A New Method for Capacity Credit Estimation of Wind Power

Lingfeng Wang and Chanan Singh, Fellow, IEEE

Abstract—Significant amounts of wind power are being integrated into power grids in recent years. However, due to intermittent characteristic of wind power, it is usually difficult to determine the appropriate penetration level to ensure a specified reliability requirement. For this purpose, the proper calculation of wind power capacity credit (WPCC) is of particular importance which is useful in both planning and operation stages of hybrid power systems with multiple power sources. The capacity credit of wind power is usually calculated based on a reliability index termed Loss of Load Expectation (LOLE). WPCC is the amount of wind power which is able to achieve the LOLE identical to the dispatchable power sources. In this study, WPCC estimation is formulated as an optimization problem, and an intelligent search method called particle swarm optimization is used to automatically search out the WPCC. It has turned out to be a viable scheme in estimating WPCC.

I. INTRODUCTION

In planning generation facilities, the planners are faced with the question of giving appropriate credit for generating capacity from intermittent sources like wind. Estimation of wind power capacity credit (WPCC) due to the intermittency of wind availability is not a sufficiently investigated area so far, and it is also a challenging task. The reliability of power-generating systems may be improved when integrating wind power into the power grid, since the penetrated wind power can be seen as “negative load”. Thus, a certain amount of additional load can be satisfied while still ensuring the original level of system reliability. This amount of additional load can be used as a measure for capacity credit of wind power from the perspective of its load carrying capability.

Probabilistic methods have been widely used in power system planning, since they are capable of incorporating various system uncertainties [1]. The estimation of wind power capacity credit is based on the reliability indices such as loss of load expectation (LOLE). Here an analytical procedure based on the mean capacity outage table is used for LOLE calculation. A trial-and-error method has been used to find out the WPCC in our previous work [2]. However, due to the complexity and nonlinearity of this problem, this method is usually not computationally efficient since it demands tedious trial effort. In this work, for the first time WPCC estimation is formulated as an optimization problem, and an automatic intelligent search method is used to search for the WPCC value in a much more efficient fashion. Particle swarm optimization [3] is used for this purpose due to its proved high search efficiency in dealing with highly complex and nonlinear problems. Furthermore, a numerical study based on an IEEE RTS power system is conducted to indicate the viability of the proposed method. The method is also flexible and opens up other possibilities like incorporating constraints, if needed, while computing WPCC.

The remainder of the paper is organized as follows. Section II presents the concept and calculation of wind power capacity credit based on reliability evaluation for hybrid power-generating systems. Mechanism of particle swarm optimization is introduced in Section III. In Section IV, the proposed PSO-based WPCC estimation method is discussed in detail. Simulation results and analysis are presented and discussed in Section V. Finally, the paper is wrapped up with the conclusion and future research suggestion.

II. WIND POWER CAPACITY CREDIT

Due to the wind speed variations, the output of wind turbine generator (WTG) does not equal its rated capacity in most time periods. This creates difficulties for system planners since the effective capacity of WTG needs to be determined based on certain criteria. Quite often, reliability indices are used to measure the impact of the wind power penetration. Thus, in calculating wind power capacity credit, reliability indices such as loss of load expectation over the specified observation horizon are used to ensure that power system meets the reliability level after the wind power is integrated.

The reliability analysis of hybrid generating systems including time-dependent sources has been investigated through different methods including analytical, simulation, and artificial intelligence methods [4]–[9]. These proposed reliability evaluation techniques are usually intended to calculate the reliability indices including Expected Energy Not Supplied (EENS), Loss of Load Expectation (LOLE), and Loss of Load Frequency (LOLF), which are three fundamental indices for adequacy assessment of power-generating systems. In the calculation of wind power capacity credit, usually LOLE is used as the reliability index. Thus in this paper only LOLE will be discussed.

Assume the load is represented as a chronological sequence of $N_T$ discrete values $L_t$ for successive time steps $t = 1, 2, \ldots, N_T$. Each time step has equal duration $\Delta T = \frac{T}{N_T}$.
where \( T \) is the entire period of observation. The LOLE of the power system without wind power integration can be calculated as follows:

\[
LOLE = \Delta T \sum_{t=1}^{N_T} P_f(C_{gt} < L_t) \quad (\text{II.1})
\]

where \( P_f \) is the loss of load probability, \( C_{gt} \) is the capacity of conventional power sources, \( L_t \) is the load demand in period \( t \). The LOLE with wind power penetration can be calculated as follows:

\[
LOLE = \Delta T \sum_{t=1}^{N_T} P_f[(C_{gt} + C_{wt}) < L_t] \quad (\text{II.2})
\]

where \( C_{wt} \) is the effective wind power at time instant \( t \). In the above definition, the term \( C_{gt} + C_{wt} \) indicates the effective total system capacity (that is, the summation of conventional sources of power and wind power at time instant \( t \)).

From the definition of reliability-based wind power capacity credit, we need to ensure the identical power system reliability (LOLE in most cases) in both situations with and without wind power penetration:

\[
\sum_{t=1}^{N_T} P_f(C_{gt} < L_t) = \sum_{t=1}^{N_T} P_f[(C_{gt} + C_{wt}) < (L_t + E)] \quad (\text{II.3})
\]

where \( E \) is the capacity credit of wind power we need to find out.

### III. MECHANISM OF PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population-based stochastic optimization procedure inspired by certain social behaviors in bird groups and fish schools [3]. First a population of particles is randomly generated with initial speeds and positions. By utilizing the best positions encountered by itself and its neighbors, each particle updates its position according to its own flight experience and that of its companions.

Assume \( x \) and \( v \) denote a particle position and its speed in the search space. Therefore, the \( i \)-th particle can be represented as \( x_i = [x_{i1}, x_{i2}, \ldots, x_{id}, \ldots, x_{id}] \) in the \( M \)-dimensional space. Each particle continuously records the best solution it has achieved thus far during its \( M \)-dimensional space. As we can see, in PSO fewer parameters need to be adjusted as compared with other meta-heuristics such as genetic algorithms. PSO has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a particular requirement.

\[
\text{IV. THE PROPOSED METHOD}
\]

In the proposed method, we intend to find out the WPCC in an automatic manner using intelligent search based algorithm PSO.

#### A. Problem Formulation

The design objective is to find the WPCC variable \( E \), which is able to minimize the difference between LOLEs of the power system with and without wind power generation. Thus, the objective function in PSO is defined as (IV.6), which is to be minimized:

\[
F = \left( \sum_{t=1}^{N_T} P_f(C_{gt} < L_t) - \sum_{t=1}^{N_T} P_f[(C_{gt} + C_{wt}) < (L_t + E)] \right)^2
\]

(IV.6)

This is a highly nonlinear and complex function, since LOLE calculation is needed for each potential solution.

#### B. LOLE Calculation

An analytical reliability evaluation method for hybrid generation system is used here for LOLE calculation [7]. Distinguished from the negative margin method and clustering method, in this method the mean capacity outage table is constructed to calculate LOLE with reduced computational cost. The overall system is divided into two subsystems including the conventional subsystem and the unconventional subsystem (i.e., WTGs). The computation procedure for LOLE is laid out as follows:

- Build the capacity outage table, the cumulative outage probability and frequency tables for the conventional subsystem, using the unit addition algorithm.
- Build the capacity outage table, the cumulative outage probability and frequency tables for the unconventional subsystem considering the availability of intermittent sources, in a similar fashion.
- Build the capacity outage table for the overall system through combining capacity outage tables constructed in the above two steps.
- Build the mean capacity outage table for the conventional subsystem based on the recurrence approach.
- Calculate the hourly contributions to the LOLE.
C. Computational Procedure

In PSO, each particle is regarded as a potential solution (i.e. the wind power capacity credit), and many particles constitute a population. The dataflow diagram of the proposed method is shown in Figure 1, and the computational flow is detailed in the following.

1. Calculate LOLE by summation over the whole period of observation.

This procedure is called to calculate LOLE for each candidate solution in the optimization process of PSO.

2. Step 1: Some initialization operations are carried out, including the initialization of particle velocity and position, setting of initial iteration number, and so forth. Note that to expedite the search process by seeding a feasible solution, here the initial wind power capacity credit $E$ should fulfill the following constraint:

$$0 < E < P_w$$  \hspace{1cm} (IV.7)

where $P_w$ is the total wind power capacity integrated.

3. Step 2: Each particle is evaluated based on the specified objective function. Note that LOLE calculation is accomplished by calling the LOLE evaluation procedure presented in Section IV.B.

4. Step 3: The stopping criterion is examined. If it is satisfied, then the PSO procedure stops; Or else, proceed to the next step.

5. Step 4: The velocity and position of each particle are updated based on (III.4) and (III.5). These operations create particles of the next iteration.

6. Return to step 2 until any termination criterion is satisfied.

V. A NUMERICAL CASE STUDY

A WTGs-augmented IEEE Reliability Test System (IEEE RTS-79) is used in simulations [7]. The original RTS [10] has 24 buses (10 generation buses and 17 load buses), 38 lines and 32 conventional generating-units. The system annual peak load is 2850 MW. The total installed generating capacity is 3405 MW. In this study, one unconventional subsystem comprising of multiple identical WTGs is added to the RTS. Each WTG has an installed capacity of 1 MW, a mean up time of 190 hours and a mean down time of 10 hours. The hourly derating factors for WTG output can be found in [7]. These hourly derating factors used in the simulation studies for reflecting hour-to-hour variations have included the stochastic nature of wind power and are stochastic variables. Reliability indices are calculated for a time span of one week and the load cycle for week 51 with peak load 2850 MW, low load 1368 MW and weekly energy demand 359.3 GWh. The number of particles used in PSO is 80, and the maximum number of iterations is used as the stopping criterion, which is set 100.

The power system used in the numerical study has the peak load of 2850 MW with wind power penetration of 400 MW. Here PSO algorithm is used to find out the capacity credit $E$ by minimizing the objective function defined in (IV.6), and meanwhile reliability evaluation is conducted to calculate the LOLE for each candidate capacity credit value. When the value of objective function becomes sufficiently close to zero satisfying the required accuracy, the last candidate capacity credit achieved is deemed as the final result. In this way, the capacity credit obtained using this optimization procedure is 163.6 MW, which is about 40.9% of the total installed wind power capacity. Obviously, this method is highly advantageous in WPCC estimation with respect to the trial-and-error method since it does not require tedious trial efforts. It is also more accurate since the objective function (IV.6) can be minimized in a more effective fashion.

It should be noted that this method can also be implemented by other stochastic search algorithms including population based intelligent search (e.g., evolutionary algorithms and ant colony optimization) and non-population-based intelligent search (e.g., Tabu search and simulated annealing).

VI. CONCLUDING REMARKS

Due to the more significant penetration of wind power into traditional power grids in recent years, it has become necessary to calculate its capacity credit for decision-making in power system operations and planning. However, reliability-based WPCC calculation is difficult due to the problem complexity and nonlinearity. In this paper, as a new estimation scheme, particle swarm optimization algorithm is used as a search tool to seek out the wind power capacity credit based on the reliability index LOLE. A numerical example is used to illustrate the viability of the proposed method. In the future research, other intelligent search algorithms will be used to find the most efficient one in dealing with this problem.

REFERENCES


**Biographies**

**Lingfeng Wang** is currently with the Electrical and Computer Engineering Department of Texas A&M University, College Station. He is the author or co-author of two books and more than 50 technical publications. He is also the recipient of several awards from IEEE for his academic excellence, including the Walter J. Karplus Summer Research Grant from IEEE Computational Intelligence Society. His major research interests include integration of wind power, electric power systems, computational intelligence, and industrial informatics.

**Chanan Singh** (S’71-M’72-SM’79-F’91) is Regents Professor and Irma Runyon Chair Professor of electrical and computer engineering at Texas A&M University, College Station. Dr. Singh received the 1986-87 Haliburton Professorship and the 1992-1993 Dresser Professorship. He also served as Director of the NSF Power System Program from 1995 to 1996. He is a Fellow of IEEE, a senior TEES Fellow at Texas A&M University, and recipient of the IEEE 1998 Distinguished Power Engineering Educator Award. His major research interests include electric power systems, theory and applications of system reliability, production costing, and power quality.