The Contribution of Capacity Credit on Reliability of Generating System Adequacy

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Abstract. A conventional generating unit is more reliable than a wind energy conversion system (WECS), in terms of capacity value. It performs an essential role in supplying reliable energy for electrical systems. Wind energy is considered a fundamental alternative source for electrical power generation. So far, it is difficult to secure wind speed data that covers a long period and is suitable for wind energy generation assessment. Generating wind power often includes uncertainties, due to the stochastic nature of wind speed. Hence, the capacity credit (CC) of the WECS is intermittent in nature. There are numerous approaches that can be adopted for evaluating the CC of wind power generation, for designing and planning new investment capacities. This paper examines the use of capacity credit from the WECS to obtain the load capacity benefit ratio (LCBR) for the reliability of power systems. To calculate CC, the IEEE-MRST-79 is used to elucidate the proposed technique. A sequential Monte Carlo simulation (SMCS) technique is used to determine the reliability of the generating systems which includes the WECS.

1. Introduction

An adequacy valuation method is deployed to investigate the generation system’s capacities and features that satisfy the load demands of power generating facilities [1]-[2]. Normally, power generating facilities include both conventional and unconventional units. Hydro, thermal, and nuclear units constitute conventional units. These units offer integrated benefits, even from disparate units that are interconnected in a single environment. On the other hand, wind turbine generators (WTGs) “unconventional units” and PV cells, provide other options to system planners [3]-[4].

In recent years, and in order to achieve power system requirements, many countries have placed great emphasis on the use of renewable energy sources (RES), such as the solar and wind systems, to assuage worries related to depletion of the reserves of non-renewable energy sources with fossil fuel as the major contender, and also the negative impacts of conventional energies on the environment.
such as carbon emission leading to global warming \[5\]. Wind energy is naturally abundant and also friendly to the ecosystem. From the perspective of system designers, these RES provide a good and clean energy, but with a limited capacity of production. The available capacity of the wind energy source is never certain, especially during peak energy demand periods.

The term ‘capacity credit’ (CC) is used generally to estimate the capacity of these intermittent sources. In other words, CC gives an estimated measure of the intermittent energy generation that contributes to reliability. The term CC is used in determining the estimated capacity value from the WECS. The effective load carrying capability (ELCC), capacity factor (CF), and reliability curve (RC) are all means of measuring CC, which can be used to determine the capacity contribution from intermittent sources in the adequacy planning of generating systems to ensure system’s reliability.

It is also used to sustain the penetration levels of generation from intermittent sources to meet future electricity demands \[3\], \[4\], \[6\]. Picking a suitable penetration level of wind power at a “conventional energy conversion system”, and deciding the impacts of the WECS on the reliability of the system are vital elements of analysing the capabilities of the wind energy source as an alternative option for clean energy generation \[7\]. Also, to achieve reliability indices (RI) at a level comparable to that of conventional units of power systems, it becomes necessary to calculate the capacity credit of the WECS.

A sequential Monte Carlo Simulation (SMCS) technique was applied alongside a frequency and duration procedure \[8\] to examine the power generation system’s reliability. The Weibull distribution model was used in establishing the simulation process of replicating wind speed in every hour. This paper examines and elaborates the impacts of capacity credit from the WECS on power systems to achieve load capacity benefit ratio (LCBR). In addition, picking a suitable penetration level of wind energy to achieve reliability indices at the same level to that of conventional units of power systems,

2. Related Work

2.1. Risk modeling

An elementary model that includes conventional and unconventional generator units paradigms is considered for evaluating the adequacy of power generating systems (PGSs). Figure 1 illustrates these paradigms, employing an appropriate load pattern to create a risk paradigm.

Quantitative risk indices are used in this paradigm to denote the systematic risk. The loss of load expectation (LOLE) is used as the fundamental reliability index to determine the reliability levels of PGSs that include the WECS, as was published in \[7\]. A level of LOLE is frequently used as part of the quantitative criteria for generating systems. The standard level to LOLE index is 1-day-in 10 years. This denotes the total accumulated hourly time of deficiencies of power supply should not override 1 day in 10 years. The selected level for LOLE index of the reliability level can have a large impact on the capacity credit value of both wind energy and conventional energy. When the reliability level is
low, the LOLE index is higher, whereas, in cases where the LOLE index is very low, the reliability level is higher, because there is relatively more capacity value in any added capacity.

![Figure 1. The risk model in generating system adequacy analysis](image)

The SMCS technique can be used to determine this index. Where the reserve available for the system at a time point is calculated based on the difference between capacity that is available and the active loading on the system. A load loss situation is denoted with a negative margin.

2.2. **Conventional unit model**

A multi-state paradigm or “2-state paradigm” is applied to every power unit in the system [9]. The power units are considered as either completely up in service or totally down in the 2-state paradigm. The power output of the power units can be simulated through the SMCS technique in the procedure [8]. The simulation process can be described based on the operation time cycle of each power unit. This can also be indicated in expressions of failure rate ($\lambda$). Also, the $\lambda$ provides information about the frequency of times the unit is down from service through the year. The repair rate (MTTR) indicates the out of service in per year period. The operation time cycle of every power unit in the system can be determined by integrating these two parameters “$\lambda$, MTTR” for a particular period of time (cycle period of one year). The capabilities of conventional generating units are grouped to estimate the total system capacity through the simulation of all components involved in the system. The load model represents via the annual load curve represented here chronological order [10], i.e., the load duration curve (with 8,760 hours).

2.3. **Modeling of the WECS output power**

In addition to the data in demand for modelling traditional generating units for analysis, the generating system reliability level, meanwhile, requires data for velocity and output power from the wind turbine generator (WTG) at least a year. The wind speed paradigm and power paradigm represent the two
major paradigms for a construct the WECS system [11]. So far, a collection of wind speed data for a long period and suitable for generating wind energy assessment is difficult to obtain. Modelling wind energy using “2-state”, this paradigm is not recommended as wind is highly changeable resource which cannot be adequately modelled by a “2-state” paradigm. Consequently, the distribution “Weibull” paradigm is employed to imitate the hourly wind velocity. Furthermore, the Weibull Distribution Function (WDF) model has merit because it is able to adjust those two Weibull parameters, the scale “c” and the shape “k” [12] to fit experimental wind data, therefore, it is frequently used in simulating the variance in the velocity of the wind.

The purpose of the wind speed sampling, hourly, for a sustained time period is for the evaluation of the hourly output power for the WECS during this time. Consequently, the WDF model can simulate the velocity of the wind at any period of time during the simulation proceedings [13]–[15]. The wind velocity can be created artificially [16] by utilizing the function in Equation (1).

\[ v = c \left( - \ln(U)^{1/k} \right) \]

where; “c” and “k” are WDF parameters, U is uniform WDF of random variables within [0, 1], and “v” is the velocity of the wind. The mean value of the WDF [17], i.e., the actual average wind speed value.

The velocity of the wind (ws) and the output power from a WTG at any hour of time has a “non-linear” relationship. Equation (2) shows the relationship of the velocity of the wind to the WTG power output. By implementing the velocity of the wind in the paradigm of the WTG, the power output can be derived.

\[
P_{WTG} = \begin{cases} 
0 & \text{ws} < V_{ci_{-WTG}} \\
P_r \times (A + B_2 + Cx^2) & V_{ci_{-WTG}} \leq \text{ws} < V_{r_{-WTG}} \\
P_r & V_{r_{-WTG}} \leq \text{ws} < V_{co_{-WTG}} \\
0 & \text{ws} > V_{co_{-WTG}}
\end{cases}
\]

Here, “P_r”, “V_{ci_{-WTG}}”, “V_{r_{-WTG}}”, and “V_{co_{-WTG}}” are the rated power output of a unit, wind speed “cut-out”, “wind rated”, and wind speed “cut-in” respectively. A, B and C are presented in [4]. Finally, the wind turbine power output can be calculated through simulated the wind speeds.

2.4. Capacity credit (CC) of wind power

The term CC is employed generally to estimate the capacity of these intermittent sources. In other words, the CC gives an estimated measure of the intermittent energy generation that contributes to reliability. In this paper, the CC of wind refers to the capability of wind power to increase the reliability of the power system. In this study, we have designed a simulated paradigm for the CC, based on the permeation scale of the wind energy in the power systems.
The penetration of wind power can be expressed by different criteria, by means of “the overall capacity factor”, “annual use of the wind turbines”, or “the reliability of the conventional part of the power system”. Usually, the overall capacity factor is used, which represents wind power production as a percentage of gross demand from consumers (total installed capacity) and wind power capacity as a percentage of peak load.

Although the wind capacity value comes from the general correlation of wind power and load demand, it is helpful to clarify the ELCC. The concept of the ELCC technique is to examine how much additional load can be served after a new generation resource is added to the system, without exceeding the specified reliability level. ELCC is defined as the increase of the system load carrying capability at a fixed LOLE level, due to the addition of raising wind power penetration. The LOLE is a measure of generation system adequacy and specifies the expectation of a loss of the load event.

The capacity factor (CF) of the wind velocity data can be utilized to provide a crude approximation of the CC of the wind energy of the WECS. The CF can describe the annual expectation of energy production from the WECS by applying the formula in Equation (3):

\[
\text{Capacity Factor} = \frac{\text{Sum of annual hourly wind power output (MWh)}}{\text{Maximum wind power output (MW) \times 8736}}
\]  

This paper examines the CC from the WECS to obtain the load capacity benefit ratio (LCBR) for the reliability of power systems. The incremental annual peak load carrying capability (IPLCC) is termed as the load capacity benefit ratio (LCBR). The LCBR explains the rate of annual incremental peak load carrying capability (IPLCC) that is added to the total capacity as shown in Formula (4).

\[
\text{LCBR} = \frac{\text{IPLCC}}{\text{Total capacity added}}
\]

3. Proposed Methodology

This section contains an explanation of the basic simulation proceedings for calculating CC from wind sources. In addition, there is an explanation of the proceedings for measurement of the LCBR and calculation of the reliability indices for power systems, which includes the WECS system.

Step 1) to estimate the CC from proposed wind farms in the simulation process:

- Set the Weibull parameters whereby the “k=2” and “c=7 m/s” and the power curve according to the data of the site in reference [2], therefore the set parameters for each WTG unit, \( P_r = 2.5 \) MW, \( V_{c_{\text{cut-out,WTG}}} = 21 \) m/s, \( V_{r_{\text{WTG}}} = 12 \) m/s, and \( V_{c_{\text{cut-in,WTG}}} = 6.3 \) m/s.
- Run with the Weibull model for generating the random speed of the wind, according to Equation (1).
By applying the Equation (2) the production of wind power randomly with different wind speed average values has been achieved.

To assess the CC we apply the CF approach. In this process, measures of the CF of the chronological wind energy output can be estimated by using the Equation (3).

Step 2) to estimate the reliability indices of the generating system:

- Use the SMCS technique to build a capacity model that is suitable for conventional generating facilities.
- Combine the conventional generating capacities and power output of wind power generating units to create the aggregate system capacity. Next, the computation of LOLE is the reliability index that expresses the reliability contribution of the wind farms to the power generating systems. A loss of load expectation (LOLE) occurs only if the load is more than the available capacity of the system.
- Observe the deficiency of the system’s capacity reserve within a certain time frame, to mark the required reliability indices.

Step 3) to calculate the LCBR as follows:

- ELCC is examined after adding WTG units to define the increase of the ELCC caused by the addition of wind energy capacities at a fixed LOLE level.
- The LOLE indices are plotted against the system peak load per year, before adding the WTG units, and also after adding the same units. Then, the load capacity benefit ratio is calculated by using the Formula (4).

Step 4) Estimate the LCBR ratio, which can be done by applying the Formula (4)

4. Discussion of Results

For many practical applications, it is necessary to investigate the power output form the wind farm, in order to get a clearer view of the chosen location. The Weibull distribution is used in the simulation process for predicting the wind speed per hour. Reference [2] provides wind power curve parameters for WTGs. From the simulation process, Figure 2 shows the forecast for wind speed hourly at a specific location in [2], for 300 hours. Figure 3 shows the simulation of wind power output for WTG with a power rate of 2.5 MW for 300 hours.
It can be interesting to compare the impact of penetration level with the impact of the LOLE, and the number of available WTG units. The system reliability index (LOLE) decreases as more WTG units are added. Figure 4 shows the LOLE indices as a function of the number of WTG units added to the MRST-79. Each WTG unit has a rated capacity of 2.5 MW.

To assess the CC we apply the CF approach. The average annual wind energy production by the 40 WTG units with 100 MW capacity penetration is around 190631 MWh/year, the equivalent (21.82 MW) of the CC, which represents around 3% of the total installed capacity of the conventional units.
for power systems. Table 1 shows the estimations of the CF of the different wind power penetration levels, which can be conducted by applying Equation (3). Also, the table shows the CC has a little effect in terms of increasing the wind energy penetration.

Table 1. The capacity factor of the wind penetration with the percentage of the installed capacity in power systems.

| Case No. | Wind penetration (MW) | Capacity factor (%) | Percentage penetration (%) |
|----------|-----------------------|---------------------|---------------------------|
| 1        | 100 MW                | 21.82 %             | 3 %                       |
| 2        | 200 MW                | 22.15 %             | 6 %                       |
| 3        | 300 MW                | 22.72 %             | 9 %                       |
| 4        | 400 MW                | 22.17 %             | 12 %                      |

The reliability indices assessment simulation in this paper is executed at the MRST-79 system that includes the WECS; results of this study have been compared with results from Ref. [2]. The WTGs that are installed in WECS have the following specifications: \( P_r = 2.5 \text{ MW}, V_{CO_{WTG}} = 21 \text{ m/s}, V_{R_{WTG}} = 12 \text{ m/s}, \) and \( V_{CI_{WTG}} = 6.3 \text{ m/s}. \) The MRTS-79 [18] comprises 32 conventional units, with capability ranging from 12–400 MW. The peak load of the system is 2850 MW and the overall output power the system is 3405 MW. The MRST-79 was simulated for several trials using the SMCS method. The simulation proceeded in chronological order from one hour to the next, repeatedly, using yearly samples unit the specified convergence criteria were met. Figure 5 represents the respective systems’ available capacities, realized from the generating unit and the WECS. Figure 6 shows the available power system capacity that is based on the simulated process superimposed along with the chronological load model.
The LOLE is used as the fundamental reliability index to determine the levels of reliability for the PGs that include the WECS. Table 2 lists the reliability indexes for the MRTS-79 test system prior to addition of the CC and after combination with the 100 WTG units (of 250 MW). Also, the table highlights the significant improvement caused by the addition of 250 MW of the 100 WTG units. SMCS results were compared with those obtained from the technique reported in [2], as listed in Table 2. Furthermore, this table represents the comparisons in the reliability indices between techniques represented, to obtain precise results. The results indicate that the reliability indices derived from the use of the SMCS approach correspond closely with those derived from the use of an analytical approach.

| Reliability index | prior adding (WECS) [2] | After adding (WECS) [2] | prior adding (WECS) | After adding (WECS) |
|-------------------|-------------------------|-------------------------|---------------------|---------------------|
| LOLE (hour/year)  | 9.38                    | 7.41                    | 9.40                | 7.35                |
| LOEE (MWh/year)   | 1111.86                  | 877.44                  | 1197.7              | 873.3               |

After addition of the 100 WTG units in the MRTS-79 system, the ELCC are examined. The LOLE indices are plotted against the system peak load per year, before adding the (100) WTG units with MW (250 MW), and also after adding the same units. It obvious that there is an ELCC benefit from
the WECS addendum. The IPLCC is termed as the load capacity benefit ratio (LCBR), at LOLE around 2.2 hours/year is approximately 36 MW after adding 100 WTG units with 250 MW to the system. Figure 7 shows the system LOLE index versus the system annual peak load prior to and after integrating CC form wind power.

![Figure 7. LOLE indices vs. the annual peak load after and before adding wind power.](image)

The LCBR is calculated through applying Equation (4), by \( \frac{36 \text{ MW}}{250 \text{ MW}} = 14.4\% \). Many factors affect the power production from WTG units. The speed of the wind is the main factor affecting the power production of WTG units, so, the ELCC of the WECS system can be influenced by increasing wind velocity. The high LCBR values denote efficiency in harnessing wind energy.

5. Conclusion

Many factors affect power production from WTG units. Consequently, the capacity credit of the WECS is intermittent in nature. A capacity factor is an index representing the ratio of the installed capacity credit from incorporating a WECS, to the total installed capacity of conventional generation in the electric network.

This paper assesses the load capacity benefit ratio (LCBR) of power systems having a huge penetration level of wind power.

Also, this paper examines the potential of capacity credit from the WECS to secure LCBR for power systems. So, the high LCBR values indicate competence in harnessing the power of the wind. Picking a suitable penetration level of wind power in a conventional energy conversion system, and estimating the impacts of the WECS on the reliability of the system, are vital factors in analyzing the capabilities of the wind energy source as an alternative option for clean energy generation.

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