A Systematic Comparison of Operating Reserve Methodologies

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E. Ibanez, I. Krad, and E. Ela
National Renewable Energy Laboratory

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A Systematic Comparison of Operating Reserve Methodologies

Eduardo Ibanez, *Member*, Ibrahim Krad, *Member*, and Erik Ela, *Member*
Transmission and Grid Integration Group
National Renewable Energy Laboratory
Golden, CO, USA

***Abstract*—Operating reserve requirements are a key component of modern power systems, and they contribute to maintaining reliable operations with minimum economic impact. No universal method exists for determining reserve requirements, thus there is a need for a thorough study and performance comparison of the different existing methodologies. Increasing penetrations of variable generation (VG) on electric power systems are posed to increase system uncertainty and variability, thus the need for additional reserve also increases. This paper presents background information on operating reserve and its relationship to VG. A consistent comparison of three methodologies to calculate regulating and flexibility reserve in systems with VG is performed.**

***Index Terms*—Operating reserve, power systems economics, power systems reliability, solar energy, wind energy.**

I. INTRODUCTION

Power system operators have a number of responsibilities that focus on maintaining reliability [1]-[3]. System generation must be as close as possible to the system load and electrical losses to ensure that system frequency is maintained at or very close to nominal levels (60 Hz in North America). In large, synchronous interconnections, standards require that tie-line flows between areas are kept close to their scheduled flows. Also, a system must be able to withstand contingency events by implementing preventive control actions, such as holding reserve and limiting pre-contingency flows, so that the system can survive the event and normal operations can be fully restored shortly afterward.

Many properties of a power system—including its generation levels, load levels, and transmission equipment availability—are both variable and uncertain. Variable generation (VG), such as wind and photovoltaic (PV) solar power, increases the amount of variability and uncertainty on power systems because VG units have a maximum available limit that varies with time (*variability*) and that limit is not known with perfect accuracy (*uncertainty*). Variability and uncertainty occur at multiple timescales (e.g., 5-minute or hourly ramps) and time horizons (e.g., day-ahead or hour-ahead forecasts) [4]. Variability and uncertainty on power systems cause the need for additional capacity above or below the energy that is scheduled to meet the average expected demand. This capacity is referred to as operating reserve. There are different types of operating reserve, and they are utilized for many different reasons. In this paper, operating reserve is defined as the capacity above or below that which is scheduled to meet the expected energy demand, used to maintain the active power balance of the electric power system during operation time frames [5].

Variability is the expected changes in power system conditions, such as load or generation output. In many ways, variability is accommodated by the use of security-constrained unit commitment or economic dispatch solutions. These solutions meet the expected changes in power system conditions at least cost while obeying operational and security constraints. Operating reserve might be needed if variability occurs at time resolutions for which scheduling procedures are not prepared. For example, an hourly schedule might hold operating reserve for variability that occurs at a 5-minute resolution because the hourly schedule is not prepared for that variability. This operating reserve may be deployed by the 5-minute scheduling procedure to ensure balance of supply and demand. Similarly, the 5-minute scheduling procedure may hold operating reserve for variability at a time resolution faster than 5 minutes. Operating reserve rules might be designed to ensure that appropriate ramping capability is available for this variability. The characteristics of the operating reserve needed for variability depend on the characteristics of the variability.

Uncertainty is the change in power system conditions that is unexpected. Operating reserve is needed for uncertainty when a different supply-demand profile is needed than that scheduled. For example, when a day-ahead scheduling procedure commits and dispatches resources to meet the expected demand, a system operator would have to ensure that operating reserve is also available for when the realized demand is different than expected. Uncertainty can come from VG output, load demand, or generation and transmission availability. Although new strategies are being developed to accommodate uncertainty, such as robust and stochastic unit

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commitment and dispatch models [6]-[7], using operating reserve is still the most common strategy in current industry procedures to accommodate uncertainty. Contingency reserve, the most common form of operating reserve, is an example of reserve held in case a generator unexpectedly becomes unavailable. The characteristics of operating reserve needed for uncertainty depend on the characteristics of the uncertainty.

Although the use of operating reserve is ubiquitous, there is no universal methodology to determine the amount of reserve that should be carried, thus virtually each power system around the world follows different procedures. The advent of VG may raise the importance of different forms of both upward and downward reserve and the methods for determining the amounts needed [8]. In traditional power systems, requirements are based on heuristic needs that have been in place for decades. These methods are typically static and are rarely based on updated system information in real time. This means that if the characteristics of variability and uncertainty change with time and time horizon, the reserve requirements are not taking advantage of this information for more reliable and efficient requirements. However, operating reserve is traditionally needed as a result of the uncertainty from conventional generator or large transmission outages. The characteristics of this uncertainty—the probability of these facilities being forced offline—generally does not change significantly with time. Even so, researchers have discussed ways to improve upon representing reserve used for this type of uncertainty as well [9]-[10].

With rapid increases in the penetration of VG, researchers and system operators have been developing new methods to determine operating reserve requirements based on more-complex characteristics of variability and uncertainty [5]. Although many of the improvements are justified, the significant differences among methods are remarkable. It is likely that many of these differences are caused by differences in generation portfolios, existing standards, network configurations, and other market or operational structures unique to each area. Although a "one size fits all" methodology is probably not realistic for operating reserve requirement methods, an understanding of how different these methods are is a first step toward the general improvement of the methods. Understanding the differences will also help in determine whether striving toward consistent standards is appropriate to ensure reliable, cost-efficient power systems with fair treatment of all resources.

Determining reserve strategies and comparing them is nontrivial. First, there are two competing objectives: to maximize reliability while minimizing system operating costs. A continuum of solutions exists between the extreme cases, i.e., carrying no reserve (with minimum cost and poor reliability) versus carrying vast amounts of reserve (with considerable cost but superior reliability). Second, the dynamic nature of power systems suggests that certain methodologies might be better during certain periods, e.g., day/nighttime or low/high load or VG availability.

This paper presents some examples of operating reserve requirement methodologies. It is one of the first "apples to apples" comparisons of the methods across a common system. Each method uses the same system information and load and VG data at multiple timescales to show a consistent comparison. This information can help to identify the best characteristics that contribute to a more reliable and cost-effective operation of the power system. Operating reserve is calculated for a wide range of VG penetrations, which allows for the distinction between the effects of wind and PV. The rest of the paper is organized as follows: Section II further describes the types and needs of operating reserve, Section III describes three methods that we focus on in this paper, Section IV provides comparisons of those methods, and Section V provides a conclusion and set of next steps needed for further research.

II. OPERATING RESERVE

Certain procedures are set forth by different entities (e.g., reliability regulators such as the North American Electric Reliability Council; balancing authorities, or BAs; and independent system operators) on the amount of operating reserve required, who can provide them, when they should be deployed, and how they are deployed [11]-[12]. The standards are generally based on certain reliability criteria and allowable risk criteria, but they often differ, sometimes substantially, from region to region. Many studies have found that standard rules must be accompanied by new, innovative methods and adjusted rules and policies to account for the increased variability and uncertainty characteristics introduced by high penetrations of VG [13]-[14]. Using today's standards alone simply may not capture these characteristics while still maintaining reliable and cost-efficient operations. Different studies have used a number of different methods, all attempting to answer these same questions.

Operating reserve is carried for a variety of reasons related to balancing active power generation and load demand. It may be needed for normal conditions to balance the variations that occur continuously on a system. It may also be used for severe yet rare events. Overall, operating reserve categories can be further characterized by response speed (e.g., ramp rate and start-up time), response duration, direction of use (up or down), and type of control (e.g., control center activation, autonomous, automatic). Fig. 1 shows an example of common operating reserve type terms and how they are categorized [5]. However, the terms and classification can be different from region to region. The distinctions also do not necessarily mean that each type needs separate requirement methods, although some may be combined or separated further in certain regions.

Both normal and event categories could be classified based on the required response speed. Some events are essentially instantaneous (contingency reserve), whereas others take finite time to occur (ramping reserve). Different qualities are needed for different purposes. An instantaneous event requires an autonomous response to arrest frequency excursions, whereas non-instantaneous event may require such an autonomous response. However, operators must ensure that both types of errors are corrected so that frequency is maintained at its nominal setting and that the reserve is then replaced so that the system is prepared for a subsequent event. Nonevent reserve are classified as regulating reserve (that which is used to correct the current imbalance during normal conditions) and following reserve (also referred to as flexibility reserve; that which is used to correct an anticipated imbalance during normal conditions). In this paper, we focus on regulating reserve and flexibility reserve. Because VG impacts occur continuously during normal conditions, these two types reserve are most likely to be affected by increasing penetrations of VG.

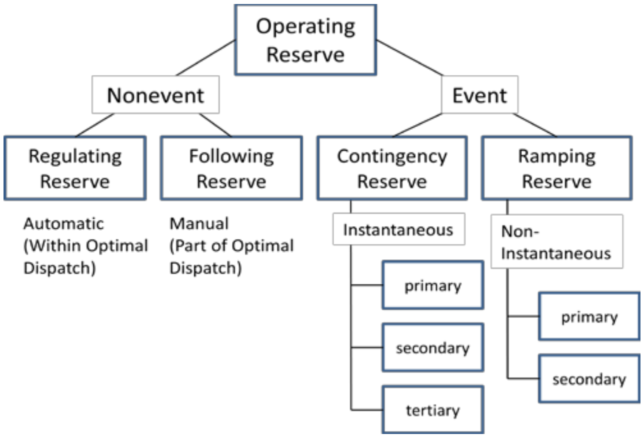

Figure 1. Operating reserve is needed for various reasons to balance a power system.

III. RESERVE REQUIREMENT METHODS

In this paper, we focus on the first two steps of the strategy previously introduced. Understanding how reserve requirements change across different methodologies can later be tied to the simulation results. We apply three methodologies for regulating and flexibility reserve.

Contingency reserve is held in the simulations in each of the three reserve methods. The contingency reserve method is held consistently in each method and is adopted on Western Electricity Coordinating Council (WECC) criteria [15].

The total capacity of contingency reserve is based on 6% of the total expected load of the system for each hour. Of this total, half (i.e., 3% of total expected load) must be online (i.e., spinning). Contingency reserve that is spinning must be able to ramp to their contingency reserve obligation in 10 minutes. Contingency reserve that is offline must be able to start up and provide their obligations within 10 minutes. This reserve is required only in an upward direction. In practice, this reserve is commonly provided as part of reserve sharing groups, but we allocate this requirement to each BA in our analysis.

The following is a brief description of the three regulating and flexibility reserve methodologies and their implementations. The methods are based on three different approaches: long-term planning studies (Current WECC), a high-penetration research study (Phase 2 of the Western Wind and Solar Integration Study, WWSIS-2), and current operational requirements (Electric Reliability Council of Texas, ERCOT).

A. Current WECC

The first method intends to capture current practices that do not estimate a contribution of VG to reserve requirements. This method is not practiced consistently throughout WECC, but taken from a mix of methods often used in interconnection-wide studies and from WECC-specific reliability criteria. Regulation reserve is calculated as 1% load without any contribution from VG. The requirements are both upward and downward but have no ramp rate requirements. Flexibility reserve requirements are set to zero for all hours.

B. WWSIS-2

Developed for WWSIS-2, this method incorporates characteristics of VG in requirements [16].

The regulating reserve requirements are calculated as the geometric sum of the base requirement (1% of load) and the contribution of wind and PV (which cover 95% of 10-minute forecast errors), as shown in (1). Wind forecast errors are based on persistence, and PV forecast errors are based on the persistence of cloudiness. The latter method removes the daily solar power cycles from the forecasts. Calculations are performed upward and downward separately, based on under- and over-forecast errors, respectively. This method also enforced a response time requirement of five minutes for all contributing units.

$$\mathit{RegulatingReserve} = \sqrt{(.01 * \mathrm{Load})^2 + \Phi 95_{10\mathrm{min-wind}}{}^2 + \Phi 95_{10\mathrm{min-PV}}{}^2} \qquad (1)$$

where Φ represents the confidence interval that covers 95% of 10-minute forecast errors for wind and PV in this case.

Flexibility reserve is calculated as the geometric sum of hour-ahead load, wind, and PV forecast errors (covering 70% of errors), as per (2). This is done upward and downward separately. This method has no ramp rate requirement for flexibility reserve.

$$\mathit{Flexibility\ Reserve} = \sqrt{\Phi 70_{\text{hour-load}}{}^2 + \Phi 70_{\text{hour-wind}}{}^2 + \Phi 70_{\text{hour-PV}}{}^2} \qquad (2)$$

C. ERCOT

The third method is an extension of current practices at ERCOT [17] to include the effects of PV (on top of the wind and load contributions already in place). Unlike the WWSIS-2 method, the calculations in the ERCOT method rely on net load calculations (net load variability and net load day-ahead forecast errors, specifically). Another singularity of the ERCOT method is that it utilizes historical data (from the previous month and the previous year) to create the reserve requirements for the current month.

Upward and downward regulation reserve requirements are calculated to cover 98.8% of positive and negative load changes, respectively. These calculations are performed for each month and hour of day using the information of the current and the previous month.

The flexibility reserve calculations in this paper are based on ERCOT's non-spinning reserve service (NSRS) method. Only flexibility in an upward direction is calculated for this method as the 5th percentile of the forecast error, i.e., covering 95% of errors and discarding the largest 5% of events that were under- forecasted. The calculation for each month is done by taking blocks of 4 hours of the day. This method has no ramp rate requirement for flexibility reserve.

IV. COMPARISON

These methods are applied to the scenarios developed for WWSIS-2 [18]: one with standard VG penetration, or TEPPC (approximately 8% wind and 3% solar), and three 33% penetration-by-energy scenarios: High Solar (8% wind, 25% solar), High Mix (16.5% wind and solar), and High Wind (25% wind and 8% solar). The following time series were developed for each BA from the TEPCC 2020 and WWSIS-2 dataset for this analysis, unless otherwise noted: 5-minute actual demand power, 5-minute actual wind power, 5-minute actual and clear-sky PV power, day-ahead and hour-ahead demand forecasts [19], day-ahead wind forecasts, and day-ahead PV power forecasts. BAs were aggregated to the zones designated by TEPPC's Loads and Resources Subcommittee. Each methodology was applied to each of the U.S. zones.

Fig. 2 presents the aggregated time series for power, regulation, and flexibility reserve for the entire footprint for a few illustrative days in June. All four scenarios in WWSIS-2 are represented. Upward requirements of reserve are represented as positive numbers and downward are negative.

The current TEPPC regulating reserve requirements are consistently the smallest of all three methods. There are a few exceptions in some regions (not shown here) where the ERCOT method results in smaller values. In cases with small VG penetrations (e.g., the TEPPC scenario), regulating reserve requirements are similar for the current TEPPC and ERCOT methods, except for times with consistent load changes, such as the morning load pickup, the evening load pickup, and the nighttime load drop-off.

The WWSIS-2 regulating reserve results are affected differently by increasing amounts of wind and load. In general, the presence of wind raises the requirements fairly evenly. In contrast, the effects of PV vary more, with contributions during daytime and notable peaks in requirements around sunrise. Although it is hard to appreciate here, the contributions from PV requirements are more pronounced on cloudy days.

VG affects the flexibility reserve requirements of the WWSIS-2 method with similar patterns to those of the regulating reserve; that is, there is a consistent increase of base requirements for wind and a significant dependency on time of day and cloudiness for PV.

The calculations for the ERCOT method of regulating reserve requirements rely on daily patterns of the 5-minute net load shape. The effect by region depends greatly on the VG-to-load ratio. As was the case with the WWSIS-2 method, wind increases requirements evenly throughout the day. On the other hand, the more consistent pattern from PV creates moderate reserve increases at specific times of the day, especially surrounding sunrise and sunset/peak load.

The boxplots in Fig. 3 present a summary of the reserve requirements by type for the entire year of data for regions of Southern California and Colorado. The Current WECC usually yielded the smallest regulating requirements, followed by the WWSIS-2 method, and then the ERCOT method. Maximum values for WWSIS-2 and ERCOT are similar under certain conditions.

For flexibility reserve, the WWSIS-2 values are significantly smaller on average than the ERCOT results. The latter were usually at the maximum allowed for each zone, especially with high penetrations of renewables. Contingency reserve values were usually larger than regulating reserve, comparable to WWSIS-2 flexibility reserve and smaller than ERCOT flexibility reserve.

For WWSIS-2 calculations (regulating and flexibility), increasing amounts of wind tend to increase average requirements with smaller variations. On the other hand, higher penetrations of PV tend to create a larger spread in the results, especially for the maximum values. The previous

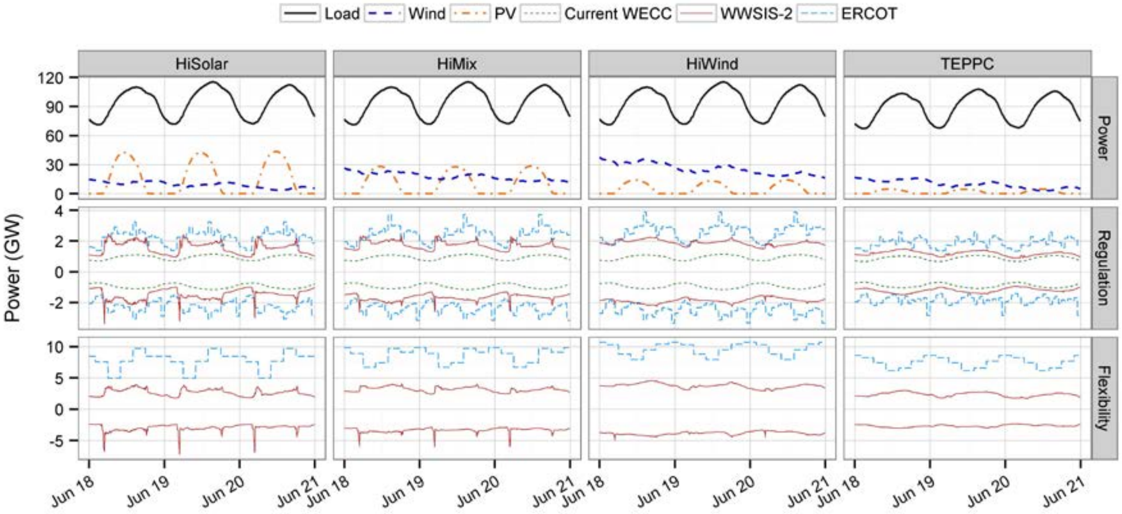

Figure 2. Load, VG power, and operating reserve time series in the Western Interconnection for three days in June

observations are somewhat true for the ERCOT method if the ratio of VG to load is large (e.g., Southern California). The results for this method do not change much if load is sufficiently larger than renewables (Colorado).

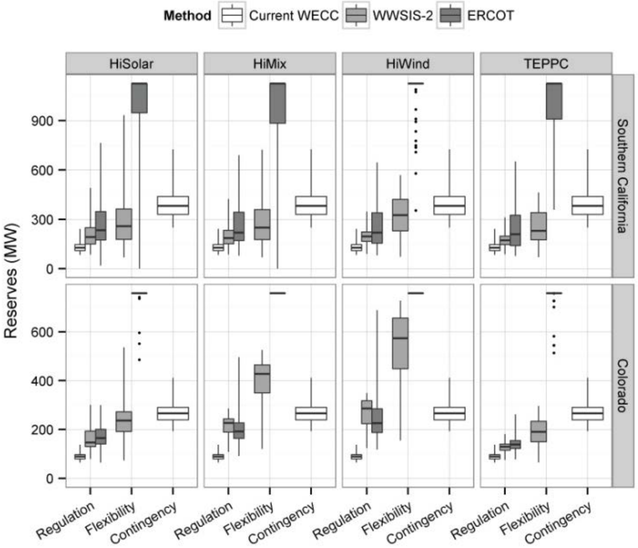

Figure 3. Regulation, flexibility, and contingency regulation across scenarios for Southern California (top row) and Colorado (bottom row)

V. CONCLUSIONS AND NEXT STEPS

This paper described operating reserve requirements and their role in power system operations. No universal method exists, and there is a need for a thorough study and comparison of the performance of the different existing methodologies. A consistent comparison of three methodologies to calculate regulating and flexibility reserve in systems with VG was performed. The three methodologies have distinct approaches and are based on different metrics: load only, short-term forecast errors, and net load variability and uncertainty. The results show some significant differences that depend on the type of reserve as well as the penetration level of VG. It is likely that other methods will have substantial differences as well that may be sensitive to different conditions.

Using this knowledge of the substantial differences between methods in quantity, future work will include examining the performance of each method's reserve requirements through power system simulation in terms of both reliability and costs. NREL's FESTIV tool can be used because it can model both reliability and costs, which is required to validate operating reserve requirement methods [4]. The model also simulates multiple operational timescales, ensuring that the impacts of variability and uncertainty at multiple timescales and horizons are captured. The performance of the system for the different reserve methods can be compared through different metrics: frequency deviation, reliability standard violations, system cost, etc. With these metrics, along with the insight gained in the comparisons presented in this paper, improved and potentially consistent methodologies can be proposed that can use the changing characteristics of the power system as a means to determine appropriate operating reserve requirements.

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