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Reliability assessment of generating systems containing wind power and air separation unit with cryogenic energy storage

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ABSTRACT

The acceptance of wind power has been increased in power systems because of environmental problems and production cost of conventional generation units. High penetration of intermittent wind power can increase risk level in power systems. The combination of energy storage with wind power is considered as a solution for problems of high wind integration. Energy storage can increase the reliability of power systems with high penetration of renewable energies like wind farms. In this paper, the cryogenic energy storage is used, which stores the air in the form of liquid and recover the power when it is needed. The copula theory is employed to generate correlated random variables to determine the wind speed of different locations. Also, for calculating the probability of availability of wind farm and energy storage system, Markov approach is adopted. Monte Carlo Simulation (MCS) method is implemented for obtaining reliability index of the system. The proposed method is verified using comprehensive simulations on Roy Billinton test system (RBTS) reliability test system considering the capacity of wind farms, level of wind penetration and size energy storage.

1. Introduction

Considering economic issues of conventional energy generation systems and public environmental concerns about greenhouse effects, wind power generation in electric power system is considerably increasing. From the viewpoint of capacity ratings and electricity production cost, the wind farms are able to compete with conventional power plants. In the last decade, the installed wind capacity has enhanced about 30% per annum in the world. New policies in many countries have been established to encourage investing in renewable energy. Wind power has been shown to be the fastest growing between renewable energy sources in the last decade [1]. In Ref. [2], the effects of wind power penetration in CO2 emission with presence of carbon tax has been studied at the power market. In Ref. [3] the main factors of effecting the penetration of wind power until 2015 have been assessed and concluded that the wind resources potential and climate targets have the largest effect between wind power penetration factors also, penetration of wind power has been widely studied in Refs. [4–7].

Because of the intermittent feature of wind speed and probabilistic manner of wind generators outage, wind farms output power are stochastic and different from conventional generation units [8]. There are several methods for forecasting wind speed and obtaining output power of wind generator like auto regressive method [9] and neural network models [10]. One of the stochastic methods that used for determining wind farms output power by considering historical data is Copula theory [11]. The wind speed of the two sides that wind farms located on, are correlated and Copula theory is used for obtaining the dependent wind farms output power and degree of dependence. This theory find suitable Copula function that well represents the dependence and generate random numbers considering the correlation structure [12].

Under this perspective, the penetration of large number of wind turbine generators into electric power system can bring some problems of uncertainty in preserving load demand. Implementing of energy storage in power system can play an important role to better manage the uncertainty of wind farms output [13]. A list of various energy storages includes pumped hydroelectric storage [14,15], compressed air energy storage [16], batteries including lead acid, nickel cadmium and lithium ion [17], hydrogen storage [18], cryogenic energy storage [19], underwater compressed air energy storage (UWCAES) which is used to store the power of offshore renewable energy resources [20] flywheel [18,21],

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Nomenclature

w_1,w_2, u_1, u_2	Random variables
$F_{12}(U_1, U_2)$	Joint CDF of random variables
C	Copula function
d_n	Euclidean distance
S_t	Wind speed at time t
$P(S_t)$	Wind power at time t
$LOLE$	Loss of load expectation
$LOLP$	Loss of load probability
X_t	Binary indicator for showing the capability of system to meet demand at each time interval t
ρ_t	Probability of failing at each interval t
Sur_w	Surplus wind power
Sur_c	Surplus power of conventional generation units
X	Percent of system load providing by combination of wind and storage system
ES_t	Energy stored in energy storage at time t
P	Matrix of defined Markov chain
P_c	Probability of each chain c

superconducting magnetic storage [22], Isobaric Adiabatic Compressed Air Energy Storage (IA-CAES) [23] and capacitor and super capacitor storage [21]. In this paper, cryogenic energy storage (CES) with air separation unit (ASU) is used. In [24] the contributing of ASU with CES in the reserve market and using demand side management application have been studied.

According to the complexity of wind farms and energy storage contribution, stochastic model must be used. One of these models is Markov approach [25,26]. In this method for calculating probability of each operational state, differential equations according to the Markov matrix must be solved. This method simplifies calculation of probability and frequency of healthy operating condition and definitely separates the healthy states from other operating states. Several approaches were used for reducing numerical difficulties in solving Markov matrix [27,28].

Reliability analysis of wind generators has been studied in Refs. [29–31]. There are two main approaches for evaluating reliability of power system with high incorporation of wind farms. First method is Monte Carlo simulation (MCS). This method used sequence checking of wind velocity and wind farm output power with load demand [32]. Other method for evaluating reliability is analytical approach. This approach usually used for power system planning reliability estimation. MCS with reliability indices, loss of load expectation (*LOLE*), is used in this paper which represent system reliability in a long period of time [33].

In this paper, Copula theory is developed for generating correlated wind speed data that used in MCS method also, Markov chain and Markov matrix are defined for calculating probability of different operating states of system and finally *LOLE* and *LOLP* of RBTS test system is obtained by considering different levels of energy storage penetration beside wind farms.

The remainder of this paper is organized as follows. Formulation of Copula theory and energy storage is presented in Section 2. Section 3 outlines operating strategy of wind farm and energy storage. Section 4 presents simulation techniques including Markov approach and reliability calculation method. The conclusion and suggestion of new direction for future works has been brought in Section 5.

2. Formulation

2.1. Copula function

Copula first represented by Sklar in 1959 [34], Copula is the function that link multivariate joint CDF to their one-dimensional marginal CDFs.

$$F_{12}(w_1, w_2) = C(F_1(w_1), F_2(w_2)) \tag{1}$$

w_1, w_2 are random variables and F_{12} is multivariate joint CDF.

If the marginal CDFs i.e., $F_1(w_1)$ and $F_2(w_2)$, are continuous, then Copula function C is unique; otherwise C is unique on the range of the marginal CDFs.

For random variable w with an invertible CDF $F(w)$, the random variable $U = F(w)$ follows as a uniform distribution on the interval [0,1] according to:

$$u \in [0, 1] : P(U \le u) = P(F(w) \le u) = P\left(w \le F^{-1}(u)\right) = F\left[F^{-1}(u)\right] = u \tag{2}$$

For random variables $U_1 = F_1(w_1)$ and $U_2 = F_2(w_2)$, the joint CDF $F_{12}(U_1, U_2)$ can be obtained by using the following equation.

$$F_{12}(U_1, U_2) = P(U_1 \le u_1, U_2 \le u_2) = F_{12}\left(F_1^{-1}(u_1), F_2^{-1}(u_2)\right) = C(u_1, u_2) \tag{3}$$

According to Eq. (3), the joint CDF of random variables that are uniformly distributed in [0,1] can be obtained by suitable Copula function. Where $F_1^{-1}(u_1)$ and $F_2^{-1}(u_2)$ are the inverse functions of $F_1(w_1)$ and$F_2(w_2)$, respectively. u_1 and u_2 fit to [0,1]. By using historical data, choosing a suitable Copula function to fit the data is an important but difficult problem. Very common Copula functions are Gaussian Copula, Gumbel Copula, Clayton Copula and Frank Copula. Based on the historical data of wind speed, different Copula functions is tested and suitable Copula function is selected Based on the empirical Copula function and Euclidian distance.

The Euclidean distance between theoretical Copula function C and empirical Copula function C_e can be obtained by:

$$d_n(C, C_e) == \left\{ \sum_{i_1=1}^{n} \cdots \sum_{i_m=1}^{n} \left[C\left(\frac{i_1}{n}, \ldots, \frac{i_m}{n}\right) - C_e\left(\frac{i_1}{n}, \ldots, \frac{i_m}{n}\right) \right]^2 \right\}^{1/2} \tag{4}$$

The optimal Copula function C with the smallest Euclidean distance d_n can be obtained to fit the given dataset.

The hourly wind speed (S_t) obtained from the Copula fitness function can be used for calculating the available power output as follows:

$$P(S_t) = \begin{cases} 0 & 0 \le S_t < V_{ci} \\ (A + B \times S_t + C \times S_t^2) \times P_r & V_{ci} \le S_t < V_r \\ P_r & V_r \le S_t < V_{co} \\ 0 & S_t \ge V_{co} \end{cases} \tag{5}$$

Where V_{ci}, V_r and V_{co} are cut-in, rated and cut-out wind speed and the data used in this paper are 4, 12.5 and 25 m/s. P_r is the rated power of wind generator and the constants A, B and C are determined by V_{ci}, V_r and V_{co}, respectively [35]. The total power output from the wind farm can be obtained by summing up the individual output power of each wind generator.

By using wind farm and energy storage has been shown that the fitness level of system can be improved. The extra energy of wind generator can be used for charging energy storage. Energy storage has significant good effect on the reliability of isolated power systems.