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Introduction

Power system is the largest manmade infrastructure in human history, playing a critical role in modern society. Electricity is indispensable for industrial, commercial, and residential activities. It is crucial to supply power to customers to satisfy their needs reliably. Keeping the lights on is essentially a top priority in power system planning and operation. However, achieving absolute reliability for power supply is impractical and prohibitively expensive. Thus, utilities and independent system operators (ISOs) undertake long-term resource planning to balance cost and risk. This process aims to build adequate resources to meet established system reliability standards. The most commonly used metrics to measure power system reliability are loss-of-load probability (LOLP), loss-of-load expectation (LOLE), and expected unserved energy (EUE).

Traditionally, resource adequacy studies have focused on planning dispatchable and firm generators, such as thermal units, hydroelectric plants, and nuclear reactors, to reliably meet peak load demands. The maintenance schedules of these generation systems are typically planned during off-peak periods to minimize disruption. Historically, uncertainties were mainly driven by load variability on the demand side and generation unit forced outage rate (FOR) on the supply side. Consequently, to meet the peak load needs, the peak hours are the focus and are carefully examined traditionally. As the resource adequacy evaluation results, the planning reserve margin (PRM) and necessary resource additions are calculated based on the availability of these dispatchable and firm generators during peak hours. Given the relatively stable load patterns and predictable generator characteristics of the past, annual resource adequacy studies were sufficient and effective.

However, today's electrical power systems are facing rapid and significant transformations due to climate, policy, demand, and resource changes. These challenges, coupled with the need for decarbonization and electrification, introduce new challenges and risks to power system resource adequacy study.

On the generation side, driven by global clean energy goals, wind turbine and solar photovoltaic panel installation are growing dramatically. These renewable

Power System Resource Adequacy for Clean Energy, First Edition. Renchang Dai.

resources, while crucial for reducing carbon emissions, are intermittent and non-dispatchable, meaning their availability does not always coincide with peak load periods. This necessitates a reevaluation of how renewable resources are accredited for capacity contribution. Moreover, the effects of global warming are becoming increasingly evident, with higher summer temperatures and more frequent extreme heat events. The high ambient temperature depresses thermal unit capability when it is most needed on hot days. Additionally, warmer winters result in earlier snowmelt, leading to less precipitation and reduced hydroelectric power generation during the summer months.

On the demand side, climate change adds greater uncertainties. High variabilities are observed on loads under extreme weather conditions in both winter and summer. The global warming trend is shifting peak loads from winter to summer for traditional winter peaking utilities. The rapid proliferation of behind-the-meter photovoltaic panel installation is also changing the net demand profile, particularly in summer afternoons, which used to be typically peak load hours for summer peaking utilities. Critical hours for capacity needs are shifting from early afternoons to late afternoons or even evenings, making the traditional peak hours no longer critical from the perspective of capacity needs.

Climate change is causing changes in load patterns and hydro generation shapes in different seasons, while clean energy goals are reshaping the generation mix and availabilities. The shifts on both the supply and demand sides challenge the effectiveness of the current annual resource adequacy approach. As power systems worldwide transition to a decarbonized energy future and confront the impacts of climate change, there is an urgent need to develop and implement seasonal resource adequacy evaluations to ensure an adequate supply of electricity to meet customer demand reliably for all seasons.

Seasonal resource adequacy evaluation involves several key processes: demand forecasting, PRM calculation, resource capacity accreditation evaluation, region and local resource adequacy coordination, and resource adequacy verification.

1.1 Demand Forecast

Demand forecasting is typically categorized into short-term, medium-term, and long-term forecasts based on the forecasting time window being considered [1]. Unlike short-term demand forecasts, which primarily support market operations, long-term demand forecasts form the foundation for resource adequacy studies. Key factors shaping long-term load include economic growth, climate change, and electrification policies. Time-series econometric methods are widely employed for forecasting long-term demand. To capture the impacts of variability in the assumptions, stochastic scenarios are developed to explore changes in economy, demographics, electric vehicle adoption, and temperature fluctuations. Hundreds of potential future demand possibilities, combined with renewable resources and hydroelectric generation variabilities, are investigated to assess system reliability needs in resource adequacy studies.

1.2 Reliability Metrics

According to the North American Electric Reliability Corporation (NERC) reliability terminology, power system resource adequacy is defined as the ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements [2]. The most commonly used metrics for measuring power system reliability are LOLP and LOLE. In North America, a 5% LOLP or a 1-day-in-10-year LOLE has been adopted for decades. The 5% LOLP is the likelihood that at least one loss-of-load event will occur over the period being evaluated. It is calculated as the number of simulations in which at least one shortfall occurs divided by the total number of simulations. The 1-day-in-10-year LOLE reflects the number of days with a shortfall in one simulation year divided by the total number of simulation years.

While LOLP and LOLE provide insights into the frequency of loss-of-load events, they have limitations in measuring the duration in hours, size in MW, and magnitude in MWh of these events. With the transition of climate change and high penetration of renewable resources in the generation portfolio, longer-duration and larger-scale outages are more common, specifically under extreme weather conditions. To measure more dimensions of loss-of-load risk, it is necessary to move beyond a single-resource adequacy metric to multi-metric criteria.

1.3 Resource Adequacy Evaluation Method

Power system resource adequacy can be determined using either deterministic or probabilistic methods and evaluated through analytical approaches or Monte Carlo simulations [3–5]. The simplest method for assessing resource adequacy is assigning a planning reserve margin (PRM), which sets a firm capacity above the normal peak load, defined as

$$PRM = \frac{P_G - P_L}{P_L} \times 100\% \tag{1.1}$$

where P_G represents the total peak capacity contribution from resources in MW and P_L represents the system's total normal peak load in MW. The PRM is a deterministic approach, with a fixed percentage set based on utility's best practices and experience as the system reliability requirement. Although not accounting for the stochastic and probabilistic nature of power system operations, it is still adopted by some utilities globally. In probabilistic methods, PRM can also be derived from probabilistic analysis results.

Probabilistic methods can be analytical- or simulation-based. Analytical methods compute reliability metrics by estimating system total generation distribution based on the availability of individual generation units through analytical processes such as convolution. The probability distribution of the system-wide generation availability is obtained by convolving the individual generation distributions. In each chronological period, system generation is computed and compared against load demand at the same chronological period. The shortfalls are calculated to determine reliability indices.

Another analytical method for reliability evolution is based on the Markov model, where states are categorized by conditions such as normal operation, failure, repair, derating, and other modes [6, 7]. The system's state is simulated with a Markov chain over time. Theoretically, all potential states can be identified that the process may visit in the Markov model. However, in practice, the state enumeration will create an extremely large model. Elimination techniques could truncate the model and reduce the size, though this can compromise the accuracy of reliability index calculations.

While analytical methods are computationally efficient, they do not simulate the actual operational processes of the system. It is particularly challenging to model transmission interfaces for multi-area reliability analysis and consider the impacts of energy-limited resource on system reliability by using analytical approaches. In contrast, Monte Carlo simulation exhibits greater flexibility to capture all possible system states and reflect the probability distribution functions of random variables, when they are implicit. As more renewable resources and energy storage are penetrating to the system and regional resource adequacy evaluation is required, Monte Carlo simulation methods are more suitable for evaluating power system resource adequacy [8–10].

1.4 Regional and Local Resource Adequacy Coordination

Power systems are highly interconnected. To balance accuracy and complexity in reliability analysis, power systems are typically divided into three subsystems as illustrated in Figure 1.1 [3, 11].

Reliability analysis at hierarchical level I focuses on the generation system in which generation adequacy is evaluated to determine whether generation capacity is sufficient to meet total system load demand. Reliability assessment at hierarchical level II integrates both generation and transmission system adequacy

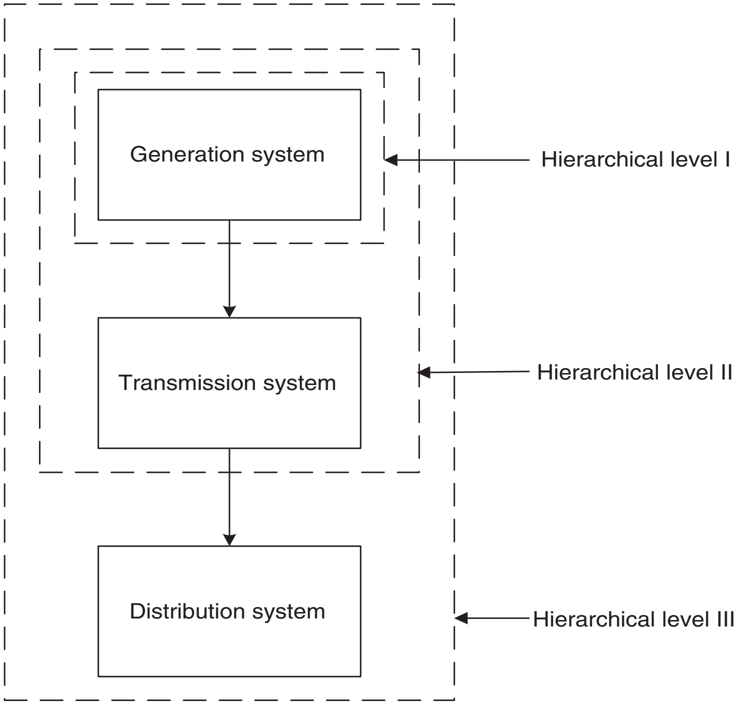

Figure 1.1 Reliability Analysis Hierarchical Levels.

studies. This level analysis is commonly referred to as composite system or bulk power system reliability evaluation [12]. Hierarchical level III analysis involves the evaluation of all three subsystems, including the distribution system. Although this level of analysis offers a comprehensive view, it is not widely conducted in practice. Distribution system reliability evaluation is typically performed separately. However, with increasing penetration of distributed generation and storage installed in the distribution system, there is a growing need to perform hierarchical level III reliability evaluations.

In this book, the focus is on hierarchical level I resource adequacy (supply adequacy) study. However, the study is extended to multi-area consideration as well, where multiple control areas are modeled and both regional and local generation resource adequacies are coordinated.

1.5 Resource Adequacy Verification

PRM in MW, as the resource adequacy study output, expresses the total additional resource required beyond the system's normal peak demand. The integrated resource planning (IRP) process takes the PRM as an input to optimize additional resources into its preferred portfolio to meet the peak demand needs and reliability requirements.

However, resource adequacy assessments and IRP are often conducted separately. As a result, the optimized portfolio may not fully align with the reliability standards. Therefore, it is necessary to verify that the IRP solution meets the defined reliability metrics. If the portfolio developed through IRP is found to be underbuilt or overbuilt during the resource adequacy verification, adjustments must be made. This iterative process continues until the portfolio satisfies all reliability criteria.

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