Session No. 718

Performing Arc Flash Hazard Analysis on Wind Farms

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Introduction

Performing Arc Flash Hazard Analysis (AFHA) on wind farms presents unusual challenges to electrical engineers performing the studies and to the wind farm personnel who must implement the AFHA results. The software used to do the Incident Energy (IE) calculations must be adapted to having literally hundreds of large generators in the system, and there are often regulatory and manufacturer limitations that make it difficult to make the changes necessary to protect turbine technicians from arc flash hazards.

This paper will identify the principle engineering issues in need of management and will specify the types of equipment changes that can be used to design Safety-into the wind farm system.

Before discussing this topic further, the reader must understand the following terms:

1. Collector System: The Collector system on a wind farm consists of the (usually) 34,500volt (34.5KV) conductors that receive the power produced by each generator and transmit it to the transmission substation.

2. Incident Energy (IE): The amount of energy impressed on a surface, at a given distance from the source, generated during an arc event. Incident energy is measured in joules per square centimeter or calories per square centimeter.

3. Nacelle: This is the housing that contains the generator and the gearbox that converts the Force of the wind to Rotational Kinetic Energy that drives the gearbox which in turn rotates the generator. A picture of a nacelle appears as Figure 1.

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Figure 1: Wind Turbine Nacelle.

4. Short-Circuit Current (SCC): The maximum amount of current (measured in amperes) that can be transmitted to a given location (called a "node") in the system.

5. Substation: The location where the collector system terminates. The substation includes the circuit breakers that protect the collector system from overloads or faults and also includes the main power transformer that transforms the 34.5KV collector system voltage to the transmission voltages that range from 69KV to 500KV.

6. Wind Turbine: This is the assembly that includes the blades and hub on the rotor that converts the force of the wind into rotational kinetic energy that turns the gearbox which then rotates the generator.

Wind Farm Basics

Wind farms most often consist of Induction-type generators that produce Alternating Current (AC) power at between 575volts to 690 volts. The generators are driven by a gearbox that converts the approximate 50 RPM of the wind moving the massive composite blades into 1,200RPM to as much as 3,600RPM. The generators range in size from 35,000 watts (35 kilowatts) to as much as 3.5 million (Mega) watts (3.5MW). Even larger generators are being designed at the time of this writing. Wind farms also "network" as many as 400 turbines together in a single farm, so it is not unusual to have as much as 200MW of generating capacity associated with larger wind farms.

The generator resides in the nacelles which are perched atop massive towers ranging in height from ~250' to well over 300'. The massive blades are as much as 300' (the length of a football field) in diameter and the entire blade and hub assembly weighs approximately 150,000 lbs. The entire nacelle assembly can weigh in excess of 500,000 lbs., which accounts for the massive size of the towers that must support and withstand the physical stresses associated with wind generation.

Due to the inefficiencies of transmitting massive amounts of power at low voltages, the low voltage power is "stepped-up" to 34,500volts or 34.5 kilovolts (34.5KV) and then transmitted via the collector system back to the main transmission substation where it is stepped-up again to between 115KV to 345KV where it joins the national grids. The most common method of transforming power from 575v-690v is via padmounted transformers (XFMRs) such as the one in Figure 2:

Figure 2: Typical Padmounted XFMR

The collector system is most often aluminum underground cable that is direct-buried in the earth. These cables can be astoundingly-long in length, sometimes exceeding 7 miles between the substation and the first turbine. The 34.5KV voltage is transformed to transmission voltage via massive Power XFMRs in the substations such as the one illustrated in Figure 3:

Figure 3: Typical Substation XFMR

The electrical components of the generator are protected by Low Voltage Power Circuit Breakers (LVPCB) such as the one illustrated in Figure 4:

Figure 4: Low Voltage Power Circuit Breaker.

Some farms also insert an LVPCB in the padmounted XFMR, and this proves an excellent (but expensive) choice because it affords the engineers options that most often allow the engineer to reduce IE levels to acceptable levels at ALL points inside the towers. The 34.5KV-side of the padmounted XFMR is most often protected by internal fuses that usually include a Current Limiting (CL) fuse to protect the unit from high SCC faults in-series with expulsion fuses that protect the XFMR against overloads or faults that have SCC of lower magnitudes.

The collector system is protected by electronic relays that control high-capacity circuit breakers that will interrupt power to the circuits when the relays sense faults. The relays are highly programmable and can perform multiple functions in a single relay. The relays can send a “trip” signal to a breaker in as little as 1.5-cycles (0.025 seconds). The circuit breaker can interrupt current to the faults within as little as 2-cycles (0.03 seconds). This means the fastest “clearing time” for faults is approximately 3.5-cycles (0.058 seconds). The speed of this system is important, as the severity of burns caused by arcs is directly related to the duration of the arc exposure.

The Training Problem

One of the most important challenges facing wind farms is the lack of Qualified Electrical Workers (QEW) on site. Wind farms have electrical equipment ranging from 48-volt control wiring to 345,000-volt transmission substations. Some wind companies will service the so-called “balance of plant” systems, which include the collector circuits and the transmission substations. Working on these systems requires specialized training which, while some technicians have received, very few of the turbine technicians have mastered. As with any trade, electrical work requires mentoring by qualified journeyman-level workers who can impart the necessary knowledge, and perhaps most importantly, the experience needed to safely and efficiently work on HV systems.

The lack of properly qualified “mentors” represents one of the most significant training deficits on wind farm (author’s opinion). In most cases, the “senior” technician (who may only have 18 months on the job) does the training for the new hires and this may serve to pass along incorrect work practices to the next generation of turbine technicians.

The significance of this problem in relation to arc-flash hazards is that the probability of precipitating arcing faults during HV operations, such as switching and installing Personal Protective Grounds, is of course much higher than if those same operations were being performed by QEW for HV systems. This exposure places an even higher premium on using engineering controls, such as AFHA, to limit IE exposures to acceptable levels.

The Arc Flash/Blast Problem

The principle hazards associated with arcs and blasts include thermal-burn injuries and physical trauma from the blast concussion and flying projectiles caused by partially melted components being propelled by the force of the blast. Wind farms present even greater hazards to workers because the equipment on which work is being performed is almost always in enclosed spaces or the work is over 300’ aloft in the nacelles of the turbines. It often takes an inordinate amount of time to effect a rescue of a burned worker from that height and this further increases the likelihood that arc-flash accidents could result in a fatality when they may not had they occurred in a different type of installation.

Further, system protection schemes on wind farms are often configured in a manner that can result in long-duration electrical faults that can produce extreme IE levels and also places extreme electrical stress on the system components. The author has performed AFHA on wind farms where the collector system relays were actually disabled and therefore would have never responded to a fault. Obviously, this situation would have resulted in a catastrophic arc-flash accident had a fault developed on those circuits.

It is noteworthy that Arc Flash Hazard Analysis (AFHA) is a relatively new development in electrical engineering. The Institute of Electrical & Electronic Engineers (IEEE) 1584 committee produced the methodology used by engineers to calculate IE in 2002 (IEEE, 2002). There had been other research done as far back as 1969, but the IEEE 1584 has become the primary reference for AFHA calculations today.

It is also important to understand that the focus of AFHA is to mitigate hazards and not merely to select Flame Resistant (FR) clothing. Many electrical engineers have used the methodologies discussed in this paper to calculate the “heat” associated with electric arcs but then used that information only to recommend that electrical workers wear appropriately-rated FR clothing. The correct approach would be to first exhaust reasonable attempts to make engineering changes to the system to reduce the “heat” and then select the appropriate FR clothing for the residual risk that cannot be adequately controlled through engineering interventions.

The AFHA Process Defined

An AFHA consists of 4 distinct engineering functions, including:
  Stage 1: System Modeling
  Stage 2: Data entry and validation
  Stage 3: System Analysis
  Stage 4: Reporting and Recommendations
A brief description of each phase follows:

Stage 1: System Modeling

Given that all subsequent analysis of the project hinges on the accuracy of the front-end information (GIGO) it is critically important to accurately capture the electrical system in a commercially available AFHA software. This step involves physically gathering data relative to the system components, the length/size of conductors and settings on protective relays.

Modeling wind farms can be quite challenging because the farm often shares a transmission bus with multiple other wind farms that represent a source of SCC that must be taken into account when calculating the available SCC at each farm to be studied. So, it often is necessary to contact electrical engineers from the neighboring wind farms and secure SCC information from them before the study on the farm in question commences. It is also necessary to secure SCC information from the utility that operates the transmission system that receives the power generated by the farm, as the utility source represents a major contributor of SCC to the farm.

Another challenging aspect of modeling wind farms is that the impedance included in collector system must be properly modeled; this is accomplished by including the size of the conductors between the generators (or other nodes) and the length of those conductors. Normally, this data is provided by the site managers on each farm, but our experience has been that there are a surprising number of wind farms that do not have accurate schematic diagrams for the site and it may become necessary to calculate the cable runs via GPS coordinates or possibly even physically measuring the circuits.

Stage 2: Data Entry

Stage 2 includes populating the AFHA software with the needed information to predict system function in both normal operation and during faulted conditions. An added benefit of Stage 2 is that an accurate schematic diagram of at least the main feeders of the facility is created as a natural output of the study.

Stage 3: Analysis

The analysis section includes evaluation of the system from several perspectives, including:

1. **Short Circuit Analysis:** The amount of SCC generated by the system during faulted conditions at each node on the farm. This information is valuable for ensuring protective devices are properly rated to interrupt the available short circuit current and also for selecting the properly-sized grounding cables for shock protection of electrical workers.

   The amount of available SCC on wind farms can be truly astounding. The author has studied wind farms where the SCC exceeded the interrupting ratings (see PDDA below) of even heavy-duty substation circuit breakers. It is noteworthy that any transmission system capable of receiving massive amounts of power is also capable of supplying perhaps 10 times that amount of power back to the farm when a system element becomes faulted. Further, each of the generators on the farm also will supply SCC to a fault via the shared buses in the substation and the other units on the same collector circuit. The amount of SCC is a major contributor to the amount of IE produced in arc flash events, and it most often becomes a problem due to "Protective Device Duty" considerations which are discussed in the next section.

2. **Protective Device Duty Analysis:** One key element of the SCC analysis is a report known as the "Protective Device Duty Analysis". This report compares the capability of protective devices (fuses, circuit breakers) to interrupt SCC to which it is subjected. In cases where the SCC exceeds the interrupting rating of the protective device, a "through-fault" results which means the protective device operates but is unable to interrupt the flow of SCC. The result s the same effect as not having a protective device in the circuit, and the SCC must then be interrupted by the next protective device "upstream" toward the source. This results in much longer arc-clearing times, which in turn translate into far greater IE exposures for electrical workers. See the coordination discussion below for more detail.

3. **Coordination Analysis:** Coordination analysis involves evaluating the Time Current Characteristic curves (TCC) of the protective devices to ensure that the electrical system will clear faults in an orderly or "coordinated" manner. A TCC refers to the speed at which a device will "clear"(shut-off) SCC as a function of the amount of SCC to which it is exposed. In general, the higher the SCC, the faster the protective devices will operate.

   The coordination study evaluates two scenarios that will later appear in reports. The first scenario evaluates the coordination of the current configuration (the "As Built" or "Base Case") of the system. The second scenario evaluates the system once the recommended engineering changes have been implemented (Proposed Case). The "recommended engineering changes" can involve any combination of the following:

a) Reducing trip times on adjustable circuit breakers
b) Using current-limiting fuses
c) Reducing fuse sizes of expulsion fuses
d) Replacing fuses with other styles of fuses that have better TCC characteristics
e) Reducing protective relay settings on systems where an electronic relay actuates a separate circuit breaker.

A complete discussion of this important topic is well beyond the scope of this article, but suffice it to say that wind farms often have very unusual coordination schemes, and engineers will often have to work with the generator manufacturers to adjust protective device settings such that IE levels are reduced while still maintaining the required system reliability.

Incident Energy Calculations:

AFHA is always a delicate “balancing act” between safety and reliability. The focus is to optimize safety while maintaining reliability. The normal approach to making IE calculations is to use commercially available software programs that have “automated” the IE calculation process (Kolak, 2009).

Wind farms often afford the engineer the opportunity to substantially improve safety for workers via engineering controls. However, generator manufacturers are often reticent to make any changes to their systems for warranty reasons. Further, many generators are produced in foreign countries and those countries often do not adhere to U.S. safety standards. While this can be frustrating, there are some engineering interventions possible that will improve safety while not requiring the manufacturers to change their equipment. They include:

1. Use different fuses on Padmounted XFMRs: Some padmounted XFMRs are equipped with Bay-o-net style “well fuses” that are replaceable in the field. This affords the engineer options regarding the types of fuses that are used to protect the XFMR from internal faults and faults that may occur in the Low Voltage compartments of the XFMR.

2. Use Photo-sensing Relay Systems: Photo-sensing relay systems use specialized fiber-optic sensors that are “strung” inside an electrical enclosures to “see” an arc-flash when it occurs and immediately trip the unit offline. These sensors use a controller that must sense a flash of light and the current flow (measured in amperes) must exceed a level set by the engineer who designed the system. This system prevents the unit from accidently tripping offline when the door to the unit is opened, exposing the interior to bright daylight.

   The primary benefit of photo-sensing systems is that they do not need to “coordinate” with any of the other protective devices (fuses, circuit breakers) in the system. These systems are expensive but do provide an excellent tool for engineers to use when the situation warrants this level of sophistication.

3. Insert LVPCB on the Low Voltage (LV)-side of Padmounted XFMRs- One of the most beneficial ways to control AFHA on wind turbines is to install circuit breakers in the LV or secondary-side of the XFMRs. See Figure 5:

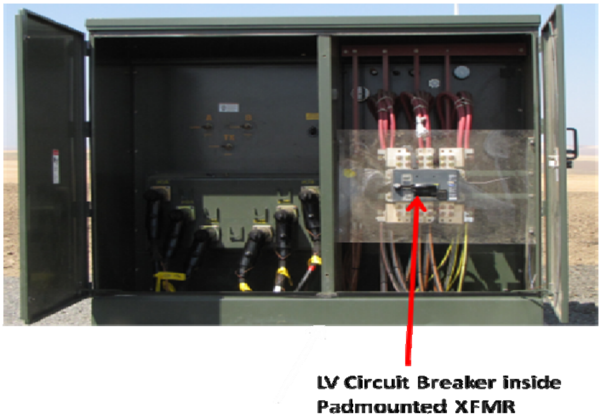

Figure 5: Circuit Breaker in a padmounted XFMR

> This option is very expensive (~$8K-$12K per tower), but having this circuit breaker in the XFMR usually allows the engineer to reduce IE to acceptable levels at <u>all points inside the tower</u>.

<u>Stage 4: Reporting</u>

The Reporting stage of an AFHA typically includes 5 sections:

1. Tabular data from the study: It is very important to provide tabular data for each section of the report because doing so allows critical review by other engineers and allows others to catch potential data-entry mistakes in equipment labeling, etc.

2. Protective Device Duty Analysis: Identifies devices at or near their interrupting duty ratings.

3. Incident Energy calculations: Provides IE calculations at all points in the system where IE levels exceed 1.2 cal/cm^2.

4. Recommended Engineering Interventions: This includes the engineering controls discussed in this paper and may include other options as deemed appropriate by properly-qualified engineers. This section also includes a cost-benefit section for recommended interventions that necessitate either equipment replacement or significant retro-fitting of equipment to lower IE exposures.

The final step in the process is to install the AF labels used to warn QEW of the AFH in the equipment on which they work and help them select properly-rated flame resistant clothing. The National Electrical Code (NFPA, 2008) requires that all equipment with AF hazard potential (i.e. >1.2 cal/cm^2) be "field marked" to warn electrical worker of the hazardous condition. This label normally includes the Incident Energy calculated value and other important safety information needed to safely work on the equipment.

Conclusion

Performing AFHA on wind farms presents some rather unique challenges to engineers due to the unusual configurations and sheer capacity presented by these installations. However, wind farms also afford engineers the opportunity to truly make significant improvements to worker safety on the job.

Performing AFHA on High Voltage systems requires specialized training for Electrical engineers because these systems employ different protective systems than those found in most industrial applications. Further, the “networking” of adjacent wind farms along with being interconnected with the national grids makes performing SCC calculations far more difficult than in other types of systems.

It is imperative for all parties to understand that IE levels on wind farms can often be extreme, and use of flame resistant clothing must be viewed as a last resort because IE levels can often exceed the Arc Ratings of any FR clothing available.

Bibliography

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