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Novel Modeling of Forced Outage Rate Effect on the LOLP and LOLE

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Abstract: Two important terms, the LOLP and LOLE, are helping to plan, design, operation and maintenance of the power system is the reliability study. Therefore, the future expectation needs the electric load historical data. The present study concentrates on these two terms used in the reliability. These terms are the Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE). These terms followed, when the loss of load occurred as the electric load exceeds the available generating capacity of the system. As a measure of the LOLP and LOLE, mean how much in time the load exceeds the available capacity of the system using the MATLAB (R2014b). A power plant has six power-generated units combined and considered to form one power system plant. Then, the LOLP and LOLE calculated for the system under different loads. This type of consideration is helping to plan the future of the power plant and finding the effect of load on power system reliability. At the same time, the LOLP-FOR and LOLE-FOR models investigated.

Keywords: LOLP, LOLE, FOR, Power Plant.

1. Introduction

In smart cities, electricity services managed in appropriate ways to provide minimum energy reduction and cost to customers. In addition, smart cities rely on a smart network to ensure that the system can absorb electricity delivery to provide a set of actions and activity. Energy infrastructure is probably the single most important quality in any city. One should note that electricity trade between developed and undeveloped countries would put undeveloped countries at a disadvantage. The reason lies in the fact that developed countries will have the economic power to construct enough or more generation capacities for the appropriate LOLP, whereby undeveloped countries will not be able to do so. The LOLP is an economic parameter. The load factor decreases in the case of a small value of LOLP, where this is not acceptable from an economical point of view. Since a significantly lower LOLP is optimal for them and considered as main criteria for security of supply, where it depends on the power plants technology and changing over time. The main conclusion of the paper is that, for generation expansion planning on the electricity market. The least acceptable LOLP should be a criterion for the necessary constructions in power system and particularly referred to the generation capacity needed to fit the economic condition of the considered country and its power system. The present study started with survey. This survey presents a comprehensive review for the most carried out studies in the planning technology and includes some reported models and solution strategies. This state-of-the art survey organized to serve as planning guide step for the engineers and researchers.

Esan et al [1] present in their paper the use of a novel approach in assessing the generation reliability of a hybrid mini-grid system. A typical Nigerian rural com-munity–Lade was used as a case study of energy demand. The optimized results obtained of a solar photovoltaic, diesel generators and battery storage. The capacity outage probability table (COPT) was utilized in validating the reliability of the simulation results. The loss of load probability (LOLP), loss of load expectation (LOLE), and total expected load loss (ELL) obtained. Esan et al [1] performed in their study the design and techno-economic analysis of a hybrid mini-grid system and validated the reliability of adopting the simulation results obtained.

Saleh et al [2] in their research paper deal with the case for smart cities, because it is focusing on the optimal solution. The planning process utilizes reliability indices as criteria to decide on new investments in new generation capacities. In addition, the authors study both the loss of load probability (LOLP) and Loss of Load Expectation (LOLE). The forced outage rate tested on the LOLP index and LOLE index. The LOLE and LOLP were determined. These indices help for the analysis of the plant. The LOLE

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index analysis forms the basis of calculating how many generators, or group of generators contribute towards planning reserve. The output calculation of this capacity contribution called the effective load carrying capability.

Jayed et al [3] highlight in their study on the hybrid renewable energy systems. They have proved in their study to be capable and emission-free sources of power generation. In their study, they have developed a mathematical model to optimize a hybrid solar-wind energy system with storage for a remote island with genetic algorithm (GA). Four different cases considered and evaluated. Two systems with different wind turbine size are analyzed and their results presented. Moreover, the simulated performance of the system and the effects of loss of power supply probability (LPSP), variation of load and renewable energy resources on the system cost are analyzed. In addition, simulated performance of the whole system and sensitivity analysis is performed at different resource rate, loads and Cost of Energy to analyze the effects of loss of power supply probability.

Qamber [4] in his study focuses on calculating the LOLP for different values of loads. Calculating these values procedure helps for plan the future of the power plant and finding the effect of load on power plant reliability. The solutions were found using the Microsoft Excel.

Li et al [5] in their study aiming at the statistical characteristics of wind power. The study proposes a method to access the wind power accommodation by considering adequacy indices. Based on historical operating data, four adequacy indices, namely peak-load regulation not enough probability, peak-load regulation not enough expectation, loss of load probability (LOLP), and loss of energy expectation are proposed. The obtained results of adequacy indices are obtained, where the wind power accommodation is established to satisfy the preset adequacy level. To calculate the requirements for comprehensive net load and peak-load regulation for wind energy storage system presented and found by the practical method. The results compared and analyzed, where the proposed method is verified.

The author [6] focuses in his study on calculating the LOLE of a power plant. He obtained the LOLE needs. The reliability index (LOLE) calculated for the electric power plant in days per year based on the historical data obtained as a full-considered period. The solutions were found using the Microsoft Excel.

Jeong et al in their study [7] aim to analyze the reliability of wind power generator in Jeju Island power system. To maintain the operational state of power system at the reliability levels is the main objective of the study. In their study they described the probabilistic production cost credit evaluation of Wind Turbine Generators. An analysis on generated capacity of wind power generator with Tamla offshore wind farm have been carried-out in terms of Effective Load Carrying Capability and Capacity Credit in power system from the perspective of LOLE. The study demonstrates how it changes the effective load carrying capability and capacity credit demonstrated as case studies.

Moghaddam et al [8] in their study concentrate on the optimal design and energy management of the hybrid systems including the photovoltaic panels, wind turbine and fuel cell based on hydrogen storage. They have been presented to minimize the total net cost using intelligent flower pollination algorithm. The reliability indices considered are the loss of energy expected and the loss of load expected (LOLE). The simulation results are presented including decision variables such as LOLE.

Choi et al [9] propose a conversion function and a method to transform LOLED (days/year) using daily peak load curve into LOLEH (hours/year) using hourly load curve. The conversion function is formulated as variables of capacity and a forced outage rate of generator. In the year 2015, the proposed conversion function is applied to (Korea Power System). The exponent coefficients of the conversion functions are assessed using the proposed method.

The author Čepin [10] in the study include a larger number of more dispersed and smaller power generating units. Based on the LOLE study, the power plants are slowly replacing larger and more concentrated power sources. Therefore, the objective of the study is to analyze the replacement of nuclear power plant with wind power plants to compare both cases from the viewpoints of power system reliability. The study concentrated on the loss of load expectation (LOLE). The upgraded method considers plant power as a function of the time instead of its nominal power. The original plant has twelve power plants including one nuclear power plant. The nuclear power plant is then replaced by three wind power plants with their total power five times larger than the power of the nuclear power plant. In terms of comparing the loss of load expectation using the real weather data for one calendar year. The replacement procedure decreases the power system reliability.

The performance of the present study is shown through the calculation of both parameters LOLP and LOLE with respect to the FOR. This will help for future studies by considering the average load-weight. Both calculations are highlighted on the risk approach with respect to the capacity levels and evaluated the average load weighted for LOLP and LOLE.

2. PROGRAM AND COMPUTATION

It well known that in the power systems has a main objective. This objective is to supply power to the consumers as economically as possible. This means that the supply aimed to be with a high degree of quality and reliability. As an application, consider six power generated units combined to form one power system plant. The considered power plant has two 75MW capacity-unit, two 120MW generating-units, one 150MW generating-unit and one 300MW generating-unit capacity. These six generating-units are summarized in Table (I).

Table I. Proposed Six Generating-Units with their specifications [4, 6]

TABLE I. PROPOSED SIX GENERATING-UNITS WITH THEIR SPECIFICATIONS [4, 6]

Number of Generating-Units	Capacity of Each Generating-Unit (MW)	FOR
2	75	0.03
2	120	0.02
1	150	0.01
1	300	0.01

The probabilities are calculated for the power system plant considering each generating-unit with states that is passing through. In addition, the results found for the six generating-unit as a power plant.

For electric energy-limited systems, the engineers, as planners, are more concerned about the power generation limit. At the same time, the LOLP results resource planners an indication of how often the power generating-units will be insufficient to meet all customers' needs. The term Loss-of-load-probability (LOLP) and Loss-of-Load-Expectation (LOLE) are often used as a metric to assess the adequacy of electric power supply. In addition, the loss of load probability is defined as the likelihood (probability) and the loss of load expectation (expectation, hours per year). This means that the electric power system demand will exceed the generating capacity during a given period. Furthermore, this means that the average peak load will exceed the system generating capability. The reliability study in the present research presented by the flow-chart (Figure 1).

The calculation of both LOLP and LOLE are helping the power system in producing a set of parameters values showing the performance of the system; such as system availability. This means that the estimated unsupplied energy, estimated number of hours of interruption are calculated.

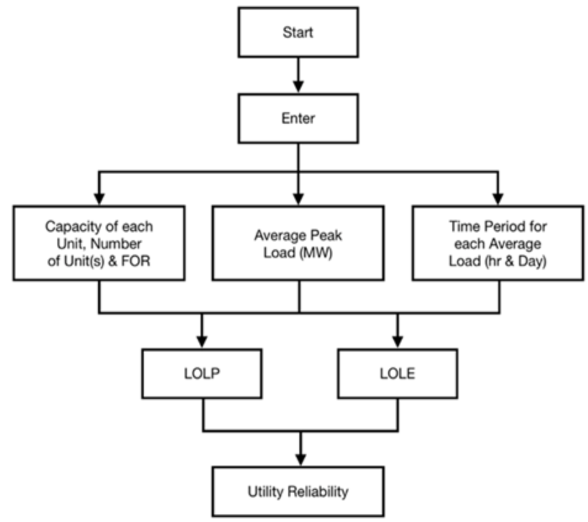

Figure 1. Reliability Study Flow-Chart

At the electricity market, the reliability self-evaluation of a power system is important issue. It helps in security of supply the electricity market. In general, this will help the power system to be reliable to meet the required electrical power demand. It concluded that a required reliability to be considered, where LOLP and LOLE parameters are required for security of supply. The present study presents the way of calculating both the LOLP and LOLE. As a conclusion, the present study analyzed both parameters how to impact the electricity market.

3. RESULTS & DISCUSSION

After the MATLAB program was constructed and adapted. Several different Forced Outage Rates values were considered and shown in Table (I). The LOLP and LOLE indices are calculated. Moreover, the next step was to find an equation connecting these values for each respective index LOLP and LOLE.

The obtained data for the power plant under study are illustrated in Table II. The historical data found through one-year period and recorded. The recorded data formed the peak load (MW) and the time in both days and hours. The relationships the three variables are illustrated in Figures (2-5).

Each generating-unit has a FOR, where it is known regularly as unavailability of the unit. The Forced Outage Rate (FOR) is a basis for strategist modeling. The impact of FOR changes on system LOLP. Generally, the FOR defined as:

$$FOR = \frac{Forced\ Outage\ Hours}{In\ Service\ Hours + Forced\ Outage\ Hours} \quad (1)$$

The LOLP is calculated as:

$$LOLP = \sum_{j=1}^{n} \frac{P_j t_j}{100} \quad (2)$$

Where:

P_i *is the probability of Capacity Outage*

t_i *is the percentage of time when the load exceeds* C_i

C_i *is the premaining generation capacity*

In the same manner, the LOLE is calculated as:

$$LOLE = P(O_j)\ t(O_j) \quad \frac{hour}{Year} \qquad (3)$$

Where:

$P(O_j)$ *is the probability of Capacity Outage j*

$t(O_j)$ *is the time of Capacity Outage j* $(\frac{hour}{Year})$

TABLE II. AVERAGE PEAK LOADS WITH THEIR PERIOD OF TIMES

Series	Days	hours	Peak Load (MW)
1	12	288	600
2	83	1992	495
3	107	2568	375
4	116	2784	315
5	47	50	150
		Σ = 8760	

The area that forms the basis of the engineer's measurement design of module is known as the project Surface Area (Fig. 2). The optimum results represent the values having the same color range. The relationship between the three variables (Peak Loads, days and hours) illustrated is the area that makes the basis of the engineer's measurement design of module. The surface area is recommended based on the obtained results for the power system plant which compared with the customer's need. A two-dimension power plant is formed after obtaining the data results. The obtained results are found through the history of the electric power plant, which are formed by figures (3-5).

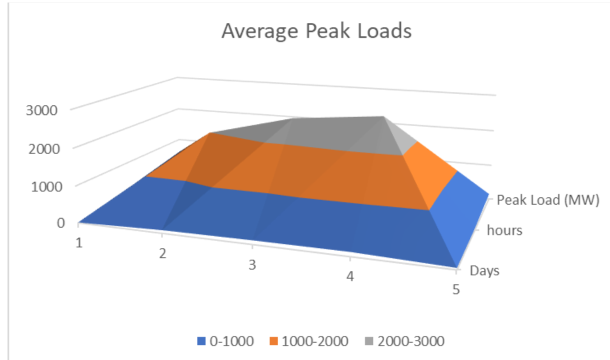

Figure 2. Average Peak Loads through the year

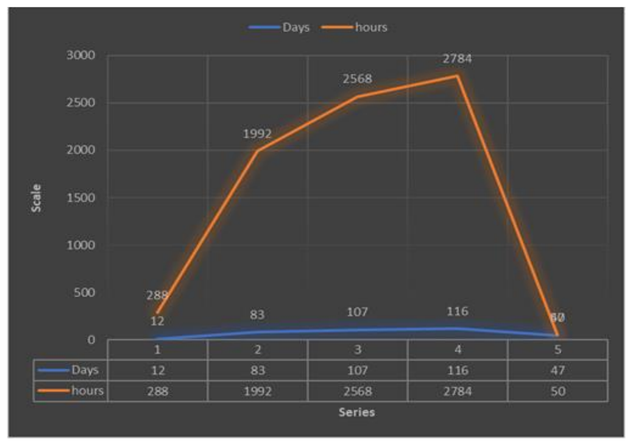

Figure 3. Variation of the days and hours through the year

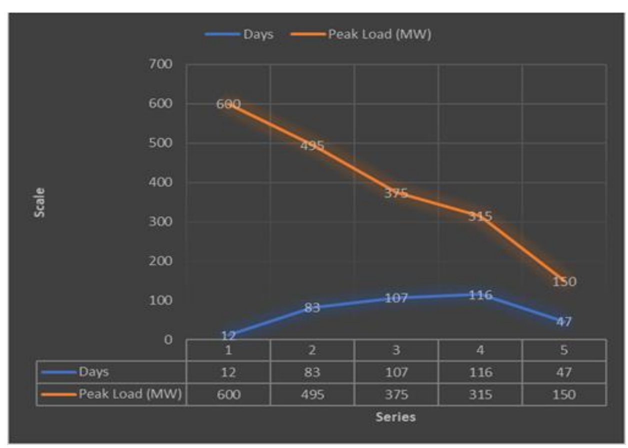

Figure 4. Variation of the Peak Loads and days through the year

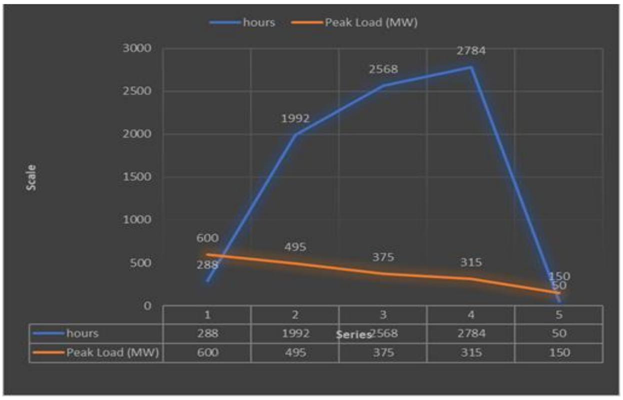

Figure 5. Variation of the Peak Loads and hours through the year

To establish a relationship between the variation of the FOR with calculated LOLP for different required peak load of electric power plant, the MATLAB (R2014b) simulation is used. The results obtained are recorded in Table III. The results helping the engineers to find the suitable time when the unit(s) need replacement or only maintenance to perform better operation. The lifetime history of a repairable electric power generation unit during its useful time needs a maintenance to keep the utility in a better condition. This means that the utility will continue in keeping the utility in a better performance. The electric power market needs a necessary study to determine the LOLP. In addition, the utilities need the customer's satisfaction. The obtained results are plotted in Fig. (6).

TABLE III. SIMULATION RESULTS, VARIATION OF *FOR* VERSUS *LOLP* FOR DIFFERENT POWER PLANT LOADS

Forced Outage Rate	LOLP OF 615MW	LOLP OF 495MW	LOLP OF 375MW	LOLP OF 240MW	LOLP OF 120MW
0.01	0.001999	9.72E-05	1.75E-06	1.57E-08	7.94E-11
0.02	0.0039922	0.00037807	1.37E-05	2.46E-07	2.52E-09
0.03	0.0059738	0.00082679	4.50E-05	1.22E-06	1.90E-08
0.04	0.0079386	0.0014283	0.00010383	3.79E-06	7.95E-08
0.05	0.0098812	0.0021683	0.00019748	9.08E-06	2.41E-07
0.06	0.011797	0.0030329	0.00033224	1.85E-05	5.94E-07
0.07	0.013681	0.004009	0.00051354	3.35E-05	1.27E-06
0.08	0.015529	0.0050841	0.00074598	5.61E-05	2.46E-06
0.09	0.017337	0.0062464	0.0010334	8.80E-05	4.41E-06
0.1	0.0191	0.0074844	0.0013788	0.0001314	7.40E-06
0.15	0.0271	0.0145	0.004	5.98E-04	5.39E-05
0.2	0.0336	0.0219	0.0082	0.0017	2.18E-04
0.25	0.0382	0.029	0.0138	0.0037	6.35E-04
0.3	0.041	0.0351	0.0202	0.0067	0.0015
0.35	0.0418	0.0398	0.0269	0.0108	0.0031
0.4	0.0408	0.0429	0.0335	0.016	0.0057
0.45	0.0382	0.0442	0.0392	0.0219	0.0098
0.5	0.0344	0.0438	0.0438	0.0281	0.0156
0.55	0.0296	0.0417	0.0466	0.0342	0.0237
0.6	0.0243	0.0382	0.0477	0.0394	0.0342

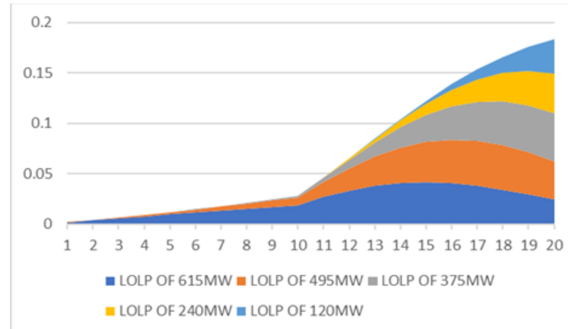

Figure 6. Variation of LOLP for different variation of Peak Loads

In the other hand, to form a relationship between the variation of the FOR with calculated LOLE for different required average peak load of electric power utility, the MATLAB R2014b simulation is needed. The results obtained are shown in Table IV. The results helping the engineers to find the suitable time when the unit(s) need maintenance or replacement of unit or units to perform better operation. The electric power market needs a necessary study to determine the LOLE. In addition, the power utilities need always the customer satisfaction. Finally, the obtained results are plotted in Fig. (7).

TABLE IV. SIMULATION RESULTS, VARIATION OF *FOR* VERSUS *LOLE* FOR DIFFERENT POWER PLANT LOADS

Forced Outage Rate	LOLE OF 615MW	LOLE OF 495MW	LOLE OF 375MW	LOLE OF 240MW	LOLE OF 120MW
0.01	17.5113	0.8517	0.0154	0.00013754	6.9554E-07
0.02	34.9713	3.3119	0.1198	0.0022	0.000022089
0.03	52.3306	7.2427	0.3939	0.0107	0.00016646
0.04	69.5418	12.5121	0.9095	0.0332	0.00069609
0.05	86.5597	18.9939	1.7299	0.0796	0.0021
0.06	103.3413	26.5678	2.9104	0.1618	0.0052
0.07	119.8454	35.1187	4.4986	0.2938	0.0112
0.08	136.0332	44.5371	6.5348	0.4912	0.0216
0.09	151.8678	54.7184	9.0524	0.7709	0.0386
0.1	167.3142	65.5633	12.0783	1.1511	0.0648
0.15	237.6498	126.5978	35.3583	5.2397	0.4723
0.2	294.2239	191.9631	72.2104	14.8009	1.9062
0.25	334.916	254.0742	120.6211	32.0801	5.5605
0.3	358.7588	307.5075	176.8224	58.6097	13.1978
0.35	365.8491	348.6529	236.074	94.8446	27.1454
0.4	357.2398	375.4045	293.3268	139.9357	50.2333
0.45	334.81	386.89	343.77	191.64	85.673
0.5	301.13	383.25	383.25	246.38	136.88
0.55	259.25	365.43	408.59	299.4	207.21
0.6	212.59	335.04	417.79	345.13	299.72

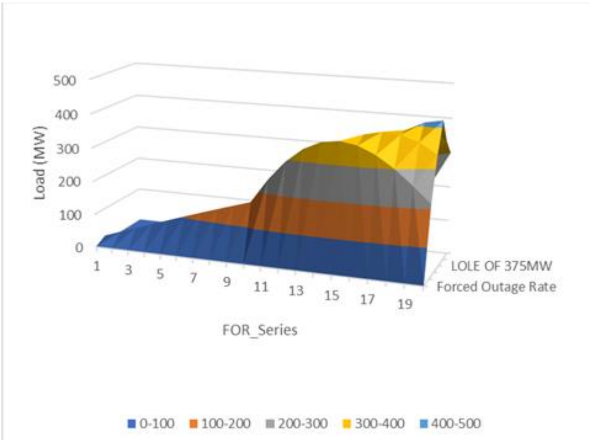

Figure 7. Variation of LOLE for different variation of Peak Loads

Using the MATLAB R2014b software to calculate the LOLP versus FOR with different average of loads result the figures (8-12). The results illustrate the effect of the Forced Outage Rate (FOR) on the LOLP calculation. It is observed that the variation of FOR of the considered plant are nonlinear. In addition, the relationship of LOLP versus FOR of each required electric average load is non-linear, where the equations are obtained by curve-fitting and recorded. In the same way, the results are summarized in Table (III). The engineers always looking for the reliable power plant with the improvement of the utility and finding the best situation by considering the curve results. Based on that this will give the system planner a clear indication for proposing other power generation resources to meet and satisfy the demand and system reliability. The application of curve-fitting technique will results Table (V) which shows the equations that represent each figure's curve.

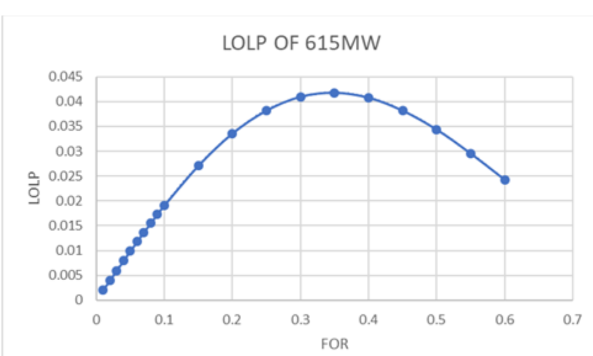

Figure 8. LOLP versus FOR for 615MW-Load

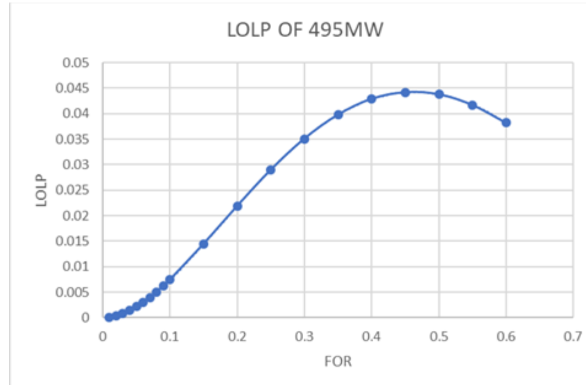

Figure 9. LOLP versus FOR for 495MW-Load

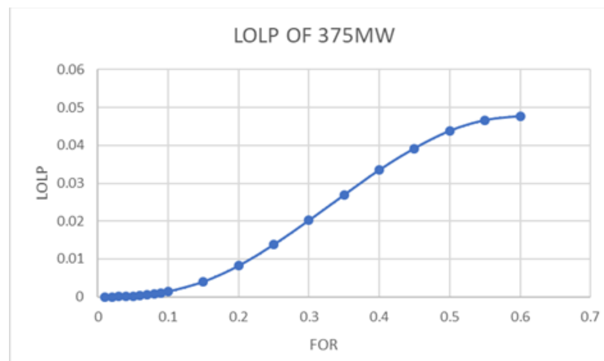

Figure 10. LOLP versus FOR for 375MW-Load

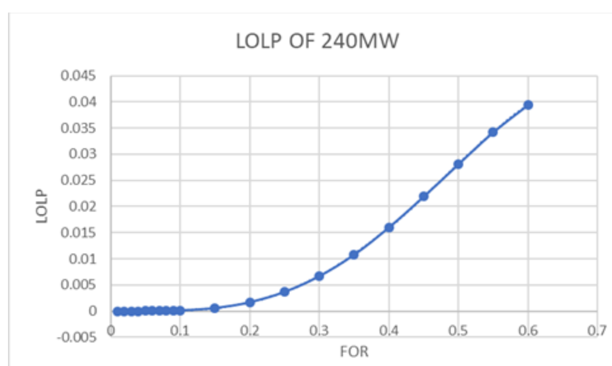

Figure 11. LOLP versus FOR for 240MW-Load

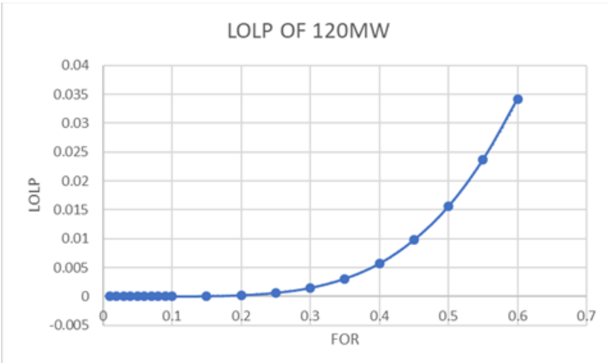

Figure 12. LOLP versus FOR for 120MW-Load

TABLE V. CURVE FITTING RESULTS FOR LOLP

Fig.	Eqn	Equation (Model)
8	4	$y = -0.3015x^5 + 1.1643x^4 - 1.0409x^3 + 0.0053x^2 + 0.1996x + 7E-06$
9	5	$y = -0.8907x^5 + 2.5132x^4 - 2.6394x^3 + 0.9747x^2 + 0.0016x - 3E-05$
10	6	$y = 1.8646x^5 - 3.1743x^4 + 1.3589x^3 + 0.0631x^2 - 0.0036x + 6E-05$
11	7	$y = -0.5043x^5 - 0.0652x^4 + 0.5122x^3 - 0.0719x^2 + 0.004x - 6E-05$
12	8	$y = -0.34x^5 + 0.8149x^4 - 0.2696x^3 + 0.0407x^2 - 0.0024x + 4E-05$

The term Loss-of-load-expectation (LOLE) often used as a metric to assess the adequacy of electric power supply, which is the same argument that can be made for the LOLP. If the intent is to measure the LOLE, then adequacy measures can be compared across different utilities. In addition, using the MATLAB R2014b software to find the LOLE versus FOR with different average of loads result the figures (13-17). The results illustrate the achievement of the Forced Outage Rate (FOR) on the LOLE calculation. It is observed that the variation of FOR of the considered plant are nonlinear. In addition, the relationship of LOLE versus FOR of each required electric average load is non-linear, where the equations are obtained by curve-fitting and recorded in Table (IV). The engineers always looking for the reliable power plant with the improvement of the utility and reaching the best situation by considering the curve results. Based on that this will produce to the system planner a clear indication for proposing other power generation resources to meet and satisfy the demand and system reliability. The application of curve-fitting technique will results Table (VI), which illustrates the equations that represent each figure's curve.

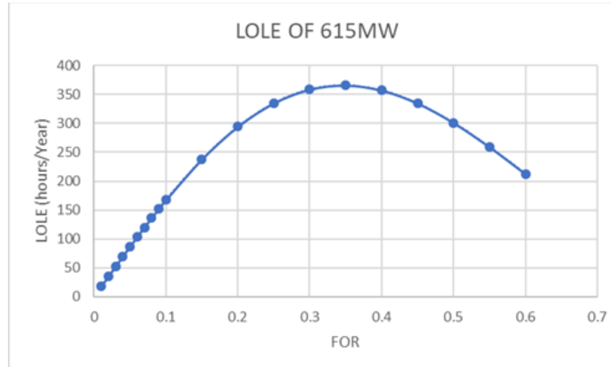

Figure 13. LOLE versus FOR for 615MW-Load

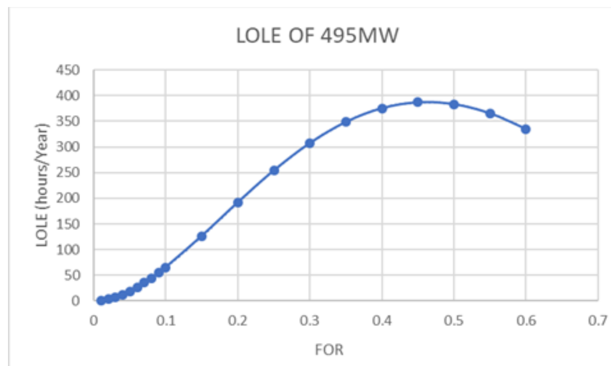

Figure 14. LOLE versus FOR for 495MW-Load

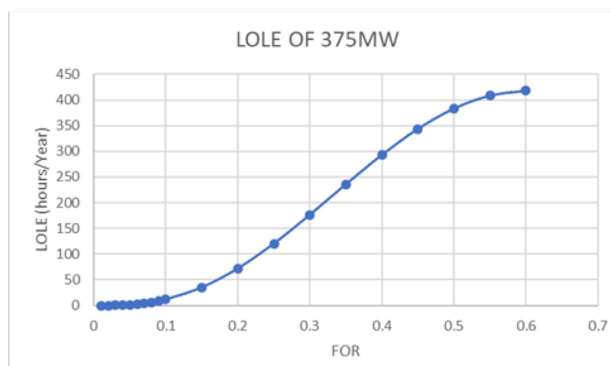

Figure 15. LOLE versus FOR for 375MW-Load

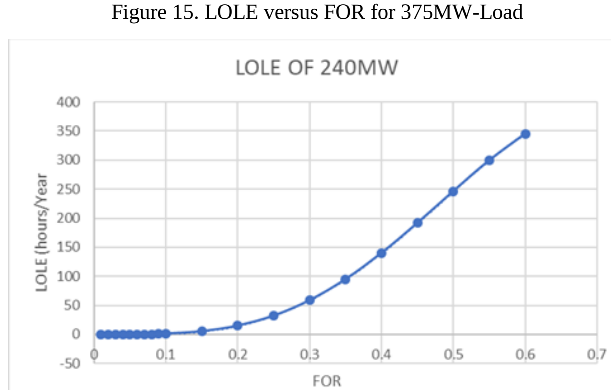

Figure 16. LOLE versus FOR for 240MW-Load

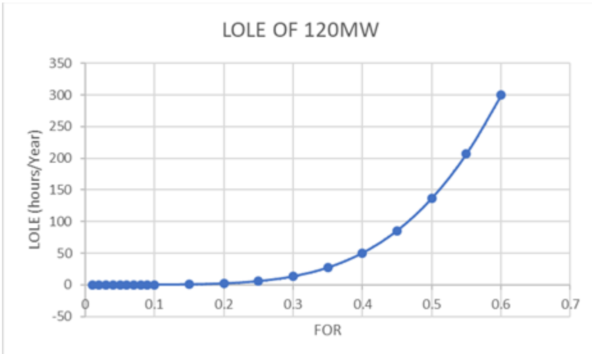

Figure 17. LOLE versus FOR for 120MW-Load

TABLE VI. CURVE FITTING RESULTS FOR LOLE

Fi	Eq	Equation (Model)
13	9	$y = -3158.8x^5 + 10899x^4 - 9431.5x^3 + 96.844x^2 + 1746.6x + 0.0798$
14	0	$y = -7706.3x^5 + 22011x^4 - 23189x^3 + 8567.1x^2 + 10.826x - 0.1588$
15	1	$y = 16112x^5 - 27490x^4 + 11752x^3 + 578.73x^2 - 32.491x + 0.4767$
16	2	$y = -4197.5x^5 - 923.6x^4 + 4685x^3 - 675.2x^2 + 37.91x - 0.5563$
17	3	$y = -2458.4x^5 + 6405.7x^4 - 2009.1x^3 + 289.56x^2 - 16.256x + 0.2385$

As a summary for the obtained curve-fitting results, Table VII summarized the maximum limit of both LOLP and LOLE.

TABLE VII. FOR AT MAXIMUM LOLP/LOLE

Figure(s)	Average Load (MW)	At maximum (LOLP/LOLE), the FOR is
8, 13	615	0.35
9, 14	495	0.45
10, 15	375	0.60
11, 16	240	0.60
12, 17	120	0.60

4. CONCLUSION

The calculation of LOLP and LOLE terms is helping in the review of power system utility design and sizing. In the same way, both terms estimate and indicate how long it takes to loss the generating-unit (i.e. generating-unit/any component needs a replacement or maintenance). Furthermore, both terms assisting, from the point of, the utility's economics and saving money. In addition, they both help to make the electric power system utility more efficient after replacement/maintenance the generating unit(s) or part(s), as well as, the maintenance. The calculation of electric load loss is preceded by connecting and merging the available power generation units. The LOLP and LOLE are calculated successfully. Moreover, the simulation results illustrated in the Tables and Figures through the article.

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