A Unified Framework for Reliability Assessment of Wind Energy Conversion Systems

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***Abstract*—This paper proposes a framework for assessing wind energy conversion systems (WECS) reliability in the face of external disturbances, e.g. grid fault, and internal component faults. The proposed reliability assessment allows a quantitative analysis of WECS designs; analysis of WECS control schemes, e.g. fault ride-through mechanisms; identification of key design parameters that influence overall WECS reliability; and computation of WECS reliability with respect to different grid codes/performance requirements.**

***Index Terms*—Reliability, Wind Power, WECS, Faults, Transient Stability, LVRT.**

I. Introduction

IN recent years, thanks mainly to political and social support, and as a consequence of high fossil fuel prices and greenhouse effects, electric power generation from renewable resources has seen a rapid development. For renewable resources, such as photo-voltaics or hydrogen fuel cells, research has led to various preliminary designs. However, wind power is at a different stage of development. Most of the WECS constructions that are currently installed are based, especially when it comes to mechanical and aerodynamical properties, on their forerunners from the 80's and 90's. The construction of wind farms with dozens of WECS is economically feasible and leads to relatively large amounts of generated power. For these reasons many utilities have chosen wind power as the renewable source that they will support and invest in.

According to U.S. Department of Energy achieving 20% of wind power penetration in the U.S. by 2030 will require: i) enhancement of the transmission infrastructure, ii) increased U.S. manufacturing capacity of wind generation equipment, iii) improvement of reliability and operability of WECS. This paper focuses on the last issue. In this regard, there are three intimately reliability-related issues that still hinder the widespread use of with generation based on wind energy are: the impact of wind speed variability on system reliability [1]; WECS' reaction to grid disturbances and its impact on system reliability [2]; and reliability of individual WECS. However, as discussed next, the analysis of these three issues has remained separate. We argue that these three issues need to be treated in a unified fashion and we presents a conceptual framework for reliability analysis of WECS that attempts to provide such a unified view.

The remainder of this paper is organized as follows. In the remainder of this introductory section, we provide an extensive literature review of reliability analysis methods that has been developed over the years to tackle each of the three aforementioned reliability-related issues. In Section II, we provide our vision for a unified reliability analysis framework of WECS. Concluding remarks are presented in Section III.

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A. Impact of Wind Variability on System Reliability

This problem has been widely investigated in past years. This problem has been approached from two main directions: massive simulation and analytical methods. A brief review of the methods proposed in the literature is discussed.

In [3] statistical analysis, based on load and wind generation curves, is presented. The goal is to produce an optimal operational point that maximizes reliability and minimizes cost. Unfortunately an analysis like this assumes only a binary model for the unit availability, i.e., the unit is either fully operational or completely failed. Furthermore, there is no model of WECS components and their dynamic reaction on different internal and external phenomena. This approach is justified by the fact that studies like [3] are mainly economical analyses.

In [4], wind farm modeling in the reliability assessment of the power system is presented. Even though this approach has very little in common with our famework, it is worth emphasizing that it concentrates on assessing the reliability of the entire power system. This assessment forces the authors to make numerous simplifications and to concentrate only on concept of steady-state power generation.

Studies presented in [5], [6], [7] utilize the Markov chain to describe power generation changes and generator failures. Using slightly different approaches than the ones mentioned in the paragraph above, they present a method to compute reliability measures, such as loss of load probability or loss of load expectation curves.

There also has been extensive work which uses stochastic models to describe the reliability of different combinations of generating systems. In [8] reliability evaluation of a system consisting of WECS, diesel engines and batteries is presented. While in In [9] the reliability of microgrid with photovoltaic panels and WECS is analyzed. But those studies still concentrate on the reliability analysis form economical perspective without including dynamic phenomena.

B. WECS Reaction to Grid Disturbances and its Impact on System Reliability

WECS reaction to grid disturbances has also been a subject of extensive research, but in most cases it lacked proper analysis of its effectiveness and impact on system reliability. The first intuitive approach to include WECS on system-level studies, is to model wind generators (primarily induction machines) as negative loads, see, e.g., [10] for details. Unfortunately, many contemporary WECS are more complex than typical induction generators. This is why so many single dynamic WECS models have been developed [11], [12], [13], along with aggregated models [14].

Many researchers have acknowledged the fact that future WECS must adjust to grid standards—not the other way around—as seen in the large number of publications involving WECS control. Different control strategies and designs of WECS include, real power control for smoothing shaft fluctuations [15], control strategies incorporating core saturation [16] or control to minimize the impact of inter-area oscillations [17]. Designs such as redundant lay for WECS back-to-back converters [18] or switching fault ride through strategy [19] are also interesting samples of new design trends. The fact, that WECS has to adjust to the grid standards, means also that the WECS reliability analysis can not be performed only on the WECS model, but also on the grid model. What is more, the WECS and grid control schemes have to be modeled precisely, as their coupling may have high influence on the overall reliability.

Extensive research has also been done on WECS reaction to grid failures [20], [21], [22]. Each of these studies presents different techniques that can improve WECS reaction on grid disturbances. For example [20] proposes usage of a series of breaking resistors that could help dissipate the additional energy stored in rotor circuits during the fault. In [22] the idea of using two switches that can active rotor protection device during the fault (crowbar) and connect the rotor converter in parallel with grid side converter is presented. While those concepts mentioned in this paragraph might prove to be very successful, it can be argued that they lack proper validation and reliability analysis. Those designs are tested for just a few different voltage drops. While the reliability analysis presented in this paper tests the designs for numerous combinations of parameters that WECS will encounter during a fault. The work presented in this paper provides a concept for quantitative analyzes of WECS designs and comparison of different vendors' WECS, along with key parameters that influence WECS reliability.

C. Reliability of Individual WECS

At the WECS level, statistical data of individual components within a WECS has been used for assessing reliability of individual WECS, disregarding the correlation between failures in each of those components and faults in the grid [23]. A similar approach can be found in [24], where the failure rate of single WECS components is calculated based on their base failure rate and environmental stress factors, such as temperature. Reliability of WECS computed in this manner disregards any correlation and influence between components. Furthermore, this method does not include events such as grid faults, which can cause a much faster degradation of components than their failure rate would suggest. In [25] WECS semiconductor fault-tolerant design is presented. It superiority over typical designs is proved, based on a reliability analysis of both systems. But this analysis is based on Markov chains, that only represent distinct failures of each component. While during an actual semiconductor failure, most likely to occur during stressful conditions (such as external or internal WECS short-circuits), many different components can exert pressure on other components. Those mutual relations cannot be presented using the reliability analysis shown in [25]. Reliability analysis as in [26] conducts a yearlong fault observation of one wind power plant. Even though [26] reflects reality exactly, it does not define any computationally amenable analysis scheme.

II. A Unified Framework for Reliability Assessment of WECS

To capture overall WECS reliability, as shown in Fig. 1, a reliability measure will be computed. Reliability measure characterizes particular WECS working under specified conditions (grid characteristics) with regard to specified fault types. This means that for reliability measure computation characteristics of WECS, grid and injected faults are needed. Those characteristics consists of deterministic and random variables. Those chosen to be random variables must have their probability distribution functions. For example, a wind speed could be defined as WECS characteristics random variable. Assessing WECS reliability for just one wind speed would lead to over or under estimation. Thus WECS should be tested for different wind speeds with corresponding probabilities. Fault characteristics can be treated in similar way. Three-phase faults that create the most severe and problematic conditions for WECS are much less likely than one-phase faults that lead to low voltage drops. Disregarding one-phase faults would not lead to reliability measure that corresponds with reality.

A. Reliability Framework Inputs

The reliability framework consists of four main input groups/characteristics. The first three define WECS, grid, and

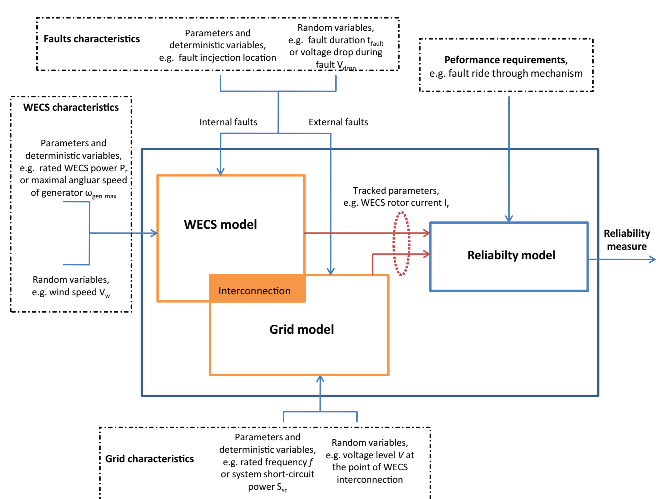

Fig. 1. WECS reliability framework assessment defined trough reliability measure.

faults characteristics. The forth group comprises of performance requirements that the WECS has to met in the presence of internal and grid faults given different operational scenarios. Each group of characteristics consist of different variables, which are divided into two groups: deterministic and random. The choice of random variables is arbitrary. Indeed, most of the variables are assumed deterministic. Random variables $x_1, x_2, ..., x_n$ are characterized by their probability density functions $f_1(x_1), f_2(x_2), ..., f_n(x_n)$.

WECS characteristics feed the WECS model. Similarly, grid characteristics are an input for the grid model. Fault characteristics can feed both models. If the fault variables are an input to the WECS model, then a simulation of an internal fault takes place. When the grid model receives fault parameters, an external fault is being simulated.

Performance requirements are defined slightly differently than WECS, grid and fault characteristics. These requirements can consist of maximum and minimum values that certain variables can take. For example, performance requirements can set a maximum value of the rotor current. In this case if the rotor current value will exceed the maximum value defined by the requirements, this particular simulation has not fulfilled performance requirements. Such information is essential for a reliability model, as the reliability framework treats simulations that have and have not fulfilled the requirements differently. In most of the cases performance requirements track not one, but multiple values.

B. Reliability Framework Models

The proposed framework consists of a WECS model, a grid model and a probabilistic reliability model. The WECS model can range from a very simple relation between wind speed and output power relation, to an extremely detailed model that can simulate electromagnetic transients in WECS generator. Similarly, the grid model can use the infinite bus concept or detailed dynamic model of numerous grid lines with loads and generators. The choice of detail level of those models is based on the goals of the analysis. For utility purposes, where numerous simulations for different grid conditions are needed, simplified models might be a better choice. But for a wind turbine vendor, for whom a simulation time requirement is not an obstacle, very detailed models are better.

The WECS and grid models are connected by an interconnection sub-model. This interconnection is especially important in cases when grid and WECS models are using different reference frames and a transformation between them is needed (such as the $dq0$ to abc transformation).

C. Reliability Model

The goal of the reliability model is to provide a unified measure of WECS reliability R_{wecs}, based on the performance requirements for the values of the variables of interest. In order to compute the R_{wecs}, it is necessary to provide the probability density functions for each framework input variable modeled in a probabilistic manner. Then, the reliability measure is defined as

$$R_{wecs} = 1 - \int \int \int ... \int_D f(x_1, x_2, ..., x_n)\, dx_1 dx_2 ... dx_n \tag{1}$$

where $f(x_1, x_2, .., x_n)$ is the joint probability density function (pdf) and D consists of zero or more $n-th$ dimensional regions, which in summary define the space for which failure has occurred. Independence of random variables is assumed. Therefore the joint pdf in (1) can be written as $f(x_1, x_2, ..., x_n) = f_1(x_1)f_2(x_2)...f_n(x_n)$. Thus, the continuous reliability measure can be rewritten as:

$$\begin{aligned} R_{wecs} &= 1 - \int \int \int ... \int_D f_1(x_1)f_2(x_2)...f_n(x_n)\, dx_1 dx_2 ... dx_n \\ &= 1 - \prod_{i=1}^{n} \int_{D_i} f_i(x_i)\, dx_i \end{aligned} \tag{2}$$

where regions D_i create the total fault space, $D = D_1 \times D_2 \times ... \times D_n$ (Cartesian product).

III. Concluding Remarks

The main motivation for the research presented in this paper is the increased penetration of wind energy into the grid. This change requires development of an adequate framework that could assess the WECS reliability in the face of specified external disturbance, e.g. grid fault, and internal component faults. In the past, design for reliability, with respect to external faults, of conventional (synchronous) generators was concerned mainly with the study of three phase-faults on their terminals. Based on the results of such study, the proper winding size was chosen along with the correct protection relay settings. But such an approach is inadequate for WECS because of two reasons. First, the control and operability of WECS is very complex. A single WECS consists of numerous control loops, whose control strategies may change as the external variables change. In addition, some of those controls are aggregated and can respond to the grid operator commands. Secondly, there are numerous WECS, grid and fault variables that have a large effect on the WECS operating conditions. In this study these “random” variables are distinguished (for reliability assessment purpose) from “deterministic” (constant) variables.

The proposed framework allows a quantitative analysis of different WECS designs and control schemes. For each WECS design and control scheme, a reliability measure R_{wecs} (ranging between 0 and 1) that describes its reliability with regard to specified requirements is given. This reliability assessment allows a comparison of different vendors’ WECS designs, when both designs are tested using the same framework for the same requirements, in result. An analogous study can be done to compare different WECS control schemes within one WECS design concept. Additionally, this framework can reveal the key parameters that influence overall WECS reliability. Within this framework, WECS reliability can also be computed with respect to different grid codes/performance requirements.

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