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Flexibility and Regulation Capability of Hydropower Systems to Balance Large Amounts of Wind Power

Influence of Plant Properties and Hydrological Conditions

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Abstract—The vast expansion of wind power in Sweden has raised questions about the regulation capability of existing hydropower resources. In this paper, the flexibility and relative regulation contribution of two large regulated rivers subject to increasing wind power penetration and different hydrological conditions is analysed through model-based simulations. A 28-day scenario is simulated using detailed models of the two hydropower systems, normally used at Vattenfall for day-ahead production planning. Numeric measures are introduced to measure flexibility and regulation contribution and two properties that characterise a good regulation plant are identified. It is found that the flexibility of a plant is correlated to the discharge factor and that the relative regulation contribution is nearly proportional to the available regulating power. Further it is found that large inflow of water reduces the flexibility in plants or reaches with a small discharge factor.

Keywords-component; discharge factor, flexibility, hydropower, intermittent generation, regulation capability, regulation contribution, regulation factor, renewable power, short-term production planning, wind power integration

I. INTRODUCTION

The vast and rapid expansion of wind power in Sweden has raised concerns about the regulation capability of existing hydropower resources. Often the discussion concerns how much power that is needed in MW to balance a certain amount of wind power [1] [2] [3]. Both statistical and modelling approaches are used in previous studies.

In statistical analysis, historical data is used and scaled up to make predictions about a hypothetical scenario with a larger share of wind power [1] [4] [5]. Reference [4] uses a standard deviation approach to determine the volatility of wind power production as 20 % of installed capacity within 1 hour and 50 % within 4 hours. Reference [1] claims that the Swedish system can handle an expansion to 18,000 MW (~ 73% of 2013’s peak load [6]) installed wind power balanced by the available hydropower and gas turbines. Wind power data can be scaled linearly if the geographical smoothing effect is assumed to have levelled out. Scaling of historical hydropower production data however, may only be possible up to a certain level where physical and legal limitations in the river system restrict the regulation capability.

The modelling approach tries to capture the dynamics and limitations of a hydropower system. Reference [7] uses a stochastic optimisation of a simple hydropower system and concludes that hydropower can compensate for the variations in wind power production. References [8] [9] [10] all emphasise how hydropower can be used to firm up wind power production and the gain of a coordinated dispatch between hydropower and wind power.

This paper presents simulations of the operation of Lule River (LR) and Ume River (UR) subject to increasing penetration of wind power and different hydrological conditions using Vattenfall’s short-term hydropower planning tool. The two rivers are different in the sense that LR has an installed overcapacity in power while UR operates more like a run-on-river system. The study identifies plant properties that are vital for operational flexibility and the ability to provide regulating power. Furthermore, numeric measures to estimate flexibility and regulation capability from time-series data are suggested.

The paper is outlined as follows. In Section II, the developed method of simulation is presented. Section III defines important plant properties. Section IV presents the suggested measures of flexibility and regulating capability. In Section V and VI, a case study of two large Swedish rivers is presented. The conclusions are given in Section VII.

II. METHOD OF SIMULATION

The method is based on Vattenfall’s hydropower planning tool HOTSHOT, using a combination of linear programming and dynamical search to optimise a profit-based objective function. The tool includes detailed models of each reservoir and plant, including head dependency, individual start cost and efficiency curves for each unit in LR and UR. HOTSHOT is most likely the best simulation tool available for these two rivers; at least it is the model that determines how LR and UR are operated today.
The method uses a day-by-day simulation with a seven-day sliding spot-price forecast window, updating the wind power forecast for each iteration, see [11] for more details. Moreover, the suggested approach forces the hydropower producer to plan production upon an uncertain spot price and captures the risk of not having water in the optimal reservoir due to forecast errors in the wind power production.

III. PLANT PROPERTIES

To quantify the important parameters and prerequisites for producing regulating power, two numerical measures are introduced.

A. Discharge factor

A flexible operation pattern requires a large discharge capacity. The discharge factor is introduced as

$$F_D = \frac{Q_{\text{inst}}}{Q_{\text{ave}}}, \quad (1)$$

where $Q_{\text{ave}}$ is the maximum discharge and $Q_{\text{ave}}$ is the average yearly discharge. As such, it is the inverse of the common capacity factor, $c_f$, which measures the utilisation rate of the installed capacity. It can be realised that a discharge factor larger than one means that there is unutilised capacity which gives a certain degree of operation flexibility.

Since the installed discharge of a plant is adapted to the placement in the river reach, the discharge factor to some extent includes the relative size and discharge capacity of the upstream and downstream plants and reservoirs.

B. Available regulating power

In addition to flexibility, a plant’s ability to supply regulating power is of course also dependent on the power installed. The unused ratio of a plant’s capacity is

$$1 - c_f = 1 - \frac{1}{F_D}. \quad (2)$$

Multiplying with the installed power, $P_{\text{inst}}$, yields a number that represents the power available for regulation

$$P_A = P_{\text{inst}} \times \left(1 - \frac{1}{F_D}\right). \quad (3)$$

It can be worth noticing that $P_A = P_{\text{inst}} - P_{\text{ave}}$, i.e., the available regulating power is the difference between the installed and average power.

IV. MEASURES OF FLEXIBILITY AND REGULATION CAPABILITY

A flexible hydropower system has a high ability to alter the power production in time with respect to a varying input signal. Flexible plants that have a large power rating have a large regulation capability. Two numerical measures are introduced to estimate the flexibility and relative regulation contribution from time-series data.

A. Regulation factor

The regulation factor is defined as

$$F_{R,k} = \frac{\sum_{i=1}^{T} s[i] \cdot P_k[i]}{\sum_{i=1}^{T} s[i] \cdot P_{\text{ave}}[i]}, \quad (4)$$

where $T$ is the total number of hours, $P_k[i]$ is the power produced in plant $k$ and $s[i]$ is the spot price at hour $i$. $P_k$ can also be the aggregate production from a group of plants.

Historically the regulation factor has been used to determine the relative earning capacity of power plants because it reflects a plant’s ability to capture the high-price hours from a given spot price period. By seeing the spot price as the input signal which the hydropower system is operated to follow, the regulation factor is used here as a measure of flexibility.

B. Relative regulation contribution

The residual load, or net load, is defined as

$$P_{\text{Res}} = P_{\text{Load}} - P_{\text{Wind}} - P_{\text{Solar}}, \quad (5)$$

where $P_{\text{Load}}$ is the current consumption, $P_{\text{Wind}}$ is the wind power production and $P_{\text{Solar}}$ is the solar power production (not considered in this study). Consequently, it is also the need for power supplied by controllable power production such as hydropower and thermal power. Since thermal plants are used mainly to provide base power in Sweden, the regulated rivers are expected to balance the residual load variations. Hence, the relative regulation contribution from a plant (or a group of plants) $k$ can be estimated as the covariance between its power production $P_k$ and the residual load as follows

$$C_{R,k} = \frac{\text{cov}[P_{\text{Res}}, P_k]}{\text{var}[P_{\text{Res}}]} \cdot \frac{N_p}{\sum_{k=1}^{N_p} P_k} = P_{\text{Res}}, \quad (6)$$

where $N_p$ is the total number of controllable power plants. However, the maximum value for the covariance, corresponding to a complete regulation of the residual load, is by definition the variance of the residual load. Normalising by the residual load variance thus yields a number between minus one and one. A plant without regulation capability, e.g., run-on-river plants, would get a value close to zero.

V. CASE STUDY

The method of simulation is tested for a case study of two rivers in Sweden, LR and UR. LR has an installed power of 4.4 GW (14.6 TWh/year) while UR presents an installed power of 1.8 GW (7.6 TWh/year). The study includes all fifteen plants in LR and fourteen of a total eighteen plants in UR (85% of the installed power), all having full availability of units. LR is designed to regulate for the fluctuations in the load and accordingly equipped with an overcapacity in installed power whereas UR is designed to provide the system with energy.

The study uses historical Swedish wind power production data from November 2013 and the hydropower discharge is obtained from historical data for November between 2003 and 2013. The discharge is of three different sizes defined as wet, normal or dry, reflecting the conditions of different hydrological years.

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1 Hydrological year - Hydropower producers in Sweden define the start of the hydrological year as when the reservoirs are completely empty. The year is defined as wet, dry or normal based on the average annual discharge and is used for the long-term planning.
The simulations include a total of 28 days and are based on the following assumptions:

- The wind power production is linearly scaled for each scenario. The study takes a conservative approach to the smoothing effect and the wind power production will not curtail.
- The forecast error is implemented as a normal distributed stochastic variable added to historical production data in both time and magnitude.
- The penetration of wind power is increased by reducing the installed thermal power (nuclear power and combined heat & power) with the average wind power production.
- The wind power forecast is transferred into a spot price forecast using Vattenfall’s short-term spot price model.
- All effects originating from transmission congestions or geographical placement of the installed wind power are omitted.
- The simulations are performed respecting the long-term planning, i.e., the total amount of water used during the simulated period is restricted with respect to the historical data of November.

All results are and should be interpreted in the light of the given restrictions.

VI. RESULTS

In this section, the suggested measures of flexibility and regulation contribution obtained from simulated time-series data are plotted against the corresponding plant properties calculated from rated plant data.

A. Flexibility

As is shown in Fig. 1, the increase in the regulation factor is correlated to the discharge factor of each plant. A high discharge factor provides the flexibility to alter the production to maximise the profit, thereby producing power when the need for regulating power is high.

The plants in LR, which generally have a higher discharge factor than the plants in UR, generate higher values for the regulation factor displaying the superior flexibility of the river.

Fig. 2 illustrates how the regulation factor generally is higher for dry conditions in LR and UR. The small average discharge associated with dry conditions reduces the impact of reservoir limits and eases a more profit-optimising dispatch. This effect is more pronounced in the plants characterised by a low discharge factor, but since these plants are bottlenecks, dry conditions may enhance the flexibility of the whole river system.

B. Regulation capability

As shown in Fig. 3, the relative regulation contribution is correlated to the available regulating power. A plant presenting a high installed power provides a significant span of production while a high discharge factor ensures the free capacity in order to maximise the production of regulating power. It is evident that the plants in LR are able to provide the system with more regulating power than UR due to the superior installed power and discharge. The decrease in provided regulating power for a growing penetration of wind power originates from the increasing variance of the residual load.

Fig. 4 shows that the majority of the plants increase the relative regulation contribution during normal and dry conditions. The two plants with the highest available regulating power in LR exhibit enough flexibility to increase their relative regulation contribution also during wet conditions. The two plants with the highest available regulating power in UR suffer from the low flexibility of the plants located upstream.

A hydropower system can artificially alter the hydrological conditions as long as the revenue covers the increased cost. Increasing the spill in UR can mimic dry conditions hence improving the regulation capability of the river.
Figure 3. Relative regulation contribution versus available regulating power for an increasing penetration of wind power and normal hydrological conditions. The relative regulation contribution decreases for an increased penetration of wind power because the variance of the residual load increases more than the rivers are willing to regulate.

Figure 4. Relative regulation contribution versus available regulating power with 7,000 MW installed wind power for different types of hydrological conditions. The relative regulation contribution is generally lower during wet conditions except for the plants in LR with the highest available power.

VII. CONCLUSIONS

This paper presents a method to analyse and quantify the flexibility and regulation capability of a hydropower system. The method is used to correlate plant properties to measures of flexibility and regulating capability of two hydropower systems in Sweden subject to increasing wind power penetration and different hydrological conditions.

It is shown how the regulation factor of a plant is correlated to the discharge factor. A plant characterised by a high discharge factor will have a high flexibility of production due to free capacity. The relative regulation contribution primarily depends on the available regulating power, i.e., the installed power and the discharge factor.

In power plants characterised by a low discharge factor, the ability to produce regulating power may be reduced during wet conditions because the available regulating power is lower.

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