ON THE ASSESSMENT AND MANAGEMENT OF RISK IN WIND FARM DISTRIBUTION SYSTEMS

Jorge MARTINEZ
Siemens AG - Germany
jorgemartinez@siemens.com

Armando FERREIRA
Siemens Industry, Inc. - USA
armando.ferreira@siemens.com

ABSTRACT

Assessing and managing the risk associated with the performance of the distribution network of renewable energy projects by means of probabilistic methods could lead to significant risk exposure. Such probabilistic methods include, for example, those employed in the calculation of classical availability/reliability related performance indicators (such as SAIDI and SAIFI). This situation may be particularly crucial when predicting the availability of the distribution system associated with the Electrical Balance of Plant (EBoP) of wind farms. The concepts and results associated with a real-case system presented in this paper point out that risk assessments for distribution networks of renewable generation (using indicators such as EBoP Network Unavailability and its associated "shortfall": the Expected Energy Generated but not Transferred onto the HV Grid) could be underestimated when probabilistic methods that are more suitable to large-scale power system, are applied on the "small scale" distribution and grid access systems of wind farms.

INTRODUCTION

Together with load-flow and short-circuit studies, reliability/availability assessments of distribution systems using probabilistic methods are fundamental to:

- Evaluate system configuration options considering diverse substation arrangements and the design of distribution circuits, including the optimal placing of disconnect switches/breakers and prevision for emergency interconnections among circuits. Reliability computations together with optimization methods are also used to place automation and switching devices for fast reconfiguration of distribution networks in emergency conditions [1].
- Recommend component redundancy guidelines (such as N-1 criterion) or, in general, specify redundant capacity at some critical points of the network to minimize the impact of individual component failures.

Probabilistic methods are also used to allocate resources (e.g. spare parts inventories), analyze different maintenance strategies (time based, condition based, reliability based) as well as to plan in detail maintenance activities.

In the case of wind farms, availability computations are performed considering two major subsystems: 1) the generation system comprising the wind turbine generators (WTGs) and 2) the associated T&D system that connects these WTGs with an external HV Grid. The latter is generally referred to as the Electrical Balance of Plant (EBoP). Further information about wind farm's availability computations may be found in several publications [2].

MAIN CONCEPTS – EFFECTIVENESS OF PREDICTIONS BASED ON PROBABILITIES

Probabilistic methods provide attributes useful to assess, compare, and rank design options by using a consistent evaluation criteria. For example, these methods help to predict expected revenues with respect to agreed targets such as system availability or expected energy generated and effectively transferred onto the HV grid. In most cases these predictions correlate strongly with measurements when the "scale" of the system under study complies with the law of large numbers [3]. Thus, the actual performance of many wind farms in operation should match with results from both probabilistic calculations and risk assessments.

One salient feature of larger regional distribution utilities (for instance, providing electrical service to hundreds of thousand customers) is that these are associated with "large networks" operated by DSOs, encompassing thousands of distribution circuits. This "large system" scale structurally ensures an operational performance that, particularly in long-term measurement periods (such as five years), complies with the law of large numbers and thus its performance may conform to values predicted by means of mathematical computations of reliability/risk indicators. These indicators are further "smoothed" in "large scale" networks via system averages when measuring, for instance, the well-known SAIDI and SAIFI indices. However, in "small scale" systems the "average behaviour" is actually the exception and, to avoid great fluctuations leading to incorrect conclusions and/or to high volatility when deviating from targets, the average parameters and subsequent yearly indicators should be subject to "post-processing" via upside/downside corrections using proper statistical and heuristic methods.

The smaller size of projects and the multiple agents/entities involved in smart grids with the advent of distributed renewable sources (such as developers of multiple renewable generation sources, smaller local utilities, outsourcing of activities to service providers) brings even more complexity and introduces discussion as to what constitutes risk and how it should be fairly measured and

assessed.
The volatility on the annual availability of individual wind farms could also be significantly reduced when data is collected from clusters encompassing many similar systems. In this case, regular patterns emerge such as predictable annual availability and expected annual energy production. This tendency is depicted in Figure 1, which shows the typical consolidated risk when considering measurements from 1, 10,.., 50 similar wind farms. The more wind farms are managed and operated by the same developer, the lower the overall risk exposure due to diversification achieved via consolidation of operations. The risk nevertheless converges to a fixed component (asymptotic value) which depends in great extent on: a) the network topology (i.e. structure) and b) the failure rate and repair time of each of its components. Finally, it should be noted that the standard availability computations provide estimates only for the asymptotic fixed value. This is one of the main reasons why risk assessments are needed to estimate the overall risk (which is comprising of a fixed and a variable component).

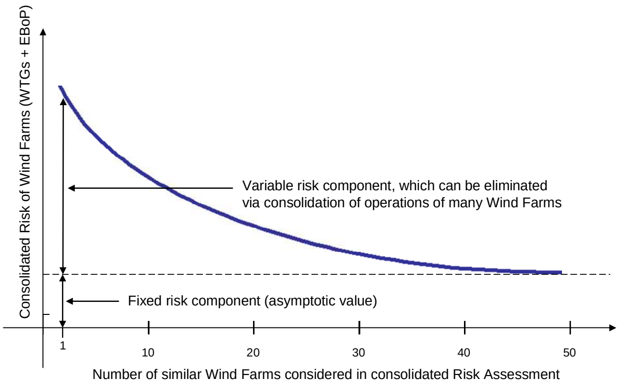

Figure 1. Consolidated risk as function of number of wind farms considered in a risk assessment

The importance of EBoP component redundancy to de-risking the performance of wind farms

A standard wind farm could encompass many wind turbine generators (for instance 50 to 100 WTGs) but depends on only one T&D system (designated as the EBoP). Figure 2 shows how significantly risks can be reduced when the number (and thus the redundant capacity) of MV/HV transformers is increased, particularly when the performance is measured and processed considering one or only a few wind farms. The latter "small size" situation is fairly common in projects of independent developers. When the law of large numbers applies, which was the typical situation of traditional utilities, the benefits of higher redundancy in wind farms is marginal since the failure of a main step-up transformer has less impact on the fixed risk component, and thus on the overall revenues or the consolidated free cash-flow of the utility.
One of the main topics addressed here is how to perform comprehensive risk assessments on small scale systems such as the "wind farm EBoP system" where the traditional "expected values" could lead to ambiguous results or inefficient technical or economical decisions. It is in these "small systems" where there could be significant differences between actual and estimated performance. The proposed quantitative analysis intends to both minimize inefficiencies and avoid heuristic upright/downright corrections, by adjusting the input parameters of failure models and/or resulting indicators according to the size of the system and its own historical reliability data, while the level of risk exposure is known.
The aim of this paper is to show the advantages of introducing a more realistic risk assessment approach to real-world wind farms avoiding technically advanced approaches when they do not have a clear methodological purpose. Many of the risk assessment tools and the associated risk mitigation measures or instruments gain more significance when contracts between customer (such as a utility or a developer) and service provider incorporate performance clauses with compensation in payments using incentives/penalization schemes.

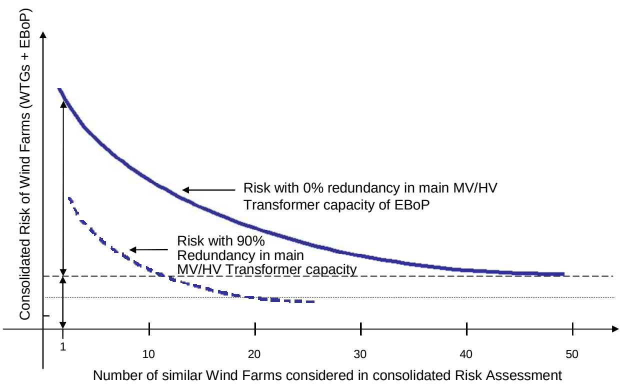

Figure 2. Consolidated risk as percentage of redundant capacity and subject to the number of wind farms considered in a risk assessment

IMPORTANCE OF RISK ASSESSMENTS FOR WIND GENERATION PROJECTS

Figures 1 and 2 were prepared to highlight the high volatility of risk when measured on one or only few wind farms and to also demonstrate the need for comprehensive risk assessment tools that take into consideration the perspective of those developers (or service providers) who run few wind farms. On the other hand, methodologies and tools originally developed for financial companies (such as investment funds) should be customized for analyzing "small-scale" wind farms, considering risks but also chances on revenues which depend, to a great extent, on energy sales subject to both wind speed patterns and high volatility of the EBoP network availability. Furthermore, the revenues associated with energy sales could be compensated by deferred payments based on penalization/incentive schemes. Presently typical capacities of onshore wind farms are in the range of 50 MW to 100 MW, and due to their relevance in the regional load-generation balances, should operate with minor disruptions. Moreover, the prediction of performance should be highly accurate to ensure smooth system operations as well as continuous and sufficient cash inflows. These facts bring much more pressure on the performance of each project, whose revenues should be secured via higher and predictable energy production figures achieved by boosting the availability of both wind turbine generators (WTGs) and the associated EBoP T&D network. The stress on availability is so high that risks should be mitigated (technically and/or financially) even in case of low probability and high impact events. For the latter, the impact could be reduced by means of insurance policies or by the consolidation of risks at the corporate level. The enhanced availabilities can be also achieved via better designs (configurations with higher redundancy on critical equipment and/or procurement of more reliable components), and/or the implementation of asset management systems (covering: processes, IT systems, and organization for maintenance). The owner frequently outsources services to specialized providers upon agreement on yearly fees but also subject to compensation schemes (incentives/penalizations) based on results measured via key performance indicators (KPIs). This performance is difficult to predict for each individual wind farm due to the intrinsic high volatility of the energy finally transferred onto the HV Grid. Therefore, it should not be only assessed by risk estimations based on expected/mean values.

In the following sections we present further relevant concepts and several tools to perform risk assessments from the developer's perspective. An example is also presented, which corresponds to a typical onshore wind farm, focusing on the EBoP as the key distribution sub-system.

RISK DEFINITIONS AND PURPOSE OF RISK ASSESSMENT TOOLS

There are many definitions of risk in the technical literature, all of them more or less valid or useful depending on the field of application [4]. While risk assessment tools, particularly when evaluating financial enterprises, benefit from significant "portfolio diversification" and thus rely to a great extent on expected values (such as Value at Risk, VaR), the tools needed to assess risks of wind farms should consider the higher volatility of its performance because: a) they are usually managed by much smaller companies (such as independent developers) than traditional utilities/DSOs, and b) their performance is frequently measured in the short-term (yearly basis) and not considering more equitable multi-year time spans, which could reduce fluctuations on revenues by balancing both negative (in "bad years") and positive deviations (in "good years"). Therefore, risk assessments of T&D systems of wind farms should be based on overall risk definitions as depicted in Figure 3. These definitions are not new, but there is a common practice to associate risks only to losses or hazards (that is underperformance) while ignoring the chances/rewards when performance exceeds agreed targets on KPIs.

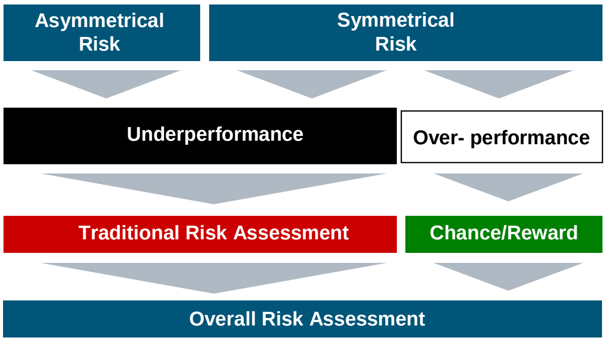

Figure 3. Performance-based Risk Definitions considering Traditional and Overall Risk Assessments

If a scheme of incentives and penalizations is feasible, the developer (or a service provider if operations are outsourced) will commit to targets that lead to symmetrical risks (or at least chances/rewards fully or partially compensate risks associated with hazards/losses). If over-performance is not rewarded then it is not possible to balance risks with rewards and the logical consequence of this would be that all parties involved shall commit to less challenging (i.e. conservative) targets.

Based on the above, risk assessments should be carried out in all stages of wind farms' project lifecycle in order to:

- Configure the wind farm T&D system (one-line diagrams, redundancy, spare parts inventory requirements, etc.),
- set up performance indicator targets (such as network availability, guaranteed annual energy production) to be used afterwards as reference to ascertain over-performance and under-performance,
- implement penalization/incentive mechanisms that encourage symmetrical risks and also lead to long-term financial performance stabilization since losses in "bad years" can be compensated (partially or fully) with additional revenues collected in "good years".

Reliability/availability computations are based on probability (Poisson and/or exponential) distributions for component failures, as well as failure rate and repair time for each component as input data. This information is obtained to a large extent from reliability surveys of electrical equipment (by IEEE, CIGRE, VDE, etc.) which should be adjusted using operational experience gained within the wind generation sector. Therefore, one of the first tasks when performing reliability computations is to properly select the input data from these surveys and pre-process it using "safety factors" determined by means of statistical methods (such as confidence intervals).

MANAGEMENT OF THE EXPOSURE TO SYMMETRICAL AND ASYMMETRICAL RISKS

As mentioned before, the consideration of symmetrical risks is desirable but not always negotiable among all parties involved in a project. Thus, losses are not frequently compensated with rewards, which leads to an exposure to risk that should be analyzed and addressed in order to avoid the chance of disastrous consequences for the financial health of the participants.

Two basic actions are here proposed for the assessment of the risk exposure, which should provide the required knowledge to make the best decisions and manage risks conveniently. They are particularly focused on enabling a convenient process for determining the satisfactory and fair performance targets. Their description is especially based on availability but the underlying methodology can be similarly applied to different performance indicators.

The first action is to adjust the failure rate λ of the Poisson/exponential distribution of each component to be used for the probabilistic computations of the EBoP. The value used is frequently based on statistical information and defined as the historical average of number of failures per year. This means that the value specified for the parameter λ has been historically 50% lower and 50% higher than the estimate. The problem occurs when the actual failure rate is higher than the average value used for the simulations.

If the estimator $\hat{\lambda}$ used for λ is the statistical mean $\bar{x}$, which follows a normal distribution, it is possible to build intervals around the average value with specific levels of confidence. If the upper limit value of one of these intervals is used instead of the mean, then additional risk coverage is obtained and the probability of a failure rate higher than expected is quantified on the confidence level of the interval defining it. For instance, if the interval is $\pm 1\sigma$ (one standard deviation, σ) wide then it is expected that a 68% of the failure rates will lie within this interval, and then only 16% would be higher, in contrast with 50% for the average estimation of λ. Eq. (1) shows how these intervals are defined for the case of 1-sigma (σ) [5]:

$$P\left(\hat{\lambda} - z_{\sigma/2} \cdot \frac{\sigma}{\sqrt{n}} < \lambda < \hat{\lambda} + z_{\sigma/2} \cdot \frac{\sigma}{\sqrt{n}}\right) = 0.6826 \qquad (1)$$

Following traditional confidence interval theory, if σ is unknown and the estimation of standard deviation S is used instead, then the intervals will be defined based on a t-distribution [6]. In addition, n represents the sample for calculation of $\hat{\lambda}$. In this context, it also indicates the understanding of the failure process and/or the existence of both shared resources and consolidated free cash flows from a portfolio of projects that significantly reduce the negative impact of a failure in one project.

When using estimators of λ adjusted following this procedure, the probability of failure is higher, the availability lower and consequently, the risk exposure is also lower. These results should be used when setting more conservative performance targets. In some way or another, all these elements have been traditionally considered in the analysis and negotiations of this kind of systems, but the difference here is that the exposure can be quantified as a probability value and, with additional and relatively simple calculations, as a monetary amount.

However, conducting this first proposed action is insufficient by itself if the risk is asymmetric, because the coverage still lies in an "average zone", i.e., the resulting availability is lower and the risk coverage is higher than in the case of historically average estimator of λ, but there will be a point in time when a failure occurs and the penalization takes place because the availability targets cannot be met.

For this reason, a second action is proposed. This comprises the analysis of high impact and low probability (HILP) type events. One or more EBoP components representing failures of high impact (for example, main MV/HV step-up power transformers) is selected to be the subject of detailed analysis. Usually, during the simulations it's expected to "observe" a failure of this component in a "mean (average) time", when the probability of failure is relatively high. But, as part of this proposed action, an early occurrence of a failure (during the first year or so) is evaluated, when the probability of failure is relatively low. Under this approach, a failure of any impacting EBoP component can be analyzed as a HILP event.

It should be noted that even when an early occurrence is analyzed the number of failures is expected to be, on average, as indicated by λ. The probability of these early failures can be calculated by using an exponential model.

Again, the elements of this proposed action have been traditionally considered, but the difference here is that the exposure can be quantified.

MAIN RESULTS

The proposed actions and calculations for assessing the risk exposure were tested using an onshore wind farm that comprises 50 WTGs, each with an output power of 2.3 MW, with a distribution system at 33 kV and a 33/220 kV main substation.

The first result obtained is referred to the consideration of the adjusted failure rate $\hat{\lambda}$ by using confidence intervals. As can be observed in Figure 4, after an early period of infant mortality the availability increases; also, the higher the sigma (σ) and wider the confidence interval, the lower the expected availability of the EBoP.

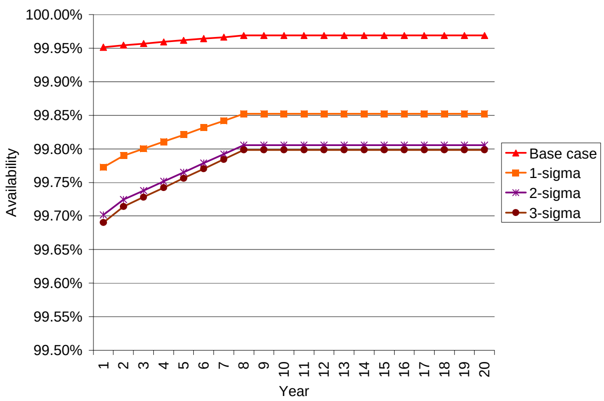

Figure 4. EBoP Availability Computation Results

As mentioned before, the base case represents a risk exposure of 50%; in addition, the system availability lies above 99.95%. For the 1-sigma case, the failure rates used in the probability computations are adjusted by using a multiplying factor of 2.67 and the risk exposure decreases to (100%-68%)/2 = 16% of the likely events; the availability stabilizes at approximately 99.85%. For the 2-sigma case, the base case failure rates are multiplied by a factor of 3.33 and the resulting risk exposure is (100%-95.44%)/2 = 2.28% and for the 3-sigma case the multiplying factor is 3.44 and the risk exposure is only 0.13%; for these last two cases, the availability stabilizes at approximately 99.80%.

Regarding the HILP event analysis, the outage of a power transformer during the first year was modeled. The base case failure rate correspond to $\hat{\lambda}$ = 0.05 failures/year, which represents a failure every 20 years. In this case the HILP event has a significant impact over the EBoP yearly availability, which decreases to approximately 80% at the year the outage occurs. However, if the availability is measured over a first 5-year period, it represents an average reliability of 95-96%, independently of the (1-, 2- and 3-sigma) case observed and around 99% over the whole 20-year period. Based on this analysis, we also wanted to illustrate that the large impact (shock on revenue losses) of a HILP event could be spread across several years only if there is an agreement that performance (and its associated penalization or incentive payments) should be measured using multi-year periods.

Because the probability of occurrence of the considered HILP event is known (0.0488), then is possible to adjust the risk exposure calculated with the first proposed action (i.e. by means of confidence intervals) and also provide quantitative results. Indeed, the risk exposure for the base case would be 1.22% (versus the previous 50% value), while for the 1-sigma case would be 0.77% (versus 16%); for the 2-sigma and 3-sigma cases, it is 0.11% (versus 2.28%) and 0.01% (versus 0.13%), respectively.

CONCLUDING REMARKS

This paper describes how a comprehensive risk assessment of a wind generation project should be carried out and identifies the main limitations of probabilistic methods when analyzing the electrical balance of plant (EBoP) of one or only few wind farms. Different risk definitions are presented and guidelines are given on what needs to be reassessed to obtain better results and how to address the problem of minimizing the impact of major (but very unlikely) operational disruptions. This impact is mitigated by means of: a) structurally/topologically more reliable ("redundant") network configurations, b) comprehensive risk assessments with better methodologies for measuring risk exposures, c) risk "consolidation" by combining, when possible, similar renewable energy projects within the developer's company, and d) direct or indirect risk transfer to external parties (such as major re-insurance companies or specialized subcontractors) that can afford to build-up and better spread risks within a large portfolio of projects whose overall performance meets the "law of large numbers" and is thus predictable by means of probabilistic computations.

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