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A novel approach to address reliability concerns of wind turbines

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Abstract. Designing and manufacturing a system in the current industrial world cannot be accomplished without addressing safety related issues. For this purpose, system reliability is a powerful tool to ensure that failure probability of the system is below an accepted level while the system is operational. A commonly used approach to deal with these considerations is to define a performance function for the system in order to investigate its reliability. In this case, renewable energy systems (RESs) are not different. When a wind turbine, as a RES, is designed, its reliability cannot be ignored or underestimated. Therefore, stable and efficient models are needed to make sure that the turbine remains operational and is able to safely generate electricity power. In this paper, a new approach is proposed to set up a reliability analysis model for the wind turbines. The introduced model takes two important factors, i.e. the wind speed and the wind angle, and their probability distributions into account. These two factors are indeed considered as random variables to design a new system performance function and set up the new model in order to investigate wind turbine's reliability.

Introduction

Climate change has recently attracted attentions around the world. This has made many researchers and organizations to focus on renewable energy systems (RESs) and their related issues. However, fossil fuels still play important roles, either in financial markets and/or international relationships, as RESs, such as wind turbines and solar panels, are not yet efficient enough to replace fossil fuels in a foreseeable future [1, 2].

There are always challenges when designing every single RES, regarding their economic feasibility, safety checks, engineering design, reliability features, etc. These challenges need to appropriately be addressed as otherwise they could bring catastrophic consequences, like shutting down entire renewable energy station [3].

Renewable energy resources often have random behavior. For instance, there needs to be irradiance and wind available and this availability depends on randomness of the resources. Data mining and machine learning techniques are often employed to predict this availability in order to investigate the system's behavior in the future [4, 5].

Moreover, the Internet of Things (IoT) has been used to oversee solar power stations [4]. As these panels often need a vast area to install large-scale systems, it is crucial to find the right place and also analyze functionality of the panels in real-time tasks. To do this, there are some algorithms which employ the IoT techniques to improve these systems' reliability. Also, a widely applied technique is to estimate their parameters in order to formulate deterministic optimization models of solar panels. A method has been introduced that uses stochastic fractal search algorithms to estimate current-voltage parameters for modelling purposes [6].

Also, various data mining methods are used to predict solar cell's energy production. However, a new finding proposes a hybrid method incorporating machine learning algorithms and statistical methods is going to perform better in terms of PV energy predictions [4, 5, 7].

Other RESs have their own associated challenges and risks. However, the main challenges to generate electricity power by wind turbines are again related to randomness of the main factor; i.e.

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the wind. It has been reported that wind turbines have great potentials to generate green energy and help environment, as they produce low emission compared with traditional fossil fuels. On the other hand, there are new barriers to research and industry in order to design these systems due to randomness and intermittent characteristics associated with these turbines. As a result of these challenges, uncertainty level is high that needs to be addressed by introducing efficient reliability analysis models and methods [8].

Further, many researches work on offshore wind power stations as another way to produce renewable energy. It has been found that many untouched offshore locations are rich in terms of resources of available wind. Among available structures for offshore wind turbine stations, fixed structures, such as monopile, jacket and tripod support are often preferred. These structure however do have uncertainty problems. It has been reported that uncertainty of these systems can be considered by using semi-probabilistic nature of the existing frameworks [9].

There are also researches that have found offshore wind turbines would bring more reliability related consideration into energy production process. It has been reported that the Gaussian process regression is of the most stable and efficient methods to handle these problems [10]. Although it is believed that offshore wind resources have great potential for energy production, these stations often require huge maintenance costs which means it could be very challenging to deal with these systems and therefore there are projects have been abandoned due to the financial problems [11].

Wind Turbines' Reliability Considerations

Moving towards renewable energy has motivated researchers to work on mathematical models of RESs. It is reported that hybrid renewable energy systems (HRESs) could be more efficient than single renewable source systems. However, more challenging problems are expected when working with a HRES. This often happens due to a large number of factors that need to be considered to set up HRESs' mathematical models.

Reliability related issues are of the highest importance when it comes to developing new systems. In this case, reliability concerns of RESs are mainly originating from random nature of their required natural resources [12, 13]. A system's reliability is often studied by employing a reliability function which can be defined by the system's failure rate λ as below [14]:

$$R(t) = e^{-\lambda t} \tag{1}$$

Reliability analysis problems are another tool to investigate a system's reliability. For this purpose, a reliability analysis problem, as an optimization problem, needs to be solved in order to find a reliability index. Analytical and simulation approaches are widely used to perform a reliability analysis problem, either by using a mathematical model to evaluate system reliability or by applying simulation techniques to approximate the reliability index [15].

A wind energy conversion system (WECS) can also be used to formulate a wind turbine's reliability analysis problem [12]. The wind speed is a major factor in this system and so its probability distribution needs to be determined. It has been reported that the Weibull distribution is an appropriate choice for this purpose, which is often shown as a matrix representing time. α_w and β_w, as a scale parameter and a shape parameter respectively, are applied in the Weibull density and distribution functions.

$$f_v(v) = \frac{\beta_w}{{\alpha_w}^{\beta_w}} v^{\beta_w - 1} e^{-\frac{v}{{\alpha_w}^{\beta_w}}} \tag{2}$$

$$F_v(v) = 1 - e^{-\frac{v}{{\alpha_w}^{\beta_w}}} \tag{3}$$

Materials Research Proceedings 43 (2024) 82-87 https://doi.org/10.21741/9781644903216-11

As random variables play significant roles in reliability analysis problems, it would be crucial to find these variables for a wind turbine reliability model. It is reported that wind speed and wind angle are two random variables of a reliability analysis problem of wind turbines [16]. To work out these variables, two boundaries of the wind speed must be considered as cut-in V_{ci} and cut-off speeds V_{co}. If the wind speed was below V_{ci} or above V_{co}, then wind turbine would stop working (either due to the lack of enough energy or because of safety concerns) [12, 13, 17]. The power generated by the turbine can be worked out as:

$$P_w(v) = \begin{cases} 0 & if\ v < V_{ci} \\ \dfrac{v - V_{ci}}{V_R - V_{ci}} P_R & if\ V_{ci} \le v \le V_R \\ P_R & if\ V_R \le v \le V_{co} \\ 0 & if\ V_{co} < v \end{cases} \tag{4}$$

The coefficient $\frac{v-V_{ci}}{V_R-V_{ci}}$ could be replaced by a quadratic polynomial and multiplied into the rated capacity [18].

Wind Turbines' Performance Function

A system performance function, which is also known as a limit-state function, is often employed to set up a reliability analysis problem and a reliability-based design optimization (RBDO) problem [19]. Once random variables of a wind turbine were determined, they would be used to define the system performance function. A probabilistic constraint as $P[G(t) \le 0] \le \Phi(-\beta)$ is then formulated in an RBDO problem to take reliability concerns into account.

This performenc function is then used to setting up a reliability analysis problem for the wind turbine. A first-order direct reliability analysis problem is defined as below [20]:

$$\begin{aligned} &\min\|(u_1, u_2, \dots, u_n)\| \\ &s.t.\, G_U(u_1, u_2, \dots, u_n) = 0 \end{aligned} \tag{5}$$

where $(u_1, u_2, \dots, u_n)$ represents standard normalized design variable and G_U is standard normalized system performance function. It has been reported that the conjugate gradient direction-based (CGDB) method is the most stable and efficient method to solve this problem and find a reliability index β [21].

Probability distribution and also their relevant density function are the basis of all reliability analysis problems. In this case, for power generated by the WECS, the following density function is available, in which F_v shows the probability distribution function of the WECS [12]:

$$f_{P_w}(P_w) = \begin{cases} F_1 = 1 - F_3 & if\ P_w = 0 \\ F_2 & if\ V_{ci} \le v \le V_R \\ F_3 & if\ P_w = P_R \end{cases} \tag{6}$$

where

$$F_2 = \frac{V_R - V_{ci}}{P_R} \frac{\beta_w}{\alpha_w^{\beta_w}} (V_{ci} + (V_R - V_{ci}) \frac{P_w}{P_R})^{\beta_w - 1} e^{-(\frac{V_{ci} + (V_R - V_{ci})\frac{P_w}{P_R}}{\alpha_w})^{\beta_w}}$$

and

$$F_3 = F_v(V_F) - F_v(V_{ci})$$

It is found that the random variable v in the above function can follow two probability distribution functions as the Weibull distribution [12] or the Normal distribution [22]. In the next section, it will be shown how to set up a reliability analysis problem of wind turbines based on the random variables and probability distributions discussed in this paper.

Introducing Reliability Analysis Problems for Wind Turbines

To investigate reliability concerns of a wind turbine, a performance function should first be defined. It is elaborated here how to formulate such a system performance function based on two previously discussed random variables and then a new approach is proposed to set up new reliability analysis problems for wind turbines.

Random Variables

The first task is to determine random variables. The wind speed and the wind angle are considered in this paper as two random variables of a wind turbine using which a performance function can be formulated. Once the performance function was available, then a reliability analysis problem can be set up.

It is required to find (or identify) probability distribution function(s) of each random variable. It is already known that the wind turbine, as the first random variable, may follow two probability distributions, either the Gaussian distribution (also known as the Normal distribution) or the Weibull distribution. Data collected in different geographical locations prove that these two distributions are appropriate choices to explain behavior of the wind speed.

The second random variable would be the wind angle. However, no valid data is yet available for this variable to determine its probability distribution function. Therefore, it remains a big challenge to determine the wind angle's distribution in order to set up a wind turbine's reliability analysis problem.

System Safety and Failure

The cut-in speed V_{ci} and the cut-off speed V_{co} should also be considered when setting up the reliability analysis problem. Considering V_{ci} and V_{co} as two thresholds and given the wind speed v must be between these thresholds, the system safety and system failure could be defined for a wind turbine.

Based on the Eq. 4, a turbine is supposed to work properly when $V_{ci} \leq v \leq V_{co}$. Therefore, this condition is assumed as system's safety which means the turbine is able to generate electricity power only if the wind speed is between its boundaries. However, when the wind speed is out of the above-mentioned range, i.e. $V_{co} < v$ or $v < V_{ci}$, then the turbine stops working and no power could be generated, and so it would be considered as system failure.

However, it must be mentioned that total failure of the system, which means the turbine needs maintenance or replacement, is different from the system failure defined in this Section.

For simplicity reasons, let's assume x is a random variable representing the wind speed. Also, d_1 and d_2 are the thresholds of random variable x, which represent the cut-in and cut-off speeds, respectively. Then, the discussed safety and failure conditions can be used to formulate the wind turbine's performance function(s) as below:

$$G_1(x) = x - d_1 \tag{7}$$

$$G_2(x) = d_2 - x \tag{8}$$

Therefore, $G_1(x) > 0$ and $G_2(x) > 0$ show the system safety which means electricity power can be generated, and so $G_1(x) < 0$ and $G_2(x) < 0$ indicate system failure meaning no power can be generated.

So, the failure surface of a reliability analysis problem (such as Eq. 5) or the probabilistic constraint of an RBDO problem for wind turbines can be set up as $G_1(x) = 0$ and $G_2(x) = 0$.

Future Works and Conclusion

Reliability has always been one of the most important considerations when designing any new system, and in this case, the RESs in general and wind turbines in particular are not different. In this paper, new approaches are proposed to deal with reliability issues of wind turbines.

The main focus here is to identify random variables of the system, i.e. a wind turbine, and then employ them to define a performance function for the turbine. This performance function can then be used to design a direct reliability analysis problem, or an inverse reliability analysis problem, or even an RBDO problem.

Based on the discussions on reliability issues in the previous Section, it can be concluded that an important step in the future works to setting up the required problem(s) is to figure out probability distribution of the wind angle, as a random variable of the system. The other random variable is the wind speed for which at least two probability distributions are available. Once probability distribution and statistical data of both random variables were available, then they can be used to set up a system performance function.

The wind speed characteristics, such as the cut-in and cut-off speeds, and the power function can also be used to define a performance function for a wind turbine. In all these cases, the wind turbine's performance function should be set up based on the safety conditions to ensure electricity power can be generated.

Once a system performance function was formulated using any of the above approaches, a reliability analysis problem, either direct or inverse, and/or an RBDO problem can be modeled to address reliability issues of a wind turbine.

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