peak load 155 MW also as a unity i.e. 1.0. LOLE is computed as 0.029846 days/year. Projecting load growth over the years, the same computations are repeated for these peak load values. The results are depicted graphically each time as a relation of the LOLE and Peak Load. These curves are similar in the Fig. 7. Then, the EPLCCP of new unit to be added is determined repeating same computational procedures and using new curves obtained.

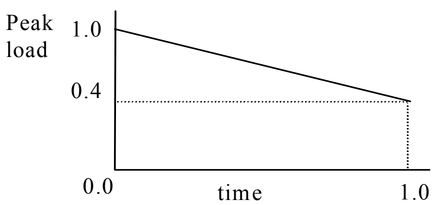

Figure 6. Normalized load duration curve of example system.

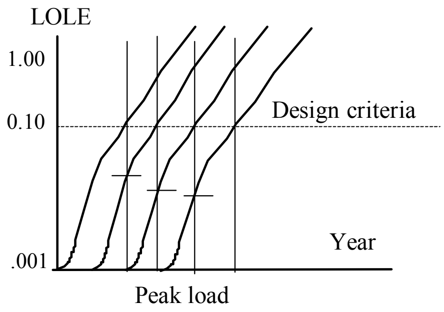

Figure 7. Variation in risk with adding new unit.

V. CONCLUSION

This paper has concerned the issues of generation system reliability evaluation, especially generating system adequacy assessment. The reliability indices are computed based on capacity outages probabilities and the load probabilities. The capacity expansion and its effects on the generation system reliability level are analysed using simple example system. This effect can be seen in terms of EPLCC due to unit addition. The EPLCC can be determined as a function of the risk level. It is concluded that this probabilistic methods is very efficient to decide how much generation capacity is needed to assure reliability level since the uncertainties inherently included in the process. The utilization of probability techniques even in the relatively simple form LOLE evaluation permits the factors that do not influence the system reliability to be included in the analysis and gives proper weight to the unit size and outage rates and to the system load characteristic. All the required software is developed for the purpose of power system reliability evaluation and Generating System Reliability Assessment (GSRA) module has been used for the capacity expansion analysis.

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