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Impact of modelling non-normality and stochastic dependence of variables on operating reserve determination of power systems with high penetration of wind power

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ABSTRACT

A method is presented for dynamic determination of the operating reserve requirement in power systems with high wind penetration, by considering the non-normal nature of wind power uncertainty and variability as well as their stochastic dependence on the wind power forecast. Distinct from previous methods, a generalised approach is proposed to characterise the probability density of wind power uncertainty and variability at distinct wind power forecast levels. As an illustration, the approach is applied in Ireland to determine the required operating reserve at different time scales within hourly scheduling periods to meet a certain reliability level. Statistical analysis indicates that the results are sensitive to normality and independence assumptions generally adopted in previous studies, and such assumptions may lead to under/over-estimation of the required operating reserve. Thus, the proposed method, which is not based on these limiting assumptions, emerges as a more realistic solution to define operating reserve targets dynamically. It further provides insight for planning studies and the operation of power systems with high wind power penetration.

1. Introduction

During the last decade, grid integration of wind power has been growing steadily throughout the world. While at low penetration levels, wind power may offer various benefits to grid operation, system operators are concerned about its limited controllability at high penetrations, which requires extra flexibility from the power system. The flexibility requirement mainly is in the form of additional operating reserve which increases system operating costs, while ensuring an acceptable level of reliability [1]. From this viewpoint, it is essential to determine the required operating reserve to maintain a balance between cost and reliability on a prudent basis.

Much effort has been devoted in the literature to study the impact of wind power on operating reserve requirements. A general conclusion from these studies is that while wind power has limited impact on contingency and regulation reserve [2], it requires additional imbalance and load following reserves to correct deviations from schedule caused by its uncertainty and variability [3].

Wind power uncertainty and variability have been modeled through specific approaches in the literature. In some instances [4,5], deterministic methods were applied. However, according to [6], such approaches may lead to an overestimation of the reserve requirements. To overcome this problem, stochastic methods have been proposed following two basic approaches. The first represents a static approach, assuming the same operating reserve requirement across a year, or season, regardless of system conditions, as applied in [7,8]. The main disadvantages are a high operating cost, and a varying risk of exceeding a certain power imbalance due to carrying a fixed amount of reserve at every instant [9]. An alternative approach, as recommended by [10–12], is based on a dynamic determination of the reserve requirement as a function of the load and wind power. Such an approach quantifies the reserve requirements by accounting for the uncertainty risk from load and wind power generation variability [13]. The importance of this approach was illustrated in [14], where operating reserves were determined based on maintaining a predefined level of risk, and the impacts of wind power forecast horizon time scale and forecast errors were discussed. Similarly, the authors in [9] first established a direct relation between reserve levels and a reliability criterion. Then, the required level of reserves was tied to a satisfactory reliability level, which allows system operators to define reserve targets based on a trade-off between reliability and cost. The authors in [15] adopted such an approach to quantify the operating reserve required in each hour by considering the number of load shedding incidents per year as their objective measure. Reserve requirements were also quantified

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dynamically in [16], in an effort to assess the costs of power balancing and the capacity benefits of wind generation. The same approach was applied in [17] to estimate the increased hourly reserve requirements after the integration of wind power. Similarly, a Monte Carlo simulation was performed in [18] to investigate the incremental operating reserve that should be carried to integrate a certain amount of wind power.

For the above studies and others, wind power uncertainty and variability are generally assumed to be normally distributed. However, the validity of such an assumption was challenged in [19] and [20], where it was shown that a normal distribution cannot describe the skewed and fat-tailed distribution of realistic wind power uncertainty. To solve this problem, other distributions, including Beta [19], Weibull [21], and Laplace [22] have been proposed for modeling the non-normality. However, in these studies, wind power uncertainty was assumed independent from the wind power forecast. This latter assumption has been challenged [23–28], where moment-matching [23], *a priori* analytical method [24], gamma-like functions [14], copula functions [25], quantile-copula kernel density estimator [26], versatile distributions [27], and levy α-stable distributions [28] have been applied to model the distinct statistical characteristics for various levels of forecasted wind power. However, the main disadvantage of the above works is that they did not subdivide operating reserves based on their response time, and thus, they could not analyse the conditional distribution of load/wind power variability for different wind power forecasts.

Despite the importance of applying realistic models to determine the required operating reserve in power systems with high wind penetration, less attention has been paid to it in the literature. Most studies concerning operating reserve [7–18] are based on limiting assumptions of normality for wind power uncertainty and variability, and their independence from the wind power forecast. Although these assumptions are challenged by [24–28] when setting imbalance reserve on the basis of wind power uncertainty, fundamental questions remain to be resolved when using the same assumptions to set load following reserve based on wind power variability. Further, there is a knowledge gap concerning the extent to which these limiting assumptions affect the operating reserve requirement.

The presented methodology contributes to the literature by presenting a generalised approach to determine the required imbalance and load following reserve, which eliminates the limiting assumptions, e.g. normality of the wind power variability and uncertainty, and their independence from the wind power forecast, adopted in previous methods. The methodology captures the stochastic nature of load/wind power uncertainty and variability at different forecast levels by deriving distinct probability density functions (PDFs). A computational algorithm is proposed to combine the derived PDFs with a reliability level and day-ahead load/wind power forecasts to define the required reserve on the imbalance and load following time scales for each scheduling period. Results from the proposed and existing methods are compared, and the implications of the limiting assumptions are highlighted. Using actual wind data from Ireland, exemplar results are generated using the proposed methodology to illustrate the effectiveness of the approach. This paper presents a generalised methodology to capture the stochastic features of wind power uncertainty and variability to define reserve targets. Such features have been previously justified in [23–28] based on various single- and multi-year historical data. Thus, the data from Ireland relating to the year 2009 (with less than 1% curtailment) are used to generate exemplar results to isolate the impact of wind power curtailment in the study as subsequent years have seen higher curtailments. The methodology may be applied to multi-year historical records and forecasts of load/wind power when adopted as a tool by system operators to define reserve targets. This paper is organised as follows. Section 2 addresses the problem statement. Section 3 presents the proposed solution method and analysed scenarios. Simulation results are outlined in Section 4, and Section 5 concludes.

2. Problem statement

As mentioned in Section 1, determining the operating reserve requirement against a background of high wind power penetration may be less reliable if assuming wind power uncertainty and variability as normally distributed variables independent from the wind power forecast level. In this context, load/wind power uncertainty and variability are defined by Eqs. (1) and (2).

$$Uncertainty\ (x) = Long{-}term\ average\ (x){-}Long{-}term\ forecast\ (x) \tag{1}$$

$$Variability\ (x) = Short{-}term\ average\ (x){-}Long{-}term\ average\ (x) \tag{2}$$

where x is load/wind power, and the time scale of *'short-term'* quantities, used to derive uncertainty values, is related to the imbalance time scale, i.e. the frequency of the scheduling periods (e.g. 30–60 min), and that of 'very *short-term'* quantities, used to derive variability values, is related to the load following time scale (usually 5–30 min). In this paper, the imbalance and load following time scales are set to 60 min and 15 min, respectively.

Moreover, independence implies that the occurrence of a specific value of load/wind power forecast has no impact on the associated load/wind power uncertainty and variability. Further, normality implies that load/wind power uncertainty and variability values are distributed normally for all load/wind power forecast levels. Analysis of a load/wind power time series reveals the non-normality of load/wind power uncertainty and variability, and their dependence on load/wind power forecasts. For instance, Fig. 1 shows the distinct behaviour of

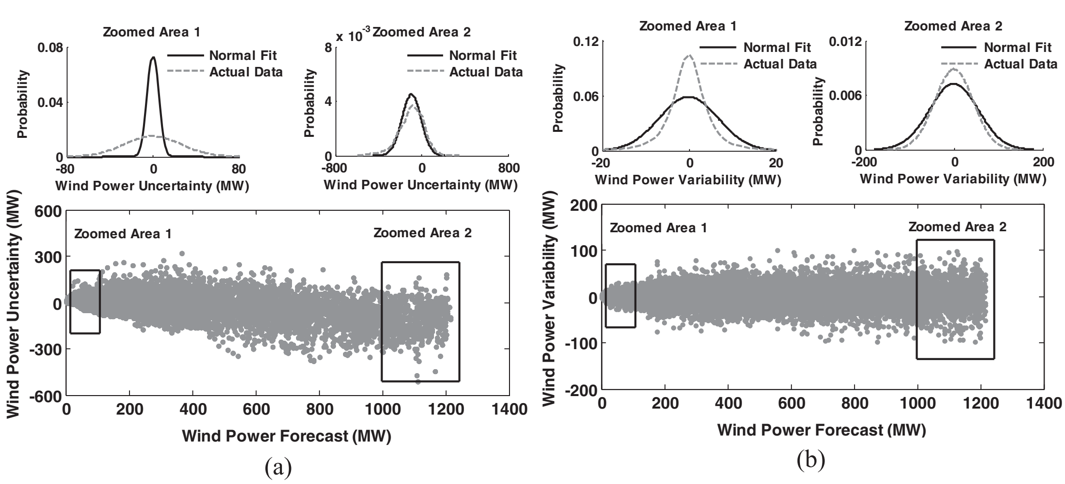

Fig. 1. (a) Wind power uncertainty (b) wind power variability as a function of wind power forecast in island of Ireland for year 2009.