Efficient Uncertainty Analysis of Wind Farms in the Time Domain using the Unscented Transform

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***Abstract*—In this paper, an efficient method of uncertainty analysis, the so-called Unscented Transform, is applied to a wind farm numerical model. Particularly, the effect of an uncertain wind speed on the DC bus voltage of the power converter, as a fault occurs, is considered. We show that the DC bus voltage is strongly influenced by the wind speed. Moreover, the proposed uncertainty analysis method computes the results with similar accuracy than the Monte Carlo method, but with a significant computational effort reduction.**

I. INTRODUCTION

Sustainable solutions are attracting the attention of the energy industry for decades already. The idea that the consumers take responsibility for pollution caused by energy generation is increasingly adopted, leading to a surge in the use of renewable energy sources and technologies [1]. There are several sources of renewable energy: solar, hydro, biomass, geothermal, tides, wind and many others. In this work, we focus on wind energy, even if the presented ideas may be applied to any renewable energy system.

The wind energy has being used for at least 3000 years by windmills for grinding grains or pumping water. If we consider its use in sailing ships this source of power has been used for even longer. The very low level of CO_2 emission over the entire life of a wind turbine is the main reason for its use. Moreover, the wind power has economical benefits since it reduces the fossil fuel dependency and its price volatility, specially for fuel importing countries which import from politically unstable areas [1].

Nowadays, the analysis and design of wind energy systems are strongly dependent on numerical simulations. These simulations allow the assessment of crucial electrical characteristics of a given wind energy system model at a relatively low cost. There are different categories of models that can be simulated, with different goals and techniques. For instance, in a time-domain simulation, the time step can be as low as $5\mu s$ to capture switching effects of the power electronics. Some examples of these relevant analysis tools are: power flow, fault effects, transient stability and electromagnetic simulations. These numerical simulations of wind energy systems can be performed by software packages, such as MATLAB/Simulink, PSS/E, and PSCAD/EMTDC.

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Although the software packages available today are capable of simulating large-scale power systems and provide accurate results, renewable systems are highly affected by uncertain inputs, such as the wind speed for wind farms and solar incidence in solar panels. As the wind speed plays a major role in wind energy systems, its uncertainty must be taken into account in order to carry out a reliable numerical simulation.

The most common method for treating uncertainties is the Monte Carlo (MC) method. The Monte Carlo method can be briefly explained as follows: a large number of samples (N_{MC}) is generated according to the multivariate input Probability Density Function (PDF). For each sample, a numerical simulation of the considered model is carried out, producing a collection of N_{MC} results. Then, the quantity of interest, such as the average and standard deviation or the output PDF is computed from the collection. The MC method has a low rate of conversion and therefore it requires typically tens or hundreds of thousands of simulations in typical electrical engineering problems in order to produce accurate results. For example, if the time required to carry out one simulation is 1 minute, then the MC method would require approximately 7 days to complete, if 10000 samples are considered.

In this context, there has been a great effort to develop alternative Uncertainty Quantification (UQ) methods that are more efficient and require less simulations for accurate results. Some examples can be found in [2]–[5]. One example of an efficient UQ method that has been used lately is the Unscented Transform (UT) [6].

The Unscented Transform method has being applied for uncertainty quantification in [7], [8] as an alternative to the Monte Carlo method. The UT approximates a nonlinear mapping by a set of points, called *sigma points*, which allow one to obtain both the expected value and the variance from a weighted average of the simulation outputs generated by the sigma points [7].

In this paper, we apply the UT to a wind farm model and show that: (1) it requires significant less time to compute the results; (2) its accuracy is similar to the MC method and (3) the wind speed uncertainty must be taken into account for components specification.

II. PROBLEM STATEMENT

Consider an arbitrary wind energy system. This wind farm system includes generation, transmission and distribution systems which can be modeled using linear and nonlinear components such as resistors, inductors, capacitors, IGBT's, generators, controlled current and voltage sources. This model is essentially a system of nonlinear ODE's.

The problem considered in this paper consists of determining the average (μ) and standard deviation (σ) of any current or voltage of the model, given the μ and σ of each uncertain parameter.

The mathematical formulation is given as follows. The uncertain parameters of the system, such as the wind speed, the transmission line capacitance per unit length and fault level, are represented by the vector of real random variables $\vec{U} = [U_1, U_2, ..., U_{N-1}, U_N]$, with dimension N. Each of these parameters may have a different statistical distribution and, in this work, it is assumed statistical independence between them. The vectors $\vec{\mu_u} = [\mu_{u_1}, \mu_{u_2}, ..., \mu_{u_{N-1}}, \mu_{u_N}]$ and $\vec{\sigma_u} = [\sigma_{u_1}, \sigma_{u_2}, ..., \sigma_{u_{N-1}}, \sigma_{u_N}]$ are the vectors of averages and standard deviations of $\vec{U}$, respectively. The output variable, or the so-called quantity of interest, which is any voltage or current of the wind energy system, is represented by Y. The quantities μ_y and σ_y are the average and standard deviation of Y, respectively.

The system model (G) is described as:

$$Y(t) = G(\vec{U}, t) \tag{1}$$

Note that $Y(t)$ is a time-dependent random variable. Thus, the problem consists in computing μ_y and σ_y.

III. METHODOLOGY

Let $\vec{S} = [S_1, S_2, ..., S_{N_S}]$ and $\vec{w} = [w_0, w_1, w_2, ..., w_{N_S}]$ be the so-called sigma points and the weights, respectively. Note that the dimension of these vectors is the number of sigma points N_S.

The method to obtain μ_y is given as follows [7]:

$$\mu_y = E\left\{G(\vec{\mu_u} + \vec{\hat{u}})\right\} = w_0 G(\vec{\mu_u}) + \sum_{i=1}^{N_S} w_i G(\vec{\mu_u} + S_i) \tag{2}$$

where $E\{.\}$ is the expectation operator and $\vec{\hat{u}}$ is a vector of zero mean and unit variance random variables.

Once the mean is calculated, it is possible to obtain the variance σ_y^2 given by the equation 3.

$$\begin{aligned}\sigma_y^2 &= E\left\{(G(\vec{\mu_u} + \vec{\hat{u}}) - \vec{\mu_u})^2\right\} \\ &= \omega_0 (G(\vec{\mu_u} + \vec{\hat{u}}) - \vec{\mu_u})^2 + \sum_{i=1}^{N} \omega_i (G(\vec{\mu_u} + S_i) - \mu_y)^2\end{aligned} \tag{3}$$

The details of the derivation of the UT method can be found in [7].

IV. APPLICATION

This work addresses a 1D problem of a wind farm, considering the wind speed as the input random variable with a uniform probability density function, shown in Figure 1, and analyzes the voltage of the DC bus capacitor, when a fault of $0.5pu$ happens at $0.3s$. This model is an example of the Simscape Power Systems toolbox, which simulates a wind farm with 6 turbines of 1.5MW each [9]. A discrete solver with time step $5\mu s$ was used to capture switching effects. Moreover, each simulation requires a pre-processing, which consists of computing the initial states. The time to complete one simulation is $38.8s$. The wind farm schematics is shown in Figure 2, where the fault is implemented in the voltage source (1).

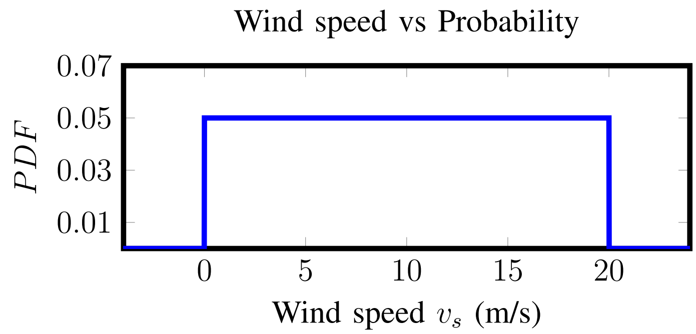

Fig. 1. Probability density function of the wind speed, uniform, average = 10m/s and $v_s = 5,7735m/s$

Method	Time
Monte Carlo	6 hours and 36 minutes
Unscented Transform	2 minutes and 46 seconds

TABLE I
TIME REQUIRED BY THE PRESENTED METHODS

V. RESULTS

This section presents the results of the UT method. A comparison was made with the Monte Carlo method, using 1000 samples. For the UT method, it was required only 5 simulations.

In Fig. 3, it can be seen the nominal voltage V_{DC} of the bus capacitor at $1150V$. At $t = 0.03s$, a $0.5pu$ fault occurs on the element (1) of the schematic in Fig. 2. The fault causes the V_{DC} to oscillate, with a peak value of about $1185V$ and a lowest value of about $1130V$. This result corresponds to the average behavior of V_{DC} when the wind speed varies from $0m/s$ to $20m/s$.

In Fig. 4, it is shown the probabilistic upper and lower bounds of V_{DC}, with a 0.1% confidence level. Note that the V_{DC} also oscillates, but with a peak of approximately $1200V$. Additionally, the undershoot reaches values of around $1100V$.

The simulation time for each method was also computed and Table I shows the results. The UT method presented a reduction in the simulation time of 160.93 times over the MC method.

VI. CONCLUSION

This work presented the Unscented Transform method for uncertainty quantification of wind energy systems.

The scheme was applied to a relevant model based on a real world wind farm and later compared with the MC method. The results presented a similar accuracy between the MC and UT methods, with a time reduction factor of over 160. Additionally, this work shows the importance of considering the variability of the wind speed when specifying the components.

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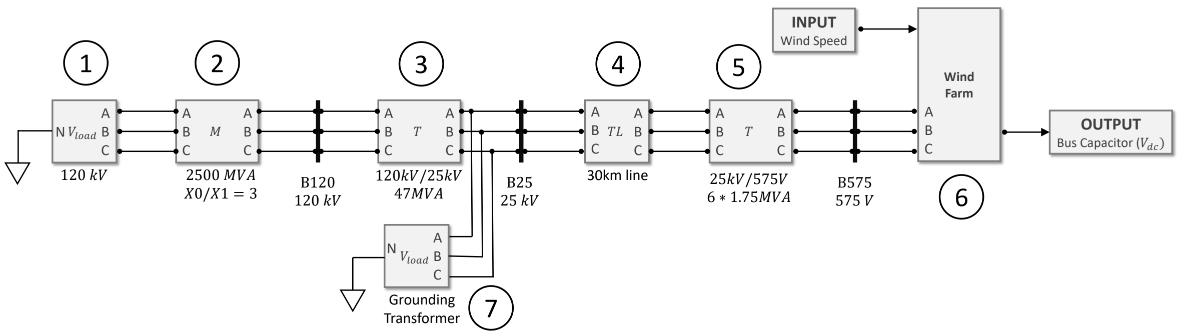

Fig. 2. Model of the wind farm consisting of: (1) 120-kV faulting system, (2) three phase impedance with mutual coupling between phases, (3) 120 kV grid, (4) 30 km transmission line, (5) 25 kV distribution system, (6) DFIG wind turbine , and (7) transformer providing a neutral to the three phase system.

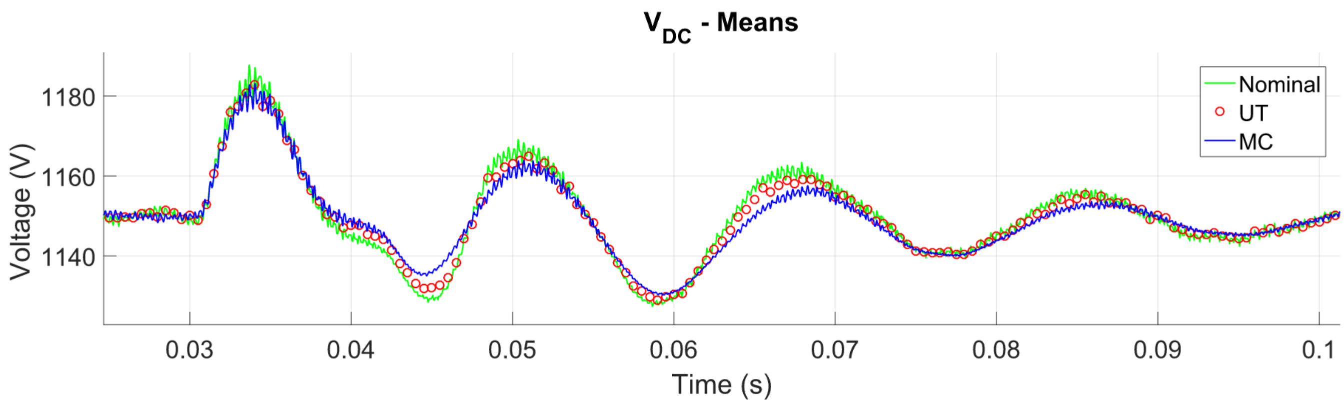

Fig. 3. Average voltage on the bus capacitor for both methods and nominal input.

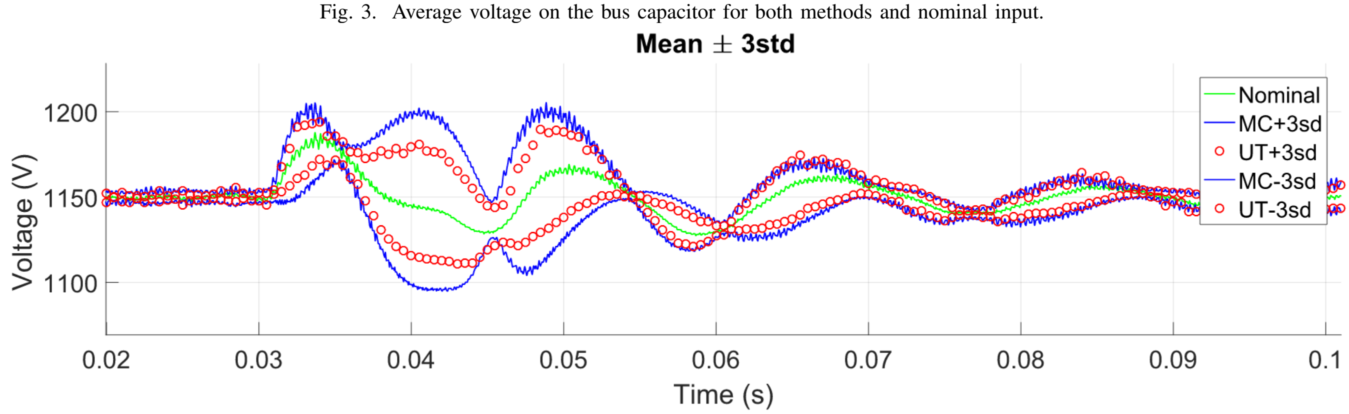

Fig. 4. Average voltage on the bus capacitor ± 3 SD for both methods.