Operating Experience and Suggestions for Reliability and Resilience Indices – A Study in Taiwan

Yuan-Kang Wu
National Chung-Cheng University
Chiayi, Taiwan
allenwu@ccu.edu.tw

Quoc-Thang Phan
National Chung-Cheng University
Chiayi, Taiwan
thangphanquoc2407@gmail.com

Duc-Tung Trinh
National Chung-Cheng University
Chiayi, Taiwan
tungtd@alum.ccu.edu.tw

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***Abstract*—This paper mainly focuses on the issue about reliability indices and the corresponding measured methods. These indices cover the operating aspects on distribution, transmission and generation systems. Additionally, this paper discussed about the reasons that affect reliability indices, including the effects of distribution automation on reliability. Moreover, the frequent occurrence of major accidents caused by natural disasters, especially typhoons and earthquakes, has highlighted the importance concerning about grid resilience, leading to a requirement to design appropriate resilience indices. By surveying various definitions and research works on grid resilience with related indicators, this paper provides feasible methods for calculating resilience indicators, thereby providing a tool for assessing whether the power grid resilience can be improved gradually.**

Keywords—reliability indices, distribution, transmission, generation, grid resilience

I. Introduction

As the requirements for power supply reliability and optimization of power system operations continue to increase, there is a need to re-examine the existing procedures to calculate reliability indices and the corresponding methods of data acquisition [1]. The trend of various reliability indices provides an important reference whether the improved strategies are useful. If these indices show a negative trend, the power system planners and operators should re-design their strategies on planning, scheduling and maintaining [2]. Additionally, the reliability indices on different supply areas, types of generators, voltage levels, or electrical components would be different. The statistics of historical reliability indices provide a crucial reference to strengthen the reliability on specified areas or power components. Currently, the main issues on smart grids become more important since the number and duration of power interruptions must be reduced to maintain a high power supply reliability. Furthermore, advanced information or communication technologies also help improve power reliability.

To evaluate power system reliability, each country has applied different reliability indices [3-4]. However, SAIDI and SAIFI are widely used in the world, but the detailed calculations and data collections would be modified by different countries. This paper first reviews international standards to survey the basic definition and formal process to calculate various reliability indices. Next, various causes to reduce distribution system reliability in Taiwan are analyzed according to the outage records in recent years. It reveals that finding the main causes to affect reliability indices is significant, which provides significant references to improve system's weak points. Then, this paper provides a real experience in Taiwan concerning about the distribution automation and its impacts on reliability indices. Moreover, several key technologies for distribution automation are introduced in this study. They include geographic information system, the availability of automation equipment, and so on. In addition to distribution system reliability, this paper also summarizes the operational experience and the corresponding reliability indices for thermal power generators in Taiwan. These indices are utilized to evaluate the availability and performance of traditional thermal power generators. These statistical results can reveal the system performance on the generation side. Finally, this paper highlights the importance to evaluate power system resilience. Thus, various potential indicators to represent system resilience are discussed in this paper. It covers the definition of resilience, required data to calculate indicators, various curves to describe an outage process, and the suggested indicators. Most importantly, this paper collects the experience and suggestions from power system experts. These surveys can provide important references to enhance both reliability and resilience in power systems.

II. International Standards and Definitions for Transmission and Distribution Reliability Indices

The current international indices for distribution system reliability with associated calculations are primarily based on the IEEE 1366 Standard [5]. Figure 1 illustrates the classification of reliability indices in IEEE 1366, which provides the main categories for sustained outages (large than 5 min) and momentary outages (less than 5 min). Furthermore, the indices in IEEE 1366 are calculated annually, and major event days (MEDs) can be considered or excluded in the calculation. Among these indices, SAIFI and SAIDI are the most widely adopted indices internationally. SAIFI measures the average number of outages experienced by each customer over a given period (typically one year). SAIDI, on the other hand, represents the average outage duration experienced by each customer within a service area. Additionally, other important sustained outage indices include Customer Average Interruption Duration Index (CAIDI), Customer Average Interruption Frequency Index (CAIFI), Average Service Availability Index (ASAI), Customers Experiencing Multiple Interruptions (CEMIn), and

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Customers Experiencing Long Interruption Durations (CELID). Among the above indices, CAIDI indicates the average outage duration for customers experiencing an interruption, revealing the speed of power supply restoration.

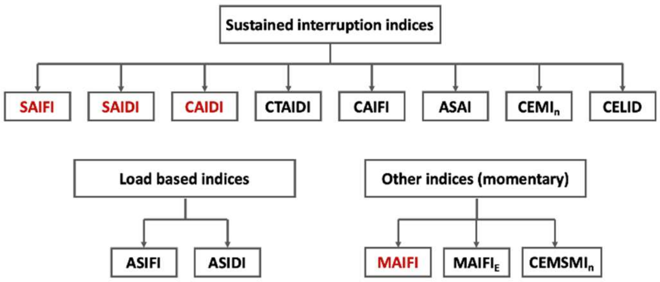

Fig. 1. Classification of IEEE 1366 reliability indices

Numerous countries utilize various reliability indices to assess the reliability performance of their distribution systems [6]. For instance, California Public Utilities Commission (CPUC) in the US requires utilities to annually provide the statistics about four reliability indices: SAIDI, SAIFI, CAIDI, and MAIFI. Tokyo Electric Power Company (TEPCO) primarily relies on SAIDI and SAIFI for evaluating gird reliability. In 2019, TEPCO's annual average SAIDI and SAIFI is 85mins and 0.23 interruptions per customer, respectively. South Korea also applies SAIDI and SAIFI to evaluate the reliability performance for its distribution system. During the period between 2019 and 2021, South Korea achieved an annual average SAIDI of approximately 8.8 mins and 0.1 interruptions per customer. Singapore stands out as a leading country to maintain a high reliability performance in distribution system. From 2018 to 2022, an average SAIDI or SAIFI is approximately 0.5 mins and 0.01 interruptions, respectively. This exceptional performance can be attributed to its highly loop distribution network design. Australia utilizes SAIDI, SAIFI, and MAIFI to evaluate its distribution system reliability; the statistics are divided into planned and unplanned outages, and MEDs are considered. Between 2010 and 2020, the annual average SAIFI for planned outages in Australia is around 0.3 interruptions. Unplanned SAIDI, on the other hand, ranges from 265 mins to 26.5 mins. Significant weather events contributed most to high SAIDI values.

For reliability assessment in Germany, it employs SAIDI, SAIFI and CAIDI as key indices. In recent years, the average SAIDI for the medium and low voltage systems in Germany is approximately 12mins and 2.5mins, respectively. The average SAIFI is around 0.4 interruptions for the medium voltage system and 0.02 interruptions for the low voltage system. Notably, the establishment of underground cable systems in Germany significantly improves low voltage reliability. UK considers both long and short power interruptions in its reliability indices. For short interruptions, the MAIFI index is employed, while SAIDI and SAIFI are also used for longer outages. From 2010 to 2018, the annual average unplanned SAIDI ranges from 42mins to 91mins, with an average SAIFI of approximately 0.6 interruptions.

In Europe, the threshold between short and long interruptions for most countries is 3 mins. An outage exceeding 3 mins is classified as a long outage, while an outage lasting between 1s and 3 mins belongs to a short interruption. Most European countries utilize SAIDI and SAIFI as reliability indices for long interruptions, but some countries like Netherlands, Belgium, and Sweden also incorporate CAIDI as an additional indicator for reliability assessment. Taiwan currently adopts SAIDI and SAIFI as reliability indices. According to the reliability statistics, the annual average SAIDI and SAIFI in Taiwan are approximately 16.5 mins and 0.2 interruptions, respectively, from 2009 to 2019.

III. THE CAUSES TO REDUCE SYSTEM RELIABILITY

Typically, incidents in distribution systems are recorded in the outage management system (OMS), initiated either by customers' calls or system operators based on feeder circuit breaker. Subsequently, the OMS data are imported into the OTG system for SAIDI and SAIFI calculations. For the statistics of reliability indices, It is suggested to divide the indices into different areas and months, and it is required to categorize unplanned and planned outages. Furthermore, to understand the monthly variations in grid reliability across different regions, it is better to identify the highest and lowest indices at each region over several years, revealing the reliability performance at different regions.

In addition to calculate reliability indices based on the raw outage data, historical records about the causes of all outages are also important. Such an analysis provides an important reference to improve the reliability of distribution systems. For instance, the analyses in Taiwan reveal that the most frequently damaged components include high-voltage cables (lines), insulators, and transformers, and the primary causes of these damaged components include natural degradation, animal contact, and salt contamination in coastal areas. Different countries and areas would have different causes for power outages. It is required to analyze them to improve system performance.

Based on the historical statistics of power outages in Taiwan, at urban areas, a high proportion of component damages involve high-voltage cables (lines) and related equipment. The main causes are natural degradation and insulation deterioration. Additionally, the trend for the damages of transformers and load breakers has increased in recent years because of equipment aging. At the eastern region of Taiwan, the proportion of damages on fuse tubes is high, and the main causes include natural degradation, insulation deterioration, and animal contact. Furthermore, the rate of lightning strikes in the eastern area is also higher than other areas. In summary, high-voltage cables (lines) and related components remain the primary sources of outages in Taiwan's distribution systems. Regarding to the causes of outages, insulation and natural degradation are the primary factors in several cities, particularly in areas with a high degree of underground cables. In contrast, animal contact is more common in mountainous areas to cause outages.

The statistics to find the main causes of historical outages can provide insights on the aging trend of power system components. Consequently, these statistics can help power companies or owners for equipment maintenance and replacement schedules on aging assets. The causes of various

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outages vary across different areas. For instance, at the coastal area, the northeastern monsoon during autumn and winter in Taiwan may increase the frequency and duration of electricity outages. In urban areas, frequent damages on underground cable networks could lead to high SAIDI values.

In addition to distribution systems, certain high-voltage transmission lines often experience outages due to seasonal lightning strikes, frequent animal activities, human errors and others. For example, the main causes of outages on several high voltage transmission lines are animal contacts or lightning strikes. According to the operating experience in Taiwan, it is difficult to build new double-circuit transmission lines in some areas. Thus, to improve power supply reliability, installing energy storage systems could be a good option to solve that problem, which enhance system reliability at certain local areas.

IV. Distribution Automation and its Impact on Reliability Indices

The installation of distribution automation (DA) equipment can potentially enhance distribution reliability. As a fault occurs in a feeder, the DA monitoring system will alert and obtain information about the affected feeder. Each circuit breaker on the faulted feeder is equipped with a feeder terminal unit (FTU), which aims to detect fault currents. Then, the fault detection & classification system (FDCS) can automatically determine the fault location and isolate it, and rapidly restore upstream power. Subsequently, the downstream feeder will be re-dispatched by other feeders. Next, the maintenance department will inspect the actual fault location within the affected area and repair the faulted components.

In Taiwan, automatic feeders have been increased 14% from 2018 to 2022. The number of automatic line switches under monitoring has increased up to 22% from 2018 to 2022. Currently, the ratio of automatic feeders in Taiwan's distribution system is around 82%, and it is still increasing from 2023 to 2024. It is expected to complete the automation of all feeders by the end of 2025. However, each feeder has different number of automatic devices, which affects the reliability performance in the real system. The operation modes for automatic feeder switches include FDIR (fault detection, isolation, and recovery) automatic processing and remote control. The former relies on fault flags to automatically detect the fault area, isolate it, and restore power to upstream customers. The latter approach is used when FDIR is disabled in certain situations, bit fault flags are still returned to control center, which would allow for remote control operations.

One of the key aspects of distribution automation includes the geographic information system (GIS) and the availability of automation equipment. The GIS platform employed in the distribution automation system presents feeder distributions in various colors, enabling users to distinguish different feeders easily. This system can convert geographic feeder information into single-line diagrams and highlight faulted feeders to alert dispatchers. In Taiwan, the power flow calculations on the developed GIS platform utilize OpenDSS software and incorporate pre-fault measured parameters for the calculations. Apart from the GIS system, the availability of the DA system equipment, including communication devices, is also crucial to the success of feeder automation. If the availability of automation components is high, the outcomes of automation will be exceptional.

V. Reliability Indices for power generation systems

In addition to evaluating distribution reliability, the reliability evaluation for the generation side; i.e., the availability of power plants, is also important. In Taiwan, equivalent availability factor (EAF), forced outage rate (FOR) and equivalent forced outage rate (EFOR) are calculated annually. Thus, it should concern about the calculation procedure to obtain these indices, and data recording of unit start-ups and shutdowns. Generally, the standard of IEEE 762-2006 is utilized to calculate generation unit availability indices [7].

According to the statistical analyses in Taiwan, the EAF for coal-fired steam units experienced a significant decline in 2019 and 2020 compared to 2018. The drop in the EAF for coal-fired steam units in 2019 was primarily due to an increase in the average outage duration, caused by the emission restrictions on coal usage. In 2020, the decline in the EAF for coal-fired steam units is mainly attributable to environmental protection outages. Additionally, the EAFs for gas-fired steam and oil-fired steam units fluctuate considerably, primarily due to variations in planned outage durations. However, since gas-fired steam and oil-fired steam units account for only 4% each of the total reference capacity for thermal units, the fluctuations in their EAFs have minimal impact on the overall generation capacity in Taiwan. In contrast, for coal-fired steam and combined cycle units, which each account for over 40% of the reference capacity, the planning of scheduled outages must consider the potential impact on overall generation capacity. According to our statistical analyses, the EAFs of generation units in Taiwan are significantly higher than those of NERC units in North America, demonstrating a high operating performance on Taiwan's thermal power plants.

VI. Resilience Assessment Indices in Power Systems

In recent years, the increasing natural disasters and human-induced extreme events has made the resilience of power systems to become an important issue. However, appropriate resilience indices need to be designed and adopted, and these indices should be used annually to assess the performance of power system resilience. Currently, there are no specific international standards or regulations for resilience indicators. Most utilities or organizations are still in the process of developing appropriate resilience indices [8]. However, several potential variables and calculating processes could be utilized to define resilience.

A. Definition of Power System Resilience

To enhance system resilient, a power system must be capable of absorbing potential disruptions, adapting to these disruptions, and ultimately recovering promptly. In other words, a resilient system must possess the abilities to absorb, adapt, and recover any large outage. Before a disturbance occurs, a resilient power system requires the ability to predict possible contingencies, assess their impacts, and implement preventive measures to mitigate outages. During the disturbance, the power system needs to resist and mitigate the impacts, ensuring its continuous operation. The power system should maintain essential

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functions at an acceptable level during outages, absorb the effects of events, prevent potential cascading impacts, and minimize system damage. After an accident, the power system should be capable of rapid restoration. Finally, the system must learn from past incidents.

Based on the review on literatures and technical reports, the resilience of a power system can be defined as "Resilience refers to the ability of a power system, when subjected to high-impact, low-probability events, to anticipate and assess risks, and implement preventive measures. During the event, it is required to prevent cascading effects, implement potential rescheduling, and mitigate any impact. After the event, it is necessary to maintain sufficient system survivability with adequate functionality, automatically learn the experience in the past, and enhance measures and operations to enable rapid recovery".

B. Required data for calculating resilience indicator

To assess system resilience and calculate relevant indicators, establishing a data base to record faults on generation, transmission, and distribution is essential. For instance, The North American Electric Reliability Corporation (NERC) in the US has established generation availability data system (GADS), transmission availability data system (TADS), and distribution availability data system (DADS) to collect relevant data for calculating resilience indicators. In other words, NERC can calculate resilience indicators separately based on different parts or components, including generation, transmission and distribution systems. Typically, the effects of extreme contingencies can be represented by the impacted load (MVA), affected geographic area, outage duration (days, hours, or minutes), the product of impacted system elements and time (Element-days lost), and the product of unserved load and time (MVA-days lost). As a result, the above variables can be used as resilience indicator.

C. Performance curve and recommended resilience indicators

During a contingency event, NERC has categorized the outage process into three curves: outage curve, restore curve, and performance curve. The y-axis values represented by these curves can be the number of affected transmission lines, generators, or load customers. In the outage curve, the resilience indicator can refer to several important factors, such as the interrupted load number, total power, number of elements, the duration of outages, and the outage rate. During the restoration process, resilience indicators can refer to the time difference between the first-stage restoration and the complete restoration, or the required time for the system to achieve 95% restoration. To access the performance curve, it is recommended to consider the total duration of the contingency, the maximum instantaneous outage in MW, MVA, or number of customers, the product of affected system elements and time (element-days lost), or the product of unserved load and time (MVA-days lost).

Related resilience indicators suggested by NERC require extensive data and the establishment of databases such as GADS, TADS, and DADS. For simplicity, the total unserved energy during an extreme contingency can be referred to the resilience indicator. Such a concept is similar to the definition of "element-days lost" or "MVA-days lost", as mentioned before. Figure 2 depicts two performance curves to illustrate the difference in unserved load between a resilient power system and a traditional un-resilient system. It is observed that the resilient power system exhibits a relatively smaller unserved load. Thus, potential resilience indicators can be represented as a function of the unserved load. Reducing the area under the unserved load curve can enhance the system resilience. In other words, the system resilience related to a contingency can be quantified as the inverse of the unserved load, which can be calculated by integrating the unserved load function.

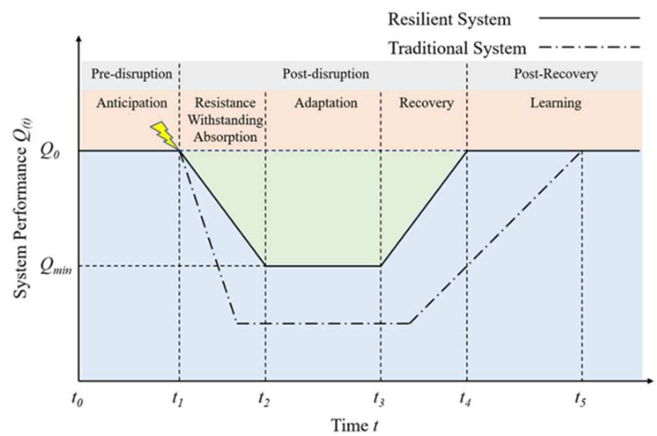

Fig. 2. Resilience indictor calculation based on unserved loads

VII. Suggestions to Evaluate Reliability and Resilience in Power Systems

This paper aims to investigate the calculation and associated discussions concerning about the indices to evaluate power system reliability and resilience. Through historical outage records, these indices can be calculated regularly based on international standards or rules. Currently, most countries applied SAIDI and SAIFI as reliability indices for distribution systems, but some indices, such as CAIDI or MAIFI, were also adopted in several American or European countries. Additionally, this paper has analyzed the main components and causes that affect SAIDI and SAIFI in Taiwan, providing a significant reference to other power systems in the world. For example, the faulted components and the corresponding reasons in different months or counties in Taiwan are different. Thus, it requires to plan different maintaining schedules for different counties and seasons. Additionally, the replacement plan for some old components should be made owing to the aging of facilities. These actions rely on the statistics of system reliability indices.

Identifying the bottlenecks for existing transmission or distribution systems is also crucial. In addition to distribution systems, certain high-voltage transmission lines often experience outages due to seasonal lightning strikes, frequent animal activities, human errors and others. For example, the main causes of outages on several transmission lines are animal contacts or lightning strikes. According to the operating experience in Taiwan, it is hard to establish new double-circuit transmission lines in some areas. Thus, to improve power supply reliability, energy storage systems can be installed there to increase reliability.

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Regarding to the issue to enhance system reliability, distribution automation is one of important works to improve the reliability of distribution systems. It requires to install more FDCSs, a flexible and stable GIS, and a high availability of automation equipment. According to the statistics, distribution system reliability has been improved gradually in Taiwan owing to a great effort on distribution automation.

Regarding to the generation reliability, this paper introduces the used indices to evaluate the performance of thermal power generation units in Taiwan. These reliability indices include EAF, FOR and EFOR. According to the long term statistics, the trend of these indices can be clearly observed, which can be a significant reference for generator planning, scheduling and maintenance.

As for the resilience indicators, this paper has collected associated definitions by many organizations and research institutions, and provided a complete definition for power system resilience. Then, this paper discusses about the required data for calculating resilience indicators. For example, NERC has established GADS, TADS and DADS to collect relevant data for calculating resilience indicators. That is, an appropriate resilience indicator and the corresponding calculations require a complete data base to store fault information accurately. Furthermore, the effects of extreme outage events can be represented by the impacted load, affected geographic area, outage duration, the product of impacted system elements and time, and the product of unserved load and time, which can be selected by power system operators.

This study has collected numerous suggestions and comments from power system experts in Taiwan. These suggestions cover the issues about reliability indices on generators, transmission systems and distribution systems, as well as potential resilience indicators. Although these suggestions aim to improve the power reliability in Taiwan, and they were based on actual operating conditions and experience in Taiwan, they could be useful to provide valuable references to other countries for enhancing power reliability. Table I summarizes several valuable suggestions to the selection, measurement and associated issues about reliability indices in transmission and distribution systems. Table II summarizes the suggestions to calculate generator reliability, including an appropriate verification mechanism, a complete collection on generation data, and the methods to strengthen the availability on the generation side. Notably. The suggestions in this table only concerns about traditional thermal power plants. Table III summarizes the suggestions to design resilience indices, and addresses the importance of AMI measurements.

TABLE I. RECOMMENDATIONS FOR TRANSMISSION AND DISTRIBUTION SYSTEM RELIABILITY INDICES

Recommendation		Description
1	The calculation method to obtain reliability indices	It is suggested to design the reliability index by: • Separating indices with/without major event days (MED). • The reliability indices should include all outage events; even the outage duration is less than 1 min, or adding MAIFI index into the reliability indices. That is, it is required to consider both long and short interruptions. • Considering load interruption (kVA) measurements into the calculation of reliability indices, rather than the count of customers only. However, it is required advanced measurement devices and data bases.
2	Considering CAIDI index	CAIDI index is an effective metric for assessing restoration speed and resilience in distribution systems. It is suggested to increase CAIDI index if the countries only utilized SAIDI and SAIFI to evaluate reliability.
3	Enhancing automated measurement system	It is crucial to enhance automation for data recording, outage identification, and reliability calculations by investing in sensors, computers, and other automated devices to reduce manual efforts. A smart grid must consider advanced automated measurement systems.
4	Adopting advanced energy management system, GIS, and communication systems	Adopting advanced energy management systems, GIS, and communication capabilities can improve operational efficiency significantly. It includes the improvement on feeder automation, ADMS, GIS, and the meters on branch lines or feeders
5	Improving the quality of outage reports	It is important to improve the quality of outage reports by providing detailed causes for the outages and addressing unreasonable values. These historical statistics and reports can provide good references to maintain power systems. That is, a high quality of outage reports can be a good reference for reliability improvement.
6	Evaluating the impacts of feeder automation on system reliability	It is significant to conduct a detailed statistical analysis of several key metrics on feeder automation. These metrics include: the required time for upstream and downstream re-operations, restoration speeds after outages, identification of system weaknesses exposed by automation, and the availability of communication equipment necessary for feeder automation to function effectively.
7	Installing more feeder automation facilities	It is suggested to install more feeder automation facilities in high-voltage branch lines and low-voltage distribution feeders. The goal of these installations is to assess the impact of increasing feeder automation facilities on the accuracy of reliability assessments.

TABLE II. RECOMMENDATIONS FOR GENERATION SYSTEM RELIABILITY INDICES

Recommendation		Description
1	Establishing a verification mechanism among different departments	It is recommended to improve the accuracy of calculating power generation reliability indices through collaboration between plant operations, power generation department, and dispatching department, which would provide accurate statistics on generator reliability.
2	Following NERC data processing standards	It is recommended to follow NERC's GADS standards for data processing, classification, and calculations, which provide a complete reference to evaluate generator reliability.

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TABLE II. RECOMMENDATIONS FOR GENERATION SYSTEM RELIABILITY INDICES (CONTINUE)

3	Publishing the important operating data	• It is suggested to consider unit operating hours and reserve hours to provide insights into reliable reserve capacity. • It is suggested to provide operating hours of each unit along with forced outage rates to avoid misinterpretation.
4	Providing detailed raw data to verify the reliability report	It is important to share detailed raw data used in reliability calculations and outage reports. This will facilitate third-party verification and increase the credibility of the results.
5	Developing frequency regulation standards for different types of thermal generators	It is suggested to consider the characteristics of different unit types such as coal and natural gas fired units when developing the standards for frequency regulation. This will balance grid security and unit lifespan.
6	Enhancing grid resilience by thermal power plants	Strengthening the capability on house load and black start from thermal power plants could improve grid resilience when renewable energy increases. This would reduce the risk of outages under extreme events.
7	Assessing the balance between unit flexibility and operational lifespan	• It is suggested to assess the impact of ON/OFF frequency of each generator on the lifespan of thermal generating units. • It is crucial to develop risk mitigation strategies when a large-capacity thermal unit trips offline.

TABLE III. RECOMMENDATIONS FOR POWER SYSTEM RESILIENCE ASSESSMENT INDICES

Recommendation		Description
1	Enhancing the function of AMI meters for collecting data related to grid resilience	• The data from AMI meters can provide an important basis for calculating resilience indicators. AMI can record any power outage and restoration information completely. Thus, the connection between AMI functions and power system resilience calculations is required. • Each accident should be analyzed through AMI measurement data, and the records of AMI should be fully utilized to calculate resilience indicators.
2	Collecting detailed outage information from natural disasters	• Collect detailed information on outages caused by natural disasters for a long term. It can provide a good reference or data base to enhance system resilience in the future. • Explore and analyze the potential risks caused by natural disasters, which would affect power supply reliability in the future.
3	Suggested indicators to calculate power system resilience	• Initially, some indicators are suggested to evaluate grid resilience. They include the maximum number of affected customers, restoration speed, and total energy lost. • In addition to the number of affected customers, it is also recommended to count the number of failed power components (such as transformers, switches, and others) for evaluating power system resilience.
4	Apply the same rules to all power system participants	• In addition to the power facilities within national power company, there should be the same regulatory and review standards for other independent power producers (IPPs) and renewable energy suppliers. That is, a country needs to supervise and review all system participants, including IPPs, renewable energy, and fuel suppliers. • It is recommended to refer to NERC's practices.

VIII. CONCLUSIONS

This paper has surveyed the basic definition and standard processes to calculate various reliability indices. These indices cover different aspects on generation or distribution systems. Additionally, the real operating experience to calculate reliability or resilience indices in Taiwan was introduced in this study. Another important issue in this paper is to design the indicators for power system resilience. Thus, various potential indicators to represent system resilience have been discussed in this paper. Most importantly, this paper collected valuable experience and suggestions from experts in the power field. These surveys can provide important references to enhance power system reliability and resilience.

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