ASSESSMENT OF STEADY-STATE SECURITY IN NETWORKS WITH HIGH PENETRATION OF WIND ENERGY

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ABSTRACT: the purpose of this paper is to propose methods for statistical assessment of steady-state security in electrical power systems, when influenced by wind energy. Statistical assessment is necessary because wind parks are very variable generation systems, due to characteristics of the wind.
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1 INTRODUCTION

The concept of power system security can be found in [1], according to which reliability, security and stability are related terms.

Security is an operating problem and is determined by the relationship between reserve margins and the contingent probability of disturbances. The power system is generally assumed to be sufficiently strong and the wind penetration sufficiently low, so that there is no restriction to the power produced by the wind turbines (WT) [2]. But certain regions, such as Galicia, in the northwest of Spain, are going to receive a large amount of wind energy in future years, which makes utility managers think that such an assumption should probably not be held. In this case, a more in-depth study has to be made, which involves the development of more accurate models.

In this paper several methods are commented, for steady-state security assessment of electrical power systems, when affected by a large injection of power from wind farms. The methods explained can be classified into two groups:

1. Methods for simulating wind speeds.
2. Methods for analysing the effects of a given distribution of wind speeds on the electrical power system.

Both allow us to obtain correlated series of wind speeds. But the following observations have to be taken into account:

- The series obtained in the proposed simulation methods do not have a chronological meaning, even in the case of those based on chronological series. They only have a cumulative meaning.
- As the data needed for power flow analysis are powers, and not wind speeds, the wind speed series must be converted into electrical power series. For this reason, the wind park model, which allows the conversion of wind speeds into electrical powers, must be described.

2 MODEL OF THE WIND PARKS

One thing that is common to the four commented methods is the model of the wind parks.

In order to carry out the simulation some assumptions can be made. The first assumption is the fact that all the wind parks are constituted by asynchronous machines, which is almost always true in our region, where the total amount of wind energy being produced nowadays is by this kind of machine, and where the trend seems to be the same in the future.

Also, before introducing the model of the wind farm, it can be said that this model is relatively simple. Although there are more complex models for every part involved in the conversion of wind speed into power, the simple model proposed here is accurate enough for the purposes of the paper.

According to available data, the following can be said:

Sometimes there are electrical data, and no wind speed series. When generated data are real powers and consumed reactive powers, wind parks are simulated as PQ nodes.

When, on the other hand, available data are wind speeds or wind speed distributions, wind parks can also be modelled as PQ nodes, by means of the following operations:

1. The power generated by a WT can be obtained from its power curve P=f(U), where U is the wind speed, when the power coefficient curve against tip speed ratio $c_p=g(\lambda)$ is known [3]. Generally, the power curve is given by the manufacturer.
2. The reactive power consumed by an asynchronous WT can be obtained from the real power generated Q=h(P), under several assumptions [4, 5, 6]. The expression used here is $Q=-XP^2$, where X is the sum of the rotor and stator leakage reactances of the machine, data that can be given by the manufacturer [7]. The previous equation is generally an acceptable approximation, when operated in p.u. values.
3. The power generated by the wind park is the sum of the powers generated by all WT's of the wind park, under the assumptions that all WT's are equal and the wind speed is the same for them all. Considerations about availability of machines are here neglected. Relating to this point, better approximations can be made depending on the degree of knowledge about the wind park.

3 THE PROPOSED METHODS

The major concern for utilities is system reliability. According to this, the typical question that can be asked by them is: “how much time a year will our utility have problems caused by the existence of wind parks in the electrical network?”

In order to answer questions like this, the following methods are proposed.

3.1 Method based on simulation of wind speed distributions

This first method [4] is based on the use of Monte Carlo simulation to obtain groups of simultaneous wind speeds for different locations. These wind speeds will then be used to obtain the powers of the wind generators, according to the wind park model previously presented.

In order to carry out the Monte Carlo method, an inversible distribution function must be used. This condition is fulfilled by both Weibull and Rayleigh distributions, widely accepted and generally used to simulate wind characteristics. The difficulty using this method appears when trying to obtain adequate correlation between wind speeds for different places. In this case, the expression:

$$\mathbf{y}=\mathbf{L}\mathbf{x}+\boldsymbol{\mu}$$

is used, where **y** is the vector whose components are the correlated wind speeds, **x** is the vector of uncorrelated wind speeds, **L** is a lower triangular matrix and μ is the vector with the mean wind speeds of the different locations. Matrix **L** can be obtained from the covariance matrix **M** by means of the Cholesky method, fulfilling:

$$\mathbf{M}=\mathbf{L}\mathbf{L}^{T}$$

As mentioned, **M** is the covariance matrix whose elements are the covariances (this can alse be made with the correlation matrix) between the different wind speed series.

The main problems that appear when trying to use this method are the following:

1. The distributions used in **x** should be typified. Even so, in the case of Weibull distributions, when they have different scale and shape factors, the shapes of the resulting distributions are different. This problem is avoided by using Rayleigh distributions, recommended by IEC standards, such as IEC 61400. The Rayleigh distribution is defined by its mean value, and for a given mean value, its shape factor is fixed, and so is its shape.
2. The other problem is that, when using this method of simulation, negative speeds appear in some series. This is due to the fact that the method works correctly for normal distributions, but does not do so for other distributions. A possibility for avoiding the appearance of negative values is to reject series with negative wind speeds, which means loss of accuracy. Generally, no more than 5 % of values should be neglected, although more statistical investigation can be done here.

The result of applying this method is generally very satisfactory, although when there is a large number of wind parks, the shapes of the resulting distributions may differ greatly from the original shape. The process of simulation is sequencial, and so this is not true for the first distribution simulated, but is increasingly so for the following distributions. However, the mean values and standard deviations are not affected.

3.2 Method based on the use of chronological series

Like the previous one, this method is better explained in [4].

It is based on the knowledge of chronological series of simultaneous wind speeds, and a brief description of it follows.

Let us suppose that we have some series of simultaneously measured wind speeds at different locations. The method consists of making the assumption that future wind behaviour will be similar to the past. So, we take the measures as a sample that will be continuously repeated.

A Monte Carlo simulation procedure can be made by picking values from these chronological series.

The advantage of this method is that the average wind speeds coincide with the existing wind speeds, and the same can be said about the correlations between different series.

The disadvantage is that it can have a relatively high degree of uncertainty. The authors have applied the method with a small data sample, as can be seen in an example later.

3.3 Effect on the electrical power system

In the explained methods, the goal was to obtain series of wind speeds, that could represent the simultaneous wind speeds at different locations in a cumulative way.

The effect on the electrical power system can be analyzed by converting these wind speeds into powers, as explained before, and then power flow analyses are run with the data obtained in order to gain voltages in the different nodes and currents through the different lines.

Several ways of calculation can be followed, the first of which was already tested and consists of the realization of multiple power flow analyses. The other two methods are proposed here for discussion.

<u>Multiple power flow analyses</u>

The first method of analysing the effect on the power system consists of applying the powers obtained from the wind speeds as inputs for the load flow analysis.

The results in such a method are typical results from power flow analysis, e.g. voltages in the different nodes, powers through the lines, reactive powers in the PV nodes, and powers in the slack node.

The results should be given in a statistical way. For example, as different graphs showing appearance of frequency for the different values of the variables mentioned.

This allows us to establish the security levels, by knowing the number of cases where the values of the electrical variables are over or under their recommended values. This can be given as their relative frequencies in the simulated cases.

The main disadvantage is that, generally, a lot of power flow analyses must be carried out, which involves more calculation time, although this is not so inconvenient, with modern computers.

Later, two examples of the use of this method are presented.

<u>Classification in intervals</u>

This second method, like the third one explained later, has the intention of carrying out a lower number of power flows than the previously proposed one.

In this case, the following procedure must be carried out:

1. The powers generated in all the wind parks are classified in intervals.
2. The combinations of all the possible intervals in the different wind parks are established and codified. Codification is recommended only to deal with the problem easily.

3. The intervals with no probability of appearance (which are generally numerous) are neglected. As an example, it is not very probable for a wind park to generate more than 75% of its nominal power, when a nearby wind park is generating less than 25%. Most likely is that this case never appears and its relative frequency will probably be near to 0. The cases with relative frequency of appearance equal to 0 are, of course, not studied.
4. The combination of the other intervals (the most probable combinations), or "scenarios", are then studied, by means of their maximum and minimum values.

With this method, different power flow analyses must be carried out, not with real injected power values, but with extreme values from the intervals of the classification. This allows a classification of results. Correct application of this method is not clear yet, and is proposed for discussion. But probably, the best way of using it will be by application of the maximum or the minimum values of injected powers.

Method based on statistical operations

Finally, what we here call the statistical method, is described. For its application, an additional assumption must be made, consisting of accepting the linearity of the electrical power system. This means that the method accepts a new degree of error, because it is an approximation.

In the conventional resolution of the load flow analysis by means of the Fast Decoupled Newton-Raphson algorithm, voltage variations (modulus and angle) can be written as a funcion of active and reactive powers such as:

$$\begin{pmatrix}\Delta\delta\\ \Delta V\end{pmatrix} = J^{-1}\begin{pmatrix}\Delta P\\ \Delta Q\end{pmatrix} = \begin{pmatrix}B' & 0\\ 0 & B''\end{pmatrix}\begin{pmatrix}\Delta P\\ \Delta Q\end{pmatrix}$$

where the submatrices B' and B'' are M-matrices [8, 9, 10]. M-matrices have the property that their inverse matrices are such that their diagonal elements are of different sign from the non-diagonal elements. This can be very useful for method application purposes.

The previous equations must be used for calculating variations of voltage and angle values from their values in a given situation. In this case, the values of ΔP and ΔQ are given by the variations inside the intervals described in the previous method.

The mentioned property of M-matrices can probably be useful here, to foresee the signs of Δδ and ΔV variations, taking into account the signs of ΔP and ΔQ variations.

The method is still being implemented by the authors.

4 EXAMPLES

As an example, the methods for obtaining wind speed series were applied to a part of the Galician electrical network with seven wind parks. In table I the following data can be seen: in column 1 a number assigned to the wind park, in column 2 the C parameter of the Rayleigh distribution of the wind park, in column 3 average wind speed, in column 4 calculated average wind speed with the first method of calculation and in column 5 calculated average wind speed with the second method.

Table I: Wind park data of example 1

Wind park	C	U_s	U_{cI}	U_{cII}
1	6,54	5,8	5,9	6,1
2	6,77	6,0	6,1	6,3
3	6,99	6,2	6,3	6,3
4	5,98	5,3	5,4	5,5
5	6,54	5,8	5,9	5,6
6	7,22	6,4	6,5	6,3
7	10,49	9,3	9,5	9,3

In the same example, the correlation matrix of the wind speeds from the seven wind parks is the following:

$$\begin{pmatrix} 1,00 & 0,87 & 0,83 & 0,84 & 0,02 & -0,01 & -0,03\\ 0,87 & 1,00 & 0,91 & 0,89 & 0,06 & 0,04 & 0,02\\ 0,83 & 0,91 & 1,00 & 0,86 & 0,09 & 0,07 & 0,05\\ 0,84 & 0,89 & 0,86 & 1,00 & 0,05 & 0,04 & 0,02\\ 0,02 & 0,06 & 0,09 & 0,05 & 1,00 & 0,90 & 0,82\\ -0,01 & 0,04 & 0,07 & 0,04 & 0,90 & 1,00 & 0,87\\ -0,03 & 0,02 & 0,05 & 0,02 & 0,82 & 0,87 & 1,00 \end{pmatrix}$$

As a result, the correlation matrix obtained by means of the first method is the following:

$$\begin{pmatrix} 1,00 & 0,86 & 0,82 & 0,83 & 0,02 & -0,01 & -0,03\\ 0,86 & 1,00 & 0,90 & 0,88 & 0,05 & 0,03 & 0,01\\ 0,82 & 0,90 & 1,00 & 0,85 & 0,08 & 0,06 & 0,04\\ 0,83 & 0,88 & 0,85 & 1,00 & 0,04 & 0,03 & 0,01\\ 0,02 & 0,05 & 0,08 & 0,04 & 1,00 & 0,90 & 0,81\\ -0,01 & 0,03 & 0,06 & 0,03 & 0,90 & 1,00 & 0,86\\ -0,03 & 0,01 & 0,04 & 0,01 & 0,81 & 0,86 & 1,00 \end{pmatrix}$$

And the correlation matrix obtained by means of the second method:

$$\begin{pmatrix} 1,00 & 0,87 & 0,82 & 0,84 & 0,04 & 0,01 & -0,02\\ 0,87 & 1,00 & 0,91 & 0,89 & 0,09 & 0,08 & 0,06\\ 0,82 & 0,91 & 1,00 & 0,86 & 0,12 & 0,11 & 0,08\\ 0,84 & 0,89 & 0,86 & 1,00 & 0,08 & 0,08 & 0,05\\ 0,04 & 0,09 & 0,12 & 0,08 & 1,00 & 0,90 & 0,80\\ 0,01 & 0,08 & 0,11 & 0,08 & 0,90 & 1,00 & 0,87\\ -0,02 & 0,06 & 0,08 & 0,05 & 0,80 & 0,87 & 1,00 \end{pmatrix}$$

As can be seen in the example, the accuracy is high with both methods, because the correlations obtained are very close to those given as data.

With the first method, less than 5 % of the simulated cases had a negative value and had to be neglected.

An example of the application to the assessment of steady-state security of a network is proposed, which was solved by means of the first of the three methods commented before: it consists of a group of eight wind parks, that under certain circumstances can be injecting their powers into the electrical network through a single line. In this case, the relative frequency of the total power values given by all the wind parks was obtained. What was looked for in this method was the probability of the line transporting an amount of power over the recommended one. The characteristics of the wind parks are given in table II:

Table II: Data of the wind parks of example 2

Wind park	P (MW)	C	U
1	15	8,46	7,5
2	18	8,46	7,5
3	20	8,46	7,5
4	17	8,46	7,5
5	24	6,77	6
6	20	6,77	6
7	3	8,46	7,5
8	40	6,77	6

As the data of the wind parks were not known, they were estimated as a function of the area and altitude. For this application the European Wind Atlas was used.

The following matrix is the estimated correlation matrix between wind speeds of the wind parks, and was estimated according to the proximity of the wind parks:

$$\begin{pmatrix} 1,0 & 0,2 & 0,2 & 0,0 & 0,0 & 0,0 & 0,0 & 0,0 \\ 0,2 & 1,0 & 0,8 & 0,2 & 0,0 & 0,0 & 0,0 & 0,0 \\ 0,2 & 0,8 & 1,0 & 0,0 & 0,0 & 0,0 & 0,0 & 0,0 \\ 0,0 & 0,2 & 0,0 & 1,0 & 0,0 & 0,0 & 0,9 & 0,0 \\ 0,0 & 0,0 & 0,0 & 0,0 & 1,0 & 0,0 & 0,0 & 0,0 \\ 0,0 & 0,0 & 0,0 & 0,0 & 0,0 & 1,0 & 0,0 & 0,0 \\ 0,0 & 0,0 & 0,0 & 0,9 & 0,0 & 0,0 & 1,0 & 0,0 \\ 0,0 & 0,0 & 0,0 & 0,0 & 0,0 & 0,0 & 0,0 & 1,0 \end{pmatrix}$$

As a result, the relative frequency of the total power was as in the following graph:

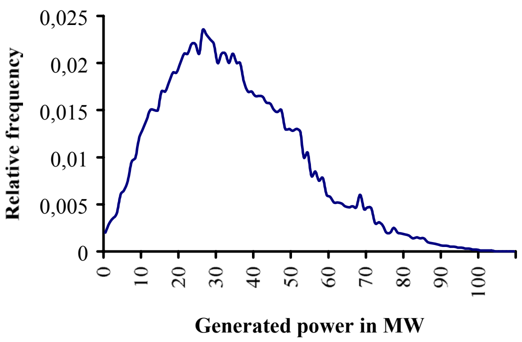

Figure 1: Relative frequency distribution of the total generated power

5 CONCLUSIONS

Several methods have been used for steady-state security assessment of electrical power systems with high penetration of wind energy.

In a first place, two methods were proposed for obtaining simulated wind speeds fulfilling the properties of their statistical distributions.

Then, by converting the obatined wind speeds into electrical powers, several ways of assessing steady-state security have been proposed.

The best way of testing the effects of the electrical power on the system is by means of power flow analysis. Having series of electrical powers, several methods are proposed for this. The first one was tested by the authors, and the other two are proposed for future work.

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