Probabilistic Reliability Evaluation for Power Systems with High Penetration of Renewable Power Generation

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***Abstract*- In this paper, a probabilistic analytical approach for reliability evaluation of power systems with high penetration of wind and solar photovoltaic (PV) renewable power generation is presented. Due to intermittent nature of wind and solar power, the traditional deterministic method cannot properly address such uncertainties, probabilistic methods need to be utilized. In this paper, the loss of load method, one of the most effective probabilistic analytical methods, is adopted. The generation model is represented by the capacity outage probability table (COPT). The load model is presented by the load duration curve (LDC). Both generation and load models are used to obtain the system reliability considering wind and PV sources with certain forced outage rate (FOR). Simulation results are obtained using MATLAB. It is found that renewable energy sources can significantly improve the system reliability, but not as good as conventional power generators with the same rated capacity due to the actual reduced capacity value of renewable energy sources caused by intermittency. This analytical analysis is useful for the power system planner to quantify reliability improvements by installing grid-connected hybrid renewable power generation.**

Index Terms— Probabilistic planning, Generation Reliability evaluation, Analytical methods, Wind Power, Photovoltaic (PV) Power.

I. INTRODUCTION

Renewable energy is playing a vital role to meet the increasing energy demand and reduce the consumption of fossil fuels. As a result, integration of renewable energy sources such as wind turbine (WT) and solar Photovoltaic (PV) systems into conventional power grid have significantly increased. North American countries such as Canada and United States have already set renewable portfolio standard (RPS) policy to increase the usage of renewable energy resources [1, 2].

With the increasing penetration of renewable energy sources, maintaining a desired level of reliability of power grid becomes challenging due to intermittent nature of renewable power generation. New robust technologies are required to be developed by researchers to address this challenge [2, 3]. This paper focuses on reliability evaluation of the generation system, which is an important part of power system planning.

The power system reliability includes 1) system adequacy, and 2) system security. In this study, the system adequacy is the main focus. The system adequacy refers to the availability of enough generation to meet the system load demand, and it can be determined by analyzing reliability indices. The loss of load expectation (LOLE), loss of load probability (LOLP), and the expected energy not supplied (EENS) are by far the most common and effective approaches for the reliability evaluation. These indices provide information on indicators such as the size of the generation unit, availability, requirement of maintenance etc [4-8]. The unavailability of renewable energy sources can be expressed by the unit forced outage rate (FOR) [4].

In the past, the deterministic method was widely used to evaluate the power system reliability. However, with the increasing penetration level of renewable energy sources, the probabilistic method appears to be the most effective method to address uncertainties associated with such integrated power grid. For the generation adequacy evaluation, there are two methods available: 1) Analytical method, and 2) Monte Carlo simulation method. The analytical method utilizes mathematical models [2, 3], whereas the Monte Carlo simulation method simulates actual process and random behavior of the system [8].

The contribution of the paper is to investigate the system reliability with high penetration of renewable energy sources integrated into conventional generation system using the analytical method. Through the case study, the influence of renewable energy sources on power system reliability is presented through quantity results.

The analytical method, loss of load method, is adopted and implemented in this paper to evaluate the system adequacy with high penetration of wind and solar PV power generation. The following two cases are used in the analysis: 1) Case 1 - the Roy Billinton Test System (RBTS) plus a hybrid wind and solar PV system with the capacity of 80.5 MW (20 × 2MW WT, and 50 × 810 W PV); 2) Case 2 - the RBTS plus 80.5 MW thermal units (2 × 40.25 MW). The system configuration for Case 1 is shown in Fig. 1. The generation system is represented by the Capacity Outage Probability Table (COPT). The load model is represented by the load duration curve (LDC). The results of the system adequacy for one year period

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are obtained using MATLAB. The reliability of the system was analyzed by comparing the reliability indices (LOLE and EENS) with the standard values.

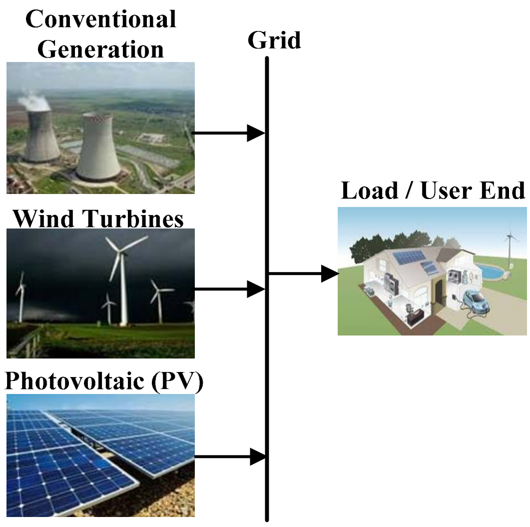

Fig. 1. The system configuration for Case 1.

II. METHODOLOGY FOR GENERATION PLANNING - ANALYTICAL METHOD

A power system can be divided into generation, transmission and distribution functional zones. These functional zones can be sub-divided into three (03) hierarchical levels: the hierarchical Level I (HL-I), the hierarchical Level II (HL-II), and the hierarchical Level III (HL-III). As shown in Fig. 2, The HL-I deals with generation systems, HL-II concerns both generation and transmission systems, and HL-III refers to distribution systems. In this study, the HL-I is the main focus in order to evaluate the adequacy of generation system, which determines the total amount of generation required to supply the load without interruption [2, 3]. The basic segments to perform the adequacy evaluation for the HL-I include: 1) Generation Model, 2) Load model, and 3) Risk model (Combination of the generation & load model) [2, 3]. The adequacy model for the HL-1 is shown in Fig. 3 [2, 3]. In order to ensure the system adequacy, the power system has to maintain certain level of static and spinning reserves [2, 3, 8, 9].

In the analytical method, the system is represented by the mathematical model. The analytical solution from the mathematical model is utilized to evaluate the system risk indices [4, 8, 10]. [4, 8, 10]. The capacity model of the generation system is represented by the COPT. The COPT provides the probability of occurrence for each possible capacity outage level, where it is assumed that the failures of individual generating units are independent events [10]. The load is represented by the LDC. The LDC and the COPT are finally convolved to calculate the reliability indices [4, 9].

If the system contains identical units, Binomial distribution can be used to determine the COPT. In the analytical method, each generating unit of the system can be represented by either a two-state or a multi-state model. In case of the two state model, each generating unit is represented by either a fully available (Up) or completely out of service (Down) as shown in Fig. 4 [2, 3]. Similarly, in case of multi-state generating unit, it can exist in fully up, fully down and one or more de-rated or partial output states [2, 3]. In this paper, the two-state model is adopted, and it is based on the Markov method.

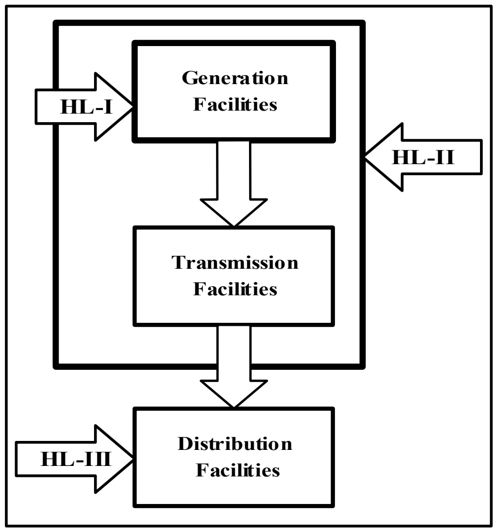

Fig. 2. The hierarchical levels of a power system [2, 3].

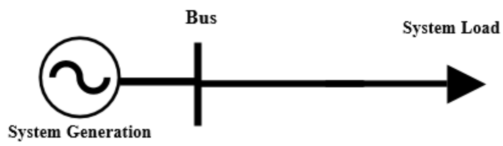

Fig. 3. The adequacy model of HL-I [2, 3].

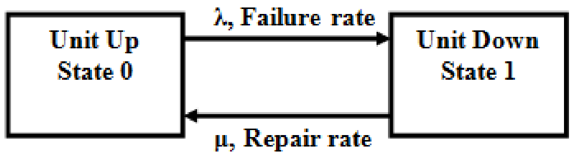

Fig. 4. A two-state model for the generating unit [2, 3]

The forced outage rate (FOR) of generating unit is the probability of a unit being in forced outage stage, denoted by U. The FOR can be calculated as follows [1]:

$$FOR = U = \frac{\sum T_{down}}{\sum T_{up} + \sum T_{down}} = \frac{\lambda}{\lambda + \mu} \quad (1)$$

$$P_{up} = \frac{\mu}{\lambda + \mu} \quad (2)$$

$$P_{down} = \frac{\lambda}{\lambda + \mu} \quad (3)$$

where λ is the unit failure rate, μ is the unit repair rate, P_{up} is the probability of the generating unit in Up State, and P_{down} is the probability of the generating unit in Down state. T_{up} and T_{down} denote the duration of the unit in operating, and failure state, respectively.

III. Reliability Model Using Loss of Load Method

Reliability is the probability that a components or a system performing desired operation for a given period of time under certain defined operating conditions. In other words, it is the probability of non-failure of the system over the time period, t. The reliability of a system can be expressed by [12, 14, 15]

$$R(t) = P\ (T > t) \tag{7}$$

Where T is the time to the failure of the system.

The cumulative probability density can be calculated by

$$F(t) = 1 - R(t) = \mathrm{P}\ (\mathrm{T} < \mathrm{t}) \tag{8}$$

The cumulative failure rate function is defined as:

$$\lambda(t) = \lim_{\Delta t \to 0}\{\frac{-[R(t+\Delta t) - R(t)]}{\Delta t}\}\frac{1}{R(t)} = -[\frac{\mathrm{dR(t)}}{\mathrm{dt}}]\frac{1}{R(t)} \tag{9}$$

$$R(t) = \exp[-\int_0^t \lambda(t')dt'] \text{ and } \lambda(t)dt = -[\frac{dR(t)}{R(t)}] \tag{10}$$

The cumulative failure rate over time (t) can be expressed as [14]:

$$L(t) = \int_0^t \lambda(t')dt' \tag{11}$$

In this paper, the analytical method, the loss of load method, is adopted and implemented. In the loss of load methods, the generation system is represented by the COPT. In the literature, the load characteristics can be represented by either the daily peak load variation curve (DPLVC) or the load duration curve (LDC). The DPLVC is created by arranging the individual daily peak loads in a descending order, while the LDC is formed by arranging the hourly load values in descending order. The DPLVC model is used frequently due to its simplicity, but the LDC is the most suitable model to approximate the load characteristics [2, 3, 17]. Therefore, the LDC is adopted in this paper.

This "loss of load" index gives the information about the expected number of days (or hours) in the given time period; in which the daily peak load (or hourly load) exceeds the available capacity. The loss of load expectation (LOLE) can be expressed as:

$$LOLE = \sum_{i=1}^{n}(p_i \times t_i) \quad (\mathrm{L}_{\max} > C) \text{ (hrs/year)} \tag{12}$$

where, n is number of days or hours of period under scope, p_i is the probability of i_{th} outage which is obtained directly from the capacity outage cumulative probability table (COPT) and t_i is the number of time units for which this outage cause loss of load. It is clear that if the capacity outages are less than the reserve then loss of load will not occur.

Currently, the loss of load probability (LOLP) index is not widely used because it indicates only the probability of system failure. The LOLP can be defined as:

$$LOLP = \sum_{i=1}^{n}(p_i) \quad (\mathrm{L}_{\max} > C) \tag{13}$$

In this paper, the LOLE index is adopted. The flowchart in Fig. 5 shows the systematic steps implemented in the evaluation of the reliability level (LOLE) in power system planning process in order to determine the appropriate capacity reserve margin in each year of the planning horizon. The desired level of LOLE is prescribed by the utility company which is denoted by $\mathrm{LOLE_p}$.

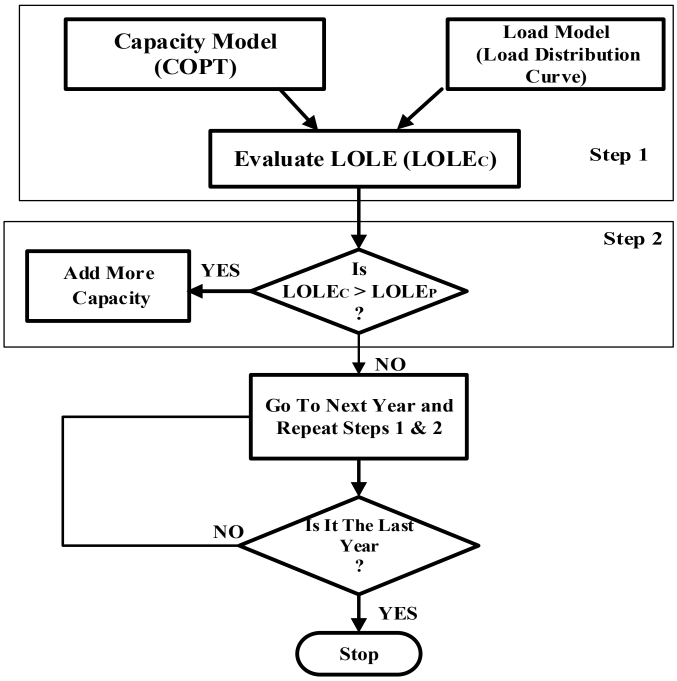

Fig. 5. Flow chart for the adequacy evaluation using the loss of load method [18]

Since the energy sale is the prime objective of the utility company, another essential and most needed reliability index is known as the EENS is also used in this paper. It can be calculated as follows:

$$EENS = \sum_{i=1}^{n}(ENS_i \times p_i)\ (\mathrm{L}_{\max} > C) \text{ (MWh/yr)} \tag{14}$$

IV. Simulation Results

In this study, the hourly load distribution curve (LDC) curve is used as the system load. The load model is assumed to be linear and varied from 100% to 40% of the peak load in the two case studies as shown in Fig. 6 [14, 18]. Since the LDC load model is designed based on the hourly data, the 100% in the load model defines the total number of hours per year, 8760 hours [14, 19]. The study period of this grid connected wind and solar system is considered for one year. The Roy Billinton Test System (RBTS) [14, 18, 20, 21] is used to verify the proposed method. The single line diagram of the RBTS is shown in Fig. 7. The system consists of a total of 6 buses with 5 load buses, 9 transmission lines, and 11 generators in buses 1 and 2 ranging from 5 MW to 40 MW. The total installed capacity of the system is 240 MW. The peak load of the system is 185 MW. Table 1 shows the generator ratings along with the RBTS reliability data.

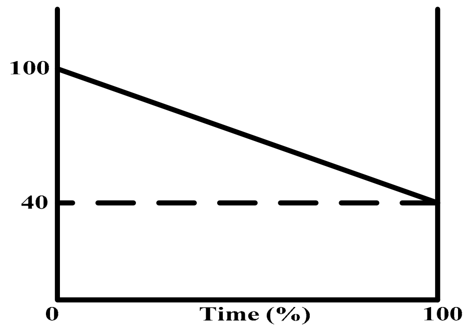

Fig. 6. Load model of the system

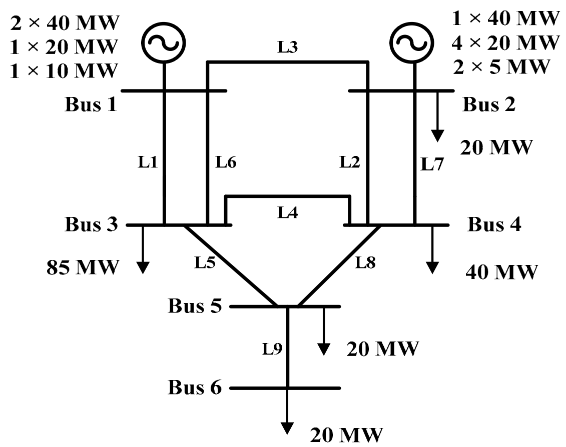

Fig. 7 Single line diagram of the Roy Billinton Test System (RBTS) [15]

TABLE I
CONVENTIONAL GENERATION UNIT RELIABILITY DATA FOR RBTS [15]

Size (MW)	Type of Unit	No of Units	FOR	MTTF/h	MTTR/h
5	Hydro	2	0.010	4380	45
10	Thermal	1	0.020	2190	45
20	Hydro	4	0.015	3650	55
20	Thermal	1	0.025	1752	45
40	Hydro	1	0.020	2920	60
40	Thermal	2	0.030	1460	45

The following three case studies are conducted in the paper: 1) Base Case – the RBTS; 2) Case 1 – add a hybrid wind and solar PV system with the total capacity of 80.5 MW (20 × 2MW WT, and 50 × 810 W PV) to the base case; and 3) Case 2 – add 80.5 MW thermal units (2 × 40.25 MW) to the base case.

In Case 1, 20 WTs of Vestas V90-2MW [22] are considered, and the capacity of the wind farm is 40 MW (20×2MW = 40MW). The FOR of the wind turbine is assumed to be 4% [24]. The solar PV system is rated at 810 Wp per one array (by assembling 9 groups of 3 series Canrom 30 Wp modules with 4% FOR) [24]. The total PV capacity is 40.5 MW considering 50 arrays (50×810 Wp = 40.5 MW).

In Case 2, the total capacity of the added thermal units to the RBTS is 80.5 MW (two thermal units with 40.25 MW capacity) with 4% FOR.

The output power of renewable energy sources depends on design characteristics, technology choice, and resource availability such as wind speed and solar radiation, therefore, the calculation of the capacity value of renewable power generation is much more difficult than that of conventional generation due to its inherent variability and uncertainty [22].

In this paper, the capacity factor is used to determine capacity value of renewable energy sources. The capacity factor is defined as the ratio of actual power output of a given power generation unit over a period of time, to the rated power over the same period of time [23]. The main advantage using a capacity factor to estimate the total power production is that the detailed resource input data such as solar radiation and wind speed variation are not required, the output power can be determined simply based on its rated value and the capacity factor [23, 24].

According to the Transparent Cost Database of the National Renewable Energy Laboratory (NREL), the maximum capacity factor under any solar radiation and wind speed variations in any region for wind turbine and PV system is 50.6%, and 28%, respectively [25]. These capacity factors are adopted in this paper. Therefore, the capacity value of one unit wind turbine and one PV array considering the capacity factor is 1.012 MW (20MW×0.506), and 0.2268 Wp (0.810×0.28), respectively. The total capacity value of wind and solar farm added to the RBTS in Case Study 1 is 20.24 MW, and 11.34 MW, respectively.

The reliability indices, LOLE and EENS, are calculated by taking the following steps:

1) Building the COPT using the FOR of the RBTS for each unit in Table I, wind turbine (FOR=0.04), and PV system (0.04).
2) Calculating the LOLE and EENS using Eqs. (12) and (14), where p_i is the probability of capacity value in COPT.

The calculation results are shown in Tables II. Table II shows the LOLE in hours per year and EENS in MWh/yr for the base RBTS and two cases studies. The LOLE in the base case and Cases 1 and 2 are 11.13, 0.61 and 0.45 hours per year, respectively. The LOLE for Case 2 is the lowest as compared to the other cases, which means the system is most reliable. The EENS for Case 2 is also the lowest (4.67 MWh/yr), followed by Case 1 (5.60 MWh/yr) and base case (116.68 MWh/yr).

Compare Base Case, Cases 1 and 2, it is found that by adding conventional power generation to the base case in Case 2 the best system reliability can be achieved. By adding hybrid renewable energy sources to the base case in Case 1 can also significantly improve the system reliability, but not as good as Case 2 due to the actual reduced capacity value of renewable energy sources.

TABLE II
LOLE (H/YR) AND EENS (MWH/YR) CONSIDERING DIFFERENT CASES

Reliability indices	Base RBTS case	Case 1	Case 2
LOLE (h/yr)	11.13	0.61	0.44
EENS (MWh/yr)	116.68	5.60	4.67

V. CONCLUSION

In this study, the reliability of a bulk power system with high penetration of wind and PV renewable generation is evaluated using an analytical method, the loss of load method. The system adequacy is assessed by analyzing the reliability indices, LOLE and EENS. The reliability of the power system with grid connected renewable energy source has been examined for the period of one year. The generation system is simulated by creating the COPT and the load system is modeled by using LDC. The reliability indices, loss of load expectation (LOLE) and expected energy not served (EENS), are calculated using MATLAB. The results confirmed that renewable energy sources can significantly improve the system reliability, but not as good as conventional power generators with the same rated capacity due to its actual reduced capacity value caused by intermittency. This analysis provides quantity values of reliability improvement of renewable energy integration, and it is helpful for power system planners when considering high penetration of grid-connected renewable energy sources.

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