A Study on Reliability Assessment for Offshore Wind Farm Configurations

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Abstract: Due to environment concern, fossil resource exhaustion issue and so forth, an attention on the use of renewable energy is being increased sustainably and various types of renewable energy are being developed. In particular, wind power plant is one of the most used resources among them. The recent trend in development of wind power is the large-scale offshore wind farm. However, the burden of investment for offshore wind power is still considerable so that comprehensive evaluation must be performed in the planning stage. For the evaluation, this paper introduces the concept and method to assess offshore wind farm according to their configurations, in the reliability aspect.

1 INTRODUCTION

Wind energy is one of the most used renewable energy resources. The related technology has advanced and a penetration of wind power has being increased sustainably. Furthermore, an installation capacity of a wind power plant has being increased.

There are two types of wind power developments according to the size. One is used as a small scale distributed generator, and the other is a large-scale wind farm. In addition, wind power plant can be developed at onshore or offshore. The recent trend is the offshore wind farm (OWF) which can gather more wind energy and avoid several problems that occur at onshore, such as noise pollution, destruction of the environment and concerns related with construction. However, compared with onshore, OWF has crucial disadvantages which are the more expensive investment and maintenance costs, and the fault effects lasted for a longer time due to a difficulty of geographical access. Therefore, OWF operator has a considerable burden on investment for OWF, so OWF operator has to determine a configuration and design for OWF comprehensively, in order to achieve the economic feasibility. The second one of disadvantages is evaluated by a cost through a reliability assessment, and the reliability and economic analysis can be performed using the result of the reliability assessment. For this, the following indices are redefined in order to represent the results of reliability assessment. PNDR is the power not delivered ratio, EEND is the expected energy not delivered. EENDC is the cost on EEND.

The rest of the paper is organized as follows; In section 2, basic compositions of OWF are described. In section 3, a method to evaluate a reliability of OWF according to wind power configurations is introduced. In section 4, brief case studies are performed in order to demonstrate the introduced method. Finally, section 5 contains a conclusion of this paper.

2 OFFSHORE WIND FARM

Basic composition of large scale offshore wind farm is represented in Fig.1, which consists of wind turbines, inner grid, offshore substations and external grid.

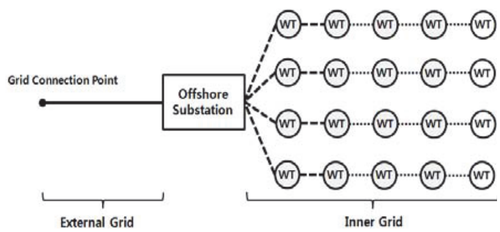

Figure 1: Basic Composition of OWF.

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An electrical energy produced at wind turbines is aggregated thorough inner grid. And then, a voltage of the energy is made higher in order to transfer efficiently toward onshore at transformers in offshore substation. Finally, the energy is delivered toward onshore through external grid.

At the planning stage for OWF, the locations of wind turbines and offshore substations are preferentially decided considering a geographical condition, in order to gather more wind energy. And then, the design and configuration for inner grid, offshore substation and external grid are decided. There are diverse alternatives based on how to connect wind turbines and how to configure substation and external grid. Each alternative of OWF has had different performance on any failure in the OWF and it is indicated as the difference in results of reliability evaluation. When the planning for OWF is performed, considerations for each component are as follows.

In case of designing inner grid, there are the following considerations;

- the voltage of inner grid
- transfer capacity of cables
- the number of feeders(wind turbines per feeder)
- the layout for inner grid: the radial, star and ring types;

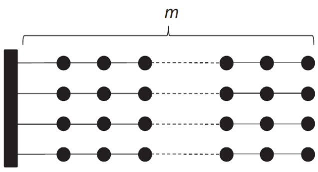

Figure 2: Layout of radial structure.

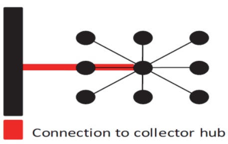

Figure 3: Layout of star structure.

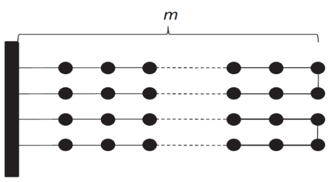

Figure 4: Layout of ring structure.

In case of offshore substation, the following factors are considered.

- the number of transformers
- a capacity of each transformer

In case of external grid, the factors to be considered are same with case of offshore substation.

- the number of transmission lines
- the capacity of each transmission lines

3 RELIABILITY ASSESSMENT ON OFFSHORE WIND FARM

In this paper, a quantitative reliability assessment is performed in viewpoint of OWF operator. Therefore, the goal of reliability assessment is to quantitate how much an expected energy is delivered to onshore from wind turbines considering interruptions in OWF. For this, the following indices are redefined. PNDR is defined as the ratio of a power not delivered by any failure to a power in non-failure state. EEND means the expected value of energy which is not delivered, reflecting all failure states defined at each component. At this time, the failures that may occur at any component, affect to the next component consecutively, so that failure states at any component should contain the failure states defined at the previous component. This fact is represented in Fig. 5.

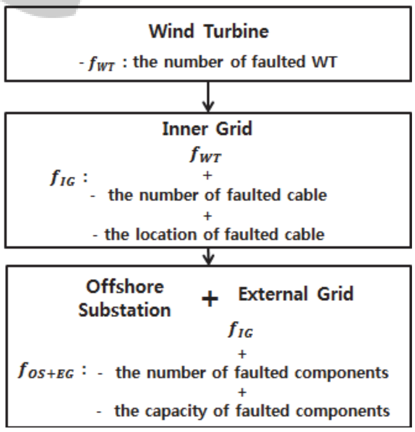

Figure 5: Failure States at each component.

3.1 PNDR at Wind Turbine

Although wind turbines are not related directly to the ability to transfer energy toward onshore, faulted wind turbines affect the transfer ability at next component. Therefore, ratio of energy not produced at wind turbine due to failure of wind turbines can be evaluated like PNDR at wind turbine. PNDR at wind turbine can be calculated as ratio of the number of faulted wind turbines to the total wind turbines.

3.2 PNDR at Inner Grid

PNDR at inner grid is influenced by sum of the number of faulted wind turbines and disconnected wind turbines according to locations where cable faults occur. Because of cable failure with a very low probability, two or more cable failures are ignored in this paper.

There are two different approaches to calculate PNDR at inner grid based on the layouts. In case of a layout of radial structure, PNDR is calculated by ratio of the net disconnected wind turbines to the total wind turbines, the net disconnected wind turbines mean the union set consisting of the faulted wind turbines and the disconnected ones. However, in case of a layout of ring structure which has the redundant cables, a more complex approach is applied. When a failure occurs at one among feeders composing a ring structure, power disconnected by the cable failure would detour through the other feeders in the ring structure. All the remained wind turbines in the ring structure, except for wind turbines connected normally toward offshore substation in the faulted feeder may be limited according to wind speed. If power to be delivered through non-faulted feeders is higher than their total rated capacity, the rated power of the wind turbines is restricted as shown in Fig. 6.

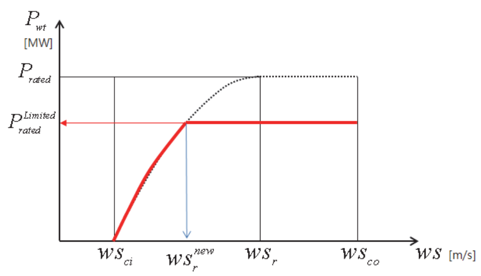

Figure 6: Normal/Restricted Output Characteristic of WT.

Therefore, in case of layout of ring structure, relationship between power delivered through non-faulted feeders and their total rated power is considered as well as the net number of disconnected wind turbines. Equation related to the limited rated power of wind turbine is represented by Eq (1).

$$P_{r,New}(f_{OS+EG}) = \begin{cases} P_r & \text{if) } P_r \le \dfrac{A\_Cap(f_{OS+EG})}{N_{WT} - n.n_{WT}(f_{IG})} \\ \dfrac{A\_Cap(f_{OS+EG})}{N_{WT} - n.n_{WT}(f_{IG})} & \text{if) } \dfrac{A\_Cap(f_{OS+EG})}{N_{WT} - n.n_{WT}(f_{IG})} < P_r \end{cases} \quad (1)$$

where, f_{OS+EG} means failure state at offshore substation and external grid and contains failure factors at formal components, $A\_Cap(f_{OS+EG})$ is total capacity of non-faulted feeders in a ring structure, P_r is the rated power of wind turbine, N_{WT} is the number of wind turbines and $n.n_{WT}$ is the number of the net disconnected wind turbines.

3.3 PNDR at Offshore Substation and External Grid

Failure factors considered at two components affect to PNDR of each component equally. Therefore, Failure factors at two components are handled together. Containing formal failure factors, failure states can be defined by combination of faulted transformers and external lines. If failures occur at transformers and/or external lines, all wind turbines may reduce their rated power only when power to be delivered toward onshore from inner grid is higher than the available capacity of offshore substation and external grid. This process for determining the limited rated power is same with case at inner grid composed by ring structure.

After obtaining all PNDR under predefined failure state at all components, an expected value of PNDR is calculated by multiplying each PNDR and the corresponding probability of failure state. And then, an expected PNDR is used in order to evaluate EEND. EEND is obtained by multiplying EPNDR and an expected energy produced by the entire OWF in non-failure state. This process is shown in Eq (2).

$$\begin{aligned} EPNDR &= \sum_{\forall f_{OS+EG}} PNDR(f_{OS+EG}) \cdot \Pr(f_{OS+EG}) \\ EEND &= EE_{OWF} \times EPNDR \\ EENDC &= EEND \times asp \end{aligned} \quad (2)$$

where, $\Pr(f_{OS+EG})$ is probability of that the failure state, f_{OS+EG} occurs. EE_{OWF} means an expected annual energy of OWF in non-failure state and asp is an average settlement price of electrical energy generated by wind turbine.

4 CASE STUDY

In the section, brief case studies are performed in order to demonstrate the proposed method. OWF is composed by 28 identical 5MW-wind turbines. Wind speed model is applied identically by historical data model obtained at the southwest coast in Korea. The expected annual energy of the entire OWF is 367,159.6MWh considering no failures.

Basic alternatives based on layouts of inner grid are represented by Fig. 7-9.

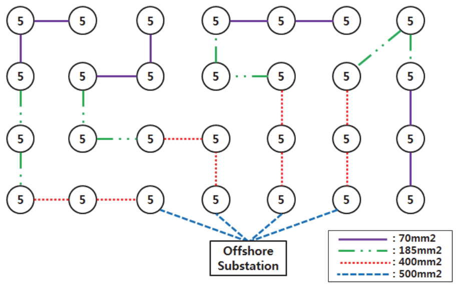

Figure 7: Basic Case 1.

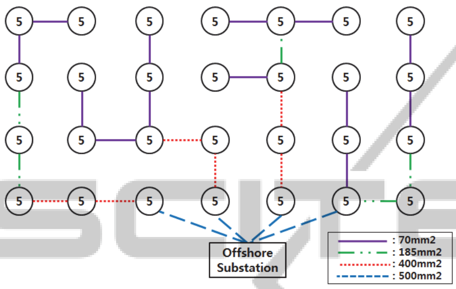

Figure 8: Base Case2.

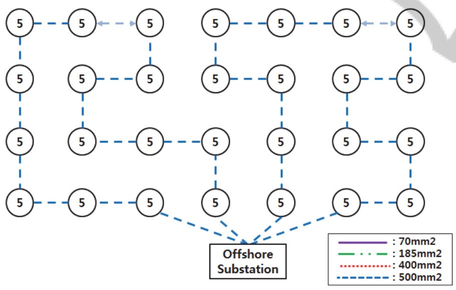

Figure 9: Base Case3.

Cable data in inner grid are represented in Table 1.

Table 1: Data for Cable in Inner Grid.

Cable type[mm2]	70	185	400	500
Available Capacity [MW]	13.0	21.5	31.5	35.5

Individual basic cases are also separated into the four sub-cases according to the number and capacity of transformers and external grid cables, as shown in Table 2.

Table 2: Data for sub cases.

No. Sub Case	-1	-2	-3	-4
Transformer	150MW x 1	75MW x 2	150MW x 1	75MW x 2
External Grid Cable	150MW x 1	150MW x 1	75MW x 2	75MW x 2

For the simplicity, it is assumed that reliability data for each component (Inner/External Cable, Transformer) is identical. The reliability data for individual components are shown in Table 3.

Table 3.

Components	WT	Inner Cable	Trans.	External Cable
Unavailability	0.016	0.00025	0.016	0.0025

The results for all cases are represented as the following Table 4-6, where 0.2$/kWh is applied as average settlement price of wind energy in order to calculate EENDC.

Table 4: Result of Case 1.

		Case 1			
No.Sub-		-1	-2	-3	-4
EPNDR [%]	WT	1.60			
	Inner Grid	1.70			
	OWF	3.51	2.17	3.30	1.95
EEND_OWF [MWh]		12,887.3	7,967.4	12,116.3	7,159.6
EENDC [10^6 $]		2.58	1.59	2.42	1.43

Table 5: Result of Case 2.

		Case 2			
No.Sub-		-1	-2	-3	-4
EPNDR [%]	WT	1.60			
	Inner Grid	1.68			
	OWF	3.50	2.15	3.29	1.94
EEND_OWF [MWh]		12,850.6	7,893.9	12,079.6	7,122.9
EENDC [10^6 $]		2.57	1.58	2.41	1.42

Compared with Case 1, Case 2 has less value of EPNDR and EENDC, respectively, due to a modified radial structure.

Table 6: Result of Case 3.

		Case 3			
No.Sub-		-1	-2	-3	-4
EPNDR [%]	WT	1.60			
	Inner Grid	1.60			
	OWF	3.41	2.06	3.20	1.85
EEND_OWF [MWh]		12,520.1	7,563.5	11,749.1	6,792.5
EENDC [10^6 $]		2.50	1.51	2.35	1.36

As shown in Table4-6, Case3-4 which has a layout of ring structure for inner grid and two transformers and external cables is the best alternative in terms of reliability aspect. On the other hand, Case 1-1 with a layout of typical radial structure and one transformer and external cable is the worst alternative. However, in particular, there is more investment cost for constructing inner grid which has ring structure. Therefore, the best alternative for offshore wind farm has to be determined considering not only reliability assessment, but also economic assessment.

5 CONCLUSIONS

In this paper, a method to perform the reliability analysis for offshore wind farm has been introduced. Basic components of offshore wind farm are divided into four components which are wind turbines, inner grid, offshore substation and external grid. According to a design or configuration for each component, there are diverse alternatives for offshore wind farm. The proposed method can evaluate reliability at each component level step by step, and then the results can be used for reliability and economic assessment to determine the best alternative for offshore wind farm.

As for future work, it is expected to study on how to design optimally inner grid using the suggested method in offshore wind farm.

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