ASSESSING THE RISK OF PERFORMANCE-BASED MAINTENANCE OF OFFSHORE WIND FARM DISTRIBUTION SYSTEMS

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ABSTRACT

This paper presents the main aspects related to the risk assessment of performance-based maintenance of medium voltage distribution systems for offshore wind farms. This assessment encompasses reliability/availability calculations using input data such as failure rates and average repair times which, during system operations, are closely correlated with maintenance processes and performance. On the other hand, the configuration of the distribution system has also significant impact on the availability of the offshore-onshore electrical interconnection network, particularly relative to component redundancy (partial or total) of critical equipment, such as the MV/HV transformer(s) in the collection substation(s). We also argue that any maintenance system should take into account aspects such as frequency of maintenance of the electrical equipment (time based, condition based, or reliability-centered maintenance), monitoring and automation of the distribution network, implementation of an efficient asset management plan to ensure optimum asset utilization, and least long-term-cost solutions.

INTRODUCTION

Risk analysis and reliability/availability studies of distribution systems for offshore wind farms are crucial to the continuous power delivery of renewable output generation into the onshore transmission system. The performance of the distribution system depends in great extent on the design criteria (e.g., redundancy of critical equipment, failure and repair rates of essential equipment, etc.) and the implementation of maintenance systems including but not limited to maintenance strategy and plans, maintenance process, modern maintenance support systems, proper organizations, suitable tools & testing equipment, and required capabilities (skills and knowledge) of the maintenance staff. This performance should be clearly measured by means of key performance indicators (KPIs) agreed upon between the maintenance organization (or contractor in case that maintenance services are outsourced) and the wind farm developer or owner.

This paper describes important risk assessment considerations and related KPIs associated with the maintenance of medium voltage distribution systems of wind farms. Today, such farms have net generation capacities in the range of several hundred MWs, and individual wind turbine generators (WTGs) of net output capacity in the range of 2.5 to 5 MW. When interconnected to the onshore transmission system via HVAC technology, these wind farms are relatively close to the coastline (10 to 40 km). Interconnection is by means of submarine cables. Typical MV voltages are in the range between 12 and 35 kV, and between 110 and 230 kV for the HV system.

WIND FARM DISTRIBUTION SYSTEM

Study Case

Our hypothetical wind farm has 525 MW of installed capacity and is shown in Figure 1. The system comprises 146 wind turbine generators (WTG) each of 3.6 MW and connected to the MV system via a 690V/33 kV transformer - and associated switchgear – and a 33 kV undersea cable. The WTGs are connected in groups of four or five (designated as "strings") by means of distribution feeders (at 33 kV) to an offshore substation (OS). The WTGs are grouped in three clusters (shown in Figure 1 in **blue**, **red** and **green** colors). For each cluster there is an associated MV/HV offshore substation platform (OSP at 33/230 kV) with a firm transformation capacity (based on the N-1 criteria) of 140/200 MVA ONAN/ONAF. As shown in Figure 2, in turn each OS is connected via 230 kV AC cables to an onshore substation and then to the bulk network of the transmission system operator (TSO) via a double circuit overhead transmission line.

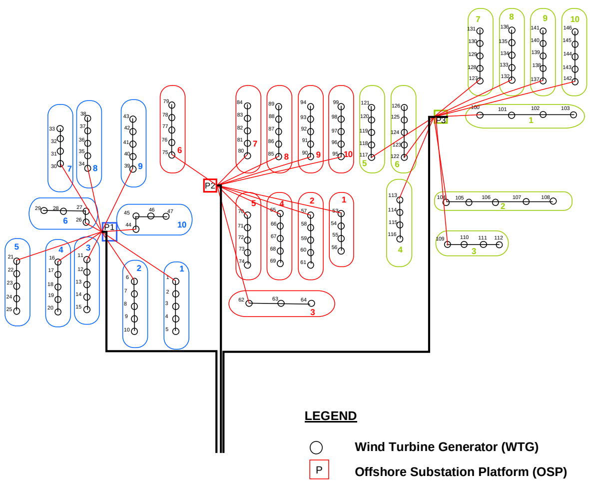

Figure 1 – Wind Farm Distribution System (Study Case)

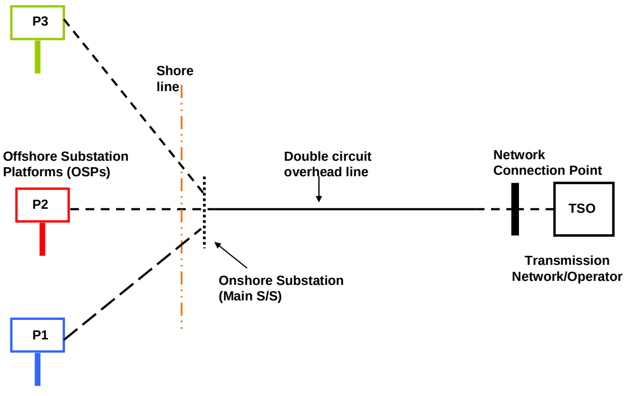

Figure 2 – Wind Farm MV/HV Offshore-Onshore Interconnection System

Wind farms are in fact distributed power generation systems requiring a reliable and secure distribution network including the offshore-onshore interconnection links. Reference [1] provides comprehensive information about the design, analysis and operation of wind farm electrical systems including its integration into the bulk transmission network.

RELIABILITY/AVAILABILITY ANALYSIS CUSTOMIZED TO WIND FARM SYSTEMS

Here we quantify the wind farm production risk associated with the unavailability of the power network by means of industry-accepted methods such as those outlined in the IEEE Standard 493 [2], Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (Gold Book).

Although the availability computation methodology is well documented in the technical literature [2] - [7], the authors would like to present here a summary of the main concepts and definitions, adapted to wind farm transmission and distribution (T&D) systems. This also sets the stage for the establishment of a framework for the implementation of performance-based KPIs for wind farm electrical systems.

Methodology and Input Data

One of the first tasks of any availability computation is to gather and, if required customize, the reliability data (failure rates and repair times of components based on statistical surveys of transmission and distribution electrical equipment). Data customization is required because of the relatively limited experience with T&D equipment working in offshore environments. The customization of the reliability input data (failure rate λ, repair time μ), presented in equations (1) and (2), considers more stringent operational conditions particularly for offshore wind farms and takes into account that more conservative computations should be performed when committing to maintenance performance KPIs such as availability targets or guaranteed availability:

$$\lambda_{adj} = \lambda * F \qquad (F > 1) \qquad (1)$$
$$\mu_{adj} = \mu + TT \qquad (2)$$

where:

- λ_{adj} is the adjusted failure rate of T&D system equipment (failures/year). λ is the failure rate found in IEEE Std. 493 [2]. F is a factor determined as a result of a risk analysis taking into account that the availability calculated with λ and μ is actually an expected value (that is, with a cumulative probability of 0.5). Typical F values are in the range between 2.0 and 3.0. For more conservative computations, required to commit to target values for availability related KPIs, is recommended to use an adjusted failure rate (λ_{adj}) that leads to more conservative T&D availability values corresponding to a higher (and safer) cumulative probability (e.g. 0.75 instead of 0.5) of continuous operation of the T&D network. This decision becomes increasingly important as the availability performance of each wind farm (or cluster of wind farms) is measured and should be continuously improved not only because its capacity (>100 MW) but also due to high penetration of wind power (values>20%) of the total generation capacity of a bulk/national power system. This higher participation and thus higher importance of renewable power sources along with the need of determining fair values to KPIs of maintenance related processes require more conservative estimations of system availability and also more predictable and accurate estimates of energy to be delivered to the network for a given period of time.
- μ_{adj} is the adjusted repair time of an equipment (in hours) calculated by adding "TT" to the actual average repair time (hours) available in reliability/availability databases [2], [3]. TT takes into account the preparation time (and associated logistics, reaction times upon service request) and travel time (by ship or helicopter to offshore wind farm facilities) and some likely waiting time due to bad weather conditions. Usually the repair time (μ) takes into account that spares to replace critical failed components are available and close to the shipping port.

This adjusted input data (λ_{adj}, μ_{adj}) is required to perform more conservative availability computations until specific reliability/availability/maintainability (RAM) data records are available in the next 5-10 years for equipment installed in offshore wind farms. The same is applicable to maintenance system performance measured by means of KPIs which, as a starting point, are estimated using these reliability/ availability studies but should then be enhanced based on both operational performance and benchmarking analysis within the wind power generation sector, the latter based on a broader installed base of distribution equipment located in offshore wind farms. In the meantime, we recommend the use of adjusted (or customized) reliability and availability input data from the IEEE [2] or the OREDA [3] surveys.

Usually in the literature, particularly in Europe, the Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR) are widely used instead of λ and μ. The correspondence between MTTF and λ_{adj} as well MTTR and μ_{adj} are presented in equations (3) and (4).

$$\text{MTTF (hours)} = (1/\lambda_{adj})*8760 \quad (3)$$
$$\text{MTTR (hours)} = \mu_{adj} \quad (4)$$

T&D System Availability Computation (One Source – One Load Traditional Approach)

According to the IEEE Std. 493-1997, the availability of a traditional distribution system can be determined as:

$$\text{Availability}_{T\&D} = 1 - \Sigma\,(\lambda_{adj} * \mu_{adj}/8760) \quad (5)$$

This applies to a conventional radial distribution system without distributed generation. The availability is equal to the sum of the $\lambda_{adj} * \mu_{adj}$ product for each component (or equipment) of the T&D system that in case of failure leads to a total interruption of the power supply to system load.

T&D System Availability Computation Adapted to Wind Farms

In the case of a wind farm system the failure of T&D system components can lead to an interruption of the power transfer of a group of generators. If the number of generators affected by a component outage is designated as $N_{gen\ lost.}$, then the availability of the T&D system could be calculated as follows:

$$\text{Availability}_{T\&D} = 1 - \Sigma\,(\lambda_{adj} * \mu_{adj}/8760)*(N_{gen\ lost.}/N_{gen\ total}) \quad (6)$$

where $N_{gen\ total}$ is the total number of WTGs in the wind farm under consideration.

The availability computation for radial wind farm T&D systems can be performed using equation (6) and a relatively simple simulation tool (such as Excel). In the case of a meshed network, calculations can be performed with a specialized power system simulation package such as PSS®SINCAL.

Overall Availability of a Wind Farm System

If the availability of the generation system (considering that the associated T&D system is 100% available) is measured and designated as $\text{Availability}_{GEN}$, then the overall availability of the wind farm (Availability_{WF}) is calculated as shown below:

$$\text{Availability}_{WF} = \text{Availability}_{GEN} * \text{Availability}_{T\&D} \quad (7)$$

Provided that the availability of the above mentioned systems should be close to 1.0, then equation (7) is usually approximated to:

$$\text{Availability}_{WF} \approx \text{Availability}_{GEN} + \text{Availability}_{T\&D} - 1 \quad (8)$$

For instance, if for a given wind farm $\text{Availability}_{GEN}$ is 0.97 and $\text{Availability}_{T\&D}$ is 0.98, then the availability of the wind farm is 0.9506 using Eq. 7, and 0.95 according to Eq. 8.

The owner/operator of the wind farm is usually concerned with the overall availability (that is, Availability_{WF}) because this determines the amount of generated energy that is actually delivered (and billable) to the transmission network at the agreed connection point.

Availability Calculation for Wind Farms - Operational Risk

The availability of the T&D system schematically presented in Figures 1 and 2 and using Equation 6 exceeds 98% when there is full (100%) redundancy (that is N-1 firm capacity) in the MV/HV transformers located at each of the offshore substations. If the transformer capacity redundancy is 0% then the expected availability drops to about 97%. It should be noted that the availability is an average throughout the lifespan (e.g. 20 or 30 years) of the installation. This means that in some years this could be very high (above 99%) but in others could be as low as 90% if the MV/HV transformers are sized with 0% redundancy. This unwanted fluctuation of the availability during actual operations is further illustrated in the next section. The decision of the degree of redundancy of the transformer capacity should be therefore a result of an overall cost/benefit analysis, where the benefits are a better and more continuous T&D (and wind farm) availability.

PERFORMANCE-BASED MAINTENANCE

Several performance metrics (or KPIs) may be established to measure the performance of wind farm operation and maintenance (O&M) activities, including:

- Overall wind farm availability (Availability_{WF}) targets (or availability guarantees),
- timely performance of maintenance activities as per an agreed maintenance strategy and plan,
- compliance with Service Level Agreements (SLAs), considering reaction times upon incidents occurrence. Reaction times may vary depending on the severity of the incident or fault.

These KPIs are also required to (a) measure the performance and (b) implement a continuous improvement of the maintenance processes as part of a total quality management (TQM) system led by either the owner's maintenance organization or a service provider, this latter in case that the maintenance service is outsourced.

High system availabilities (>90%) can be achieved for extended periods of time (spanning 20 or 30 years) only with proper testing procedures to eliminate early failures and with strict methods of preventive maintenance so that the equipment/components do not fail during their lifespan because of wear out.

While the annual availability of the generation system of a wind farm (Figure 3) is almost constant over the years (because it is actually averaged out by means of having a large number of generators), the availability of the T&D network (Figure 4) could exhibit important fluctuations (because it is a function of the performance of relatively few components, such as one or two main step-up transformers). Therefore, it is recommended that a wind farm service provider commit to T&D (or overall) availability targets only if: (a) these are measured on a multi-annual basis and/or (b) there is not only a penalization but also incentive schemes based on reference value that should be determined using conservative (or adjusted) input data (determined by means of a risk analysis) as described in this paper.

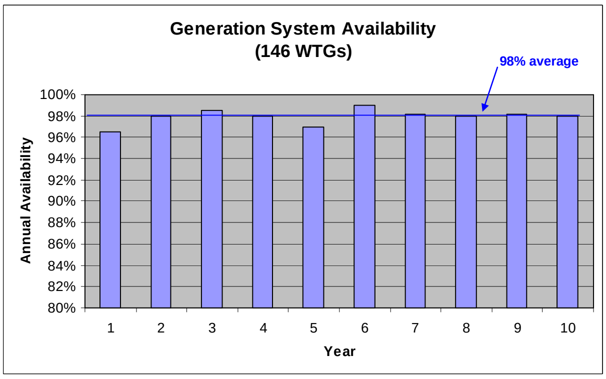

Figure 3 – Generation System Availability (Study Case shown in Fig.1)

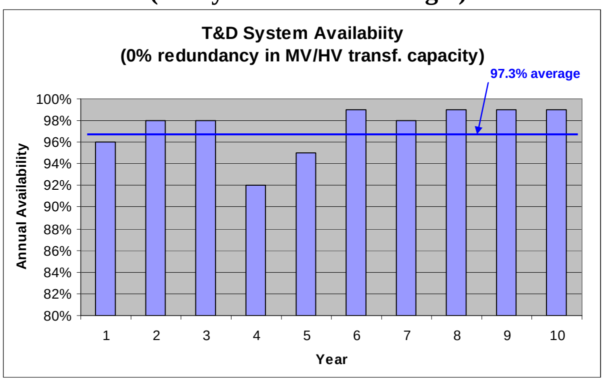

Figure 4 – T&D System Annual Availability (Study Case Shown in Fig.1)

CONCLUDING REMARKS

For an assessment of the operational risks associated with the failure of the T&D system to transfer the power generated by all available WTGs it is important to calculate the network availability during the design phase and measure its performance periodically at an agreed production period (typically one year and desirable on a multiyear or moving averages base).

The availability is a key factor for the successful operation of any wind farm because:

a) it has a proportional impact on the amount of energy that is delivered into the transmission network at the agreed connection point, and
b) there is a close relation between availability (determined by λ, μ) and the performance of the wind farm maintenance services. This statement can be derived using Eq.6 presented again below in order to show those variables with greatest impact on λ and μ throughout the entire lifespan of the T&D system:

(equipment design and technology, preventive maintenance activities including condition monitoring)

$$\text{Availability}_{T\&D} = 1 - \Sigma\,(\lambda \times \mu/8760) \times (N_{gen\ lost}/N_{gen\ total})$$

(maintenance planning & execution, procurement/logistics, spare-part availability, staff training,and knowledge, reaction and travel times to site)

REFERENCES

[1] T. Ackermann (Ed.), 2005, *Wind Power in Power Systems, Part B Power System Integration Experience*, John Wiley & Sons, Chichester, England, 197-410.

[2] 1997, Institute of Electrical and Electronic Engineers (IEEE), *Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493 (Gold Book).

[3] 2009, SINTEF Technology and Society, *Offshore Reliability Data Handbook (OREDA) Volume 1 – Topside Equipment.*

[4] R. Nadira, R. Austria, C. Dortolina and F. Lecaros, “Transmission Planning in the Presence of Uncertainties”. 2003, *Proceedings of the IEEE 2003 PES General Meeting*, Toronto, Canada, Vol.1.

[5] C. Dortolina, J. Porta and R. Nadira, 1991, "An Approach for Explicitly Modeling the Protective Relaying System in Substation Reliability Studies", *IEEE Transactions on Power Systems.* 133-139.

[6] M. Schwan, W.H. Wellßow, H.J. Koglin, 2001, "New Approach for Risk Assessment in Probabilistic Reliability Calculation", *Bulk Power System Dynamics and Control V*, IREP, Onomichi, Japan.

[7] J. Backes, A. Ostelholt, U. Prause, W. Zimmermann, 2001, "Reliability Study for the Refurbishment of a HV/MV Transformer Substation, *Proceedings of the 16th CIRED*, Amsterdam.