A review on reliability methods for wind farms

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ABSTRACT
This is a review paper that the reliability evaluation methods for wind power systems are reviewed and compared. The paper is helpful for knowing about state of the art in the area and selecting a suitable method for reliability evaluation of wind system. A common set of reliability methods and procedures used in wind energy applications systems are reviewed. A quantitative measure of reliability estimation using these methods is essential for making intelligent decisions in the operation of the wind system. These methods have been classified into some categories easy to understand and to ensure that the reliability requirements have been met. Several methods have been developed to address these objectives, but no unique method can address all the objectives. Reliability methods present both advantages and shortcomings and are the basis for the recommendation that has been made along the qualification and quality assurance to improve design and manufacturing robustness.

KEY WORDS: Failure, reliability, wind farm

1. INTRODUCTION
Reliability evaluation and enhancement are an important factors in modern renewable energy planning and operation. Consequently, the reliability assessment of wind energy applications is of great importance and will receive more attention in the future with increasing generation from wind resources. A review is conducted to investigate the various available reliability methods. Each reliability method has its own advantages and drawbacks [1]. All methods contain certain assumptions that may or may not be fulfilled. The specified approach should be made available sufficiently early to influence the reliability design and selection of the design parameters for the wind system. To the best of our knowledge, this is the first work that combines a wide range of reliable methods of wind energy systems at both wind farm level and wind energy generation system level.

Reliability methods have been used to develop, analyze, and ensure the reliability in wind energy application systems. There had been several articles on reliability methods [2-4]. As described in the history of reliability prediction [5,6], improvements in product design have been accomplished through reliability prediction since 1950s. One example is MIL-HDBK-217 developed in the 1960s. Design for reliability is a key aspect of design, as described in many design and system-engineering applications [7,8]. Literature review suggests that significant research efforts have been focused on improving the reliability of wind energy systems. A number of methods are now available for the reliability prediction in wind energy system applications [9-11]. They include physics of failure method [12,13], empirical methods [14], similar item data based method [11], test or field data based method [11], and system reliability prediction [15,16]. Concerning power system reliability techniques, the models proposed in the literature are either simulative based on Monte Carlo technique [17] or analytical based on Markov method [18,19]. These methods have advantages and drawbacks and can be very powerful with the proper application. The following selected methods are discussed and this paper is finished with a concluding remarks.

2. RELIABILITY METHODS
For the analysis of the reliability in wind farms, many methods and techniques either qualitative or quantitative, numerical or analytical have been developed as shown in Figure 1. The qualitative techniques lead to the identification of weaknesses in the design before quantitative approaches, which are executed using several iterations of failure mode and effect analysis (FMEAs) at the system level. Further, quantitative approaches are used during the design
stage. Some of these methods employ reliability prediction tools of fault tree (FT), reliability block diagram (RBD), and reliability graph (RG). Analytical methods are based on Markov while simulation methods are based on Monte Carlo.

2.1. Reliability Prediction

As the first step of reliability prediction, a set of factually possible conditions and their related consequences must be considered, by which the system can be designated as being failed. Then, converting the qualitative approach into a quantitative approach is the second stage. This is obtained by probability theory and the assignment of probabilities to each of the states that lead the system to failure. Sometimes, this rather complicated procedure can be partially circumvented by a statistical analysis of previous failure data, from which direct estimation of failure probability can be made. Thus, the prediction problem is not merely to characterize the system in some way. It also has to take into consideration further factors such as the experience of the design team, the conditions under which the design was achieved [21].

Reliability predictions for wind energy systems will have an important bearing on the future development of wind power resources. This section is concerned with understanding the reliability prediction of modern WES and power electronic subsystems. This method is not only applicable to WES but also applicable to any repairable system. The main purpose is to discuss the practical methods of predicting large WES reliability. More research efforts will provide both new insights and specifics for wind generation model development and application. Reliability prediction is considered as a quantitative reliability analysis technique. It is used to predict the failure rate of a system based on its components and operating conditions. This technique is also used to verify progress in reliability engineering.

The reliability prediction calls for building a mathematical model for the system under study and defining some reliability measures such as expected energy not supplied, annual interruption frequency, annual interruption duration, and mean time to failure. Then, it is followed by developing a technique for evaluating the reliability measures and comparing predicted data against experimental results. The comparisons of different methodologies are tabulated in Table 1.

The reliability prediction of electronic systems and equipment requires adequate knowledge and realization about the components, besides deep understanding about the design, the manufacturing process, and the expected operating conditions. The prediction models should be relatively simple and easy to maintain, fully defined in terms of their jobs, and requirements with identified constraints on their application. The choice of reliability prediction method is based on experience and the number of modes or periods of operation time that each method is effective, which is indicated by check marks as shown in Table 2.

The prediction models in different categories have been classified based on their usage, characteristics, and conditions for applications. Each model is dependent on widely different sets of physical parameters such as

<table>
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<tr>
<th>Methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Empirical</td>
<td>Implementation is very simple since models are already available</td>
<td>Historical records can result in inaccurate estimate for new components</td>
</tr>
<tr>
<td>Physics of failure</td>
<td>High level of prediction using known failure mechanism is performed to determine the wear-out function</td>
<td>High level of knowledge of component materials and process and design science is required. Hence, it is challenging to apply since too many data and parameters are needed, hard to calculate as too many data are required</td>
</tr>
<tr>
<td>Similar item data</td>
<td>Fastest way to estimate a new products reliability and it takes place when limited design information is known</td>
<td>The similar product for evaluation may be substantially different from the one under consideration</td>
</tr>
<tr>
<td>Test/field data</td>
<td>Results can be accurately determined as tests include associated uncertainty</td>
<td>The test/field data are difficult to obtain and assess</td>
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<tr>
<td>Operational translation</td>
<td>Handy and application of environmental factors for tough conditions</td>
<td>Shortage of up-to-date and limited number of translation scenarios present the challenge</td>
</tr>
<tr>
<td>System Reliability Assessment</td>
<td>Combine the field and test data with empirical prediction through statistical analysis</td>
<td>It demands augmented computation</td>
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electrical stress, environment, quality, and temperature. It is based on the assumption that systems fail as a result of failures of parts, which fail partly as a result of exposure to applied stress. Again, the selection of the method is a fundamental choice made by the design engineers and direct company policies based on the application in consideration. It also varies according to the product lifecycle and related reliability metrics. It is driven by the critical parts in the system to be modeled and by the system requirements. The fitness of a reliability prediction depends on how well it is designed, developed, and applied. It can also be assessed based on how well it matches the systems specification as well as the field-observed behavior. Depending on the assumptions and methods used, reliability numbers can vary dramatically and possibly lead to misapplication of the system being considered.

Reliability prediction is effective due to the following aspects [22]:

- Supply reliability with a quantitative forecast.
- Improve design and manufacturing process.
- Result in process that meets end-user reliability.
- Create competitive among designs.
- Highlight problems associated with reliability such as design imbalance and source of unreliability.
- Help in feasibility evaluation to achieve design reliability laudable goals.
- Predict warranty cost and maintenance support requirements.
- Assess risks and providing inputs to analysis.

Reliability prediction approaches are widely adopted throughout the electronics industry. These approaches are considered as a yardstick and a criterion for the comparison of different types of equipment. Some of these approaches have narrow scope, and some have been replaced by newer approaches or have been modified, but most of them have widespread adoption. Here, a review on the commonly used reliability predictions methodologies is presented.

2.1.1. Empirical prediction approach

Empirical prediction approach is based on modeling past-experience data and present good estimations data for the same products. Thus, empirical models have been developed from historical reliability records, which are obtained from different sources and environments, either from active field or laboratory tests. Therefore, the reliability prediction will vary as a function of the specific empirical prediction approach. Some of the frequently utilized empirical prediction techniques were initially developed for military or telecommunications, but now they have also been widely applied in many other industries.

The main advantages of empirical approach are that it serves as good performance indicators or yardstick of field reliability, simple to use if the models are available, and it provides a reflection of actual field failure rates. On the other side, it is hard to keep support data, difficult to collect data from their sources either field application or laboratory test since failure rates can depend on the diversity of the sources of data [22]. The technique based on physics of failure models each failure mechanism for each component as shown in Figure 2.

The technique based on physics of failure models each failure mechanism for each component. This method has been used in design stage before device life. Bottom-up physics of failure method requires comprehensive knowledge of the thermal, mechanical, electrical, and chemical lifecycle environment as well as processes leading to failures in the field in order to apply appropriate failure models. The ultimate goal is to predict for a certain component when the end-of-life mechanism will take place. The component failure rate is the sum of all the failure rates due to various factors such as thermal, humidity, voltage, and thermal cycling. The system failure rate is the sum of all the failure rate of the components. Examples of such failure modes include the thermal aging of electrical components, the onset of high cycle fatigue cracks in structures subject to cyclic loads or the deterioration of seals leading to lubricant leakage and contamination.

Physics of failure has prosperous long history in electronic reliability field. Typical advantages of the physics-of-failure are modeling of potential failure mechanisms, estimating of end-of-life, and determining the

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<td>Test or field data</td>
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<td>System reliability assessment</td>
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<td>Physics of failure</td>
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variability of each design parameter. Moreover, common failure models that are effective for existing designs can be effectively applied to new materials and structures. On the contrary, it cannot be used to estimate the field reliability. Furthermore, proper applications of this method require a deep understanding of failure mechanism and design process, and it is not applicable for assessing a whole system.

2.1.2. Test/field data
The method based on test/field data works in the three modes of operations. The reliability outcome can be precisely determined including the associated uncertainty of the estimate, but it is a difficult method since the data are not easy to collect and organize. It is used to evaluate reliability of electronic equipment based on both failure and time.

2.1.3. System reliability assessment prediction
This approach to reliability analysis allows system architects to analyze reliability of the system before it is built. This approach involves two successive stages: Pre-build phase and post-build phase. The first phase is based on using consolidated reliability assessment method, which takes into account the process grading factors, requirements definition, part quality, design and manufacturing in addition to initial prediction, operational profile, and software. The second stage consolidates the best estimates with system test data and process defect data.
using Bayesian combination. The Bayesian technique is a statistical theory for combining the results of separate statistical data. The technique has been proposed as a method for combining test results with previous data or with subjective judgment to derive better or more economical reliability predictions based on limited data.

2.1.4. Similar item/circuit prediction
This method has been used to collect data of the experience on the similar products. If the new product shows a good performance, then the data provide good record for comparison for the new item. During the translation process, environment and operating conditions must be considered. The main feature of this technique is that it is very quick to estimate the new product reliability and it is a valuable approach when there is shortcut in design information. Nonetheless, the possibility that the new product is different from the similar one could cause inaccurate prediction, which constitutes a main deficiency.

2.1.5. Prediction by operational translation
The operational translation method is based on empirical approach to estimate field reliability value. It depends on factors affecting field reliability, which include all failure causes, namely, induced failures resulted from incompetent system design, imperfection manufacturing. Although it is a straightforward process to apply this method, there could be limited availability of both translation scenarios and up-to-date empirical data [24].

It is worth mentioning that according to Foucher et al. [25], the best reliability prediction could only be achieved by a combined use of different methods, depending on the design, development, or manufacturing phase, provided that these methodologies are not interchangeable approaches. The reliability predictions are essential techniques, which improve reliability, and are mathematically simple but not accurate. Historical data play a major role. They take into account the design tradeoff between using a large number of low failure rate components versus using a lower number of high failure rate components.

Furthermore, through competitive analysis, a first-step approximation of the product’s inherent reliability is obtained by comparing mean time between failures of competing products against the ones predicted by models. The higher complexity of the product typically correlates to the higher probability of imperfection in the field. In summary, reliability prediction methods are coherent and mathematically sophisticated, but on the other hand, they have some limitations and they are inaccurate. The limitations can be overcome with the use of historical data and records and appropriate correction factors. Reliability predictions can achieve adequate accuracy on a practical level. The value of these methods is very high at the early phase, but the value decreases rapidly as prototypes become available for testing. Employing these methods can increase the baseline reliability of a product. Since product reliability depends mainly on design and operation conditions, other methods and techniques should be used to prove and improve reliability [26].
2.2. FT Analysis (FTA)
FTA is analytical logic technique that can be applied to analyzing system reliability. The diagram follows a top-down structure and represents a graphical model of the pathways within a system that can lead to a failure. Based on a set of rules and logic symbols from probability theory and Boolean algebra, the pathways interconnect contributory events and conditions using standard logic symbols. For the connected system in this study, the resulting FT diagram is a graphical representation of a chain of events in wind system. The probability of the top-level event can then be determined using mathematical techniques that are widely used in system reliability and safety studies. FTA offers the ability to focus on an event of importance, such as a highly critical safety issue, and subsequently to avoid its occurrence or minimize the consequence.

2.3. RBD
In this graphical analysis technique, the subsystems or components are connected according to their function or reliability relationship as shown in Figure 3. The main advantage of the RBD method is that it is easy to read. In an RBD, the logic diagram is arranged to indicate which combinations of component failures result in the failure of the system, or which combinations of properly working components will keep the system operational. A block in RBD represents the working physical component, and the failure of this component is indicated by the removal of the corresponding block. If enough blocks are removed in an RBD to interrupt the connection between the input and output points, the system fails. In other words, if there is at least one path connecting input and output points, the system is still operating properly. In general, two main types of connection, series and parallel, can be established between two or more components [27]. Series connections represent logic AND of components, and parallel connections represent logic OR. The parallel units in the system mean redundancy. A system keeps operating successfully until no valid path from leftmost node to rightmost node can be formed from available connections. Typically, the one-line diagram is preferred since it is easy to understand by engineers with minimal experience with reliability engineering. This makes RBD an
easy tool to use for determining the reliability of specific designs and for comparing multiple design variations to determine the point of diminishing returns. Using RBD, one can handle most of reliability situations even though it has some limitations. For example, it supports only standard configurations besides its inability to represent sequence dependent failures. In addition, it is not intuitive to represent failures caused by human operators, external events, and the like [4,28].

2.4. FMEA

FMEA is a subjective analysis tool, using a qualitative approach to identifying potential failure modes and their initiating risk to either the system design or manufacture or operational phase. Hence, the FMEA drives designs toward higher reliability, quality, and enhanced safety. It can also be used to assess and optimize maintenance plans. In brief, it is a method to improve reliability during design stage [29]. From the FMEA, a numerical value is assigned to individual failure modes to highlight particular areas of risk. The main goal is to identify and limit or avoid risk within a design. FMEA is usually carried out by a team consisting of design and maintenance personnel whose experience includes all the factors to be considered in the analysis. The factors include severity S, how the failure affects the capital operation of the system; occurrence O, how the failure mode is to initiate; and detection D, how likely failure is to be detected using current condition monitoring and inspection techniques. These three main factors are individually rated using a numerical scale, typically ranging from 1 to 10. These scales, however, can vary in range depending on the FMEA standard being applied. The risk priority number is then calculated as follows:

\[
RPN = S \times O \times D
\]

(1)

With final values being

\[
S \times O \times D = \sum (W_i \times x_i) \sum W_i
\]

(2)

where \(W\) is weight value of the experts, \(x\) is rank and \(i\) is number of experts [30].

2.5. The Analytical Methods

Markov models that are also known as state space diagrams or state graphs provide various measures of a system including availability and mean time to repair. Markov model may become excessively complex depending on the dimensions of the state space as shown in Figure 4. This method considers wind speed, failure and repair rates of wind turbines as well as load demands for short-term and long-term reliability calculation and comparison. Effect of change in initial number of working wind turbines and repair crew can be investigated. Hence, the analytical methods represent the system by enumerating potential incidents. The complexity of calculation increases significantly with expansion in size of power system [17]. When a wind farm is composed of hundreds of wind turbines that are grid-connected, the calculation will be confronted with great difficulties. It has to be determined when the system is represented by mathematical models and when direct analytical solutions are used to evaluate reliability indices. These techniques require some degree of approximations even if they represent the fastest solution in almost any kind of analysis. They might act as a black box and some internal aspect of the model might not be completely evaluated.

The transition rate between any two states can be estimated using the following equation:

\[
j_{ij} = \frac{N_{ij}}{D_{ij}}
\]

(3)

Where \(N_{ij}\) is number of transitions from state \(i\) to state \(j\) and \(D_{ij}\) is duration of state \(i\) before going to state \(j\). To make an acceptable estimation, the number of interstate should be as larger as possible.

In analytical methods, the system is represented by mathematical models, from which direct analytical solutions are obtained to evaluate priori reliability indices. The Markovian approach is suitable for modeling the energy production and power availability of a WES. In this approach, the wind speed’s time variability is taken into account by means of wind speed classification in a discrete number of contiguous classes with each corresponding to a range of values. The duration of each class is statistically treated to preserve information about its duration and the transition rates into all the other classes. The major disadvantage of the analytical approach is that it does not consider the chronological variation of wind speed. Moreover, the Markov model has a new technique called Voter Based State Reduction (VBSR) technique for reducing the number of states in FMEA. The VBSR technique makes reliability analysis and assessment of power electronic systems more simple and meaningful [19].
2.6. Simulation Methods

Simulation methods based on Monte Carlo technique requires unfortunately large computational burden due to the amount of data processing. Although the main drawback of a Monte Carlo simulation is usually its long computation time, computation time may not be an issue if the studied system is not large. The simulation method has advantage of including all variables of the system and featuring more flexibility in the analysis. A Monte Carlo simulation approach is based on hourly random simulation to mimic the operation of a generation system, taking into account the fluctuating nature of wind speed, the random failures of the system. The Monte Carlo simulation must be optimized to reduce required time and sample numbers.

This method estimates reliability indices by repeatedly simulating large number of trials to replicate the operation of a power system and random behaviors in the system. This method treats the problem as a series of real experiments. One of its advantages is that the multi-state components can be incorporated in the analysis without significant increase in the computing time [32]. There are two basic techniques used when Monte Carlo methods are applied to power system reliability evaluation, which are known as the sequential and non-sequential techniques.

- Monte Carlo sequential simulation is suitable for the analysis of choppy wind-generating sources. The main feature is the reliability evaluation combines the chronological characteristics of wind such as diurnal and season wind speeds, load profiles, and the chronological transition states of all the components within a system. Sequential simulation can provide realistic and accurate results related to wind power [33].
- A non-sequential Monte Carlo method has been developed to evaluate the reliability indices of interest. This Monte Carlo simulation theoretically could incorporate any number of system parameters and states. Nonetheless, in the established non-sequential simulation, only hourly uncorrelated states are considered.

In component modeling for reliability assessment, Monte Carlo simulation can include multi-state component reliability models defined by any kind of probability distribution, not only the exponential one as in other methods [34].

Monte Carlo simulation may be preferable for [34]:
- Models with non-exponential time distributions;
- Characterization of peaking units;
- Definition of distributions function of output indices;
- Use of time dependent on chronological issues.

Reliability inaccuracy leads to waste of effort and money. To avoid reliability inaccuracy, many environmental factors should be included in reliability methods. These factors include thermal cycling, thermal shock, thermal transient, temperature change rate, mechanical shock, vibration, power on/off, electrical transient, supplier quality difference, reliability improvement with respect to calendar years and aging, moisture, humidity, altitude, sand and dust, and chemical contamination [35]. The influence of large wind farms in power system operation and planning must be highlighted. Further effort is required to improve reliability of wind energy systems; additional information should be supplied for selecting high-risk components that need both research and industry developments. The question that still needs to be investigated is the exact reliability mechanism behind such observed behavior in WES failures. WES materials and manufacturing techniques, processes for repair operations, and collecting monitoring data must be proved and improved based on lessons learned from the field and on a long successful history in industrial and commercial applications.

3. CONCLUSIONS

It has been shown that the best reliability method could only be achieved by a combined use of different methods, depending on the design, development, or manufacturing phase. In addition, it should be used based on some factors such as the viewpoint of the designers or suppliers, the predefined objectives, the sources of the data, the inputs, the sensitivity of the models, environmental factors, and the outputs. Each method derives its own reliability failure rate different from the others. To come up with more accurate reliability predictions, some factors should be taken into the selected methods. This review can be considered as a useful guide for selecting the suitable reliability method and evaluating potential benefits and limitations of reliability methods.

4. ACKNOWLEDGMENTS

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5. REFERENCES


