Jurnal
Teknologi

Full Paper

RELATIONSHIP BETWEEN LOSS OF LOAD EXPECTATION AND RESERVE MARGIN FOR OPTIMAL GENERATION PLANNING

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Article history
Received
5 June 2015
Received in revised form
13 December 2015
Accepted
6 January 2016

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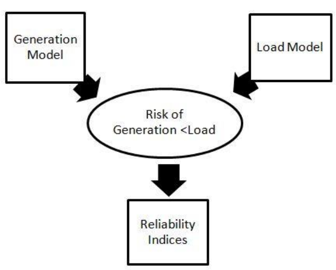

Abstract

Generation planning utilizes reliability indices as criteria to ensure adequacy in terms of total installed capacity. Reserve Margin and Loss of Load Expectation (LOLE) are the most widely-used indices in generation adequacy evaluation. Reserve Margin is a measure of available capacity over and above the capacity needed to meet normal peak demand levels. In Peninsular Malaysia, the amount of Reserve Margin has been perceived to be high. Generally, high Reserve Margin can provide high reliability. However, it acquires more generation plant, for which some of them may not be necessary. This may indicate over investment which will be reflected in the tariff structure. LOLE is a probabilistic measure which indicates the risk at which the generation capacity fails to meet the demand and its evaluation involves specific parameters such as the plant capacity and outage rate of each generating unit. Therefore, in order to have optimum generation planning and investment efficiency, it is necessary to perform a study on the practical Reserve Margin level with respect to the current LOLE requirement without endangering the overall power system reliability. This research studies the factors affecting LOLE and evaluates the relationship between Reserve Margin and LOLE under various conditions. A modified Peninsular Malaysia system is simulated using Wien Automatic System Planning (WASP -IV) to determine LOLE focusing on thermal power plants. This study concludes that peak load and forced outage rate give significant impacts to the LOLE and thus, the reliability of the system. Effort to ensure availability especially during peak load may need to be intensified. The study also establishes an inverse exponential curve for the relationship between Reserve Margin and LOLE. It is found that the outcome of the study is to enhance generation planning decision making in obtaining the optimum Reserve Margin considering the LOLE under various conditions.

Keywords: Capacity outage probability table; Forced outage rate; load duration curve; loss of load expectation

1.0 INTRODUCTION

The power system is designed to always have adequate generation capacity including operating reserve to cost-effectively meet anticipated consumer demand at all time. Getting the amount of the reserve right is the difficult part. Reserve Margin that is too low in the generation system may result in the generation system to be less reliable. High Reserve Margin can provide high reliability to the system. However, it acquires more generation plant, for which some of them may not be necessary [1]. This can cause over investment in generating capacity that can lead to excessive operating costs which may be reflected in the tariff structure [2].

In addition, Reserve Margin can only provide general guideline as it does not give or reflect any measures of risk of the generation system reliability. In Peninsular Malaysia, the amount of Reserve Margin is reported to be approximately 30% as in year 2013 and it is considered to be comparatively high [3]. For optimum generation planning and investment efficiency, it is necessary to perform a study on the realistic Reserve Margin level in Peninsular Malaysia with respect to the current LOLE requirement without endangering the overall power system reliability.

Optimal generation planning is crucial in order to achieve both technical and economic efficiencies. Therefore, it is important to take into account the LOLE which is known as the probability risk of generation capacity is being exceeded by the load demand in order to obtain the optimum Reserve Margin. Optimum Reserve Margin can provide sufficient capacity adequacy considering load demand, forced outage as well as scheduled maintenance of the generation unit without sacrificing the cost effectiveness of the generating capacity investment.

There are many studies involves in determining the generation reliability such as LOLE. Study of [1] proposed method to determine appropriate Reserve Margin by using probabilistic base method. The method is to calculate the value of appropriate Reserve Margin based on probabilistic method using a reliability index, i.e. Loss of Load Expectation (LOLE). Three generic capacities, i.e. 250, 500, and 750 MW, are used and tested with a modified Thailand system to obtain a range of appropriate Reserve Margin. It is done by continuously adding the same generic capacity known as new generation unit of each size of 250MW, 500MW and 750 MW until the system meets each of the specified LOLE criteria under peak load variation.

The other studies analysed and looked into the effect of load demand on the system reliability and also the effect of increase in failure rates of generating units on the system reliability. The effect of increment in the load on the system results in increment on reliability indices, thus, decrease the system reliability. On the other hand, if the load on system decreases, it causes the reliability indices to be decreased which results the generating system to be more reliable. Increment in the failure rates also decreases the generating system reliability [4].

The other study associated with LOLE involves in calculating the reliability of composite which is the combination of generation and transmission system by calculating probability and frequency of failure of system under different conditions. This study also includes the generation system reliability only where different load duration curves and the results shows that as the load of the increases, the reliability of system decreases. Similarly, when the load decreases, the system reliability increases [5].

Factors affecting the Loss of Load Expectation (LOLE) were insufficiently studied. Most of the previous studies were only focused on the variation in load. Therefore, in this study, in addition to the load variation factor, other factors affecting the Loss of Load Expectation (LOLE) such as forced outage rate (FOR) are also being focused.

Previous studies also calculated the LOLE but do not establish the relationship between Reserve Margin and Loss of Load Expectation (LOLE). There are several factors that influences the value of LOLE and these factors are important to be considered in supporting recommendation of determining the suitable Reserve Margin. Hence, in this study, the relationship between Reserve Margin and Loss of Load Expectation (LOLE) is being established where this relationship can be used to determine the suitable Reserve Margin of the system with respect to the requirement of LOLE which is 1 day/year.

The analysis on the important factors affecting the LOLE level in Peninsular Malaysia, which can provide a guideline to achieve capacity adequacy, is very significant in supporting recommendations on how the Reserve Margin can be optimized while adhering to the LOLE level requirement.

2.0 GENERATION CAPACITY RELIABILITY EVALUATION

The modeling approach for the generating system adequacy assessment consists of three parts as shown in Figure 1. The generation and load models are combined to form an appropriate risk model where the element of interest is the risk of generation capacity less than the load [6]. In short, adequacy evaluation of generation systems consists of three general steps:

Step 1: Create a generation capacity model based on the operating characteristics of the generating units.

Step 2: Build an appropriate load model.

Step 3: Combine the generation capacity model with load model to obtain a risk model.

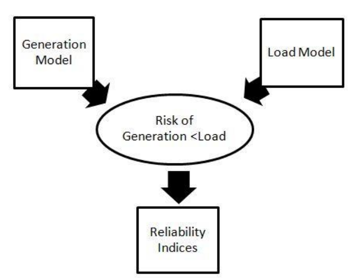

Figure 1 Generating capacity reliability evaluation

2.1 Generation System Model

A Capacity Outage Probability Table (COPT) should be, initially, generated in which various generation capacities as well as their respective probabilities are described. The COPT must consider size of individual generator and all generators' forced outage rate

(FOR) [2]. Generation unit unavailability known as Forced Outage Rate (FOR) can be represented as two-state model shown in Figure 2 where the condition of a generation unit assumed in this studies is either operating or totally forced out of service.

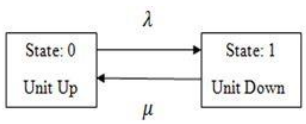

Figure 2 Two-state model

From the model in Figure 2, the unavailability which is referred as the unit of Force Outage Rate (FOR) can be calculated using (1)

$$FOR = \frac{\lambda}{\lambda + \mu} \qquad (1)$$

where
λ is expected failure rate
μ is expected repair time

Generating capacity out of service due to forced outages is multinomially distributed with outage probabilities as parameters. The total number of available (or unavailable) capacity states in an N-unit system is 2^N. For example, a 5-unit system (each unit can exist in 2 states) will have 2^5 = 32 states of available or unavailable capacity. Table 1 shows the Capacity Outage Probability of 5 x 40MW system with 1% probability of each generator outage [7].

Table 1 Generating capacity outage probability table of 5 x 40MW system

Capacity Out (MW)	Capacity In (MW)	Individual Probability, pk
0	200	0.95099
40	160	0.04803
80	120	0.00097
120	80	0.000098
160	40	0.000000
200	0	0.000000
Total		1.00000

2.2 Load Model

One of the most widely used load models is Load Duration Curve (LDC) where it is generated from the individual hourly loads in a given period, usually a year which is in descending order.

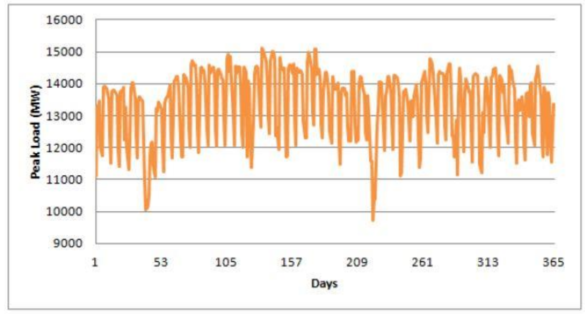

Figure 3 Daily peak load

The other common load model used in generating capacity reliability evaluation is Daily Peak Load Variation Curve (DPLVC) which is known as the cumulative representation of loads in a form of descending order generated from the daily peak loads in a given period, usually in a year [2][8].

A daily peak load in a year in Figure 3 represents the load model which can be arranged in descending order to form Daily Peak Load Variation Curve (DPLVC) as shown in Figure 4.

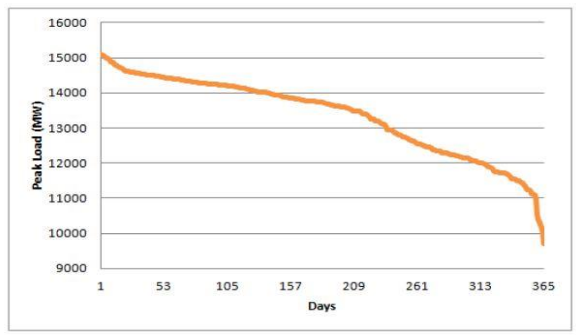

Figure 4 Daily Peak Load Variation Curve (DPLVC)

2.3 Reliability Indices

Reserve margin is one of the important reliability indices which can be defined as the differences between the total available generating system capacity and the annual peak system load divided by the peak system load. It is the excess of installed generating system capacity over the annual peak load usually expressed in percentage given in (2).

$$RM = \frac{(IC - PeakLoad)}{PeakLoad} \times 100 \qquad (2)$$

where
RM is percentage reserve margin
IC is installed capacity, MW

LOLE is a statistical measure of the likelihood of failure to which supply fails to meet demand. In brief, LOLE can be defined as the expected number of days (or hours) in a specified period in which the daily load is higher than the available generating capacity which can be expressed as (3).

$$LOLE = \sum_{k=1}^{n} p_k(O_k)t_k \qquad (3)$$

where:
p_k is the individual probability of the capacity outage of Ok
t_k is time interval
n is number of stage of the Capacity Outage Probability Table (COPT)

The general requirements and obligations concerning resource adequacy in Peninsular Malaysia is defined in the Malaysia Grid Code is Loss of Load Expectation (LOLE) or Loss of Load Probability (LOLP) [9]. In Peninsular Malaysia, the LOLE requirement issued by Malaysia Grid Code is 1 day/year [10].

2.4 LOLE Calculation

The LOLE shown in Table 2 are calculated where the detailed process can be founded in [2]. This process which requires enumeration of 2^N states is conceptually correct. According to [11], if there are 30 units in the system, this would mean an enumeration of more than a billion capacity states and this is computationally impractical. Therefore, a convolution process can be developed. Therefore, Wien Automatic System Planning (WASP) software is used to calculate the LOLE value as it can calculate the LOLE value using convolution process. WASP-IV is designed to find the economically optimal generation expansion policy for an electric utility system within user-specified constraints. It utilizes probabilistic estimation of system involving production costs, unserved energy cost and reliability [12].

Table 2 LOLE Calculation using COPT

Capacity Out (MW)	Capacity In (MW)	Individual Probability, p_k	Total Time, t_k (%)	LOLE (%)
0	200	0.95099	0	-
40	160	0.04803	0	-
80	120	0.00097	41.7	0.040449
120	80	0.000098	83.4	0.00817
160	40	0.000000	0	-
200	0	0.000000	0	-
Total		1.00000	LOLE	0.04862

3.0 SENTIVITY ANALYSIS ON FACTORS AFFECTING LOLE

A modified Peninsular Malaysia generation system which consists of 22 thermal stations is used as the base case in the WASP-IV simulation. Installed capacity and peak load are assumed to be 19,642 MW and 15,110 MW. Table 3 describes the overall LOLE sensitivity case studies of the simulation

Table 3 LOLE sensitivity case studies

No	Case Study	Purpose
1	Base	The LOLE value as the benchmark for sensitivity analysis
2	Peak Load Variation	To observe the effect of LOLE value under peak load variation
3	Forced Outage Rate (FOR) Variation	To observe the effect of LOLE value under FOR variation

3.1 Case Study 1: Base Case

Installed capacity and peak load are assumed at 19,642 MW and 15,110 MW. Reserve Margin obtained using (2) is 30% and from the simulation, the LOLE is 0.2748 day/year which is much less than the Malaysia Grid Code requirement of 1 day/year as shown in Table 4.

Table 4 Base Case WASP-IV Simulation

Base Case Input	Installed Capacity (MW)	19642
	Peak Load (MW)	15110
	Reserve Margin (%)	30
LOLE (days/year)		0.2748

3.2 Case Study 2: Peak Load Variation

The peak load of the base case study is being varied, assuming constant 2% load increment every year within 5 years. Based on the simulation, the effect of peak load to the LOLE is given by Figure 5. Based on Figure 5, it is shown that the increment of the LOLE is accompanied by the increment of the peak load.

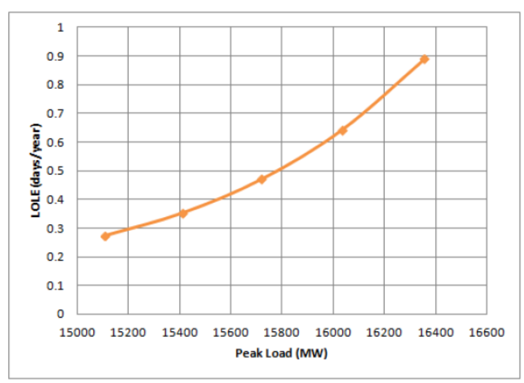

Figure 5 Effect of Peak Load Variation to the LOLE

Table 5 Effect of peak load variation to the LOLE at different percentage of load increment

Load Variation	Year	Peak Load (MW)	Reserve Margin (%)	LOLE (days/year)
Increase by 2%	1	15110	30.0	0.2748
	2	15412.2	27.4	0.3541
	3	15720.4	24.9	0.4716
	4	16034.9	22.5	0.6439
	5	16355.5	20.1	0.8899
Increase by 3%	1	15110	30.0	0.2748
	2	15563.3	26.2	0.4062
	3	16030.2	22.5	0.6409
	4	16511.1	19.0	1.0406
	5	17006.4	15.5	1.6962
Increase by 4%	1	15110	30.0	0.2748
	2	15714.4	25.0	0.4690
	3	16343	20.2	0.8786
	4	16996.7	15.6	1.6805
	5	17676.6	11.1	3.1532

As the percentage of load increment increases, the value of LOLE increases and breached the LOLE requirement of 1 day/year as shown in Table 5. It can be seen that highest load increment has highest tendency to breach the LOLE requirement of 1 day/year faster. The LOLE value increases drastically about half from 1.680 day/year to 3.153 under 4% load increment at Year 5.

3.3 Case Study 3: Forced Outage Rate (FOR) Variation

Forced Outage Rate (FOR) variation under base peak load case study are simulated using WASP-IV where the FOR of the largest generation unit is being varied and the other generation units are kept constant in order to determine the effect of forced outage rate to the LOLE.

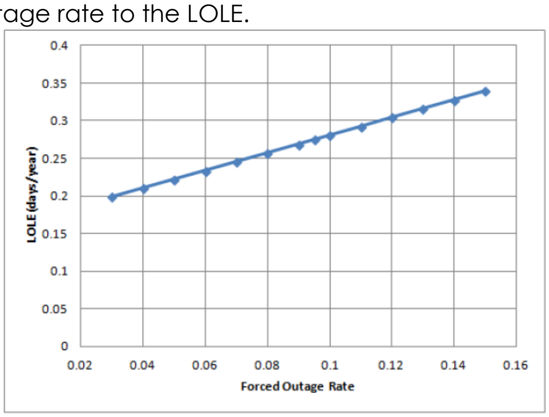

Figure 6 Effect of FOR to the LOLE

Table 6 Effect of FOR to the LOLE under peak load variation

FOR Variation	Year	Peak Load (MW)	Reserve Margin (%)	LOLE (days/year)
0.03	1	15110	30.0	0.1989
	2	15714.4	25.0	0.3121
	3	16343	20.2	0.5855
	4	16996.7	15.6	1.1939
	5	17676.6	11.1	2.4408
0.06	1	15110	30.0	0.2340
	2	15714.4	25.0	0.3847
	3	16343	20.2	0.7212
	4	16996.7	15.6	1.4191
	5	17676.6	11.1	2.7711
0.09	1	15110	30.0	0.2690
	2	15714.4	25.0	0.4573
	3	16343	20.2	0.8570
	4	16996.7	15.6	1.6447
	5	17676.6	11.1	3.1014
0.095	1	15110	30.0	0.2748
	2	15714.4	25.0	0.4694
	3	16343	20.2	0.8797
	4	16996.7	15.6	1.6823
	5	17676.6	11.1	3.1565
0.12	1	15110	30.0	0.3044
	2	15714.4	25.0	0.5300
	3	16343	20.2	0.9928
	4	16996.7	15.6	1.8699
	5	17676.6	11.1	3.4317
0.15	1	15110	30.0	0.3395
	2	15714.4	25.0	0.6030
	3	16343	20.2	1.1286
	4	16996.7	15.6	2.0955
	5	17676.6	11.1	3.7621

The base FOR of the largest unit is 0.095 and the FOR of the largest unit is being varied between 0.03 to 0.15 under constant base peak load of 15110 MW as shown in Figure 6. Based from Figure 6, as the FOR increases, the value of LOLE increases linearly.

For case study on the effect of FOR to the Loss of Load Expectation (LOLE) under peak load variation, the load increment is assumed at 4%. Based on the simulation, as the peak load and FOR increase, the value of LOLE increases under the same range of FOR variation as shown in Table 6. From Figure 6, the increment of the LOLE is accompanied by the increment of the FOR and this LOLE value getting worse due to the effect of peak load increment. Based on Table 6, it can be seen that the highest FOR which is 0.15 has the LOLE value of 0.33945 day/year at the base peak load of 15,110 MW and the LOLE value kept increasing as the peak load increases by 4% and breached the LOLE requirement of 1 day/year at Year 3.

4.0 RELATIONSHIP BETWEEN LOLE AND RESERVE MARGIN

LOLE is a probabilistic method which can be obtained using WASP-IV simulation while Reserve Margin is a deterministic method which can be calculated based on the peak load of the particular LOLE. Reserve Margin can be calculated using (2) at each peak load for each sensitivity analysis scenario-and the relationship between LOLE and Reserve Margin under the same peak load variation can be presented in order to determine the suitable Reserve Margin

4.1 Peak Load Variation

The relationship between LOLE and Reserve Margin at different load variation can be presented as in Figure 7. From Figure 7, it is shown that as the Reserve Margin decreases, the LOLE level is increased. It can be seen that LOLE value can be improved by 50% by increasing the Reserve Margin from 20% to 25%.

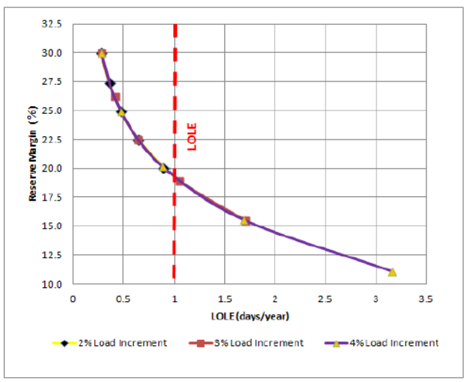

Figure 7 Relationship between Loss of Load Expectation and Reserve Margin under Peak Load Variation

The risk of the system becomes higher and less reliable as the LOLE value increases by 50% from 1.5 days/year to 3.0 days/year due to the reduction of Reserve Margin from 16.5 % to 11.5%. In order to meet the requirement by Malaysia Grid Code, it is necessary to keep a minimum of about 19% of Reserve Margin.

4.2 Forced Outage Rate (FOR) Variation

The relationship between LOLE and Reserve Margin at different FOR values under the same load variation can be presented as in Figure 8.

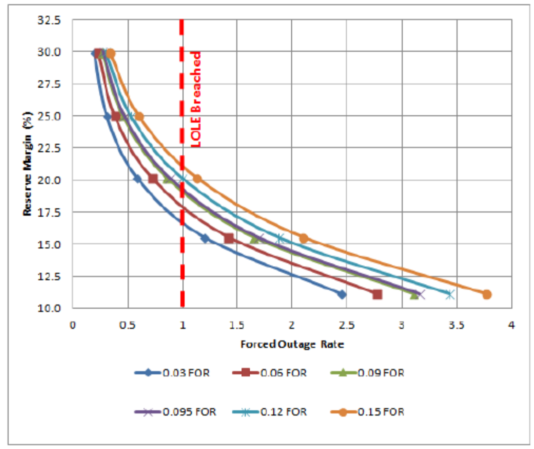

Figure 8 Relationship between Loss of Load Expectation and Reserve Margin under FOR Variation

Based on Figure 8, the smallest FOR will breach the LOLE requirement of 1 day/year when the Reserve Margin drop by 13.5% from 30% to 16.5%. Meanwhile, the reduction of Reserve Margin is only 9% for the highest value of FOR to breach the LOLE requirement.

5.0 CONCLUSION

Generation capacity planning is very important in providing adequate power supply to the system. The main aim of this study is to analyse on the important factors affecting the LOLE level in Peninsular Malaysia. This study also targeted to determine the relationship between LOLE and the Reserve Margin in various conditions. In this study, the sensitivity studies on factors affecting LOLE such as peak load and forced outage rate are performed where the LOLE is being computed using WASP-IV Simulation Tool under various conditions.

The LOLE obtained using simulation is then being analysed in detail based on the different conditions. The relationship between LOLE and Reserve Margin are being represented for each condition and these relationships give the proper and optimum Reserve Margin target which satisfies a particular condition.

The sensitivity case regarding the peak load effect to the LOLE concludes that higher peak load causes the value of LOLE to increase drastically. The relationship between LOLE and Reserve Margin shows that the load growth reduces the Reserve Margin of the system which results in the system to be less reliable as it increases the risk of generation failure to meet the demand or LOLE at the same time. Higher load increment has a greater tendency to violate the LOLE requirement.

Analysis shows that Forced Outage Rate (FOR) also gives big impact to the LOLE level. Result shows that the value of LOLE increases linearly as the FOR increases under constant peak load. Furthermore, the impact of FOR to the LOLE becomes more significant with the combination of peak load and FOR increment wherein the value of LOLE increases drastically as the FOR increases under increment of peak load.

The relationship between LOLE and Reserve Margin under FOR variation indicates that at the same Reserve Margin, higher FOR causes the system to have higher value of LOLE. This system will become less reliable when it is accompanied by the peak load increment which reduces the Reserve Margin of the system. Therefore, considering yearly peak load increment, the system reliability can be improved by reducing the FOR which will results in lower value LOLE. Otherwise, peak load shaving measures should be implemented to dampen the peak load increment.

In short, peak load and FOR give significant impact to the LOLE level. Therefore, proper maintenance may help to reduce the FOR, thus, reduce the LOLE level of existing generation units. However, investment on new generation capacity is continuously needed as to cater to the future load growth in order to provide sufficient Reserve Margin.

Acknowledgement

The authors would like to acknowledge Ministry of Education Malaysia with project code FRGS/1/2013/TK07/ UNITEN/02/4 for providing fund to carry this studies.

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