A Condensed Review of Large Scale Wind Turbine Safety and Failure Modes

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Introduction

Wind power generation is a growing field, both in the United States and around the globe. The United States in August 2018 had wind power accounting for 4.64% of net energy generation from all fuels and solar; compared to a decade prior of 0.84%. Wind energy generation production saw a 500% increase over that time [1]. In a now-emerged field, it is important to maintain specified safety guidelines and detail potential for hazards associated with wind turbine operation; perhaps the most potentially serious being various modes of turbine failure. Typical public safety and health concerns of power generation facilities do not sufficiently transfer to wind power, providing too minimal of a scope [2]. As such, identification of wind-specific hazards and procedures to mitigate them are necessary. Industrial hazard regulations vary by country; and as such, safety regulations in this review will be specified domestically (US). The main details of large scale wind turbine safety and failure will be discussed here.

Overview

The *Permitting of Wind Energy Facilities* Handbook states that “most of the safety issues associated with wind energy projects can be dealt with through adequate setbacks, security, safe work practices, and the implementation of a fire control plan” [3]. There are several aspects of wind turbine operation that are important in terms of public

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safety: lightning strike, blade throw, falling or thrown ice, tower failure, fire hazard, and worker and passerby hazards [4] [5].

Large scale wind turbines are especially susceptible to lightning strikes, as they are tall, grounded structures - situated in flat and isolated locales. Blade throw is encountered when a blade or blade fragments fail and are thrown from a rotating turbine. Falling or thrown ice can also occur when ice forms on a turbine in low temperature conditions with suitable precipitation. Tower failure may occur when vast deviation from design conditions is exacerbated by large external loads and disrepaired foundation. Fire hazards especially considered in dry, arid locales. Lastly, there are inherent hazards introduced to persons on site [5]. Offshore wind turbines introduce further considerations, including further electrical insulation, waves, sea currents, water level, sea ice, marine growth, and seabed movement and scour [6]. Extreme marine conditions should likewise be taken into account. The best ways to avoid hazardous conditions are to implement a sufficiently distanced setback, apply good engineering design practices including appropriate maintenance, proper subsurface wiring, and effectively training personnel [7].

Safety

There are mandated safety regulations that protect persons from contact with high voltage electricity, require safe tower climbing equipment, and alert air traffic. Established standards introduce minimum design requirements to be met to ensure a wind turbine will withstand conditions encountered over its design lifetime [8]. The federal register on “Electric Power Generation, Transmission, and Distribution; Electrical Protective Equipment” as well as Occupational Safety and Health Administration

(OSHA) standards 1910.140 and 1910.147 are key applicable regulations. They require practices such as minimum approach distances for high-voltage equipment and proper personal protective equipment (PPE). [9] [10] [11]. These standards mitigate and control some of the risks inherent to a wind turbine operation site.

In the same intent, the Federal Aviation Administration (FAA) requires a "Notice of Proposed Construction or Alteration" approval and appropriate lighting for a large scale wind turbine [12] [13]. Dependant on turbine location and scaling, turbines may also potentially require approval from the Federal Communications Commission (FCC), U.S. Fish & Wildlife Service (USFWS), local Department of Transportation (xDOT), local environmental and ecological agencies, and appropriate local permitting agencies [13].These are all efforts in avoidance of various forms of direct or indirect harm to the public, environment, or local wildlife.

Design criteria are provided in the well-established IEC 61400 International Standard for wind turbines. IEC 61400-1 presents key elements necessarily considered for suitable wind turbine engineering [8] [14]. IEC 61400-2 and 61400-3 identify considerations for small scale and offshore turbines, respectively [15]. 61400-24 provides a means of reducing the impact of lightning strike on a wind turbine, including risk assessment methods and grounding guidelines.

Important lightning strike design considerations include the presence of appropriate air-termination, down conductor, and earth termination systems [16] [17]. The aim of these design measures is to avoid the direct hazard of lightning strike as well as subsequent hazards - blade disrepair and fire ignition. Lightning strikes are reported as the leading cause of fire ignition in wind turbines. The following causes of fire ignition are then ordered as: electrical equipment malfunction, hot surface ignition, and lastly hot work maintenance [18]. Both passive (combustion-avoidant material selection and application of flame retardant) and active (detectors, alarms, and suppression systems) protection measures are implemented for potential ignition sources. These measures aim to minimize damage in the event of a fire, which reduces total cost of repair and investigation [19].

Failure

Failure of wind turbines can introduce safety hazards and contribute to both system downtime and maintenance and operation costs. Modern wind turbines have an availability of 98% and design life of 20 years [20] [21]. GCube Insurance Services, a renewable energy underwriting firm, provides a quantified assessment of frequency of failures. Blade damage and gearbox failure comprise 41.4% and 35.1% of total failures, respectively. Damage to the generator and transformer then follow at 10.2% and 5.1%. The most common sources of downtime were cited as poor maintenance at 24.5% of claims, lightning strike at 23.4%, design defect at 11.5%, wear and tear at 9.3%, and mechanical defect at 6.2% [22]. There is little control of the frequency at which lightning strikes a wind turbine, so it is important to cut other sources of downtime. A Failure Mode and Effects Analysis (FEMA) assessment backs up the top offshore types of failures [23].

With blade and gearbox damage commanding significant majority of failure type, it is important to isolate their respective modes of failure to enable monitoring of key conditions (the importance of which is to be discussed). Wind turbine blades can fail in various manners. Total failure at nominal rotor speeds throws blade fragments up to 400m. - the same order as ice throw. [24] [25]. However, a more generally applicable approach gives a blade encountering many large cyclic loading events through which a crack may propagate toward failure via the stress intensity factor:

$$K = Y\sigma\sqrt{\pi c}$$

where Y is a geometric constant, σ is the average stress, and c is crack length. Composite delamination and adhesive joint failure are seen as the most frequent failure modes in turbine blades [26]. Chen *et al*. observed further typical failure modes in a statically loaded blade. These modes were identified as sandwich skin-core debonding, laminate fracture, and shear web failure; without Brazier effect [27]. Gearbox considerations are important as it likewise has a lengthy downtime per failure on top of its relatively frequent failure rate [28]. "Wind turbines encounter highly variable loads that are hard to predict, so wind power is one of the most demanding applications for ... gearbox bearings and gear teeth" - Busby (2012) [29]. The Wind Energy Technologies Office (WETO) presents the majority of gearbox failures as being caused by bearing (76%) or gear (17.1%) failure [30]. In experiment, Greco *et al*. found that 3 in 4 bearings failed in a span of 18,000-43,000 hours. The mode of failure for 3 bearings was formation of axial surface cracks on the bearing raceway [31]. White-etching cracks (WECs) are also known failure modes, and a leading cause of early-life drivetrain failure [32]. Among other important modes to be consideration is vibration: "When vibrations reach unacceptable levels, wear and tear processes are accelerated, which in turn may trigger various failure mechanisms" - Rao (1996) [33].

GCube's 2013 findings set implementation of appropriate preventative maintenance as a potential for significant relative improvement [22]. With poor maintenance, wear and tear, and mechanical defects comprising a large percentage of failure sources, significant headway can be made through optimized operation and maintenance. Utilizing an approach similar to Tian *et al*. [34] cost can be optimized for a preventative maintenance time interval. This approach utilizes a condition-based monitoring system (CMS) to identify faults before causing secondary damage, balancing a minimum cost. If an optimal lightning resilience and minimization of manufacture defects could be attained, more of a true minimum cost will arise [22] [35] [36].

Conclusion

A presentation of WETO work states that between 2007 and 2012, total wind turbine downtime had a steady decline and fell by 47.1% [32]. More recently, GCube also found in their 2014 "Breaking Blades" study that there were an estimated 700,000 wind turbine blades in operation in 85 countries. About 3800 incident blade failures annually gave a failure rate of .54% failure per year [36]. From other GCube data provided above, gearbox failure rates are found to have ben .46% failure per year. Reliability rates for other turbine components can also be calculated, but are precluded from this scope. In the industrial sphere wind power generation is relatively safe, suitably regulated, and has no direct pathological impact on human health [37]. Wind power turbines are engineered to well-established and suitable standard. And in modern practices, turbines see various controls and preventative maintenance measures, such as maintenance and inspection to ensure lubrication oil is clean, seals are functioning, and that components seeing normal wear processes are replaced [8].

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