ESTIMATING REGULATING RESERVES REQUIREMENTS AS WIND GENERATION INCREASES: A PROBLEM DEFINITION

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Abstract

This paper describes the problem of estimating the quantity of regulating reserves required to meet a threshold on Area Control Error. In contrast to existing studies, which have largely used Gaussian statistical assumptions in their approach to estimating reserves requirements, we seek to develop solutions that are based on the empirical statistical properties of wind farms. Rather than proposing a solution to this problem this paper bounds the problem, formulating it as a stochastic optimization problem, and discusses an approach to the development of solutions.

1. Introduction

One of the primary responsibilities of a power system control area operator (Balancing Authority, BA) is to schedule generation to maintain a constant balance between supply and demand. On time scales of days this task is performed through unit commitment methods [13]. On hourly to 5-minute time scales, Optimal Power Flow methods are typically used to adjust generator dispatch schedules. Shorter-term (5-minute and below) schedule adjustments are frequently referred to as load-following services. In order to ensure that a supply-demand balance can be quickly re-established after sudden loss of supply, contingency reserves are purchased from generators that can quickly ramp up to meet unexpected shortages. The fastest time-scale balancing is performed by generators that perform Automatic Generation Control (AGC). Generators on AGC automatically adjust their output based on the frequency of the voltage at the generator terminal bus and signals that come from the Balancing Authority. These signals are generally a linear multiple of the Area Control Error (see definition below, Eq. 1). In the scheme described in [8, 4] these power balancing services are known as energy (day-ahead and hourly dispatch), primary reserves (frequency-based AGC), secondary reserves (ACE-based AGC and load following), and tertiary reserves (contingency reserves, with time-responses of 10 minutes or longer).

Table 1. Notation used in this paper.

Symbol	Meaning
t	Time, in seconds
τ	A variable used to represent a time difference
$G_i(t)$	The measured net real power generation from dispatchable plant i at time t (MW).
$G_{i,s}(t)$	The scheduled (net) power generation from plant i at time t (MW).
$W(t)$	Real power generation from wind farms within a balancing authority (MW).
$L(t)$	Load at time t within a balancing authority (MW).
$\Pr(x)$	The probability (or probability density) of event x
R_i	The regulating reserves scheduled for power plant i (MW).
r_i	The maximum ramp rate for power plant i (MW/s). In this formulation we assume that up and down ramp rates are the same. The extension to the asymmetric case will be explored in future work.

There is a substantial body of literature on the effect of large-scale wind on hourly dispatch and reliability effects of wind [2, 3, 12], as well some academic research into tertiary reserves requirements given large-scale wind deployment [6]. However there is less research into the effects of wind and/or solar deployment on short term frequency- or AGC-based regulation requirements. Results for the frequency effects of wind in the Irish system are reported in [7]. A report on wind integration in the South-Central U.S. [11] describes a heuristic statistical method for estimating regulation requirements, given the 95 and 5 percentile (up/down) variations in wind and the standard deviation of the load, when sampled at a fixed frequency. Potentially the most advanced methodology for the study of wind/solar generation and regulating reserves is presented in a recent California Energy Commission (KEMA) report on wind and solar integration [9], which describes results from a second-by-second dynamic model of the Western U.S. generation system, with substantial wind and solar deployments. The most notable conclusion from the KEMA report was that standard regulating reserves resources would not be sufficient to satisfy reliability criteria a high levels of wind and solar deployment. The report recommends investment in substantial quantities of high-speed storage.

The objective of regulating reserves is to minimize unscheduled power flows with neighboring balancing authorities (Area Control Error), and unscheduled frequency deviations (deviation from a 60 Hz voltage signal). For a balancing authority at time t (in seconds) with power demand $L(t)$, wind power production $W(t)$, dispatchable generation $G_i(t)$, and scheduled net exports $E(t)$ on tie-lines, Area Control Error can be defined as:

$$ACE(t) = \sum_i G_i(t) + W(t) - L(t) - E(t) \tag{1}$$

NERC reliability Standard BAL-001-0.1a [10] requires that regulation ($G_i(t)$) be scheduled such that $ACE(t)$ be controlled to meet or exceed the following criterion for a 10-minute (600 second) period:

$$\Pr\left(\frac{1}{600}\int_t^{t+600} ACE(t)dt > L_{10}\right) \leq 0.90 \tag{2}$$

where L_{10} is a constant, which is defined in as

$$L_{10} = 1.65\epsilon_{10}\sqrt{(-10B_i)(-10B_s)} \tag{3}$$

In Eq. 3 ϵ_{10} “is a constant derived from the targeted frequency bound,” B_s “is the sum of the Frequency Bias Settings of the Balancing Authority Areas in the respective Interconnection,” and B_i is the frequency bias setting for balancing authority i.

With these definitions we can define the problem of estimating regulating reserves requirements for a one-hour time period ($T = [t_0, t_0 + 3600]$). In words the problem is to find the minimum cost amount of regulation to purchase for the time period that will satisfy (or exceed) the NERC ACE criterion (Eq. 2).

$$\min_{R_i \forall i} \quad \sum_{i=1}^{n_g} C(R_i) \tag{4}$$

$$\text{subject to} \quad \Pr\left(\frac{1}{600}\int_{t+(k-1)600}^{t+600k} ACE(t)dt > L_{10}\right) \leq 0.90, \forall k \in \{1,2,\ldots,6\} \tag{5}$$

$$|G_{i,s}(t) - G_i(t)| \leq R_i, \forall i, \forall t \in T \tag{6}$$

$$|G_i(t) - G_i(t+\tau)| \leq r_i\tau, \forall i \in \{1,\ldots,n_g\}, \forall \tau \in (0,300], \forall t \in T \tag{7}$$

$$\frac{dG_i(t)}{dt} = f(G_i(t), r_i, \omega(t)) \tag{8}$$

In this formulation Eq. 4 evaluates the cost of purchasing regulation from all generators for the time period in question. Equation 5 is the NERC regulating reserves constraint, which will need to hold for each of the 6 ten-minute periods in a one-hour period. Equations 6 and 7 describe the regulation constraint and the ramp rate constraint in continuous time. The final constraint (Eq. 8) will be used to capture the rotational inertia of generators in the system. Assuming that we can develop an analytical probability density function for Equation 5, which is based on actual wind data, we will be able to solve Eqs. 4-7 using optimization methods, and produce an estimate for regulation requirements for several power plant types under a variety of conditions, such as increasing wind generation deployment.

The research questions of interest, that could be answered from this model, include the following:

1. How does the cost and quantity of regulation increase as wind power deployment increases?
2. How do optimal regulation dispatches change if high-ramp rate storage resources are available?
3. How does the answer to Question 1 change if we assume that wind varies according to Gaussian statistics, rather than what is observed in the empirical data.
4. Is the NERC reliability criterion an appropriate reliability constraint, given large amounts of wind- and solar-generation. Will reliability risks emerge as a result of higher wind penetrations, even if the NERC criterion is satisfied? What would a more optimal criterion look like?
5. How well do heuristic solutions to the regulation problem (such as using a linear function of the standard deviations of the wind and load variances, or the method described in Eqs. 9 and 10) perform?

2. Solution approach

The first step in the solution of this problem will be to develop functional probability density functions for wind and load deviations. There is substantial existing research from which we can build to complete this initial task (e.g., [1, 5]). The second step will be to study a variety of direct and heuristic methods for solving Eqs. 4-7, and report their relative merits in terms of satisfying Eq. 5 and minimizing cost. Costs will be estimated from recent market clearing prices for regulation in ISO New England, New York ISO and PJM. UVM researchers will work with CEIC researchers and Vermont electricity industry members (e.g., Dynapower) to develop cost-estimates and capability limits for high ramp-rate storage resources.

We propose to solve two versions of this problem. In the first we will assume that load and generation are random variables that derive from a Gaussian random walk (Wiener) process. In the second solution we will use a formulation that is based on the frequency-domain statistical characteristics of actual wind farms. We will investigate both analytical and simulation-based solution methodologies. Figure 1 Illustrates the difference between these two using empirical wind and simulated Gaussian data.

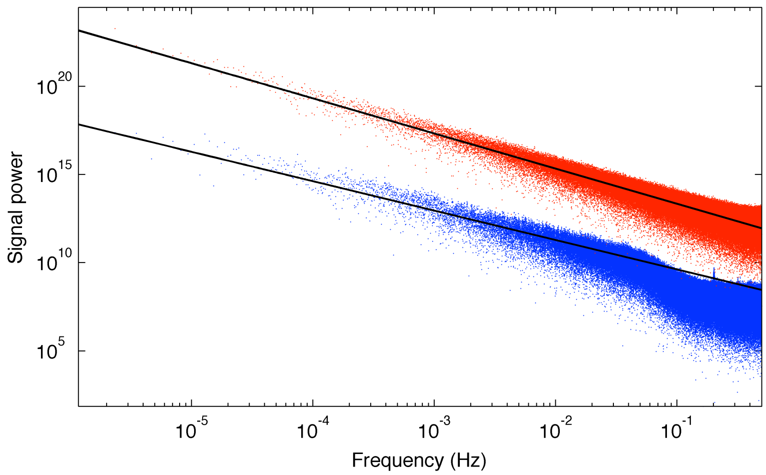

Figure 1: The power spectral density of the 6 turbine wind farm described in [1] and a random signal generated from a Wiener Process ($x_{t+\Delta t} = x_t + N(0,\Delta t)$) with the same signal variance (s^2) as the wind farm. As described in [1], the wind power spectral density follows $f^{5/3}$, where f is frequency. A least squares fit to the Wiener Process follows f^{2}, which is the theoretical power spectrum of a Wiener Process. Wind power output modeled as a Wiener process would underestimate the power of high-frequency motion.

As previously mentioned, all existing solutions to this problem are heuristic in nature, and are often based on very limited actual wind farm data, thus largely ignoring the statistical natures of wind and load deviations. In a recent wind integration study performed by Charles River Associates [11], the following solution is proposed:

$$R_{up} = \sqrt{(0.01L_{peak} + L_{10})^2 + a\Delta W_{95}^2} - L_{10} \quad (9)$$

$$R_{down} = \sqrt{(0.01L_{peak} + L_{10})^2 + a\Delta W_{5}^2} - L_{10} \quad (10)$$

where ΔW_{95} and ΔW_5 are the 95 and 5 percentile wind deviations for a given 10 minute time period, L_{peak} is the expected peak load for the time period, and a is a constant. This will be among the heuristic solutions that we investigate in this project.

3. Conclusions

Because regulating reserves (primary reserves) are typically the most expensive (in $/MW terms) of the standard balancing services, they will inevitably affect the cost of integrating renewable sources of electricity. If regulation is not well scheduled, they will adversely affect either the economics of renewable power, by over-scheduling regulation, or the reliability of the electricity infrastructure, by under-scheduling. This paper outlines the problem that needs to be solved in order to determine the interactions between variable renewable power resources, such as wind and solar, and regulation schedules.

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