A Review of Approaches to the Quantification of Operating Reserve Requirements in Systems with Large Scale Wind Power Integration

Brian K. Wamukoya, Bonface O. Ngoko, and Christopher M. Muriithi

Abstract—The need to diversify power generation sources, increase security of supply, incorporate sustainability in energy sources and reducing fuel usage and emissions has significantly led to the integration of variable renewable energy sources such as wind to power grids globally. However, increased integration of wind power into a grid necessitates the need to update unit commitment and operating reserve algorithms since wind power is highly variable, intermittent and non-dispatchable. In addition, operational decisions in these grids are made on the basis of wind and load forecasts which are not perfect. Therefore, variability and uncertainty due to wind power introduced in the system requires an increase in operating reserve allocation to maintain reliability levels after wind power integration. This paper reviews recent work on determination of additional operating reserve requirement for power systems with large scale wind power integration. It also highlights different methods incorporated in solving the optimization problem in balancing between economics and reliability of power systems in sizing of additional reserve. In conclusion, gaps in literature that require further research are identified.

Keywords—Large scale wind integration, Operating reserve, Reserve quantification, Wind variability and uncertainty.

I. INTRODUCTION

IN the last couple of decades, the need to diversify power generation sources, increase security of supply, incorporating sustainability in energy sources and reducing fuel usage and emissions has significantly led to the integration of variable renewable energy sources (VREs) such as Wind power to power grids globally. Integrating VREs is far much less complicated if they are incorporated to large power systems which can take advantage of natural diversity of variable sources [1]. However as wind capacity increases, considerable measures have to be taken to ensure that the wind power variation does not reduce the reliability of the power system.

Wind power possess great challenges to power system operators in grid management and generation scheduling as a sudden and severe loss of generation might occur at a high penetration level of wind power. The inherent variability, intermittency and uncertainty that characterize wind power require that current industry practices be altered which necessitates a need to update unit commitment and operating reserve procurement algorithms to accommodate smooth integration [1], [2]. The additional variability and uncertainty introduced in the system will result in an increase in operating reserve requirement in the system to maintain reliability levels after wind integration [3]–[5]. The objective is to meet high load demand and withstand the impact of wind power fluctuations.

The requirement for additional reserve capacity is determined by critically monitoring the variation of wind power production, hourly and intra-hourly, together with load variations and prediction errors [1]. Therefore accurate forecasting tools such as numerical weather prediction are critical to wind integration as it contributes to risk reduction. Accuracy of wind power production forecasts depends on several factors such as the forecast horizon, the size of wind power plants and their geographical dispersion, experience with wind power generation and the accuracy of forecasts for individual wind power plants [6]. Wind power forecast errors (WFEs) increase as the forecasting horizon gets longer [6]–[8]. Large geographical spreading of wind power will also increase predictability [9], [10].

Since the cost associated with provision of additional reserve capacity as a result of wind integration is far from being negligible, quantification of operating reserve has become a subject of intense interest for researchers and power engineers in the recent past. In this regard, system models and analytical methods using time series of wind power production together with a host of other power system variables and constraints have previously been presented to estimate reserve requirement and the cost associated with it [1].

Statistical methods that rely on the use of standard deviation (σ) like the n-sigma criterion are one of the most widely used to quantify the effects of increased wind power on operating reserves due to its simplicity. However, this method is most applicable in power systems where the wind power capacity is decentralized over a large geographical area with different wind flow regimes. Consequently, the variability of total wind power injections is attenuated, even more with increasing number of wind turbines (WTs) installed at different locations [11], [12]. Under these circumstances, both wind power variability and wind forecast errors (WFE) are assumed to follow the Gaussian distribution [13], [14]. Suffice to mention, wind variability and forecast errors do not necessarily follow a Gaussian distribution [15], [16].

Alternatively, sophisticated probabilistic methods can be deployed to quantify operating reserve by integrating different sources of uncertainties using reliability theory of power systems [17]. They are based on generation margin which is defined as the difference between total available generation

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and load. Classical reliability indices such as loss of load expectation (LOLE), loss of load probability (LOLP) and expected energy not supplied (EENS) are calculated based on the distribution of generation margin and used in the sizing of appropriate operating reserve levels.

This paper summarizes recent work on the determination of operating reserve requirement for power systems with large scale wind integration with the main focus on solution approaches on the sizing and allocation of different categories of operating reserves. It also highlights the different methods incorporated in solving the optimization problem in the balancing between economics and reliability of the power system in the sizing and allocation of operating reserve requirement. Eventually, research gaps are identified after a thorough evaluation of existing methodologies in this field of research.

II. PROBLEM DESCRIPTION

Problem formulation in quantifying additional reserve requirement is mostly anchored on balancing minimization of operating cost with guaranteeing required reliability levels while considering other system constraints.

A. Objective Function

The objective is not to be overly conservative in scheduling additional operating reserve racking up costs unnecessarily while also not excessively minimize cost to levels compromising system security. The objective function of the reserve allocation problem in [18] is given as:

$$\min \sum_{i=1}^{N_R} \rho_i R_i \tag{1}$$

where N_R is the number of generators to provide operation reserve, R_i- is the selected reserve of the generator, ρ_i- is the reserve cost of generator i. An illustration of the cost (reserve) / reliability curve (EENS) in [19] is shown in Fig. 1.

Reference [18] focuses on the day-ahead allocation of operation reserve considering wind power forecast error and network transmission constraints in a composite power system.

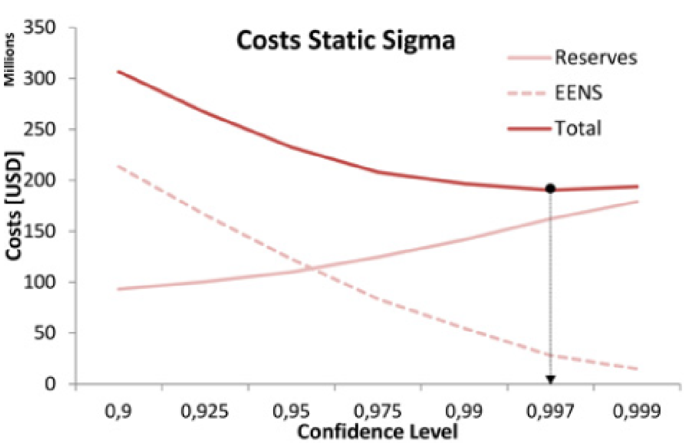

Fig. 1. Cost vs. Reliability curves [19]

The authors in their methodology were determined to minimize operating cost associated with allocation of operating reserve while at the same time meeting required system reliability levels.

Reference [19] seeks to demonstrate economic benefits of using a probabilistic-dynamic approach (PDA) in the quantification of operating reserves as opposed to the traditional quantification methods. The PDA considers conventional generation outages; load and wind forecast uncertainty on an hourly basis; and load and wind variability in 10 min time frame. The authors objective was to determine the amount of operating reserves hourly in real time that minimizes the total cost of the power system, that is, the sum of operating costs and the socioeconomic costs related to the EENS.

In [20], authors address the critical problem of spinning reserve (SR) allocation for active power dispatch with large-scale wind power penetration. In particular the SR allocation for a multi-area power system where not well optimized SR allocation may make the inter-zonal reserve supplies constrained by the transmission interface limits jeopardizing the operational security of the power system. The objective of the study is to ensure operational risk is shared evenly among all sub-areas in SR allocation to avoid the possibility of a large blackout or wind power curtailment while considering economic and technical constraints.

A stochastic programming approach is used in [21] for quantifying reserve allocation based on scenarios generated by Monte Carlo Simulation. The objective was to demonstrate the benefits and drawbacks of the stochastic approach in reserve allocation by a comparison to deterministic approaches. This approach was found to be attractive as it enabled co-optimization of generation schedules and reserve requirement in the same problem formulation. It outperforms deterministic models in analyzing economic impacts of wind integration as it provides a means of assessing the sensitivity of operating costs in wind integration levels. However, it was found to present significant challenges in developing appropriate scenarios to be used as input to the stochastic programming model as well as computational intractability of the resulting problem.

In [22], the authors seek to address the problem of how to determine and schedule the additional SR requirement due to wind power fluctuation, more particularly how to jointly dispatch SR with power generation economically. Authors aim to investigate utilizing automatic generation control (AGC) units in both power supply to meet load demand as well as providing spinning reserve.

Using actual wind power and load data for two grids (ERCOT and MISO) in the US, authors in [23] aimed to demonstrate that both wind power and load forecast errors do not follow the normal distribution discrediting statistical approaches such as n-sigma criterion that assume this distribution in quantifying operating reserve. Authors demonstrate that using net load forecast error the dispatchable operating reserve requirement can be quantified based on certain reliability levels required.

B. Operational Constraints

In general operating reserve allocation problems consider the following constraints in their formulation.

LOLE threshold constraint: The resultant LOLE value after operating reserve allocation must be less than or equal to the incumbent LOLE to guarantee required levels of operational reliability of the power system.

Active power balance constraint: This requires that power balance between active power generation and load demand must be kept at all times during normal operations of the power system as expressed in the equation below

$$CG + Wind\ Power = Load\ Demand + Losses \quad (2)$$

Unit capacity constraint: Generation units usually have operational maximum and minimum power output limits within which the unit output must be maintained. *Ramp rate limits*: The ramp rate limits confine the power output increase or decrease between adjacent hours for certain units.

Transmission interface capacity constraints: The transmission capacity limits must be observed for accurate operating reserve allocation to ensure the reserve can be evacuated to demand centers without overloading the lines.

III. Solution Approaches

In the past several years, various researchers and organizations have participated or initiated wind power integration studies. The spine of each study is to evaluate the incremental need for additional operating reserves for the future system that result from high wind penetration. Basically study teams propose needed changes to maintain reliability while accommodating the variability and uncertainty present in the wind power. In most studies, statistical methods are used in the analysis and modelling of wind power time series data which forms a basis for quantification of operating reserve. Significant progress has been on methodologies used to compute theses values as successive studies addressed shortcomings of 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 [3]. Generally methods to determine additional operating reserve can be classified as follows:

A. Statistical Approach

These rely on historical data of wind power and load which are analyzed to establish their statistical properties [7]. A commonly known statistical approach is the n-sigma criterion that is based on a comparison of the load and net load time series data, where net load is defined as load minus wind power production [9]. The probability distribution function of the net load is used to quantify additional operating reserve due to wind power integration at different time scales. Therefore assuming these data sets to be uncorrelated, the standard deviation of the net load time series is obtained as [4], [6], [8]

$$\sigma_{NL} = \sqrt{\sigma_L + \sigma_W} \quad (3)$$

where σ_L and σ_W are the standard deviations of the load and wind power time series respectively. From the analyzed time series of load and wind power data either variability or forecast error deviations can be established. The additional reserve ΔRes due to wind power integration can then be quantified according to [10]:

$$\Delta Res = n\left(\sigma_{NL} - \sigma_L\right) \quad (4)$$

The multiple n is defined a priori and represents the confidence level (CL) used. It varies from one power system to another. The remaining uncertainty not covered by n is met by energy balancing using the spot market.

According to literature review quite a number of studies have incorporated statistical approach in quantifying operating reserve requirement. In [24] authors proposed a model to incorporate the uncertainty of wind forecasts in unit commitments. Reference [6] presented a reserves procurement model that combines wind forecast uncertainty with load forecast uncertainty and generator forced outage probabilities.

Studies in [15], [16], each presented decision analytic frameworks to determine operating reserves in systems with wind power by balancing the cost of reserves and the cost of load curtailments. Authors in [25] presented an economic dispatch algorithm that accounts for wind forecast uncertainty. In these studies cited above statistical approach is applied, wind and load forecast errors are generally modeled using Gaussian distribution. On the contrary references [23], [26], [27] show that wind and load forecast errors are not normally distributed and demonstrate that wind forecast errors have distributions that can be highly skewed when the forecast is for a very low or high value of wind power. Wind forecasts near the middle of the forecast range have more symmetric error distributions (although not necessarily Gaussian). Fig 2 illustrates typical wind forecast errors as reported in [23]. The forecast horizon considered for wind power is therefore critical in determining more accurate results of operating reserve requirement using the statistical approach.

B. Probabilistic Approach

In more recent studies, reliability theory of the power system has been used to quantify operating reserve by integrating different sources of uncertainty [17]. Probabilistic approaches are based on system generation margin (SGM) which is defined as the difference between the total available generation and load demand. The SGM is a function of two random variable which makes it a random variable [15], [28]. In computation of SGM distribution, the probability distribution of CG, Wind Power generation W and load L must be considered.

$$SGM = CG + W - L \quad (5)$$

For a specific level of reserve R, the distribution of $SGM + R$ describes the probability that R is sufficient to cover the deficit in generation. Usually the SGM distribution forms a basis for calculation of classical reliability indices such as LOLE, LOLP and EENS [17], [29]. Operating reserve requirement are computed to meet these indices.

Authors in [18], present a two-level model that solves the allocation problem for composite power system. The upper model allocates operation reserve among the subsystems from

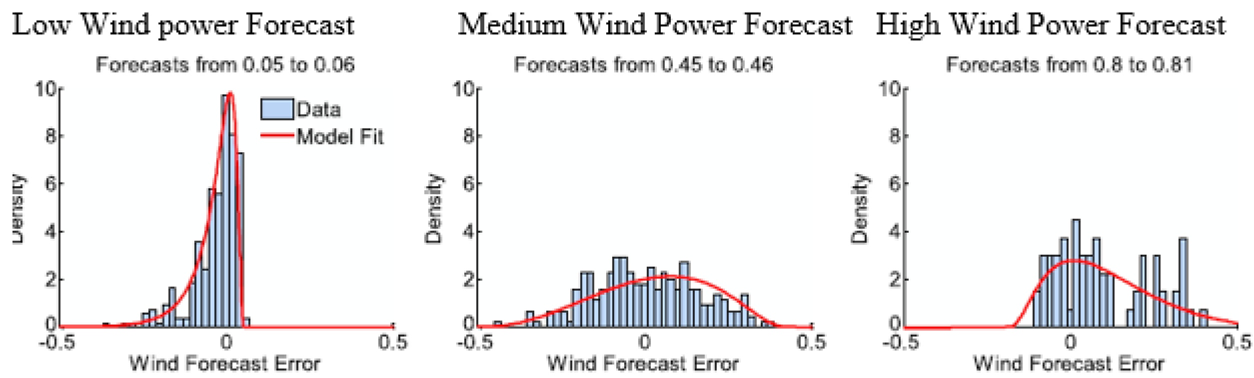

Fig. 2. Wind power forecast error distributions at three different wind forecasts [23].

the economic point of view while the lower model evaluates the system in the reserve schedule considering reliability levels. Optimization of the reserve allocation to achieve balance between reliability and economy is achieved through iteratively adjusting the reserve requirement by the upper model with the resulting reliability indices from the lower model.

The study team in [19] proposed a probabilistic-dynamic approach to quantify different operating reserve categories within a real-time system operation is based on an iterative process where the total costs (operating cost and cost of expected energy not supplied EENS) of the system are minimized. The PDA considers CG outages; load and wind forecast uncertainty on an hourly basis; and load and wind variability in 10 min time frame. The study demonstrates economic benefits of using a probabilistic-dynamic approach (PDA) in quantification of operating reserves as opposed to the traditional quantification methods in power systems with high penetration levels of wind power.

In [20], the authors propose a risk-based multi-objective SR optimization model which considers coordination of multiple control sub-areas to effectively handle the problem of local reserve inadequacy and transmission interface load. A probabilistic approach that considers forced outages of generators and forecast errors of load and wind power is used to establish relationship between SR allocation and LOLE. The resultant SR allocation problem is multi-objective. Fuzzy optimization method is used to transform the multi-objective optimization problem to a single-objective problem which can easily be solved. The single-objective problem characterized by nonlinearly coupled and not continuously differentiable constraints is solved using Particle Swarm Optimization (PSO) method.

A two-stage stochastic programming model for committing reserves in systems with large amounts of wind power is presented in [21]. The first stage formulates the UC problem of slow generators while the second stage formulates the hour-ahead economic dispatch problem for the entire system given the fixed day-ahead schedule of slow generators. Scenarios representing daily wind time series based on probability of occurrence are selected as part of input to the stochastic program. Lagrangian relaxation decomposition algorithm is used for solving the stochastic program.

Authors in [22] propose a joint optimization dispatch model of active power and additional SR requirement using AGC units for wind power integration systems. In formulation a model to accomplish this, both the probabilistic distributions of load and wind forecast errors were introduced to deal with uncertainties. Multiple scenarios are adapted to simulate the fluctuation of wind power and load. The actual output of AGC generators is adjusted according to the AGC unit modification strategy in each scenario.

Despite the attractive features presented by probabilistic approaches, the complexity of the formulated problem introduces computational intractability that can be rather time consuming to solve. However recent increased availability of high speed computing coupled with reduction in costs means that this problem can be overcome.

A summary of the general concept, advantages and disadvantages of the statistical approaches and probabilistic approaches are given in Table 1.

IV. Research Gaps

A review of literature on the sizing and allocation of additional operating reserve requirement due to large scale wind power integration as undertaken in this paper reveals that there has been commendable effort over the last decade or so in proposing solution methodologies and models to quantify and optimize allocation of operating reserve. Nevertheless, there exists a number of research gaps as outlined below:

1. An assumption of CL defined a priori still dominates the reviewed literature in quantifying operating reserve. Theres need for an objective method of determining this factor to guarantee consistency.
2. Most research done do not incorporate certain critical constraints such as network transmission capacity constraints in formulation of the reserve allocation problem. This undermines the practical applicability of the proposed methodologies.
3. Apart from ignoring important constraints, most work is silent on the different categories of operating reserve that can be deployed to meet the supply deficit as of wind power

TABLE I
A SUMMARY OF GENERAL CONCEPT, ADVANTAGES AND DISADVANTAGES OF SOLUTION APPROACHES

Approach	Concept	Advantages	Disadvantages
Probabilistic	• Based on system generation margin (SGM) - the difference between the total available generation and load demand. • Reliability theory of power systems is incorporated in quantifying of operating by integrating different sources of uncertainty. • Usually the SGM distribution forms a basis for calculation of classical reliability indices such as LOLE, LOLP and EENS and the operating reserve requirement are computed to meet these indices.	• Dynamic reserve allocation at desired time interval which eliminates the need to hold large amounts of reserve at every instant. • Allows incorporation of a variety of sources of uncertainty (variables) in determination of operating reserve which makes it more practical. • Uses an optimal CL determined based on a cost benefit analysis considering operating cost and reliability of the system.	• Computational intractability due to the complexity of the resultant problem. • Significant challenge presented in selecting appropriate scenarios and their probabilities.
Statistical	• Relies on historical data of wind power and load which are analyzed to establish their statistical properties. • A commonly known statistical approach is the n-sigma criterion where the probability distribution function of the net load (Load − Wind Power) is used to quantify additional operating reserve due to wind power integration at different time scales.	• Results in relatively simple problem formulation hence provides quick solutions to operating reserve determination. • Useful as an easier way of providing an approximation close to reality of reserve determination.	• Static reserve allocation which results in unnecessarily holding of large amounts of reserve thereby increasing costs. • Assumes WFE and variability follows Gaussian distribution which is not necessarily the case. • It is implicitly assumed that present and future behavior of the power system resembles observations of the past. If this assumption is not valid, the n-sigma criterion or any statistical approaches will fail.

fluctuation which is equally essential in minimizing cost and avoiding wind power curtailment.

V. CONCLUSION

This paper presents an overview of the methodologies used in the sizing and allocation of additional operating reserve requirement with large scale wind power integration. Recent reviewed literature on this subject reveals that significant progress has been made in the quantification of additional reserve. Generally the solution methods to the reserve problem formulated are based on statistical or probabilistic approaches. However, there are still some inconsistencies with data and methodologies used where improvements can be made. Finally, a number of research gaps have been identified such as the need to incorporate critical system constraints such as network transmission capacity constraints in the problem formulation; limited direction on the different categories of reserves to be deployed after quantification; and lack of consensus on the CL to be used on quantification.

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