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Reliability Evaluation of Riyadh System Incorporating Renewable Generation

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Abstract: *In this paper, the experience of Saudi Electricity Company (SEC) in analyzing the generation adequacy for Year 2013 is presented. This analysis is conducted by calculating several reliability indices for Riyadh system hourly load during all four seasonal periods. The reliability indices are gauged against the international utility practice. SEC also plans to introduce renewable energy into the network in order to secure the environmental standards and reduce fuel costs of conventional generation. Thus, the reliability improvement due to different integration levels of Solar and Wind generating sources has also been investigated. The capacity value provided by these variable renewable energy sources (VERs) to reliably meet the system load has been calculated using effective load carrying capability (ELCC) technique with a loss of load expectancy metric.*

Keywords:*Reliability indices, generation adequacy, Solar and Wind systems,capacity outage table.*

I. Introduction

Kingdom of Saudi Arabia (KSA) was ranked as the 12th largest consumer of total primary energy in year 2013, of which about 60% is petroleum based and the rest was accounted to natural gas. Energy consumption per capita is twice that of Europe and three times the world average [1]. By the Year 2032, the electricity peak demand is anticipated to surpass 120GW [2]. To meet this high demand and to ensure the continuity of electrical supply, SEC dedicates their primary attention on reliability of the generation system. The generation system breakdown always believed to be more severe than transmission or distribution system as it leads to prolonged interruption and uneconomical recovery processes [3].

Generation reliability evaluations are performed for many purposes, and may have a variety of uses; while at the present such studies are almost always based on deterministic tests [4]. Great efforts are being made to develop suitable probabilistic models and programs. Probabilistic approaches can provide more insight and an accurate representation of the system modelling when they reach maturity. [5]. One effective method of estimating the generation reliability based on probabilistic technique is the calculation of Loss of load expectancy (LOLE). The LOLE is a statistical measure of likelihood of failure of meeting the expected load demand and is generally expressed in number of days in a year that generation system will be unable to supply the demand[6].

The inability of generation system to meet system demand results in a Load Shedding Event which can be quantified based on Demand Not served and Expected Un-served Energy[7]. There are various circumstances in which a load shedding event may occur. Loss of Load Expectation studies, however, are undertaken to address two critical causes of a Load Shedding Event. The first cause is due to a narrow Capacity Margin (the difference between the expected demand and the deliverable capacity). A Capacity Margin that is too "narrow" introduces a risk of supply interruption due to forced outage of generation. The second reason a Load Shedding Event may occur is due to transmission inadequacy. Often, for any system, LOLE studies are conducted with the assumption that the system's ability to match generation and load will not be limited by its transmission capability[8].

Another challenge that Saudi Arabia confronts is the increasing reliance on fossil fuels which causes a rapid growth in domestic demand for oil from power plants that burn heavy crude oil[9]. Recognizing the seriousness of the above consequences, the Government and sector stakeholders are working towards diversifying the sources of power generation by developing renewable energy. The King Abdullah City for Atomic and Renewable Energy (KACARE) program seeks to ensure that half of the electricity generated in Saudi Arabia comes from renewable sources by 2032[10]. Among the renewable energy resources, Photovoltaic (PV) and Wind are becoming cost competitive with conventional thermal power plants[11]. However, as the penetration of variable energy resources increases within power systems, the challenge of estimating the secured contribution of the VERs to the installed generating capacity of the power systems becomes more prominent[12].

Most of the utilities and system planners concern about the extent to which these VERs contribute towards system adequacy. One such metric to calculate the capacity value, not only for renewable generation, but also for any plant, is the effective load carrying capability of an additional generating source. With this technique, the system reliability can be compared with and without renewable generation using LOLE metric[13]. The modelling of renewable generation in generation planning adequacy studies for calculating loss-of-load expectancies can be done using load modifier or generator unit technique. In each approach, preferably a year or more of actual power output data is used to create the wind plant's reliability model [14]. In this paper, the load modifier technique has been utilized to introduce solar and wind energy sources in the generation reliability studies.

The generation adequacy analysis of KSA has always been based on reserve margin of around 8-10% over the forecasted most likely load. The reserve margin is calculated after subtracting a forced outage rate (FOR) of 3%. Transfer capabilities between areas are utilized to level area-wise reserve margins. However, these calculations do not directly reflect system parameters such as unit size and load shape.

In response to the questions raised regarding the credibility of the adequacy assessment, the present case study is conducted to assess generation reliability of Riyadh System for the year 2013 based on probabilistic methods. Therefore, this research will provide a valuable methodology for system planners in SEC to quantify the generation addition required in future to reliably meet the expected load forecast considering the uncertainties of generating units. The system performance is judged by comparing hourly, daily and monthly reliability indices against the performance of the whole year. This paper also investigates the impact of solar and wind energy integration on the reliability benefits. In addition, the effective load carrying capability of these renewable generation will be estimated and discussed.

II. System Description

The Saudi Electricity Company (SEC) operates an Interconnected Transmission System for all main areas in the Kingdom of Saudi Arabia. SEC system is divided into four operating areas, named as Central, Eastern, Western and Southern Operating areas. Since Riyadh city is the major load center in Central operating area it faces unique issues in every day operation of the system [15]. The study assumes the transmission system to be fully reliable.

2.1 Generation

The objective of the SEC generation planning is to develop Least Cost Generation Expansion Plan for long term planning horizon (20-30 years) by considering fixed reserve margin for satisfying forecasted peaking loads during whole of the year. It considers the efficient use of indigenous resources to minimize the total cost of fuels satisfying forecasted energy demand. Riyadh system has a total of 8 power plants with a total installed capacity of 12000 MW. Table 1 shows the amount and of each power plant in the system. The studied system also interconnects with east operating area with 4 double circuit 380 kV transmission line which provides the maximum import capacity of 9900 MVA considering N-2 contingency of the transmission line.

Power Plant	Total MW
PP 4	300
PP5	473
PP 7	1200
PP 8	1867
PP 9	4062
PP 10	2261
PP11	1750
LAYLA	87

Table-1: Installed generation capacity of the Riyadh System.

2.2 Demand

SEC load forecast is an annual exercise, and updates are performed regularly every year, based on the latest (verified) information regarding actual demand, expected new loads, and other factors which will have an effect on power demand. Since the load in a power system in any time period is a stochastic process, it is difficult to describe with a simple mathematical formula. To retain the time aspect of the data, the model used in this paper is the hourly load curve which can be converted to load duration curve by arranging the data in descending order. Figure 1 shows the hourly load curve of the Riyadh system of the year 2013. The system encounters peaks during summer in the month of July and during fall in the month of September. Similarly the system experiences two minimum load periods during winter in November and during spring in February.

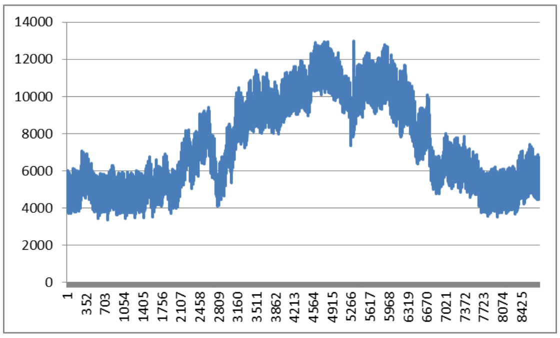

Fig-1: Load curve of the Riyadh system.

2.3 Renewable generation

Several methods have been proposed to model intermittent nature of the renewable generation for generation adequacy studies. The most commonly used are the multi-state generating model and the load modifier model. This paper assumes the load modifier which integrates the renewable generation as the negative load in the system. Figure 2 shows the average profiles per month for a PV power plant normalized to 200 kW. The PV power plant starts generating electricity between 6:00 to 16:00 all year while it stops generating between 18:00 to 24:00.

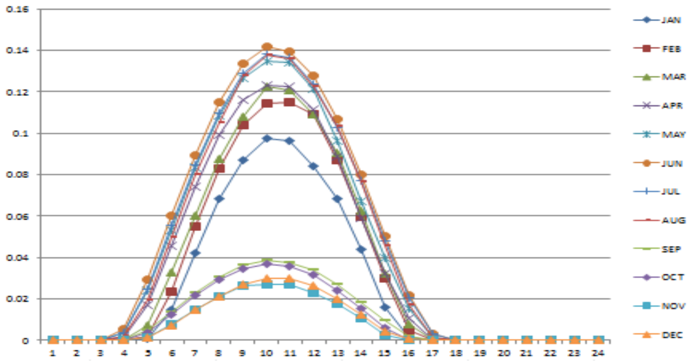

Fig-2: Average PV output of the Riyadh system.

Figure 3 display the average wind generation profiles per month in COA. Wind power output is variable during the day and tends to have its peak in the early mornings. The electricity generated is normalized to 200 kW.

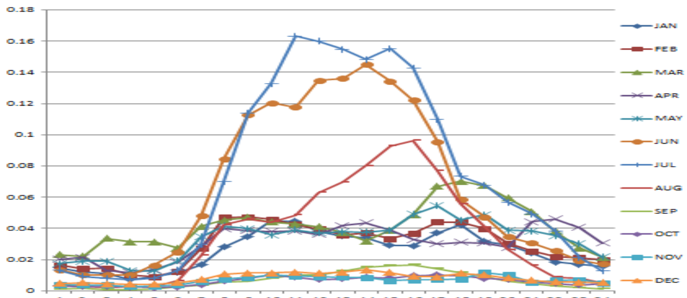

Fig-3: Average Wind output of the Riyadh system.

III. Reliability Indices

In order to evaluate the adequacy of the generation capacity, various reliability indices have been used in the literature. Generation reliability evaluations can be divided into deterministic and probabilistic. The most common deterministic index is the fixed reserve Margin of 8-10% which SEC has been using for years. An important shortcoming of this method is that it does not account for the stochastic nature of load behavior [16].

Probabilistic methods can provide more meaningful information to be used in design and resource in planning and allocation. There are two approaches that use probabilistic evaluation. The analytical methods and Monte Carlo simulation. As for the Monte Carlo simulation, reliability indices are estimated by simulating the actual random behavior of the system which makes the approach computationally difficult. So the commonly used probabilistic evaluation in practice are based on analytical methods [17].

The most important input quantities required in calculation of reliability indices are the capacity and the failure probabilities of individual generating units. If a simple two state model is assumed for the operation of a unit, its failure probability is given by its unavailability U, which can be expressed in terms of the unit failure rate λ and repair rate μ in the below equation.

$$U = \frac{\lambda}{\lambda + \mu} \quad (1)$$

Where,
U = unit unavailability
λ = unit failure rate
μ = unit repair rate

Usually, the unavailability of a generation unit, also known as Forced Outage Rate (FOR), is calculated for a long period of time (e.g.365 days) [18]. The analytical methods utilize the concept of Forced outage rate to construct, in a recursive manner, the so called Capacity Outage Probability Table (COPT).The calculation of the Capacity Outage Probability Table is no more no less than the enumeration of all system states and their probability of occurrence, each state represented by its outage capacity. The outage capacity is discrete and obeys an exponential distribution [19]. After obtaining all the entrances of this table a discrete convolution with the system load curve is made to obtain the loss of load risk in terms of several reliability indices. Most of these indices are basically expected values of a random variable. Typical reliability indices used in power system evaluations are explained below.

3.1 Loss of Load Probability (LOLP)

Loss of load occurs when the system load exceeds the generating capacity available for use. Loss of Load Probability (LOLP) is defined as the probability that the load on a power system is expected to be greater than the capacity of the available generating resources under the assumption that the peak load is constant during the period of calculation. For an expected maximum load L_{max} and available generation capacity C_{Ai} after the i^{th} outageO_i, the loss of load probability is:

$$LOLP = \sum P_i \quad \text{for all } (L_{max} > C_{Ai}) \quad (2)$$

Where P_i is the probability of the i^{th} outage.

LOLP calculation is effective for short-run generation adequacy such as hourly outage calculation of a particular day as the load and generation dispatch is assumed to be constant between each hour. LOLP can be read directly from the capacity outage table for a given dispatch. Its limitation is that it defines the likelihood of encountering trouble (loss of load) but not the severity; for the same value of LOLP, the degree of trouble may be less than 1 MW or greater than 1000 MW or more. Therefore it cannot recognize the degree of capacity or energy shortage.

3.2 Loss of Load Expectancy (LOLE)

The LOLE risk expectation index is the most widely accepted and used probabilistic method in system reliability evaluation for generating systems. LOLE is based on combining the probability of generation capacity states with the daily peak probability so as to assess the number of days during the year in which the generation system may be unable to meet the daily peak. This concept implies a physical significance not forthcoming from the LOLP, although the two values are directly related.

If t_i is the percentage of time during which the peak load L is higher than the available capacity C_{Ai} then load of load expectancy is given as

$$LOLE = \sum \frac{P_i t_i}{100} \text{for all } (L_{max} > C_{Ai}) \quad (3)$$

LOLE has the same weakness as that of LOLP.

3.3 Expected Demand notserved (εDNS)

Expected demand not served (εDNS) or expected load not served (εLNS), indicate the amount of MW (or MVA) that is not likely to be supplied to a system load center due to randomly occurring single or multiple contingencies (outages) in the system.

$$\varepsilon DNS = \sum (L_{max} - C_{Ai})\, P_i \quad (4)$$

It is presently less used than LOLE but is a more appealing index since it encompasses severity of the deficiencies as well as their likelihood.

3.4 Expected Energy Not Served (εENS)

Since power system are in fact energy systems, where the real revenue generated are accounted in terms of energy sale, the calculation of unserved energy is more relevant to the power utilities. The Expected Energy Not Served (εENS) is defined as the expected amount of energy (MWh) not being served to consumers by the system during the period considered due to system capacity shortages or unexpected severe power outages.

$$\varepsilon\mathrm{ENS} = \sum(\mathrm{L_{max}} - \mathrm{C_{Ai}})\mathrm{t_i}\ \mathrm{P_i}/100 \quad (5)$$

3.5 Energy Index of Reliability (EIR)

This reliability index, also known as energy index of fulfillment (EIF), designates the percentage of the total planned energy that was effectively fed into the network. It is the counterpart of energy index of unreliability (EIU) which is normalized value of εENS obtained by dividing the total energy demanded

$$\mathrm{EIR} = 1 - \mathrm{EIU} = 1 - \frac{\varepsilon\mathrm{ENS}}{Total energy demand} \quad (6)$$

IV. Simulation Results

This section analyze the generation reliability of Riyadh system for the Year 2013 based on the analysis presented in the paper. Section-A presents the numerical calculation reliability indices based on daily, monthly and yearly load profiles for conventional generation. Section-B presents the impact of integrating renewable generation and their effective load carrying capabilities. The results are compared against the common practice.

4.1 Reliability Evaluation with Conventional Generation

4.1.1 Daily Reliability Assessment

For the initial test simulation, the reliability analysis of a particular day has been done to explain the methodologyadopted in the analysis. Table-2 shows the generation reliability assessment of 27th July which encountered the peak load in the year. To represent the operational perspective of generation reliability assessment, hourly available generation have considered in calculation of LOLP and LOLE. Also, in order to account for the power import from EOA to Riyadh system, the hourly transfer import has been subtracted from the hourly load demand. The reserve has been calculated by subtracting the net load from the installed generation capacity. The forced outage rate of all machines are considered to be 0.04. It can be seen that the LOLP of the generating system is in accordance with the reserve. For higher values of reserve margin, LOLP of the generating system is lower.

Table-2: Generation reliability on 27th July 2013.

Hour	AvailGen	Hourly Load	Import	Net Load	Reserve	LOLP
0:00	8842	10079	4008	6071	5929	0.00007
1:00	8537	10022	4071	5951	6049	0.00002
2:00	8258	9830	3910	5920	6080	0.00001
3:00	8418	9843	4019	5824	6176	0.00001
4:00	8219	10220	4120	6100	5900	0.00001
5:00	7521	9767	3804	5963	6037	0.00000
6:00	7872	9920	3505	6415	5585	0.00001
7:00	8815	10290	3633	6657	5343	0.00020
8:00	9112	10437	3522	6915	5085	0.00032
9:00	9415	10704	3580	7124	4876	0.00043
10:00	10000	11052	3289	7763	4237	0.00626
11:00	10450	11280	3176	8104	3896	0.00644
12:00	11144	11561	2940	8621	3379	0.04601
13:00	11428	12014	2869	9145	2855	0.04873
14:00	11481	12086	2955	9131	2869	0.04873
15:00	11175	11704	3240	8464	3536	0.04330
16:00	11363	11746	3276	8470	3530	0.04340
17:00	10762	11262	3725	7537	4463	0.00626
18:00	8735	10478	3895	6583	5417	0.00014
19:00	9610	11272	4040	7232	4768	0.00196
20:00	9268	11046	3995	7051	4949	0.00048
21:00	9558	11141	4077	7064	4936	0.00054
22:00	8692	10821	4028	6793	5207	0.00020
23:00	8423	10668	4099	6569	5431	0.00013

Utilizing the same technique as above, the value of the reliability indices for the individual days of four months selected one from each season of summer, fall, winter and peak are given below. Since most of the machines

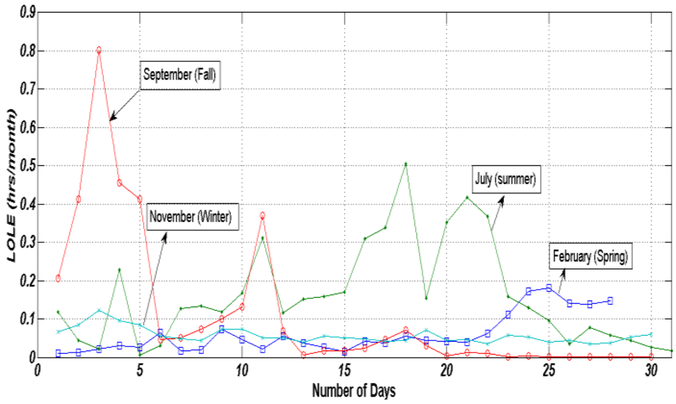

Fig-4: LOLE variation of Riyadh system during four months.

undergo maintenance schedule in winter and spring, the forced outage of the machines are considered to be higher during minimum load period.The FOR of February and November is 0.2, and for July and September is 0.03. Also instead of using the available generation in each hour, the total installed capacity of the generation has been used utilized which is more common in planning studies. Figure-4 shows the variation of LOLE during four seasons' summer, fall, winter and peak.

4.1.2 Monthly Reliability Assessment

For calculating the reliability of the generation of the complete month, the hourly load of that particular month has to be taken into consideration. The forced outage rates of machines in winter and spring are assumed to be higher similar to the values considered in figure-4. Table-3 shows the values of reliability indices considered in section-III.

Table-3: Reliability indices of the four months

Month	July	Sept	Feb	Nov
FOR	0.03	0.03	0.2	0.2
LOLP	0.0737	0.076	0.0014	0.0034
LOLE (hrs/month)	2.7229	1.906	0.1358	0.4536
εDNS (MW)	44.79	55.16	0.868	1.9
εENS (MWh)	2120	1515	85	316
EIR	0.9994	0.9995	0.99993	0.9997

4.1.3 Yearly Reliability Assessment

The aggregate generation reliability of Riyadh system for the Year 2013 can be obtained by considering hourly load and transfer from EOA of the complete year. Table-4 shows the reliability indices calculated for complete Year 2013.

The equivalent forced outage rate during the complete year is taken as 0.03. Table-5 shows the values of all reliability indices of year 2013. Although the SEC generation system meets the fixed reserve margin criteria of 8-10%, it does not comply with international utility probabilistic criteria of having LOLE of 4.8 hours/year. Thus the SEC system reliability assessment with these reliability indices is much better from the adequacy perspective than just assuming that the system should have a fixed reserve margin.

Table-4: Reliability indices of the complete Year 2013

Reliability Indices for Year 2013	LOLP	0.2163
	LOLE (hr/y)	6.5136
	εDNS (MW)	153.97
	εENS (MWh)	7950
	EIR	0.9998

4.1.4 Effect of FOR and number of units

Since the accurate FORs are unknown, the impact of different FORs on the calculated values of LOLP has been assessed. Figure 5 shows the cumulative probabilities of capacity outages of the Riyadh generators with a total installed capacity of 12000 MW (as shown in Table 2) and, varying FOR. Considering 3 generators for PP9 each of capacity 1200 MW, 1272 MW and 1300 MW, and 2 generators for PP8 each of capacity 877 MW and 990MW, the total number of generators add up to 11 units. From LOLP perspective, there is a significant difference if the units have 8% (navy blue line) or a 20% (sky blue line) FOR. Therefore it is necessary to assess in details how reliable the available units are. Otherwise the used numbers might be too optimistic or too pessimistic.

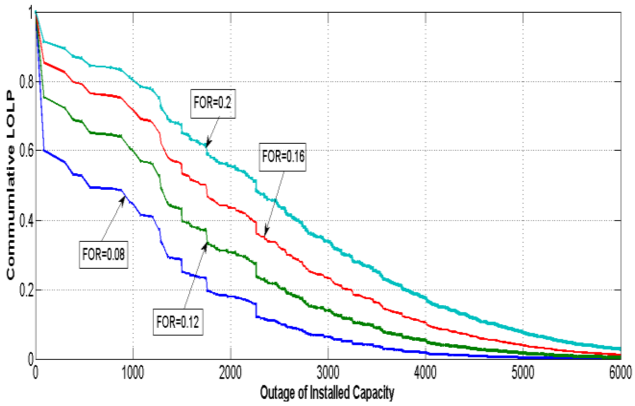

Fig-5: LOLP with 11 units and varying FORs

Figure 6 shows another sensitivity of the system's LOLP, where the number of generators is assumed to be 14. It is obvious that LOLPs decrease by increasing the number of units. So sizing as well as FOR has significant impact on LOLP.

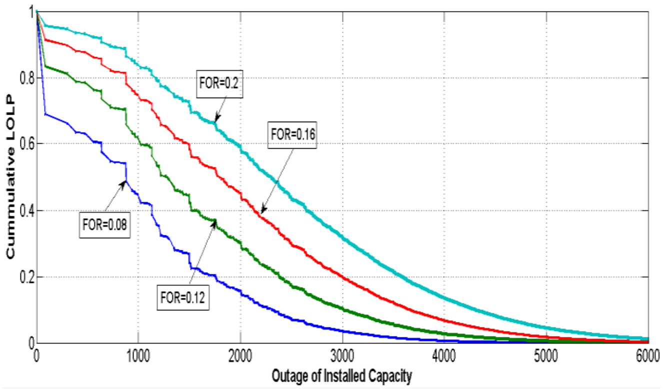

Fig-6: LOLP with 14 units and varying FORs

4.2 Impact of Renewable generation integration

4.2.1 Effect of increasing penetration level

Increasing the generation level in the system while maintaining the constant load always decreases the loss of load expectancy of the system, meaning it never degrades the generation adequacy, and this holds true for both conventional and VER generation as well[20]. In order to evaluate the extent of VER generation contribution towards the generation adequacy, the integration level of PV and Wind are increased in steps and the values of LOLE are measured as demonstrated in Figure 7. The integration level is indicated on the horizontal axis and system LOLE measured in hours/year are indicated on vertical axis. From the figure 8, it can be seen that the current SEC LOLE of 6.5 hours can be reduced to the international standard of 4.8 hours/year by adding 600 MW of PV or 1200 MW of wind. The differences in the MW contribution of PV and wind output in maintaining the same LOLE is due to the difference in their effective load carrying capability which is explained in the next section.

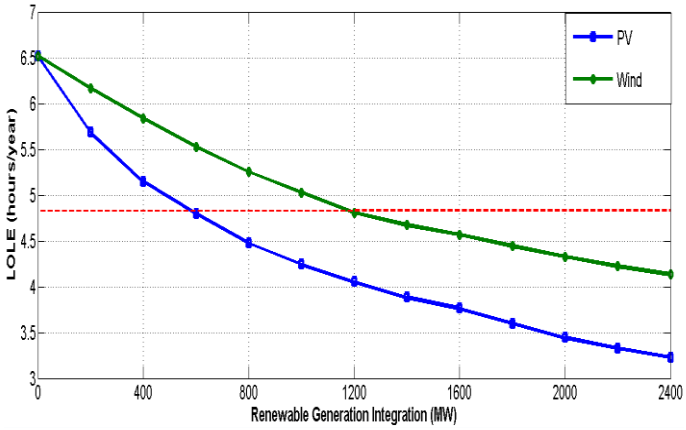

Fig-7: Variation of LOLE by increasing PV or Wind capacity

4.2.2 Effective load carrying capability

Effective load carrying capability of a VER generation is the amount of additional load that it can carry without altering the LOLE of the system [21]. The ELCC concept can be easily explained in Figure 8, by plotting the LOLE variation of the system according to the peak load variation. It can be seen that the entire load curve moves up/down with the increasing/decrease of load peak value but keeping its whole shape curve. The blue line in the figure below represents the LOLE under conventional generation only plotted against the system load. For a load of 11600 MW, the LOLE is given as 15 hours/year.

Introducing a Wind power plant with a 700 MW peak capacity in the Riyadh system, the variation of LOLE under variation of peak load is improved considerably and is represented by green line. For a fixed targeted LOLE of the previous system, 15 hours/year, the total load peak the system can now carry 11800 MW. The capacity difference between the new system and the reference system is the ELCC, in this case 200 MW. That means a 700 MW wind system integrated in Riyadh system grid has a capability to carry 200 MW of load increase in the system. In the same way, a 700 MW PV system has a capability to carry 400 MW of additional load. The reason for higher ELCC value of PV is because of its better correlation with the hourly load of the system.

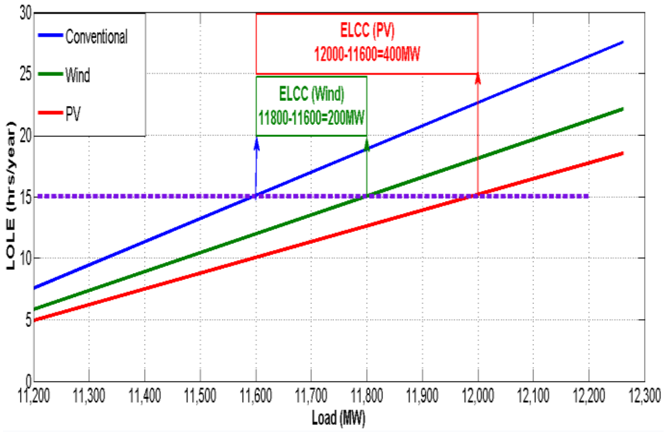

Fig-8: ELCC concept with and without renewable generation

4.2.3 Effect of FOR on VER generation

A sensitivity analysis is done again varying the FOR of all the generators, but keeping size and number of generators as in the base case, and it is found that changes in FOR has a considerable impact on the LOLE (see Figure 9 below). However, it is important to note that ELCC do not have a significant impact in FOR variation. The main reason for low sensitivity of ELCC with respect to FOR, compared to that of LOLE, is due to the nature of ELCC itself. Under the same LOLE target, ELCC is always the difference between the new load value and the reference load value, and this difference is almost equal for any FOR values.

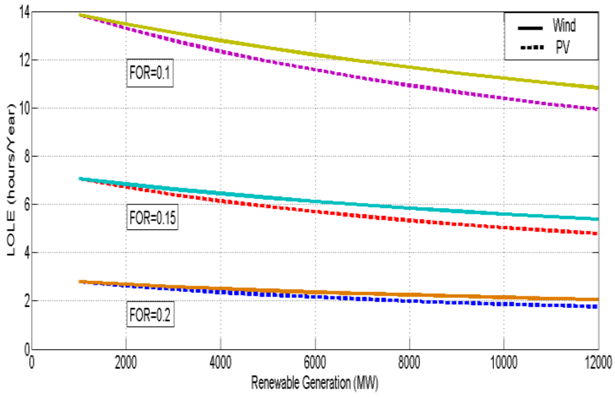

Fig-9: Sensitivity analysis of the impact of varying FOR for PV and Wind on the LOLE.

V. Conclusion

Although the present reliability assessment studies in Saudi Electricity Company (SEC) are almost based on deterministic approach i.e. fixed reserve margin of around 8-10%, the company is making great efforts to develop suitable probabilistic models and programs. This paper evaluates the most commonly used reliability indices for the case study based on SEC generation and load scenario of year 2013. For the detailed insights of the generation adequacy, the study examines the system reliability under daily, monthly and annual basis. The study findings showed that SEC has higher LOLE of 6.5 hours considering the FOR of 0.03 against the international utility practice of 4.8 hours/year.

In an effort to improve the system reliability, the case study considers the impact of introducing VER into the system. Based on the analyzed case study, the following major findings have been deduced:

- PV or wind integration always has a positive impact on system reliability irrespective of the penetration level or the existing conditions.
- Due to high correlation of PV during the peak hours of the load, PV integration results in reduced net loads which leads to higher effective load carrying capability.
- Excess generation of PV and wind does not lead to any negative impact on the system reliability but they surely have significant economic impacts.

Acknowledgements

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At Ontario Hydro, he progressed through several engineering and management positions where he ultimately filled the position of Development Planning Manager in 1986. He has been (since 1993) with the College of Engineering, King Saud University, Saudi Arabia. He has authored and coauthored over 300 publications in various power system and engineering topics. In addition to his academic activities, he has also been participating in industry funded projects and studies on issues relating to re-structuring of power utilities, energy market studies, development of bulk electricity plans, standardization of electricity services, energy efficiency, and environmental assessment.

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