Reliability Assessment for Power Systems with Large-scale Renewable Energy Sources

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Abstract—**This paper first to establish the reliability assessment models for the wind farms and the photovoltaic plant, and combined to the load model to assess the reliability of the power system based on the sequential Monte-Carlo simulation method. The influence on the power system reliability which is caused by different power generation capacities, access points of the new energy to the power system and the complementary access modes of the wind farms and the photovoltaic plant namely, simultaneously and separately, are all analyzed and compared in the case study computed in the IEEE-RTS79 testing system and programmed under Matlab7. The results show the effectiveness and efficiency of the proposed model and the algorithm.**

Index Terms—**Monte-Carla simulation; Photovoltaic plant; Reliability assessment; Wind farms**

I. INTRODUCTION

As the global economy and population growth are sped up, the fossil energy, mainly the petroleum, the gas and the coal, etc., are consumed gradually, which lead to the energy crisis imposed on the whole world and also provide the opportunity for the development of the clean energy, such as wind and solar energy. The stochastic nature and the volatility of the wind and photovoltaic power that are different from the conventional energy caused negative influence on the steady operation of the power system and call for the reliability assessment of the grid integrated with large-scale new energy.

References [1]-[3] construct the reliability model of wind power with the Weibull distribution simulating the wind velocity. In [4], [5], the system reliability with the integration of the wind farms is studied and the two methods of reliability assessment are compared. In [6], the reliability model of photovoltaic plant is constructed, and the reliability of the power system with wind and photovoltaic powers integrated complementarily is assessed. In [7], a Latin supercube sampling combined with Monte-Carlo simulation is presented. In [8], the conventional methods of assessing the power system are described. Based on the priority

sampling and the hierarchical sampling methods, hierarchical homogeneous sampling method is proposed to efficiently assess the fault state of the system. In [9], [10] assess the reliability of the power system with large-scale renewable energy by applying the Monte-Carlo simulation method, which is approved by the IEEE-RTS79 case study.

The reliability assessment models for the wind farms and the photovoltaic plant are constructed and integrated into the IEEE-RTS79 to compute the case study and compare the influence imposed by different access capacities, access points of the new energy to the power system and the complementary access modes of the wind farms and the photovoltaic plant.

II. RELIABILITY MODEL OF WIND FARMS

The wind farms are modeled according to [1], including wind velocity simulation, wake effect model and the wind power units model.

A. Wind Velocity Simulation

The two-parameter Weibull probability density equation is applied to derive the Weibull distribution for wind velocity simulation expressions, which is shown as follows

$$f(V) = \frac{k}{c}(\frac{V}{c})^{k-1} \cdot e^{-(V/c)^k} \ (k{>}0, V{>}0, c{>}1) \quad (1)$$

where k is the shape parameter, showing the skewness of the Weibull distribution, which ranges from 1.8 to 2.3, c is the scale parameter representing the average wind velocity; V stands for wind velocity.

Perform the interval integration of the equation between 0 and the given wind velocity v.

$$P(V \le v) = \int_0^k \frac{k}{c}(\frac{V}{c})^{k-1} \cdot e^{-(V/c)^k} = 1 - e^{-(v/c)^k} \quad (2)$$

Make x equals the right of (2) as follows,

$$x = 1 - e^{-(v/c)^k} \quad (3)$$

Inverse function transformation method is the commonly used method of generating stochastic variables, so by means of inverse function transformation, the following equations are obtained,

$$v = c[-\ln(1-x)]^{1/k} \qquad (4)$$

Because x and 1-x are both stochastic variables satisfying the even distribution, 1-x is replaced by x, and (5) is obtained as follows,

$$v = c[-\ln(x_i)]^{1/k} \qquad (5)$$

where x_i is the stochastic variable satisfying the even distribution. By (5), stochastic sampling of the wind velocity in each hour can be conducted.

B. Wake Effect Model

Considering wake effect models on the flat terrain and the complex terrain, the mathematical formulation for the wind farms with the same height of the wind power units is as follows,

$$v_x = v_0[1-(1-\sqrt{1-C_T})(\frac{R}{R+KX})^2]v'_{2x} \qquad (6)$$

where x is the distance to the installation sites of the wind power units where the wind blows; R is the radius of the fan blade; C_T is the pushing power coefficient which is related to the wind velocity and the structure of the wind power units; v_0 and v_X are the wind velocities blowing to and from the units separately; K is the wake effect coefficient which is proportional to the turbulence intensity. Note that,

$$(1-\sqrt{1-C_T})(\frac{R}{R+KX})^2 = d \qquad (7)$$

When the units are installed on the complex terrain, they are not at the same height. Suppose the wind velocities in the sites where the units are installed is v_0 with v'_{2X} the wind velocity in the sites where the units are not installed, the wind velocity influenced by the wake effect is as follows,

$$\begin{cases} v_{1x} = v_0(1-d_1) \\ v_{2x} = v'_{2x}(1-d_2) \end{cases} \qquad (8)$$

where d_1 and d_2 are the decreasing parameters for the corresponding wind velocities, the related formulas are shown below,

$$d_1 = (1-\sqrt{1-C_T})(\frac{R}{R+KX})^2 \qquad (9)$$

$$d_2 = d_1(\frac{v_0}{v_{2X}})^2 \qquad (10)$$

Suppose that only the wind power units along the downwind direction will be affected by the wake effect. And then, the flat terrain model will be adopted to analyze the units of the same height; the complex terrain model will be adopted to analyze the units with different heights.

The wind velocity will increase as the height above the ground increases. The exponential model is commonly used as shown below,

$$v = v_1(\frac{h}{h_1})^\alpha \qquad (11)$$

where v is the wind velocity where h meters above the ground, v_1 is the wind velocity where h_1 meters above the ground, α is the empirical exponent, ranging from 0.1 to 0.4.

C. The Power Output Characteristics of the Wind Power Units

The wind velocity is obtained through the calculation by means of the Weibull distribution simulation and wake effect model so as to fully describe the relationship between the wind velocity and the power output of the wind power units. The corresponding piecewise function expression is stated as (12).

$$\begin{cases} 0 & (v \le v_{ci}) \bigcup (v \ge v_{co}) \\ \frac{P_R}{v_R^3 - v_{ci}^3}(v^3 - v_{ci}^3) & v_{ci} \le v \le v_R \\ P_R & v \ge v_R \end{cases} \qquad (12)$$

where v is the wind velocity where the wheel hub of the wind power unit is installed, v_{ci} is the cut-in wind velocity, v_R is the rated wind velocity, v_{co} is the cut-out wind velocity, P_R is the rated power output of the wind power units.

III. RELIABILITY MODEL OF PHOTOVOLTAIC POWER UNITS

The output of the photovoltaic power is simple. According to the statistics, the solar irradiance in the given period approximately satisfies the Beta distribution, and the probability density function is stated as,

$$f(E) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot (\frac{E}{E_{\max}})^{\alpha-1} \cdot (1-\frac{E}{E_{\max}})^{\beta-1} \qquad (13)$$

where E and $E_{\max}$ are the practical and maximal light intensity respectively during the given period, Γ is the gamma function, α and β are the shape parameters for the Beta distribution. As for the solar generation system, the average light intensity μ and the related variance σ can be used to calculate the shape parameters, and the formula is specified as,

$$\alpha = \mu \cdot [\frac{\mu \cdot (1-\mu)}{\sigma^2} - 1] \qquad (14)$$

$$\beta = (1-\mu) \cdot [\frac{\mu \cdot (1-\mu)}{\sigma^2} - 1] \qquad (15)$$

The probability distribution of the power output can be obtained through the approximate relationship between the power output and the light intensity of the solar cell power system after obtaining the probability distribution of the solar light. The power output of the solar cell matrix is stated as,

$$P_M = EA\eta \qquad (16)$$

where E is the actual light intensity, A is the overall area of the matrix, η is the overall light-power conversion efficiency

of the matrix.

Because of the linear relationship between the power output and the light intensity of the solar power source, the probability intensity function of the photovoltaic array satisfies the Beta distribution, which is obtained by substituting (16) into (13), and the probability intensity function is stated as,

$$f(P) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}(\frac{P}{P_{max}})^{\alpha-1}(1-\frac{P}{P_{max}})^{\beta-1} \quad (17)$$

where $P_{max} = E_{max}A\eta$ is the maximal power output of the photovoltaic units array.

IV. CALCULATION PROCEDURE OF THE RELIABILITY ASSESSMENT

Formulate the reliability assessment model for power generation and transmission system with new energy and Fig.1 depicts the assessment flow chart.
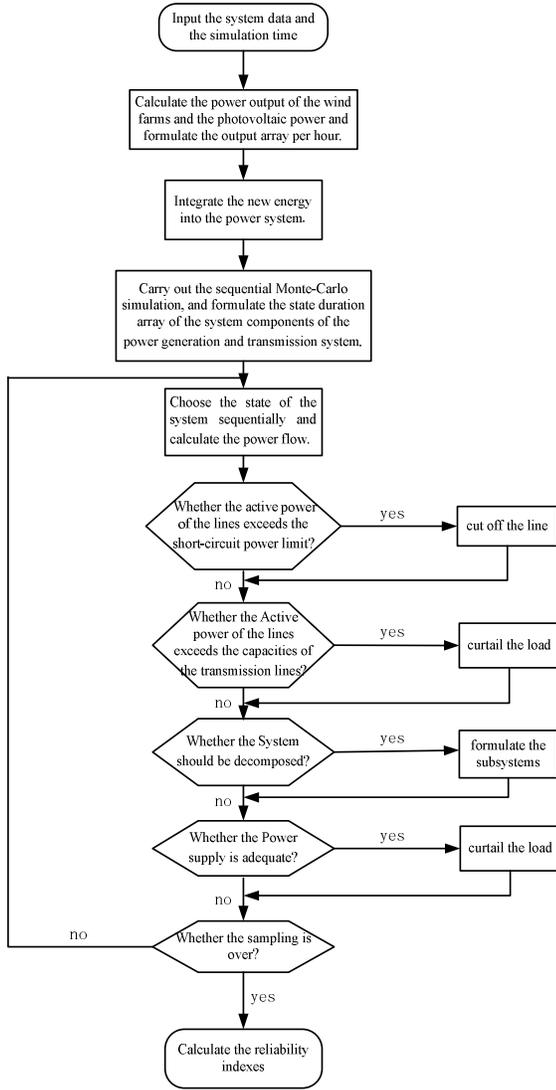

Figure 1. Calculation flow chart of the reliability indexes for the power generation and transmission system

The reliability of the power system with wind farms and photovoltaic power is assessed by applying the sequential Monte Carlo method, which samples the state duration of the component. The normal operation period and the repair period are commonly considered to satisfy the exponential distribution, which means the failure rate λ and the repair rate μ are constants. The normal operation period τ_1 and the repair period τ_2 can be computed as follows,

$$\tau_1 = -\frac{1}{\lambda}\ln\gamma_1 = -T_{MTTF}\ln\gamma_1 \quad (18)$$

$$\tau_2 = -\frac{1}{\mu}\ln\gamma_2 = -T_{MTTR}\ln\gamma_2 \quad (19)$$

In the expressions above, γ_1, γ_2 are the random numbers satisfying the even distribution, T_{MTTF} is the average normal operation period, T_{MTTR} is the average repair time.

V. CASE STUDIES

The IEEE-RTS79 is adopted to carry out the case study, which is composed of 32 power generation units，and the total installed capacity is 3405 MW, the peak load is 2850 MW, other parameters are available in [11].

A. The Influence on the Power System with Various Capacities of Wind Farms

There are totally 135 wind power units, arried in 9 lines, 15 units per line, and the equivalent reliability model is constructed according to the model of section 1. Suppose the parameters of the wind power units are all the same. The total capacity is 202.5MW, the shape parameter k=2.02, shape parameter c=8.03, empirical exponent α=0.3. And in bus 18, the wind power plants with the capacity of 202.5, 202.5*2, 202.5*3 each，will be installed separately. The calculation results are shown in Table I.

TABLE I.   RESULTS WITH WIND FARMS OF DIFFERENT CAPACITIES INSTALLED TO THE SYSTEM

Cases	Numbers of wind farms installed	LOLP	EDNS (MW)	EENS (MWh/y)
1	1	0.0864	14.5913	1.1044e+005
2	2	0.0845	14.4022	1.0655e+005
3	3	0.0836	13.8900	1.0288e+005
Original system	Without wind farm	0.0887	14.9707	1.1652e+005

The results in Table I are compared and can be concluded that as the capacity of the wind farms installed increases, the reliability of the system is improved relatively, which is indicated by the decreased reliability indexes, and proves the passive influence of the newly added wind power plants. At the same time, the improvement due to the installation of the wind farms is not obvious because of the high reliability of the system.

B. The Influence on the Reliability of the System Caused by the Wind Farms Siting

Three cases are designed.

Case 1 is three wind farms with the capacity of 202.5 MW each are installed in bus 7, 18 and 23 separatedly;

Case 2 is three wind farms with the capacity of 202.5 MW each are installed in bus 13, 15 and 16 separatedly;

Case 3 is three wind farms with the capacity of 202.5 MW each are installed in bus 18.

The results are shown in Table II.

TABLE II.   RESULTS WITH DIFFERENT INSTALLATION SITES

Cases	Installation sites	LOLP	EDNS (MW)	EENS (MWh/y)
1	7、18、23	0.0856	14.3294	1.0739e+005
2	13、15、16	0.0859	14.4182	1.0881e+005
3	18、18、18	0.0836	13.8900	1.0288e+005
Original system	Without wind farms	0.0887	14.9707	1.1652e+005

As for case 1 and case 2, the capacity of the lines will lead to different reliability assessment results. The installation modes, namely simultaneously and separatedly, will be of great difference as shown in case 1 and case 3, so the practical operation and the structure of the grid should be fully considered.

C. The Influence on the Reliability of the System with the Simultaneous Installation of the Wind and Photovoltaic Plants

The reliability assessment model adopts in section 2, and the parameters available are: the rated capacity is 50MW, the light-power transferring rate is 14.4%, and the shape parameters are 0.95 and 0.9. Five cases are designed as shown below

Case 1 is installing a photovoltaic power with the capacity of 50 MW in bus 18;

Case 2 is installing a wind farms with the capacity of 202.5 MW in bus 18;

Case 3 is installing a photovoltaic power with the capacity of 50 MW and a wind farms with the capacity of 202.5 MW in bus 18;

Case 4 is installing 4 photovoltaic powers with the capacity of 50 MW and a wind farms with the capacity of 202.5 MW in bus 18;

Case 5 is installing 2 wind farms with the capacity of 202.5 MW in bus 18.

The results are shown in Table III.

As shown in Table III, the effects are approximately the same when the photovoltaic and the wind power plants are installed separately, which shows lower reliability indexes and improves the system reliability. The simultaneous installation of the photovoltaic and wind power plants will improve the reliability than installation a wind farms only but the increase is not obvious, this is due to small capacity of the photovoltaic power. Simultaneous installation of the wind and photovoltaic power plants can improve the reliability than separately installation, which is proved by case 4 and case 5. So in order to make full use of the renewable energies of wind and solar energy, should consider using of wind and solar energy mutual-complementing power supply mode.

TABLE III.   THE TESTING RESULTS OF THE SYSTEM RELIABILITY WITH THE SIMULTANEOUS INSTALLATION OF THE WIND AND PHOTOVOLTAIC POWER PLANTS

Cases	The capacity of the new energy installed	LOLP	EDNS (MW)	EENS (MWh/y)
1	50	0.0880	14.5580	1.1222e+005
2	202.5	0.0864	14.5913	1.1044e+005
3	50+202.5	0.0862	14.4709	1.1038e+005
4	50*4+202.5	0.0853	13.9622	1.0439e+005
5	202.5+202.5	0.0845	14.4022	1.0655e+005
Original system	0	0.0887	14.9707	1.1652e+005

VI.   CONCLUSIONS

The reliability assessment models are constructed for the wind farms and photovoltaic power first, reliability model of wind farms with the Weibull distribution simulating the wind velocity considering the wake effect. By applying the sequential Monte Carlo method, the reliability differences are analyzed with large-scale new energy integrated into the system. Case study shows the improvement of the reliability caused by the integration of the new energy which is also influenced by the installation sites and the complementarity of the wind and photovoltaic power. Due to the natural scenery complementary, when installation the wind farms and photovoltaic power station at the same time, the reliability of the system is higher than individual access to.

The installation capacity of the wind and photovoltaic power plants should be optimized to fully manifest the different degree of contribution of various energy. So the nest step should be to study they capacity than finding the combination ratio, in order to ensure the reliability and economy of the wind and photovoltaic systems.

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