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Unbiased economic dispatch in control areas with conventional and renewable generation sources

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ABSTRACT

This paper describes an economic dispatch formulation for a power system control area with high penetration of renewable generation and energy storage. We develop a comprehensive objective function that is unbiased to both the conventional and renewable generation sources. Operating constraints of conventional sources are considered, wind turbine generation is treated as a dispatchable source, and solar photovoltaic generation as negative load. A simulated annealing and particle swarm optimization algorithm are separately applied to minimize the objective function. The results obtained by the proposed economic dispatch formulation show that even a variable energy resource like wind can be dispatched in a manner that benefits the control area as a whole.

1. Introduction

Economic dispatch (ED) algorithms have been traditionally used to minimize generation cost while maintaining load demand in a power system control area. Contemporary power systems consist of a mix of conventional and renewable energy sources as well as large energy storage systems [1,2]. The renewable sources can generally be sub-divided on the basis of their geographic location and whether they are dispatchable. The non-homogenous nature of the generation sources presents a variety of challenges as well as opportunities to the independent system operators when scheduling generation to meet the load demand. This paper describes an intuitively simple strategy for ED that can effectively reduce the cost of meeting the load demand while enabling a more sustainable and equitable operation of the grid. The paper involves the development of a comprehensive cost function, constraints and solving the optimization algorithm using two heuristic methods.

2. Overview of opportunities and challenges

The value of non-dispatchable renewable energy sources like wind and solar can be increased by reducing the stochastic nature of their production [1]. Although the local weather conditions put a maximum limit on the energy that can be captured at a given time, modern renewable generation technologies allow a great degree of controllability over the active and reactive power generation from individual sources [3]. Additionally renewable generation sources entail a considerable initial investment and the operation of the grid has to facilitate a recoupment of the investment costs. Also the utilization of large scale energy storage in the system to make use of excess energy by optimizing its discharge and recharge cycles is a challenge. Another critical aspect is the operating and economic constraints associated with conventional dispatchable sources. For example the heat rates of coal and gas plants will show a drastic increase when they are forced to operate at low loads. Also incessant ramp ups/ramp downs and start ups/shut downs to match renewable energy production will cause excessive thermal stresses to plant equipment. Hence any meaningful ED algorithm in a modern power system will have to take into account the constraints and costs associated with both conventional and renewable sources.

3. Recent work in economic dispatch

There have been a number of contributions recently in the area of coordinating thermal-hydel generation sources with wind power. The problem of dispatching wind turbine generation with varying degree of active and reactive power controllability to comply with system operating demands as well as maximize the revenue for the wind farms has been described in [3]. However the mechanism by which the system operator arrives at limits

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for wind power is not mentioned and generation cost of conventional sources is not optimized. The cost of wind energy has been incorporated as part of the standard ED objective function in [4]. A penalty cost for intermittency of the wind is also determined by using a Weibull probability density function. However this approach while beneficial to the transmission system operators in minimizing reserve requirements does not take into account the economic impact on the wind farm when wind variability is high. The same approach has been used to solve an optimal power flow problem in [5,6]. In [7], the investment costs of wind and solar have been used to compute the total generation cost when used in conjunction with combined heat and power (CHP) plants operating based on ED. Forecasts of wind and solar power have been used but they are considered as a negative load and are not part of the ED cost function. Various strategies using power flow sensitivity factors (PFSF) to coordinate generation in systems having multiple distributed generation sources have been described and compared in [8]. In [8], a financial evaluation has been done using net present value analysis. While this approach is feasible for real time control, the dependence of the PFSF matrix on operating condition limits its use for long term scheduling. Wind and thermal scheduling taking into account the constraints of both and generation cost of thermal power has been described in [9]. Spinning reserve requirement for meeting shortfalls in wind is also considered. In [9], the wind generation acts like a negative load with constraints imposed by the wind power profile but the long term economic state of the wind farm is not considered. In [10], the concept of balancing the risk that is incurred in using wind power and minimizing the operating cost of the thermal generation was introduced with risk being modeled by a fuzzy membership function. A recent work that proposes a means to manage the operational uncertainties in a wind–thermal system is [11] where the optimal generation schedule for a wind farm is allowed to vary within an interval instead of being limited to a fixed value. The optimization problem in [11] considers the worst case scenarios for spinning reserve and transmission line flows, but the economic condition of the wind farm is not considered. In [12], the dispatch of hydel units in a hydel-thermal power system so as to minimize the water consumption has been proposed. The water consumption in [12] is modeled as a quadratic cost function, but the relationship between water consumption and the reservoir head is not considered. The cost functions in [3–8] quantify the generation costs of wind power in one way or another but do not take into account the systems reserve availability that can offset the risk of using wind power. The problems developed in [9–11], on the other hand, quantify the risk but do not consider the economic impact of curtailing the wind power. The present work by the authors aims to develop the concept of combining the economics and the risk of using wind power in the control areas with a high degree of wind penetration as well as optimizing the generation from conventional plants. To this end the LCOE and the available system reserve will be utilized. Moreover, in the case of conventional plants, the aim of the present work is to obtain a generation schedule that optimizes certain critical performance indicators like heat rate and specific water consumption instead of minimizing the gross generation costs. Additionally, the authors have explored a few reasons that discourage the dispatching of solar PV power and justify considering it as a negative load.

4. Generation cost functions and constraints

Fig. 1 is the simplified version of a modern power system control area with high degree of renewable penetration that was presented in [2]. The same is proposed to be used as the basis of this paper. The system considered has 20% wind generation and 10% distributed PV compared to the overall generation capacity. In the following sections of the paper, the cost functions and constraints associated with each component of Fig. 1 will be developed. In order to save space the list of symbols, units, and notations is tabulated in Appendix.

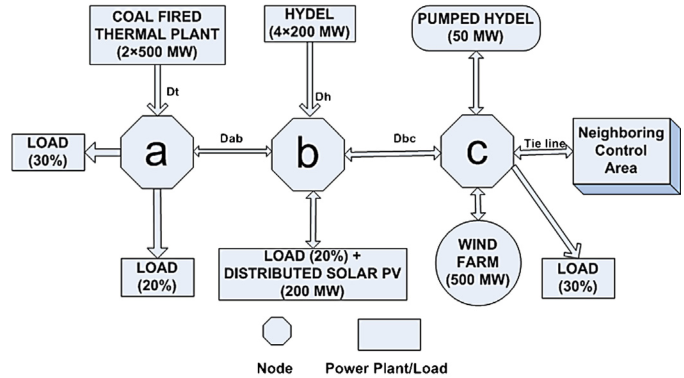

Fig. 1. Block diagram of control area.

4.1. Constraints for conventional generation

The conventional power plants in the problem have a common set of constraints for ramp rates (1) and operating levels (2). The subscript gen refers to either thermal or hydel generation while the superscript online refers to the maximum generation capacity available in a particular time block.

$$P_{\text{gen}}^{\text{min-ramp}} \leq |P_{\text{gen},i+1} - P_{\text{gen},i}| \leq P_{\text{gen}}^{\text{max-ramp}} \tag{1}$$

$$P_{\text{gen}}^{\text{min-gen}} \leq P_{\text{gen},i} \leq P_{\text{gen},i}^{\text{online}} \tag{2}$$

4.2. Conventional thermal generation

A power plant's heat rate is the amount of thermal energy used by an electrical generator or power plant to generate 1 kWh of electrical energy. An ED of the thermal power plant should enable it to operate below a specific maximum heat rate for economic and environmental reasons. The heat rate of a plant is directly proportional to its fuel cost as long as the coal calorific value and cost do not change. Traditionally a polynomial cost function has been found to be sufficient to estimate the fuel cost incurred when a specific amount of thermal power is scheduled [13] and the same is used in this paper. The equations for these are not included to conserve space and prevent redundancy. We estimate the performance of the thermal power plant for N time blocks by calculating the day average of the heat rate (kJ/kWh) using (3). Here $P_{\text{therm},i}$ is the day ahead power scheduled from the thermal plant in the ith time block. C_{therm} is the fuel cost incurred for N time blocks in dollars. Coal_{CV} and $\text{Coal}_{\text{cost}}$ are the calorific value of the coal (kJ/kg) and cost of the coal ($/kg) respectively.

$$\text{HR}_{\text{therm}} = \frac{C_{\text{therm}}\text{Coal}_{\text{CV}}}{\text{Coal}_{\text{cost}}\frac{24}{N}\sum_{i=1}^{N}P_{\text{therm},i}} \tag{3}$$

4.3. Conventional hydel generation

A conventional hydel power plant is unarguably one of the cheapest sources of power since the working fluid is water and it is available in a concentrated form. However water is gradually becoming a scarce resource and the water stored behind a hydroelectric dam cannot exclusively be used for power generation. Hence the authors propose to use a cost function that represents the cost of using water (or net outflow from the reservoir) in generating a scheduled amount of power as shown in (4) where a_h is a