Cost-Based Evaluation of the Risk of Failure Reduction Methods for the Wind Power Plants

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***Abstract*—Wind power plant (WPP) has a lot of similarities with transmission and distribution systems. It consists of power transformers and cable lines, which link generators to the load at the point of common coupling (PCC). Thus, the reliability of that system need to be maintained as well. This paper presents a approach for evaluating the cost-efficiency of risk reduction of the WPP during its planned operational time. It incorporates three methods used individually or combined to increase the system's reliability. In addition, it includes the justification of using these methods from the perspective of the associated efficiency of risk reduction and generated revenue. The results presented are based on the case study. They indicated that: i) the risk of failure is minor for most of the operational time compared to cumulative generated revenue, ii) the risk of failure maximum value can be decreased near to its average value, iii) the ratio between the cumulative revenue and cost of failure is marginal after the break-even point, iv) using monitoring solutions yields with a higher efficiency of risk reduction without the needed increase in redundancy. These methods can assist in a decision making procedure of determining the optimal configuration of the WPP.**

***Index Terms*—asset management, condition-based approach, failure risk reduction, risk-based approach, power system reliability, wind power plant**

I. Introduction

Assessment of risk of failure is commonly used in a modern-day power system. It assists in determining the system's weak links and justifying the actions taken for risk reduction. In the WPP, internal transmission system is similarly there. Thus, failures occurred causes curtailment of generated energy, disruptions in ancillary services, and decreases in overall revenue. Using risk assessment and dedicated methods allow mitigation of the risk in a cost-efficient manner. However, achieving that requires to evaluating suitable methods beforehand.

In literature, various methods are proposed for decreasing the risk of failure from the perspective of its associated cost. Main aspects of maintaining an acceptable level of reliability of the WPPs is described in [1]. The reliability of the WPP is calculated in [2], including mainly the indices related to the wind turbines and substation area, in addition to the parameters indicating their aging. It is based on the failure tree method providing a good overview of the weak links in the system. Using probabilistic characteristics in the evaluation of the reliability of the WPP is also presented in [3]. According to [4], avoiding failures in the transmission system of the WPP is an important factor in their risk reduction. Thus, choosing an appropriate configuration for the facility is a necessity. Various layouts of the WPP are analyzed in [5]. It is stated, that the economic performance and operational risk in the long perspective depends on the decisions made in the planning stage. Although, estimating the change in reliability over a time has a significant uncertainty factor.

Identifying management and financial risk in the renewable projects has a key role for selecting an appropriate risk reduction, as concluded in [6]. For that, evaluating risk in a long term perspective is similarly important. Therefore, criteria including management, economic, and reliability need to be combined in the decision process. The maximization of the revenue from the renewable energy projects with keeping also a focus on the reliability is discussed in [7]. Multiple scenarios are also used in [8] to represent the performance of the WPP from the economic and reliability perspective. It considers the availability states, including the failure, of the components in the power plant to determine their impact on risk assessment.

Failures in the WPPs can additionally cause structural changes in the modern power systems, especially, when considering their significant part in providing ancillary services. Thus, referring to [9], a centralized calculation method including various of nearby power plants need to be used to mitigate singular failures. Similar conclusions are made in [10], pointing out that the independent failures could cause cascading failure events disconnecting large areas from the grid. Decreasing the risk of failure in the WPPs also assist in load scheduling and reducing operational risk of the power system, as mentioned in [11]. Beforehand, it requires to map the risk factors to determine the optimal trade-off between the energy curtailment and reliability.

This paper contributes to ongoing research by: i) including preventive and predictive asset management strategies into the risk of failure reduction of the WPP; ii) incorporating the ratio between the cost of failure and the cumulative revenue during a planned operational time; iii) calculating the efficiency of risk reduction from the perspective of the decreased risk of failure and the associated cost.

Referring to the aforementioned aspects, this paper presents preventive and predictive methods for risk reduction of the WPP. It evaluates the achievable efficiency of risk reduction during a longer time frame and includes three independent

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levels - system, substation, and element. These are used separately or combined in various schematics of the WPP. The decrease in risk is evaluated based on associated costs. Besides the risk of failure, the assessment criteria consider the parameters related to the cumulative cost of energy supplied, the cost of failure, and the cost-efficiency of risk reduction. The methods are incorporated in a case study. The results can be used as part of a decision process for choosing the configuration and the extent of risk reduction for the WPP.

II. Methodology

A. Risk of Failure

Reliability of the power systems is related to the failures of equipment. Another crucial aspect is the extent of load curtailment after the failure. Thus, the importance of equipment or similar element in the system is expressed by the risk of failure (RoF). Commonly, the RoF is based on the probability of failure (PoF) and the cost of failure (CoF). Latter incorporates the cost of repair (CoR), mean time to repair ($MTTR$), and the value of load curtailment based on the cost of energy (CoE).

The RoF is commonly calculated for N-1 and N-2 contingencies. In case of WPP, N-1 contingencies can cause the maximum load curtailment. The likelihood of having maximum load curtailment in N-2 contingencies is higher. However, each element in the system has specific CoF and PoF. Thus, the RoF of WPP is expressed by its average (1) and maximum (2) value considering all elements n.

$$RoF_{average} = \frac{\sum_{i=1}^{n}(CoF_i \cdot PoF_i)}{n} \tag{1}$$

$$RoF_{max} = \max(RoF_i), \quad i = 1..n \tag{2}$$

B. Methods of Risk Reduction

The RoF in WPP can be decreased by using multiple methods, such as:

- A - Increasing the redundancy of the cable system
- B - Increasing the redundancy of the substation
- C - Decreasing the probability of failure of system elements

In method A, the redundancy is increased by using parallel cable lines instead of commonly used single lines. Firstly, parallel lines can be added to the main line between the main gathering node of wind turbines and the substation or PCC. Secondly, additional lines can also be added to the specific areas of the electrical facility in order to minimize the load (generated power) shedding. In that option, they are added between clusters of wind turbines or individual units. Overall, the aim is to provide an alternative path for redirecting the load and bypassing the failed path.

In method B, the redundancy is increased by using two power transformers in parallel instead of a single unit. An option is also to use power transformers with higher nominal apparent power, if already having two units in parallel, for lower load curtailment in case of a failure.

In method C, the frequent or real-time condition evaluation of the system elements is performed. This means of using dedicated measurement solutions to detect the changes in the measured parameters. Thus, the PoF of the system's elements is decreased instead of increasing its redundancy.

C. Cost of Risk Reduction

Each risk reduction method incorporates specific cost components. Methods A and B are mainly related to strengthening the power system of the WPP. Thus, the associated total cost of risk reduction ($CoRR$) depends on the number of added parallel elements or the increase of their nominal apparent power. In method C, the associated cost depends on the frequency of condition evaluation and measurement solutions used. Total $CoRR$ is described by (3). It includes the cost of changing the substation schematic ($CoSSC$), the cost of strengthening the system ($CoTSC$), and the change of condition assessment cost of the system ($\Delta CoCA$).

$$CoRR = CoSSC + CoTSC + \Delta CoCA \tag{3}$$

Usage of a specific risk reduction method can be justified based on the efficiency of risk reduction ($EoRR$) described by (4), where RoF_a and RoF_b are indicating risk of failure value after and before the risk reduction, respectively.

$$EoRR = \frac{RoF_b - RoF_a}{CoRR} \tag{4}$$

In case of generated revenue, two separate stages are related to the operation of WPP. In the initial stage, the cumulative cost of generated energy ($CoGE$) is negative due to the $CAPEX$ used for developing the electrical facility. After the break-even point, the cumulative $CoGE$ becomes positive. The increase in that value depends on the $OPEX$, including the CoF and the CoR after equipment failures. Therefore, it is also necessary to consider the ratio between the cost of generated revenue (energy supplied, $CoES$) during time (t), the CoF, and the $CoRR$. This is expressed by $raCoES$ in (5).

$$raCoES = \frac{\frac{\sum_{i=1}^{n} CoF}{n}}{\sum_{i=1}^{t} CoES - CoRR} \tag{5}$$

D. Configurations Considering Methods of Risk Reduction

Commonly, the redundancy of the WPP is relatively low due to avoiding the unjustified increase of the $CAPEX$. Thus, it is necessary to analyze the cost-efficiency of increasing the reliability or redundancy of the WPP by combining the risk reduction methods. In this analysis, following schematics including different methods are used:

- 1 - Normal schematic with no redundancy
- 2 - Increased redundancy of power transformers, without increasing the total apparent power
- 3 - Increased the redundancy of the main cable line between the main gathering node and substation or the PCC, without increasing the transmission capability
- 4 - Combining schematics 2 and 3

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- 5 - Schematics 4, with increased redundancy between clusters of wind turbines and individual units
- 6 - Schematics 2 and 3, with full redundancy of power transformers and the main cable line
- 7 - Schematic 1, using condition evaluation for power transformers and cable lines
- 8 - Schematic 1, using condition evaluation for power transformers and cable line between the main gathering node and substation or the PCC

Schematic 1 describes the normal layout of the electrical facility. Because of lacking redundancy, a failure of an element causes the disconnection of all wind turbines connected to that element. Thus, a failure of the power transformer or the main transmission line means the full load curtailment.

Schematics 2...6 use risk reduction methods A and B. In the case of schematic 2, a single power transformer is replaced by two units, each of them having half of the nominal apparent power of a single unit. Thus, after a failure of the power transformer, load shedding is around 50% of the full load compared to full load shedding in the normal schematic. A similar pattern is used in schematic 3, where a single line is replaced by two parallel ones, without increasing the maximum permissible current of the path. Therefore, in case of cable failure, only half of the load is curtailed instead of a full load curtailment in normal schematic. Increased reliability is achieved in schematic 4 by combining schematics 2 and 3.

In schematic 5, additional cable lines are added between groups of wind turbines and between individual units. Therefore, each wind turbine has two connections - main one with either the gathering node of the group or another wind turbine, second to another wind turbine. This does not avoid the load curtailment completely, as the load is shifted to a nearby cluster. Its connection might have been configured to the load of that cluster, and therefore, partial load curtailment is needed.

Schematic 6 has full redundancy of power transformers and the cable line between the gathering node of the clusters of wind turbines and the substation or the PCC. Thus, the reliability of the system is increased by eliminating the full load curtailment in case of failures of two main elements - power transformer or the main cable line.

In schematics 7 and 8, risk reduction method C is used. Thus, the condition-based asset management, such as described in [12], [13], is implemented for power transformers and all cable lines in schematic 7. This makes it possible to decrease the PoF, which decreases the RoF as well. In schematic 8, the condition-based approach is only used for power transformers and the main cable line. These are elements through which all the power of the electrical facility is transmitted. Therefore, their PoF contributes to the overall risk of failure the most. It is also a more cost-efficient method compared to schematic 7.

III. Case Study

The aforementioned schematics are used in a case study. The principal schematic of the WPP analyzed, common in Northern Europe, is given in Figure 1. It consists of 25 similar wind turbines with a maximum power of 7.5 MW each. They are grouped into 5 clusters with common gathering nodes C2...C6. These clusters are gathered at node C1. The normal layout of cables with power transformer TA is indicated in solid lines. The dotted lines indicates the added cable lines and power transformer TB. The additional cable lines are also between C2...C6, providing re-routing possibility. For a similar purpose, the redundancy is increased by cable lines between individual wind turbines. It is assumed in methods A and B, that only a partial amount of power can be re-routed in these cable lines.

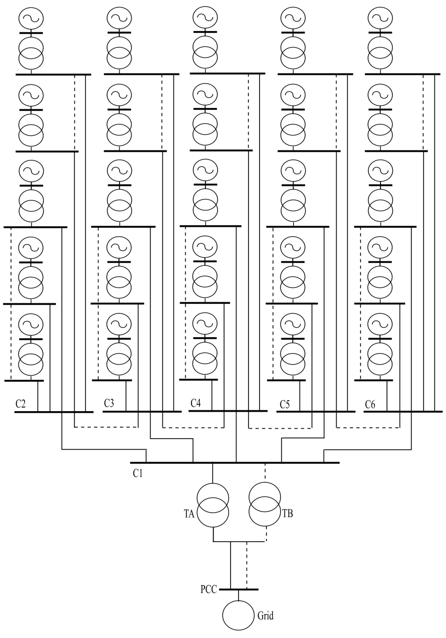

Fig. 1. Principal schematic of a wind power plant used in case study

It is assumed in risk reduction method C, that the PoF of cable lines and power transformers is decreased by 80% due to relatively frequent monitoring. This and other parameters used are estimated from the equipment in the main grid. For condition assessment, frequent inspections with dedicated measurement solutions are used. Thus, the irregularities related to element condition, such as appearances of partial discharges, are detected before the failure and a preventive repair procedure can be scheduled. It is also assumed that the failures in the WPP are individual and are not overlapping. Impact from latter is also minimized by having only one connection at the PCC.

The CoE is taken as 45 €/MWh, half of the average in [14] due to the different entry level of the WPPs to the electricity market. The capacity factor of the WPP is 30%. The assumed operational time of the WPP is 30 years. The $CAPEX$ is 1000 €/kW. The $MTTR$ of power transformers is 1000 hours, and for cable lines it is 500 hours. Theoretical repair of power transformers could take more time, but it is expected that the power plant is not generating constant power during that period. In case of cable lines, the failure event could occur entirely during a higher load of the WPP. Figure 2 describes

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that principle, where time period A indicates the failure of cable lines and time period B indicates the failure of power transformer. Due to the characteristic of power generation, their total CoF can be relatively similar. The PoF of elements is increasing yearly reaching 0.25 at the end of the time-frame. Due to the lack of statistical data, the probabilistic characteristics are estimated based on elements in main grid.

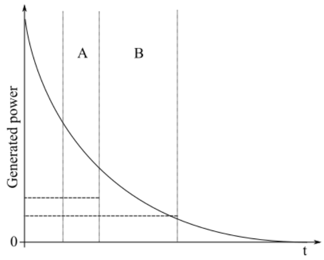

Fig. 2. Principal generation characteristic of a wind power plant

IV. Results

The results of the case study are presented in Fig. 3 to Fig. 6. Initially, the $RoF_{average}$ values for schematics 1...6 are depicted in Fig. 3. The RoF of schematic 1 yields the highest values due to having no redundancy. However, the RoF itself is below 50 k€ for most of the operational time. As redundancy increases and the CoF decreases, the RoF also decreases. The difference between the schematic 1 and 6 is around 100 k€ at the end of planned usage of the WPP. In addition, overall RoF is relatively low before year 10, making the difference in schematics minor.

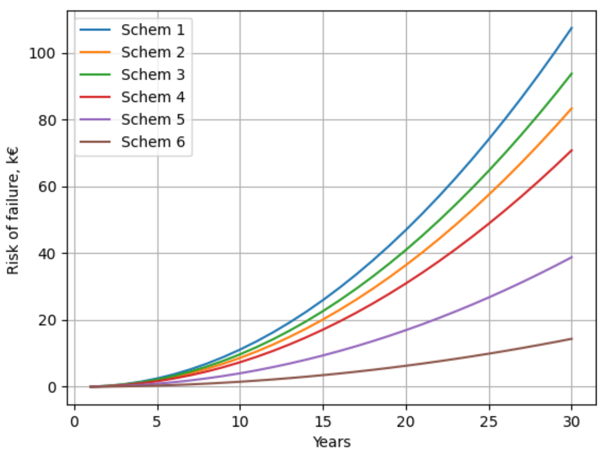

Fig. 3. The $RoF_{average}$ values for schematics 1...6 (only preventive methods)

Secondly, the $RoF_{average}$ for schematics 1, 6, 7, and 8 are depicted in Fig. 4. When including predictive management, the RoF remains below schematic 1, but above schematic 6. When using condition-based monitoring for all elements in the transmission system, schematic 7 allows to gain relatively similar results as schematic 6. Eventually, it depends on the achievable decrease in PoF. However, if using predictive approach only on transformers and the main line, in schematic 8, the RoF is around half of the value in schematic 1.

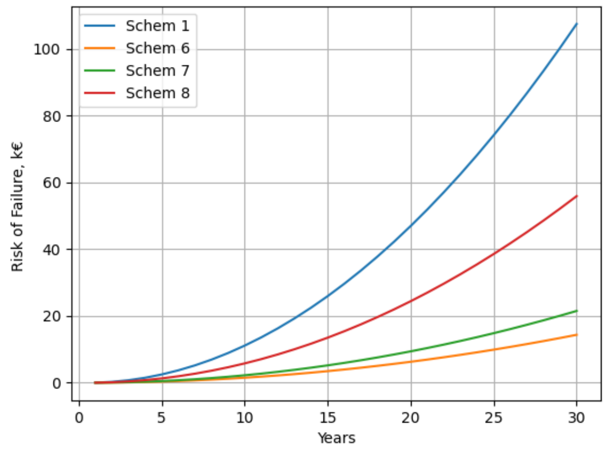

Fig. 4. The $RoF_{average}$ values for schematics 1, 6, 7, and 8 (additionally predictive methods)

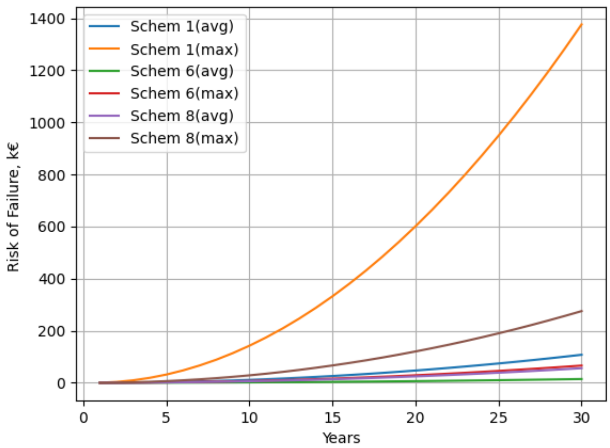

Fig. 5. The $RoF_{average}$ and the RoF_{max} values for schematics 1, 6, and 8

Thirdly, the maximum and average values of the RoF for schematics 1, 6, and 8 are depicted in Fig. 5. Due to lack of redundancy, the RoF_{max} in schematic 1 is significantly higher compared to other schematics. The least difference is with schematic 6, its RoF_{max} is around half of the $RoF_{average}$ of schematic 1. If using condition monitoring solutions, the maximum value in schematic 8 is twice as high as in schematic 1. However, overall RoF is still below 100 k€ for the initial 15 years of the WPP.

Fourthly, the $raCoES$ is depicted in Fig. 6. The peaks in the graph represent the break-even point of the $CAPEX$ and cumulative revenue. Before the peaks, the $raCoES$ is below 2%, but negative. Thus, occurred failures will shift the break-even point further in the future. After that, the ratio starts to decrease because of the higher difference between

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the cumulative $CoES$ and the CoF. The lowest peak and the $raCoES$ is with schematic 6 due to the lowest CoF.

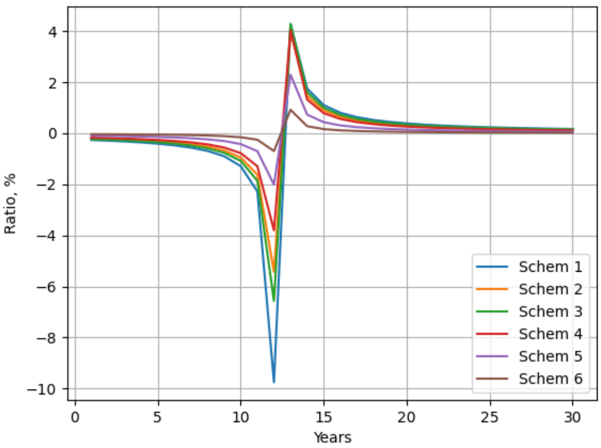

Fig. 6. The $raCoES$ values for schematics 1...6

Finally, the $EoRR$ is depicted in Fig. 7. Due to the higher achievable decrease in the RoF compared to the associated $CoRR$, the $EoRR$ is highest with schematic 6, if only considering preventive methods without condition monitoring. However, the decrease in the PoF results with higher $EoRR$ in schematics 7 and 8. In case of more affordable monitoring solutions, the $EoRR$ increases even more. When comparing schematic 6 to schematic 2, the $EoRR$ is around 50% lower. However, in the initial 15 years, most of the schematics have relatively similar $EoRR$.

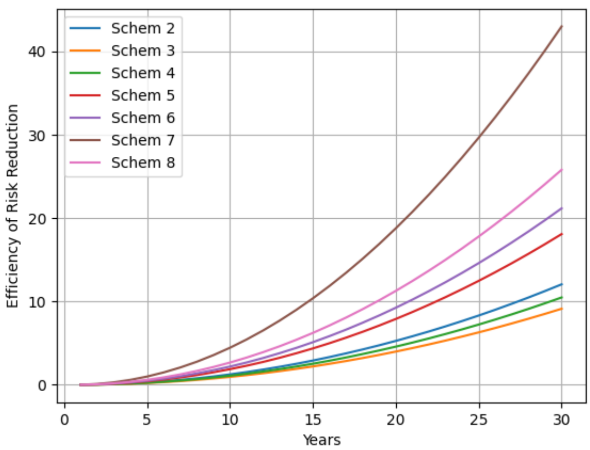

Fig. 7. The $EoRR$ values for schematics 2...8

V. Conclusions

In this paper, the cost-efficiency of risk reduction methods for the WPP is analyzed. These methods incorporate three different levels, allowing the risk of failure to be decreased separately or combined. They are evaluated based on the various schematics and multiple parameters, such as the cumulative cost of generated energy, the cost of failure, and the cost of risk reduction. The analysis is based on the case study, where their efficiency of risk reduction is compared. Key takeaways from the results are: i) the RoF is relatively low for the most of the operational time, especially when considering the generated revenue, ii) in schematics with lower redundancy, the difference between the RoF_{max} and the $RoF_{average}$ can be up to 10 times, iii) the $raCoES$ is below 2% after the break-even point, meaning the low impact from the CoF compared to the overall revenue, iv) the $EoRR$ is higher when using condition monitoring, even on schematics with lower redundancy. Thus, the risk reduction correlation to the availability of ancillary services should be analyzed in future research. These methods can be useful for determining the extent of risk reduction and associated cost for the WPPs.

References

[1] P. Kumar, S. Paul, S. Kumar Saha, and Y. O., "Recent advancements in planning and reliability aspects of large-scale deep sea offshore wind power plants: A review," *IEEE Access*, vol. 30, pp. 3738–3767, 2024.

[2] S. A. Hosseini, M. R. Karimi Gharigh, and S. Peyghami, "Advanced top-down reliability evaluation of wind power systems using fault tree analysis and aging effect modeling," in *2025 IEEE Kiel PowerTech*, June 2025, pp. 1–6.

[3] H. Yang, L. Wang, Y. Zhang, X. W. Qi, L., and H. Wu, "Reliability assessment of wind farm electrical system based on a probability transfer technique," *Energies*, vol. 11, no. 4, p. 744, oct 2018.

[4] E. Gulski, G. J. Anders, R. A. Jongen, J. Parciak, J. Siemiński, E. Piesowicz, and I. E. Irska, "Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability," *Renewable and Sustainable Energy Reviews, 151, 111580*, vol. 151, p. 111580, 2021.

[5] J. Serrano González, M. Burgos Payán, and J. Riquelme Santos, "Optimum design of transmissions systems for offshore wind farms including decision making under risk," *Renewable Energy*, vol. 59, 2013.

[6] Y. Wu and T. Zhang, "Risk assessment of offshore wave-wind-solar-compressed air energy storage power plant through fuzzy comprehensive evaluation model," *Energy*, vol. 223, p. 120057, 2021.

[7] L. Reichenberg, T. Ekholm, and T. L. Boomsma, "Revenue and risk of variable renewable electricity investment: The cannibalization effect under high market penetration," *Energy*, vol. 284, p. 128419, 2023.

[8] M. Liu, D.-G. Lu, J. Qin, Y.-Z. Miao, W.-H. Zhang, J.-S. Zhu, and M. H. Faber, "Risk-informed integrated design optimization for offshore wind farm electrical systems," *Reliability Engineering and System Safety*, vol. 250, p. 110299, 2024.

[9] G. Han, K. Zhang, A. Tang, T. Wang, X. Li, and H. Yang, "Risk assessment of composite transmission and substation system with multi-state wind farms," in *2024 IEEE 7th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, vol. 7, March 2024, pp. 112–116.

[10] N. A. Masood, R. Yan, and T. Kumar Saha, "Cascading contingencies in a renewable dominated power system: Risk of blackouts and its mitigation," in *2018 IEEE Power and Energy Society General Meeting (PESGM)*, Aug 2018, pp. 1–5.

[11] Y. Fang, S. Zhao, and Z. Chen, "Multi-objective unit commitment of jointly concentrating solar power plant and wind farm for providing peak-shaving considering operational risk," *International Journal of Electrical Power and Energy Systems*, vol. 137, p. 107754, 2022.

[12] Y. Yan, P. Huo, and H. Y. Li, "Robust on-line partial discharge measurement of 35-kv cables in wind farms via dual sensors," *Energy Reports*, vol. 9, 2023.

[13] Y. Yan, Y. Zhao, K. Zhao, R. Trinchero, Stievano, I. S., and H. Y. Li, "A high efficiency portable system for insulation condition assessment of wind farm inter array cables with double-sided partial discharge detection and localisation," *Iet Generation Transmission and Distribution*, vol. 17, pp. 2523–2534, 2024.

[14] "Electricity market, period 2023," *NordPool*, 2023.

979-8-3315-8138-1