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Evolution of Operating Reserve Determination in Wind Power Integration Studies

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***Abstract*--The growth of wind power as an electrical power generation resource has produced great benefits with reductions in emissions and the supply of zero cost fuel. It also has created challenges for the operation of power systems arising from the increased variability and uncertainty it has introduced. A number of studies have been performed over the past decade to analyze the operational impacts that can occur at high penetrations of wind. One of the most crucial impacts is the amount of incremental operating reserves required due to the variability and uncertainty of wind generation. This paper describes different assumptions and methods utilized to calculate the amount of different types of reserves carried, and how these methods have evolved as more studies have been performed.**

***Index Terms*--operating reserves, power system operation, power system reliability, power systems, wind power generation**

I. Introduction

WIND power has seen rapid growth in the past decade. Its zero-cost fuel and emissions-free output provide great benefits to consumers and society. Utility-scale wind is a new resource and is increasing at such a rapid rate that utilities and system operators are becoming concerned about the integration issues and costs that it introduces. Wind power integration studies have been performed by numerous entities to help understand and quantify these impacts [1], [2]. The studies typically simulate a future power system with high wind penetrations, and evaluate the impacts on the grid and the incremental operating costs that result [3]. These studies have been maturing continuously as the state of the art advances, with each study generally building on previous studies.

Some of these studies have compared the costs and operational differences between a system with high wind penetration and a system that does not bring the incremental variability and uncertainty that wind presents. The additional costs generally occur because the unit commitment is inefficient due to forecast errors and because it is adjusted to provide more flexibility, accommodating wind's increased variability and uncertainty. Additional flexibility can be in the form of increased ramp rates, decreased minimum generation limits, and increased amounts of operating reserve. Noting that these are studies and that the results should be realized as such, much controversy often occurs over these costs due to the many assumptions that are required to be made. For example, wind forecasts used in the study are usually based on a model of how a forecast may be produced some time in the future (looking at a past weather year). Since predicting the actual output of the wind resource from a model is a difficult task in itself, predicting what the forecast error may be can add more uncertainty to the results.

Secondly, the determination of operating reserves has been analyzed using many different methodologies and can differ significantly from study to study. Operating reserves are subject to many different naming conventions in different regions throughout the world. This paper defines operating reserve as the real power capacity that can be called on at any instance of imbalance between generation and load.[1] Most wind power integration studies run hourly simulations of bulk power system operations for a particular study area, and therefore the actual utilization of the designated operating reserve capacity is not in fact realized in detail. Therefore, operating reserve requirements are determined statistically, but usually not validated in simulations. Two important objectives that often form part of these studies are the costs or savings of integrating additional wind power and the operational changes that are recommended at high penetrations of wind power. Many of the studies recommend the use of incremental operating reserves, which will also affect the total costs. This makes the assumptions used in the methodology to assess operating reserve a very important component of the overall study. Many areas will adopt these methodologies from the studies as wind penetrations increase and therefore it is additionally important for actual system operations in the future.

This paper will focus on methods of determining operating reserves for power systems with high penetrations of wind power. Section II will describe current practices and definitions of operating reserves in North America, mainland Europe, and Ireland. Section III will cover some recent wind power integration studies that have been performed, and will focus on the methods used in each study when calculating the operating reserve requirements. In section IV, the authors will provide insight into the strengths of different methods, including analysis on how the operating reserve determination problem may change in wind power integration studies and in actual system operations. Section V concludes the discussion.

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[1] Additionally, operating reserves or ancillary services can include voltage or reactive power support as well as black start service.

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II. Operating Reserve Definitions and Standards

Variability and uncertainty are not unique to wind generation: similar characteristics in aggregate electric demand and even supply resources have always posed challenges for power system operators. Future loads cannot be perfectly predicted, loads and generator outputs can vary substantially in different time frames, and large power system equipment can fail at any given time without notice. Power system operators secure different amounts and types of operating reserves to compensate for these characteristics in order to serve load reliably and maintain the system frequency. There are many different definitions and rules concerning what operating reserves entail. For example, the North American Electric Reliability Corporation (NERC) defines operating reserves as the following:

"That capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages and local area protection. It consists of spinning and non-spinning reserve." [4]

In most of North America, these reserves can be further placed in three categories:

- *Spinning reserve – The portion of Operating Reserve consisting of: Generation synchronized to the system and fully available to serve load within the Disturbance Recovery Period following the contingency event; or Load fully removable from the system within the Disturbance Recovery Period following the contingency event.*
- *Supplemental reserve – The portion of Operating Reserve consisting of: Generation (synchronized or capable of being synchronized) that is fully available to serve load within the Disturbance Recovery Period following the contingency event; or Load fully removable from the system within the Disturbance Recovery Period following the contingency event.*
- *Regulating Reserve – An amount of reserve responsive to Automatic Generation Control which is sufficient to provide normal regulating margin.*

Further definitions can separate the second category by response time and response sustainability. In North America, the spinning reserve and supplemental reserve described above are often combined and referred to as "contingency reserve", only being used for instances of generator or network contingency events. Though contrary to the NERC definition of operating reserve described above, regulating reserve is generally procured in both the upward and downward directions (i.e. in cases of over-generation). Fast frequency response (governor response) is not yet explicitly addressed by NERC as a distinct operating reserve, but the Western Electricity Coordinating Council (WECC) has started to study the need for a 30 second response: frequency responsive reserve (FRR). Transmission also impacts the need for operating reserves, since it can provide access to additional reserve supplies and reduce the overall need for reserves by increasing the reserve sharing pool. Limited transmission may also mean more localized reserve requirements. Transmission lines may be operated at levels below their maximum capacities to account for other transmission contingencies, similar to generator operating reserve.

Other standards and policies detail how much a balancing area will require of each type of operating reserve [4]. For instance, the NERC BAL-002 standard requires that a balancing authority or reserve sharing group maintain at least enough contingency reserve to cover the most severe single contingency. For the western interconnection, this is extended by a proposal by WECC to state that the minimum amount of contingency reserve should be the greater of the most severe single contingency or the sum of 3% of the balancing area load and 3% of the balancing area generation. Detailed specifications of contingency reserve requirements, including the amount of spinning compared to supplemental reserve, are established by each Regional Reliability Organization. Regions typically require at least half of the contingency reserve to be spinning. An example of how reserves are deployed following a contingency is provided in Fig. 1. Regulating reserve usually does not include explicit requirements. Instead, balancing areas will maintain sufficient regulating reserves so that they meet their CPS1 and CPS2 performance requirements. In some areas that currently have high penetrations of wind power, such as the Electric Reliability Council of Texas (ERCOT), the forecasted wind power output is considered when defining regulating and other types of operating reserve requirements [5].

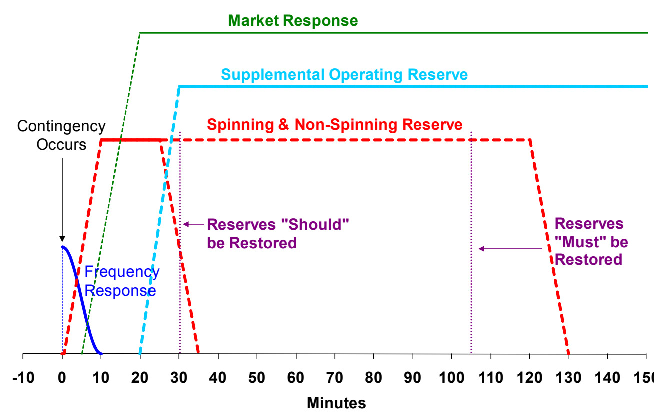

Fig. 1. Reserve deployment as defined by NERC [6]

In Europe, broad guidelines are given by the former TSO groupings such as Nordel and the Union for Coordination of Transmission of Electricity (UCTE), now part of the European Network for Transmission System Operators for Electricity (ENTSO-E). ENTSO-E defines reserve in three categories; primary, secondary and tertiary control [7]. Primary control is activated when system frequency deviates by 20 mHz from the set point value (nominally 50 Hz) and must be fully operational within 30 seconds. The purpose of primary control is to limit the deviation of system frequency following a system event.

Secondary control consists of units controlled by automatic generation control (AGC) and fast starting units. These are engaged 30 seconds after a contingency event and must be fully operational within 15 minutes. This category of control attempts to restore the frequency to its nominal value and reduce the area control error. Tertiary control has a slower response and is engaged to restore primary and secondary control units back to the reserve state.

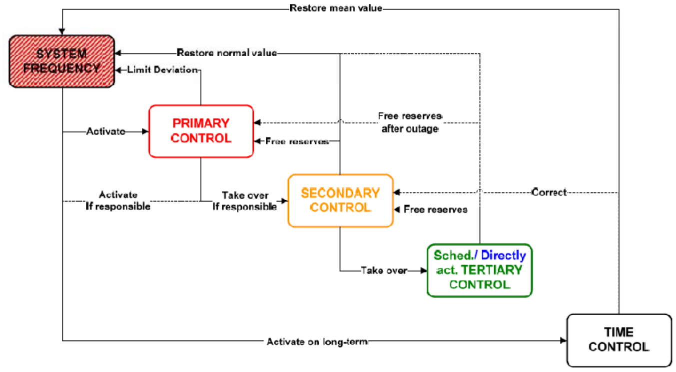

Fig. 2. ENTSOE-UCTE control mechanisms [7]

The Irish system represents a much smaller, isolated power system, and has a more granular approach to its definition of reserve [8]. There are five main types including: regulating, operating, replacement, substitute, and contingency reserves. Regulating reserve acts within 30 seconds of a frequency deviation to restore the frequency to within 0.1 Hz of the set point value and controls inter-system transfers on the North-South interconnector which joins the two systems on the island. This is a subset of primary operating reserve. Operating reserve, as defined in the Irish system, is divided into three parts: primary, secondary, and tertiary operating reserve. Primary reserve acts for the first 15 seconds to avoid transient nadirs below 49 Hz. Secondary reserve then acts to avoid continuous system operation below 49.5 Hz, and it is fully available from 15 seconds after an event for a further 75 seconds. Tertiary operating reserve is used to replace the primary and secondary reserve. It is split into Tertiary1, which restores primary and secondary operating reserve for the first 5 minutes and Tertiary2 reserve which is available after 5 minutes for an additional 15 minutes.

Replacement reserve acts as a longer term resource to restore secondary and tertiary operating reserve from operation. This is fully available within 20 minutes for a four hour period. Substitute reserve is utilized to restore replacement reserve after 4 hours for a duration of 24 hours and is available for the replacement of emissions-restricted plant. Contingency reserve is available to restore all reserves 24 hours after the event.

The names and definitions for operating reserve across different parts of the world vary but the functionality is very similar. Systems of different sizes and with different generation or load characteristics may require different response requirements or different qualifications on how the operating reserve is provided. However, it is important to note that regardless of category, response time, and qualifications, operating reserves as discussed here are all secured and utilized for essentially the same reason; imbalance between generation and load. Thus, to offer clarity and reduce confusion between North American and European readers, Table I displays the terminology that will be used throughout the rest of this paper. Reference [9] also shows a detailed mapping and descriptions of a subset of these terms for active power control as well as for voltage control services.

TABLE I
NAMES AND DEFINITIONS OF RESERVES

Name	Definition	Common terms
Operating Reserve	Used for an imbalance between generation and load at any time. All other reserve categories are a subset of this.	Operating reserve (US), reserve, balancing reserve
Spinning Reserve	Any of the categories where the resources are frequency responsive and begin responding immediately. Generators providing this service must have been committed.	Spinning reserve, synchronous reserve, on-line reserve, responsive reserve
Non-Spinning Reserve	Similar to spinning reserve but the resources do not need to respond to frequency autonomously or begin responding immediately. Generators providing this service do not have to be committed. Upward only.	Non-spinning reserve, non-synchronous reserve, off-line reserve, quick start reserve
Contingency reserve	Used during instantaneous failures (e.g. generator failures). Contingency reserves may include other types (e.g. frequency responsive, spinning, non-spinning, and supplemental). Upward only	Contingency reserve (US), operating reserve (Ireland), primary and secondary reserve (Europe)
Regulating Reserve	Used for frequency control and maintaining area control error during normal (non-event) conditions in a time frame that is faster than energy markets clear. Due to random movements. Requires automatic generation control. Upward and downward.	Regulating reserve, frequency control
Load following Reserve	Used for frequency control and maintaining area control error during normal (non-event) conditions. Due to non-random movements. Slower movements than regulation. Does not require automatic generation control. Upward and downward.	Load following, dispatch
Frequency Responsive Reserve	Reserves that provide the initial autonomous response to a major disturbance. Upward and downward.	Governor response, primary control (Europe), FRR
Ramping Reserves	Used during failures and events that are not instantaneous but occur over long time frames (e.g., wind ramps, forecast errors). Upward and downward.	Variable generation event reserve, forecast error reserve
Supplemental Reserve	Reserve that replaces faster reserve so that the system is secure and the level of pre-event reserve is restored. Upward only.	Replacement reserve, supplemental reserve, tertiary reserve (Europe), contingency reserve (Ireland), substitute reserve

The objective behind the table is to define a consistent set of categories based on the purpose of their deployment and any differences in how they are provided. Note that any of these categories could have numerous response time definitions as the current standards generally do. Fig. 3 shows a hierarchical diagram of the defined operating reserves and how they may be interrelated. Note that the definitions of spinning and non-spinning reserve are characteristics of each of the other types, as seen in the diagram.

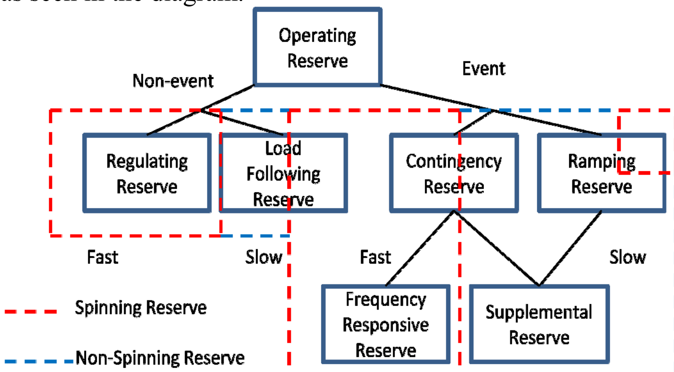

Fig. 3. Operating Reserve Diagram

III. Reserve Determination in Wind Integration Studies

In the past several years, various organizations have participated and/or initiated wind power integration studies. The studies evaluate a power system in the future with high wind power penetrations and simulate the impacts that occur. A general process for wind power integration studies can be found in [10].

A major component of each study is to evaluate the incremental need for additional operating reserves for the future system that result from high wind penetration. The study teams usually consider traditional definitions and requirement determinations and propose needed changes to maintain reliability while accommodating the variability and uncertainty present in the wind power. This value is generally calculated via statistical methods analyzing wind power time series that are modeled for the study. The methodologies used to compute these values have evolved as each study learns from past studies. The most recent studies evaluating very high penetrations are using sophisticated methodologies that are diverging further from the traditional methods used today in actual system operations.

In the US, the first two major wind power integration studies were performed in the states of New York and Minnesota [1], [2]. In New York, the study evaluated 3,300 MW of wind power on the 33,000 MW peak load NYISO system. The study concluded that no incremental contingency reserves would be needed since the largest single severe contingency would not change. The study concluded that an additional 36 MW of regulating reserve was required on top of the current 175 - 250 MW procured today. This is a result of analyzing the standard deviation of 6-second changes in load net of wind compared with that of load alone. The standard deviation with wind increased from 71 MW to 83 MW, presenting a 12 MW increase. As was the current guideline in New York, the total standard deviation is multiplied by three to ensure that the total regulation requirement is sufficient to cover 99.7% of all instances, thus giving the 36 MW increase.

In Minnesota, the study evaluated 15, 20, and 25% wind energy as a percentage of total annual demand (3441 MW, 4582 MW, and 5688 MW on a system with a peak demand of roughly 20,000 MW). Similar to New York, it was concluded that there would be no impact on the contingency reserve requirement with the added wind penetrations. The regulating reserve requirement similarly evaluated the added variability of wind but calculated it to be a 2 MW standard deviation for every 100 MW wind plant installed. This calculation was based on operational data from existing wind plants. The ratio was used to calculate the regulating reserve requirement as seen in equation (1).

$$Reg\ Req = k\sqrt{\sigma_{load}^2 + N(\sigma_{W100}^2)} \qquad (1)$$

where k is a factor relating regulation capacity requirement to the standard deviation of the regulation variations (assumed to be 5 in this study reflecting current practices); σ_{load} is the standard deviation of regulation variations from load; σ_{W100} is the standard deviation of regulation variations from a 100 MW wind plant; and N is the wind generation capacity in the scenario divided by 100. The results showed increases of 12, 16, and 20 MW for the 15, 20, and 25% cases, respectively.

The Minnesota study quantified two other defined categories that the New York study did not. In the study these are defined as load following and operating reserve margin (load following reserve and ramping reserve in Table I). Load following was calculated as twice the standard deviation of the five minute changes in the net load, and increases ranged from 10 to 24 MW for the three cases. The operating reserve margin was allocated specifically for hourly forecast errors in the net load. This analysis assumed a dynamic requirement, one that was not constant for all hours but in fact was a function of the amount of expected wind capacity. The consideration was that the variability of wind is highest when the wind capacity is in the middle range (i.e. 40-60% of total capacity) due to the wind turbines being on the steepest parts of their wind speed to wind power conversion curves. Therefore, more reserve was needed for the middle range compared to times of very low wind generation or times of very high wind generation.

These studies paved the way for future thinking of how operating reserves should be handled with high penetrations of wind. More recent studies have evolved and taken the ideas from those preceding studies with increasing sizes, penetrations, and scopes. The traditional definitions and methods used in current operations were simply not feasible with penetrations of 20% wind energy and more. We will focus on two recently completed studies and describe the operating reserve determination methods explored in each.

A. All Island Grid Study (Ireland)

The All Island Grid Study in Ireland was published in 2007 and examined, among other things, the Irish system's ability to integrate various penetrations of wind generation [11]. Six plant portfolios were examined to meet the load forecasted for 2020. Portfolio 1 contained 2 GW of wind; 2, 3 and 4 contained 4 GW; portfolio 5 contained 6 GW; and portfolio 6 contained 8 GW of wind generation. This is in the context of a projected peak load of 9,618 MW and a load factor of 63.9%. The study involved hourly scheduling of the system with the WILMAR system planning tool [12].

The study incorporated a refined implementation for reserve provision with only two categories specified in the model: spinning and replacement reserve. The definition of a unit capable of meeting the replacement reserve standard was an off-line unit with a start up time of less than 60 minutes and online units whose capacity was not allocated to the spinning reserve requirement. This is a highly simplified model given the existing structure of reserve provision in the Irish system. The requirements for spinning and replacement reserve were based on a mixture of existing and proven requirements and newer techniques for the provision of reserve for wind generators.

The spinning reserve requirement is calculated as being the size of the largest on-line unit plus an additional contribution for wind generation, calculated based on the work in [13]. Ireland is an island system with one 500 MW interconnector in operation and a 500 MW interconnector under construction. System modeling for the year 2020 assumed that 100MW of spinning reserve can be obtained through interconnection. Another 50MW of reserve is assumed to be provided from interruptible contract loads. Of the remainder, a constraint of a maximum of 50% of reserve demand can be provided by pumped storage. Wind generators are allowed to provide spinning reserve through curtailment.

The demand for spinning reserve is illustrated in Fig. 4 on a weekly averaged basis. Spinning reserve is required more frequently as the amount of wind increases in the portfolio, significantly so in portfolio 6. The scheduled outage of the largest unit on the system (480MW CCGT unit) is seen to reduce the spinning reserve requirement significantly during weeks 31 to 34. While the variable generation requires additional spinning reserve, the largest contributing factor remains the loss of the largest conventional unit.

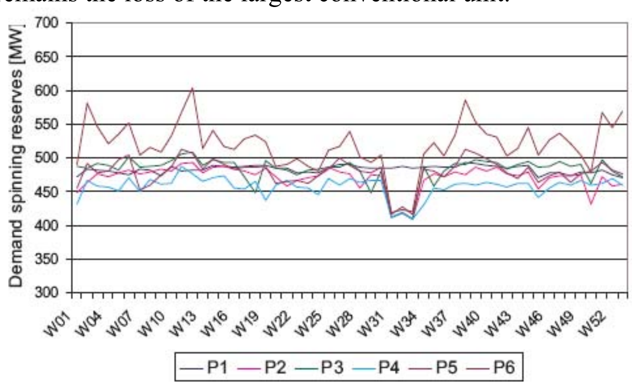

Fig. 4. Weekly demand for spinning reserve for each generation portfolio

Replacement reserve is calculated as a function of the possible forced outages of units and an additional margin which is a function of the 90th percentile of the net load (load-wind) forecast for each particular scenario. The 90th percentile was chosen as it most closely matches experience with proven reserve standards. WILMAR implements rolling unit commitment and has stochastic optimization functionality, which requires the forecast data to be an input to the scenario tree tool and thus, replacement reserve is activated accordingly by the scheduling tool. Demand for replacement reserve is a function of the installed wind power and the forecast error over longer timelines, as shown in Fig. 5 and Fig.6. Fig. 5 shows how the replacement reserve requirement is a function of how far ahead the optimization is evaluating. In other words, generally, errors will be larger further out and therefore more replacement reserve is required than more immediate horizons. In Fig. 6, where portfolio 5 contains 6 GW of wind generation, the requirement for replacement reserve is seen to exceed 3 GW in one instance. This is due to a 1 GW load rise at the same time as a 1 GW decrease in wind, combined with a forecast error.

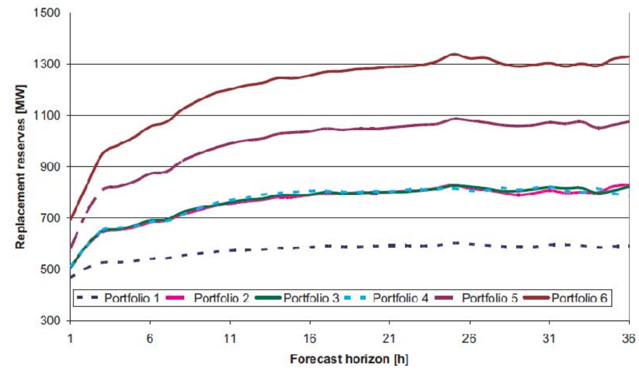

Fig. 5. Average requirement for replacement reserve by time horizon

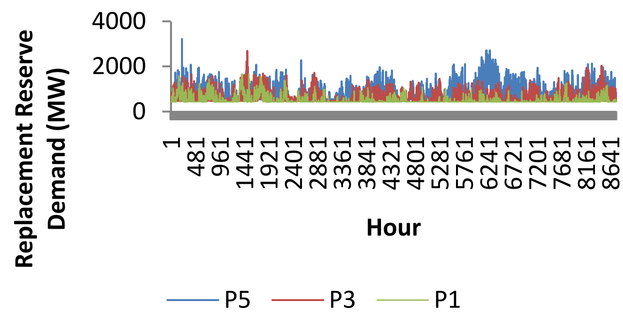

Fig. 6. Hourly requirement for replacement reserve

B. Eastern Wind Integration and Transmission Study (US)

The Eastern Wind Integration and Transmission Study (EWITS) evaluated the operational impacts of various wind penetrations, locations, and transmission build-out options for most of the US eastern interconnection. The study included three scenarios of 20% wind energy with each representing different primary locations of the wind, and one 30% wind energy scenario [14]. The majority of this region is currently operated by Independent System Operators (ISO) and Regional Transmission Organizations (RTO) who administer the wholesale electricity markets. These markets have evolved since their inception in the late 1990s. The further evolution of the rules and procedures that the markets will follow is a key assumption on how operating reserve requirements are determined in the study, with the boundary between operating reserves and what is extracted from sub-hourly energy markets also having an impact on the method used.

The first procedure of the study was to determine the contingency reserves required. As many previous US studies have done, these assumed the current rule and determined that the largest contingency was not affected by the large amounts of wind generation. One and a half times the single largest hazard in each operating region determined the amount of contingency reserves for that region.

Many prior studies in the US concluded a slight, but not insignificant, increase in the amount of required regulating reserve due to the increased variability of wind added to that of the load. In EWITS, a similar methodology to the prior studies was performed. The minute to minute variability separated from a 20 minute rolling average of a 100 MW wind plant was used for the analysis and the standard deviation was determined to be 1 MW. It was assumed that there is no correlation between wind plants for power output deltas in this time frame, and therefore the total standard deviation for a balancing area was calculated by geometrically adding the 1-MW standard deviation for all 100-MW wind plants on the system. For load-only, the regulating reserve requirement was assumed to be 1% of the total load, and assumed to be equal to three times the standard deviation of the load variability. Since load and all wind variability on this timeframe were also considered to be independent of one another, the standard deviations of all wind and all load were then geometrically added together by calculating the square root of the sum of their squares. The total standard deviation was increased by less than 1 MW when the wind was added to the load, and therefore the variability of wind was not considered as part of the regulating reserve for the study.[2]

Different from most studies, however, it was determined that the uncertainty in the wind forecasts used for economic dispatch would impact the regulating reserve much more than what was shown for the variability. Economic dispatch programs that run every five minutes would use information from at least ten minutes before the operating interval. Since it is too late to adjust the economic dispatch for any deviations, these deviations would all be met by units providing regulating reserve. Assuming a 10-min ahead persistence forecast, the additional regulating reserve was determined by looking at the standard deviation of ten-minute changes in wind output (load forecast for 10-min ahead was assumed to be quite good and load forecast error was ignored). Fig. 7 shows the standard deviation of the 10-min ahead wind forecast errors as a function of the average hourly production of the total wind. The highest variability is near 50% production, where the anticipated 10-min change can be up or down and also relates to wind turbines being at the steepest part of the power conversion curve. The function was used for the hourly wind-related standard deviation of the regulating reserve requirement and was geometrically added to the load regulating reserve requirement discussed above. Equation (2) is shown below, where σ_{st} is the standard deviation of wind forecast errors described in Fig. 7.

$$Reg\ Req = 3 * \sqrt{\left(\frac{1\%Hourly\ Load}{3}\right)^2 + \sigma_{ST}(HourlyWind)^2} \quad (2)$$

[2] Calculations based on a balancing area with 100 GW load and 60 GW wind, which was about the average for the largest ISO balancing areas that were a part of the study.

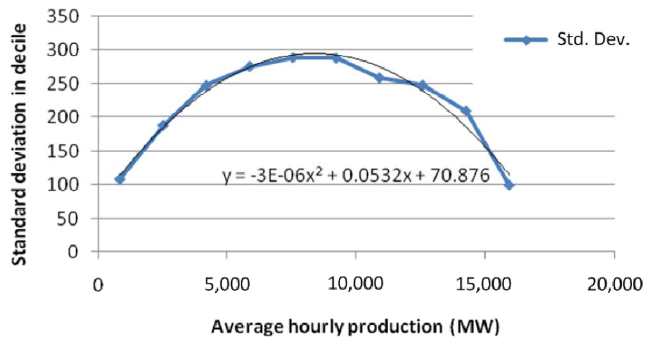

Fig. 7. 10-min ahead wind generation forecast errors as function of production

A similar approach was used for the hour-ahead wind forecast error. However, in this case it was assumed that the errors that were not occurring often could be compensated for with off-line non-spinning reserve. Therefore, one standard deviation of the hour-ahead forecast error was required to be spinning, and two standard deviations could be non-spinning. Also, since the reserves were used in the production cost simulations for the study, it was ensured that if the reserves had to be used for the hour-ahead forecast error of the hour in question, those reserves did not have to be kept in real-time. In other words, if reserves were needed because less wind was available than forecast, the model would release that amount of reserves in real-time since the reserves were used for the forecast error and not needed further. The total amounts of all reserves used in the study are shown in Fig. 8. The reserve requirement was an hourly value that was a function of both wind and load levels.

Reserve Component	**Spinning** (MW)	**Nonspinning** (MW)
Regulation (variability and short-term wind forecast error)	$3 \cdot \sqrt{\left(\frac{1\% \cdot HourlyLoad}{3}\right)^2 + \sigma_{ST}(HourlyWind)^2}$	0
Regulation (next-hour wind forecast error)	$1 \cdot \sigma_{NextHourError}\ (PreviousHourWind)$	0
Additional Reserve		2 × (Regulation for next hour wind forecast error)
Contingency	50% of 1.5 × SLH (or designated fraction)	50% of 1.5 × SLH (or designated fraction)
Total (used in production simulations)	Sum of above	Sum of above

Fig. 8 Summary of reserve methodologies for EWITS

IV. Evolving Methods for Determining Reserve Requirements with High Penetrations of Wind Generation

The treatment of the reserve determination problem has evolved substantially for both wind power integration studies and in actual system operations. The authors believe that this is a continuing trend and that there are still a number of inconsistencies with the data and methodologies used, where improvements can be made. The key issue to recognize is that it is generally not difficult to be overly conservative and hold much more reserves than is needed. The real issue is knowing what is causing the need for different types of reserves today, how high penetrations of wind power will change the needs of reserves, and how to use as much information as is available at any given time to determine an optimal and efficient amount of operating reserves.

The data quality used in wind power integration studies is very crucial in the reserve determination problem. Studies are evaluating high penetrations of wind power that do not currently exist so the estimated power output of the wind generation must be modeled. Different modeling techniques are usually employed where issues can often occur that differ the modeled output from what would be realistic. Data quantity is also important as longer data sets and higher resolution data can give much more information on the anticipated behavior of wind power and how it affects reserve requirements. Lastly, the wind power forecasts used in studies are yet another model that may not be totally representative of wind power forecasts used in actual operations. The requirements for ramping reserves, load following reserves, and regulating reserves may be highly dependent on how good a wind forecast is, so it is important that the error characteristics of the synthetic forecasts closely match those in operations today and in the future.

Dynamic reserve requirements have been proposed in many of the recent studies [2], [5], [11], and [14]. In operations today, most reserves are static and even those that vary hour by hour are usually based on hourly rules, not on forecasted conditions. It is important that if more reserves are needed because of certain operating conditions, those conditions must be taken into account when the control area operator decides the operating reserve requirement. In the future, we see it possible that each balancing area operator will have a reserve requirement that is a function of load forecast, variable generation forecast, net load variability forecast, uncertainty predictions (i.e. confidence of forecasts), and possibly even information on the predicted behavior of conventional generation.

In addition to reserve requirements that vary by time, they may also vary by time horizon. Today, the majority of operating reserves are dominated by contingency and regulating reserves (considering the first tier of Fig. 3). These reserves are mostly used today due to generation and transmission failures, and load and generation variability. These phenomena generally are as likely to happen in the next five minutes as they are tomorrow (i.e. their likelihood does not change with look-ahead horizon). On the other hand, events that are caused by wind may be much better predicted as the operating time gets closer. This was introduced in the All Island Grid Study [11] for the use of replacement reserves. When operators are more confident in the outcome of operating conditions the need to hold reserves is reduced. This applies mostly to ramping and load following reserves but may apply to other categories as well.

The last point that the authors would like to make concerns the traditional requirements that areas throughout the world have set for operating reserves. The requirements should always be set towards the needs of the power system, not towards the resources that are currently available to provide those needs. This issue has arisen recently due to requirements that originally precluded many demand response resources and storage resources from providing operating reserves, when in fact, in some cases, they could provide the service with as good or better performance than the generating resources that had currently provided them. The amount of spinning reserve, compared to non-spinning reserve, for all of the different categories should be evaluated both economically and operationally. The response times for different categories should be evaluated regarding what is optimal, and may also change depending on predicted system conditions. The sharing between reserves should also be evaluated. For instance, if all ramping reserves are used up but a net load event continues to ramp, what are the consequences from taking contingency reserves for that purpose? Also, how should reserves be accounted for with a stochastic scheduling system that inherently schedules reserves without explicitly calling for them? This team has built a high resolution power system model similar to those used in wind power integration studies. The model will focus on the utilization of reserves, however, at a very fine timescale (4-6 seconds for one day) and attempt to capture all of the different contributing factors that would cause the utilization of different types of operating reserves. This research should help highlight how different operating reserves could be determined based on a function of the predicted operating condition inputs. Table II shows further additional research ideas for each of the operating reserve categories defined in Table I.

TABLE II
OPERATING RESERVE DETERMINATION TRENDS

Name	Trends and future research questions
Spinning Reserve	For each operating reserve category, the percentage of reserve that is spinning should be based on reliability and economics. Quicker responses need to be spinning. For event reserves, events that occur frequently should have more spinning reserve, based on a tradeoff between spinning reserves having a higher standby cost, but non-spinning reserves having a higher utilization cost. Should demand response or generation that can be started in extremely quick times (e.g. < 1 minute) be considered spinning?
Non-Spinning Reserve	See above. How quickly must these resources start up for the different categories?
Contingency Reserve	Should this only be used for major failures? Can we share this with other categories? Can we use a fully probabilistic approach with forced outage rates of all generators and facilities, rather than simply using the largest hazard (for instance if many smaller units dominate a region rather than larger ones)?
Regulating Reserve	Is this based on variability or forecast errors? Can uncertainty or variability predictions (rather than energy forecasts) be used for determination of the requirement? How good does regulating reserve have to be?
Load following Reserve	Unit commitments are performed on an hourly resolution and normally load trends monotonically in one direction within an hour. High wind penetrations may change this assumption so that load following reserves are set aside for the hour to meet changes within the hour. Conditions where the short-term economic generation and load response stack has insufficient response capability need to be identified and addressed with a dedicated response service.
Frequency Responsive Reserve	What type of response is needed (appropriate droop)?
Ramping Reserves	Should the response time requirement be a function of the net load ramp prediction? Should the spinning and non-spinning contribution be a function of the

	confidence of the anticipated ramp event?
Supplemental Reserve	How quickly should each of the categories be replaced? Is there any reason that downward reserves should be considered so that if too much are used that they can be replaced?

V. Summary

This paper describes new methods of determining the optimal amount of operating reserves for systems with high wind penetrations. Wind power integration studies are analyzing innovative methods on this issue, but different methods can produce substantially different results. The All Island Grid Study and the Eastern Wind Integration and Transmission Study are two of the most recent studies of their kind and both have made key contributions to the optimal operating reserve requirement determination problem.

Most of the wind power integration studies that have been performed to date run hourly simulations of a security constrained unit commitment and dispatch of the system. Few are truly capturing the details at a level that can replicate system operations, whereby operating reserves are being utilized in detail. Therefore, the statistical methods used in the studies have not been validated extensively. The authors finish by discussing different assumptions and evolving methods on determining the optimal amount of operating reserves with high penetrations of wind power both in future studies and ultimately in actual system operations.

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VII. Biographies

Erik Ela (M ’05) received the B.S.E.E degree from Binghamton University and the M.S. degree in Power Systems at the Illinois Institute of Technology. He joined the NREL grid integration team to work on different wind integration issues. His experience lies mostly in different topics relating to grid operations and market operations. Erik previously worked for the New York ISO developing and improving products in the energy markets and operations areas. Erik is a member of IEEE and the Power and Energy Society.

Brendan Kirby (SM ‘76) is a private consultant with numerous clients including AWEA, National Renewable Energy Laboratory, Oak Ridge National Laboratory, EPRI and others. He recently retired as a senior researcher with the Oak Ridge National Laboratory’s Power Systems Research Program. He has 34 years of electric utility experience and has published over 120 papers, articles, and reports on ancillary services, wind integration, restructuring, the use of responsive load as a bulk system reliability resource, and power system reliability. He has a patent for responsive loads providing real-power regulation and is the author of a NERC certified course on Introduction to Bulk Power Systems: Physics / Economics / Regulatory Policy.

Eamonn Lannoye (S’08) received the B.E (Hons.) degree in mechanical engineering from University College Dublin, Dublin, Ireland in 2009. He joined the Electricity Research Centre in UCD as an Irish Research Council for Science, Engineering and Technology Embark Initiative doctoral student. His research is concerned with flexibility in power systems with high penetrations of variable generation.

Michael Milligan (M ’98) is part of the Transmission and Grid Integration Team at the National Renewable Energy Laboratory. He has authored or coauthored more than 100 papers and book chapters and has served on numerous technical review committees for wind integration studies around the U.S. Michael is a member of the leadership team of the NERC Variable Generation Task Force, member of WECC’s Variable Generation Subcommittee, member of the IEEE Wind Power Coordinating Committee,, and served on the Western Governors’ Association Clean and Diverse Energy Wind Task Force. Michael has M.A. and Ph.D. degrees from the University of Colorado, and a B.A. from Albion College.

Damian Flynn (M’96) is a senior lecturer in power engineering at University College Dublin. His research interests involve an investigation of the effects of embedded generation sources, especially renewables, on the operation of power systems. He is also interested in advanced modeling and control techniques applied to power plant. He is a member of the IEEE.

Bob Zavadil (M) is co-founder of EnerNex and is responsible for developing and overseeing the company’s power system engineering consulting business. He has worked on electric power system issues for wind generation for over 15 years. From 1989 to the summer of 2003, Mr. Zavadil served in various consulting and product development capacities for Electrotek Concepts and its parent company, WPT. Mr. Zavadil began his career in the electric power industry in 1982 as a special studies engineer in the Transmission and Distribution Engineering Division of the Nebraska Public Power District. He is a member of the IEEE Power Engineering, Power Electronics, and Industrial Applications Societies, and serves as Secretary of the IEEE PES Wind Power Coordinating Committee.

Mark O’Malley (F’07) received B.E. and Ph. D. degrees from University College Dublin in 1983 and 1987, respectively. He is the professor of Electrical Engineering in University College Dublin and is director of the Electricity Research Centre with research interests in power systems, grid integration of renewable energy, control theory and biomedical engineering. He is a fellow of the IEEE.