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Wind farm electrical power production model for load flow analysis

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ABSTRACT

The importance of renewable energy increases in activities relating to new forms of managing and operating electrical power: especially wind power. Wind generation is increasing its share in the electricity generation portfolios of many countries. Wind power production in Spain has doubled over the past four years and has reached 20 GW. One of the greatest problems facing wind farms is that the electrical power generated depends on the variable characteristics of the wind. To become competitive in a liberalized market, the reliability of wind energy must be guaranteed. Good local wind forecasts are therefore essential for the accurate prediction of generation levels for each moment of the day.

This paper proposes an electrical power production model for wind farms based on a new method that produces correlated wind speeds for various wind farms. This method enables a reliable evaluation of the impact of new wind farms on the high-voltage distribution grid.

1. Introduction

Wind farms are the most common and fastest growing application of wind energy [1]. Most installed wind power in Spain is used for this purpose and a total of nearly 20 GW were operating in 2009. Further massive installation of wind farms is planned in Spain and Europe in the near future [2].

The typical configuration of a wind farm connected to the transmission grid is formed of a set of wind generators connected through a medium voltage (MV) network with shared infrastructure for access and control [3]. Transformers connect the wind farms to the transmission grid are sized according to the rated power of the plants. Electricity from wind farms differs from electricity produced by traditional generators because the power flow between wind farm and the transmission grid depends on an uncontrollable source – the wind. Accurate wind forecasts are therefore essential to forecast generation for each moment of the day.

A wind farm is a complex system with many elements required for modelling purposes. For the implementation of an electrical power production model of a wind farm, it is first necessary to create a model for the wind speed at each moment. Secondly, a probabilistic outage model based on the failure probabilities of the wind farm elements is needed. Finally, the probability of supply is calculated from the current values of the wind speed; the failure probabilities; and the wind farm configuration. A compromise must also be made in the selected model between the simplification level and the time needed for calculation.

2. Proposed wind farm production model

A model to calculate production in a wind farm is proposed in order to evaluate the impact of a wind farm on the power transmission grid. This model converts wind speed data into the electrical production data injected into the PQ-bus of the grid. The following factors have been taken into account when designing the model.

- Wind farm generators are asynchronous.
- Wind speeds in the various locations of the wind farms are obtained using Monte Carlo techniques, considering correlation among wind speeds in the various wind farms, and that the probability distribution of wind speed is a Weibull distribution [3].
- Power generated by a wind turbine is a function of the wind speed, according to a power curve given by the manufacturer. The total electrical power of a wind farm is the sum of the power generated by all the modelled generators while taking into account the failure probabilities of each.
- Reactive power consumed by asynchronous generators is obtained as a function of the generated active power, $Q = f(P)$ [4,5].

The process to develop the wind farm model was implemented in the following steps.

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- Modelling of the wind speed in the wind farm.
- Correlation among the wind speeds in the considered wind farms.
- Modelling the number of wind turbines running in each wind farm.

In the first step it is well known that wind speed probability distribution is generally considered to follow a Weibull distribution. This function depends on three parameters (ξ_0, α, and c) as given by the formula:

$$F(x) = 1 - \exp\left\{ - \left(\frac{x - \xi_0}{\alpha} \right)^c \right\}, \quad x > \xi_0 \tag{1}$$

where:
x = wind speed.
α = scale parameter. The value of this parameter is related with the average wind speed at the location. If the wind speed probability distribution is given in m/s then

$\alpha \in [0.01, 20]$

- c = shape parameter, also known as the slope, because the value of 'c' is equal to the slope of the regressed line in a probability plot. Different values of the shape parameter can have marked effects on the behaviour of the distribution. In the case of wind speed probability distribution: $c \in [0.25, 2.5]$.
- ξ = location parameter. In this particular case, as the minimum wind speed is 0, $\xi_0 = 0$.

It is therefore easy to generate 'pseudorandom' observations using approaches such as:

$$U = F(X; \xi_0, \alpha, c) = 1 - \exp\left\{ - \left(\frac{X - \xi_0}{\alpha} \right)^c \right\} \tag{2}$$

while inverting the transformation produces:

$$X = \xi_0 + \alpha(-\ln(1 - U))^{1/c} \tag{3}$$

After the generation of 'pseudorandom' observations U of a uniform distribution (0, 1), the required observations X of a Weibull distribution can be obtained from the previous expression for specific values of ξ_0, α, and c. This simple process is easily programmable in a computer.

3. Wind speed correlation

There are many situations in which the generation of correlated random variables is desirable. It is possible to find in the literature many studies that develop algorithms that generate multivariate normal distributions; or multivariate lognormal distributions when the variables are positive. An alternative to these methodologies is proposed in Section 3.2.

3.1. Current methods for obtaining correlated wind speeds

Current methods do not produce predictions on a future horizon and therefore produce a series of wind speeds that are converted into electrical power outputs by the models which evaluate the impact of the wind farms on the electrical power system (SEP). These methods can be classified in two groups.

(a) Methods based on wind speed distribution simulations [4,5].

These methods start from standardised random variables that are difficult to adapt to a two-parameter Weibull distribution. A non-standard method based on the Cholesky decomposition of the covariance matrix is used. This method is only valid for normal distributions and also presents the following drawbacks.

- Weibull distributions with a fixed parameter are used (Rayleigh distributions).
- Negative wind speeds appear in some series.

(b) Methods based on chronological wind speed series [6,7].

These methods use temporary wind speed series and this implies that the speed observed in period t influences the following period. In this case, it is not a random sample.

3.2. Proposed method to obtain correlated wind speeds

The method proposed in this paper belongs to type (a) and a new algorithm has been developed to avoid the described inconveniences. This method enables the wind speed to be considered as a random variable that follows a Weibull distribution. This idea is broadly discussed and accepted [3].

The generation method proposed here requires a series of restrictions on the space of the generated distribution parameters; in particular, the covariance will not be negative (meaning that correlation among the wind speeds of the various wind farms must be positive) [8]. To generate these random values, the developed algorithm starts with the simulation (using Monte Carlo techniques) of the $n + m$ independent variables that follow a Weibull distribution; with 'n' being the number of wind farms, and 'm' being a parameter used only for simulation purposes. These variables are used in a non-lineal programming problem to obtain the Weibull distribution multivariate with the desired covariance matrix. To obtain the parameter 'c' the estimator proposed by Menon (1963) [9] is used. The steps in the proposed method are as follows.

Step 1: Simulate k values of $n + m$ independent uniform random variables (following the scheme mentioned previously) and being $n < m$:

$$U_i(0,1), \quad i = 1, \ldots, n$$

$$U_j(0,1), \quad j = 1, \ldots, m$$

Step 2: Calculate $n + m$ independent Weibull random variables:

$$X_i = \alpha_i \cdot (-\ln(1 - U_i))^{1/c_i}, \quad i = 1, \ldots, n$$

$$Y_j = \alpha'_j \cdot (-\ln(1 - U_j))^{1/c'_j}, \quad j = 1, \ldots, m \tag{4}$$

Step 3: Define $n \times m$ T matrix of the repeated value 1 (adjacent matrix).

Step 4: Calculate n Weibull random variables: $Z = X + T * Y$

$$\begin{aligned} Z_1 &= X_1 + t_{11}Y_1 + \ldots + t_{1m}Y_m \\ &\vdots \\ Z_n &= X_n + t_{n1}Y_1 + \ldots + t_{nm}Y_m \end{aligned} \tag{5}$$

Steps 1, 2, 3, and 4 enable us to obtain the 'n' correlated random variables that follow a multivariate Weibull distribution. Each of these variables is a lineal combination of the '$m + 1$' independent random variables and follows a univariate Weibull distribution [8].

Step 5: Calculate n scale parameters:

$$\begin{aligned} a_1 &= \alpha_1 + t_{11}\alpha'_1 + \ldots + t_{1m}\alpha'_m \\ &\vdots \\ a_n &= \alpha_n + t_{n1}\alpha'_1 + \ldots + t_{nm}\alpha'_m \end{aligned} \tag{6}$$

Step 6: Calculate n variables: