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Energy Procedia 87 (2016) 61 – 68

Energy Procedia

5th International Workshop on Hydro Scheduling in Competitive Electricity Markets

Smoothing of offshore wind power variations with Norwegian pumped hydro: case study

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Abstract

The solar and wind energy production in the European countries has been growing in the last years and the need of energy storage too. One of the most competitive technologies already available for large-scale balancing is pumped hydro storage with fixed operating point and one of the most promising improvements is the variable speed operation. The purpose of this research is to investigate the potential of utilizing three Norwegian revamped hydropower plants for smoothing of the offshore wind energy production in the North Sea. The investigation is carried out using two developed optimization algorithms with different time horizons and environmental constraints, managing up to seven years of wind energy production from the North Sea and seven years of reservoirs natural inflows and outflows.

Peer-review under responsibility of SINTEF Energi AS

Keywords: pumped hydro; offshore wind; power fluctuations; reservoir optimization.

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1. Introduction

Over the last years the electricity generation from variable renewable energy sources (VRES), i.e. renewable energy sources with fluctuating production according to the natural variation in weather variables, has increased significantly in Europe. According to EU energy policy targets, this trend will be even more prominent in the next 10-30 years. Integrating large amounts of VRES into the power system, as it is targeted for in order to achieve a low-carbon

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2015.12.358

economy in the long term, requires new measures to guarantee power grid stability and security of supply. In addition to increasing transmission grid capacities, improving resource forecast methods and introducing demand side management, establishing energy storage infrastructure is among the options that allow reducing imbalances between generation and load [1], [2], [3]. A large number of energy storage technologies with different characteristics with regard to storage capacity, power, efficiency and costs have been developed for various applications. Today, the only economically viable technology for storing electricity on large-scale is pumped storage hydropower [4]. The possibility to improve the high potential of this technology is to enlarge the flexibility of the fixed operating point with the variable speed operation also to enlarge the incomes from the markets [5]. In Northern Europe, the flexibility and storage potential of the Norwegian hydropower system can be used to balance VRES, e.g. wind power that is developed in the North Sea.

Norway has several hundreds of hydropower plants that are mainly fed by water from reservoirs. Their total storage capacity amounts to about 50 percent of the storage capacity of whole Europe [6]. The potential of using Norway's existing reservoirs for balancing VRES in Northern Europe by increasing installed capacities in existing hydropower plants and building new storage as well as pumped hydropower storage plants (PHSP) has been addressed in several studies [6], [7], [8]. CEDREN has studied how to upgrade 12 hydroelectric plants to pumped storage plants in South-Western Norway. The total new power generation capacity outlined is 18.2 GW. The study states that it is possible to achieve a total new power capacity of 20 GW by including some plants in Northern Norway as well.

The object of the paper is to investigate the smoothing of offshore wind power variations from the North Sea by utilizing three pumped storage plants in Southern Norway. For this purpose, two optimization models with two different time horizons are developed taking into account environmental issues like seasonal water levels fluctuations and the regulations for reservoirs limits and ramping.

2. Cases studies

To analyse the power smoothing capability of Norwegian hydro power, three specific reservoir pairs in South-Western Norway are selected. The scenarios for upgraded pumped storage plants considered are Holen, Rjukan and Tonstad with rated powers of 1000, 2000 and 1400 MW. Table 1 summarizes the main reservoir characteristics divided by PHSP. Holen has reservoirs with comparable volumes and large altitude differences between the high regulated water level (HRWL) and the low regulated water level (LRWL). Rjukan and Tonstad have relatively similar upper and lower reservoirs. For these two power plants, the lower reservoirs volumes are roughly 20% the size of the upper reservoirs volumes. Both lower reservoirs have small differences between the regulated levels. It is noteworthy that Møsvatn is relatively shallow compared to Nesjøen.

Table 1.Reservoirs characteristics divided by plant [8].

PHSP	Reservoir	HRWL (m_{asl})	LRWL (m_{asl})	HRWL – LRWL (m)	Volume (Mm^3)	Area at HRWL (km^2)
Holen	Uravatn	1175	1141	34	253	13.15
	Bossvatn	551	495	56	296	7.7
Rjukan	Møsvatn	919	900	19	1064	78.43
	Tinnsjø	191	187	4	204	51.38
Tonstad	Nesjøen	715	677	38	275	15.36
	Sirdalsvatn	51	47.5	3.5	56	19.47

The offshore wind power series are based on previous analyses that estimate 94.6 GW of offshore installed capacity in the North Sea in 2030 [9]. Time series for daily and hourly wind power generation are established by applying global weather model, regional wind power curves and wind speed adjustments as done in the EU-project TradeWind [10]. The wind power series are from the years 2000 to 2006 and the resulting estimated average capacity factor is 0.41.

The overall balancing request outlined is called 7Days-Avg, it is based on seven years wind power series [10] and calculated considering the seven days moving average [8]. 7Days-Avg is calculated day by day as the difference of the daily wind power production and the seven days moving average. For a generic day its seven days moving average is the mean wind power production calculated considering three days before, three days after and the generic day. 7Days-Avg outlined by the described procedure is 664390 GWh and Figure 1 shows the daily time-series and the corresponding moving average.

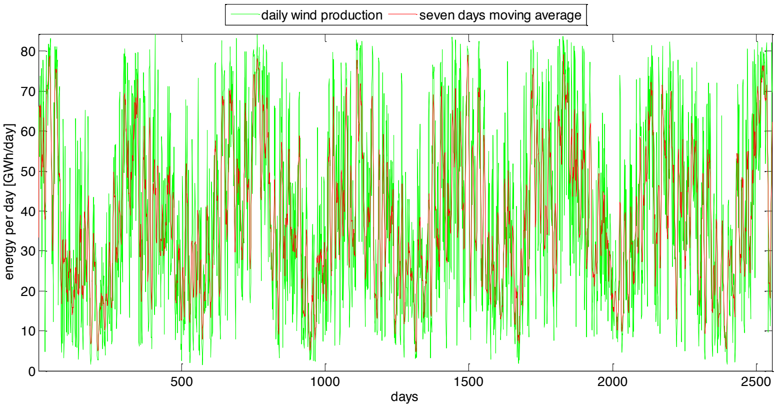

Figure 1. Daily wind production and the seven days moving average.

The balancing request E_{br} addressed to each PHSP is calculated in proportion to the ratio between each investigated power plant capacity and the Norwegian hydropower installations outlined in the so called scenario 3 in the previous literature [7] furthermore, each investigated PHSP manages the addressed balancing request shaving the peaks higher than the machineries rated power. Following this approach, the balancing request E_{br} managed by each investigated PHSP is between the 8.5% and 10% of 7Days-Avg.

To take into account environmental constraints on the reservoir operation and long-term operation strategy, the natural inflows and outflows of the reservoirs are considered. These values are obtained from recorded reservoirs levels from the years 2000 to 2006.

3. Methodology

The investigation methodology applied for the analysis is based on two optimization models, with two different time horizons, developed by the authors. The models can manage several years of data series of inflow and outflow, historical reservoir level and balancing request. All the models are based on a stochastic optimization technique developed by the authors. The two models are applied to three cases studies described before and analyses on power smoothing capability are carried out using the most detailed model.

3.1. Optimization technique

The developed models are based on differential evolution (DE) optimization technique, a population-based stochastic method introduced by Storn and Price [11]. The choice of the stochastic method comes from the capability to approach a global optimum in case of high number of optimization variables avoiding linearization of the managed functions.

3.2. Models

The two models developed for the investigations are:

- the yearly optimization model (M-Year)
- the daily optimization model (M-Day)

The optimization models are constrained by technical and environmental limitations, and the applied constraints have the same structure for all the models.

The technical constraints are applied to the plants and to the machineries characteristics. For every single plant, the minimum loads for the hydraulics machineries are defined in accordance with the actual technologies. For a given pressure head, the machinery power can be varied changing the water flow rate in accordance to the machinery characteristics. A variation of ±10% of the speed can cause a variation of ±30% of the machinery power, adjustable speed operation can also achieve an efficiency improvement at partial load and pumped storage technology can reach high performances, obtaining a total efficiency of about 80% [12]. Under these statements, variable speed operation of the machineries have been considered in all the operating regimes with maximum efficiency of 80%.

In the models, for each reservoir, the water balance equation has been considered and the value of the gross head takes into account the water level in the reservoir that is calculated considering the specific reservoir correlation between water level and water volume. The lost head is calculated as a function of the machinery flow rate. The generated power from the turbine P_t and the absorbed power from the pump P_p can be written using the following relations:

$$P_t = \rho \cdot Q \cdot g \cdot (H - H_{lost}) \cdot \eta_t \tag{1}$$

$$P_p = \rho \cdot Q \cdot g \cdot (H + H_{lost}) / \eta_p \tag{2}$$

where ρ is the density of the water, Q is the flow rate, g is the acceleration due to the gravity, H is the gross head, H_{lost} is the lost head and η_t is the efficiency in the turbine operation and η_p is the efficiency in the pump operation.

The environmental constraints taken into account are the upper and lower water regulated levels of the reservoirs and these constraints are considered fixed for all the cases analysed following the reservoirs' specifications. The regulated levels are the actual levels set by the Norwegian authority for Water Resources and Energy Directorate. In general the regulated levels are not the physical maximum levels of the reservoirs but just the regulated and allowable ones. Other environmental constraints based on the historical levels of the reservoirs are applied with the purpose to force the system to operate close to the historical levels of the reservoirs considering them as trajectory working curves. The considered allowable working bands (WB) around the historical reservoir levels are ±0.5m, ±1.5m and ±3.0m. These additional constraints must be fulfilled together with the constraints on the water regulated levels and in some days of the year the two constraints are redundant due to the historical levels of the reservoirs that are too close to the regulated levels. The working bands around the historical levels are set in order to analyse how different operating regimes influence the balancing capability of the power plants.

3.2.1. The M-Year model

The first developed model is the yearly optimization model M-Year. Its purpose is optimize each PHSP operation using a perfect forecast approach. In this model, the wind production and the natural inflow and outflow of the reservoirs are considered as well known for all the seven years of analysis. The model optimizes the management of one PHSP for one year in one single optimization step and the optimization detail is the daily management of the plant. The number of optimization variables becomes large and the computational time is quite long if accurate outcomes are required. Since the model uses perfect forecast, the outcomes in terms of constraint and object fulfilment must be considered as an upper estimate.

3.2.2. The M-Day model

Compared to real life, the perfect forecast approach adopted by M-Year is quite optimistic because it is hard to predict the wind production and the natural inflow and outflow of the reservoirs with one-year forecast. The purpose of the daily optimization model M-Day is to determine the optimal management of the PHSP optimizing just one day per time for the seven years of data series. In this model, a daily time resolution as applied, and the information about the wind production and natural flows of the reservoirs are provided to the model gradually. The number of optimization variables managed in each optimization step is lower than in the previous model. In addition, the computational effort is lower than in the M-Year model and accurate outcomes are also expected in terms of constraint and object fulfilment.

3.3. Objective function

The objective function to be minimized is the sum of the unbalanced energy and the penalty function, following the relation:

$$\mathrm{F}(x) = E_{ue} + \sum_i \lambda_i \cdot \phi_i(x)^2 \tag{3}$$

where E_{ue} is the unbalanced energy, λ_i is the penalty multiplier referred to the constraint i, $\phi_i(x)$ is the violated amount for the constraint i. E_{ue} is defined as the algebraic sum of the balancing request E_{br} and the PHSP energy production E_{hp} following the relation:

$$E_{ue} = E_{br} + E_{hp} \tag{4}$$

Positive values of E_{hp} corresponds to turbine operation, while negative values of E_{hp} corresponds to pump operation. The degrees of freedom of the models allow three different hydropower operation strategies selected by the optimization algorithms. The hydropower plant can provide exactly the balancing request E_{br}; otherwise, it can provide less or more energy than the required amount. Under these statements is possible to explore the composition of E_{ue} that is caused by E_{uel}, the lack of production of the PHSP, or by E_{uee}, the excess on production of the PHSP, following the relation:

$$E_{ue} = E_{uel} + E_{uee} \tag{5}$$

The values of the previous equations are managed as absolute values. For the previous equations, the balanced energy E_{be} can be calculated as the difference between the balancing request and the overall unbalanced energy:

$$E_{be} = E_{br} - E_{ue} \tag{6}$$

The overall penalty function can be rewritten in a general way following the relation:

$$\sum_i \lambda_i \cdot \phi_i(x)^2 = \sum_i \lambda_i \cdot [\max(0, \mathrm{c}_i(\mathrm{x}) - \mathrm{u}_i)]^2 \tag{7}$$

to highlight the dependency of penalties from the current values $\mathrm{c}_i(\mathrm{x})$ and from the target values u_i.

The reservoirs constraints are implemented using the penalties functions where the values of λ_i determines the relative weighting between the objectives; minimizing unbalanced wind energy versus minimizing deviations from target reservoir level.

4. Results

As preliminary analysis, the outcomes form the yearly model and the outcomes form the daily model are compared. Furthermore, detailed analysis are carried out from the M-Day's outcomes.

4.1. M-Year and M-Day outcomes comparison

As expected, the perfect forecast considered in M-Year provides slightly better outcomes than those provided by M-Day. As an example, we have analyzed the optimal management strategy outlined by the two models for Rjukan hydro power plant considering the operative range of ±1.5m around the historical levels (target levels). From Table 2 it is observed that the balanced energy in the yearly model with perfect forecast is 3% higher than in the daily model. This is caused by the slight different variation of management of power plant and reservoirs. In Figure 2, the water level in the Møsvatn reservoir is plotted for the two different management strategies. The red lines are the allowed operating bands and the regulated water levels while the blue lines are the reservoir levels obtained by the two different models. The operative levels of the reservoirs are always in the allowed bands but the different management strategies selected by the models provide two different yearly levels for the reservoirs and two different performances for the plant. M-Year and M-Day have been performed for every PHSP varying the trajectory working bands and providing comparable outcomes than the discussed one.

Table 2.Outcomes of the first year of analysis by M-Year and M-Day for Rjukan with ±1.5m as working band.

Rjukan	E_{br}	E_{be}		E_{ue}	
	(GWh)	*(GWh)*	*(%)*	*(GWh)*	*(%)*
M-Year	9381	6504	69	2878	31
M-Day	9381	6223	66	3158	34

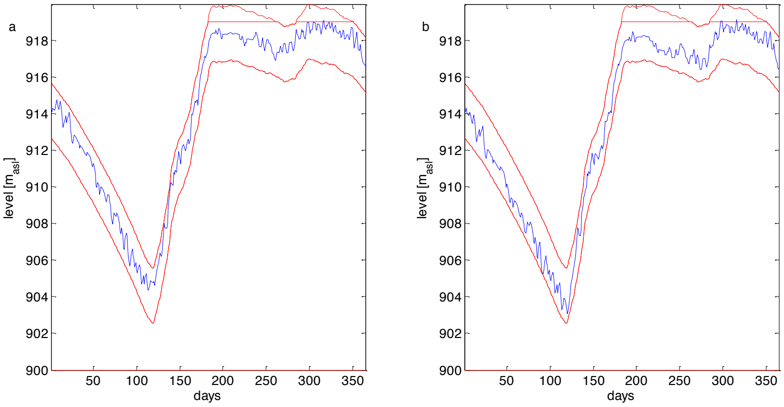

Figure 2. First year of management for Møsvatn reservoir outlined by M-Year (a) and by M-Day (b).

4.2. M-Day outcomes

As mentioned earlier, to get closer to realistic PHSP scheduled management, the M-Day model has been developed. The main outcomes of the simulations are summarized in Table 3. For Holen and Tonstad power plants, it is clear to see how the WB enhancement can affect the balancing capability and the E_{be} improvement. A noteworthy case is Rjukan power plant because the change of the operative range from ±1.5m to ±3.0m does not provide any improvement to the balanced energy. This is caused by the interaction between the historical reservoirs levels and the small differences between the HRWL and the LRWL for the reservoir pair that do not allow getting additional reservoirs exploitation.

Table 3.Collection of outcomes from M-Day with different allowed bands on the historical levels of the reservoirs.

PHSP	WB	E_{br}	E_{be}		E_{ue}		E_{uel}		E_{uee}	
	(m)	*(GWh)*	*(GWh)*	*(%)*	*(GWh)*	*(%)*	*(GWh)*	*(%)*	*(GWh)*	*(%)*
Holen	±0.5	58359	0	0	58359	100	58359	100	0	0
Holen	±1.5	58359	18052	31	40306	69	39310	98	997	2
Holen	±3.0	58359	34282	59	24076	41	22495	93	1581	7
Rjukan	±0.5	65999	39314	60	26685	40	20967	79	5718	21
Rjukan	±1.5	65999	45245	69	20753	31	14384	69	6370	31
Rjukan	±3.0	65999	45210	69	20789	31	14277	69	6512	31
Tonstad	±0.5	56866	2422	4	54443	96	54307	100	136	0
Tonstad	±1.5	56866	31985	56	24881	44	23386	94	1495	6
Tonstad	±3.0	56866	39599	70	17266	30	15338	89	1928	11

The overall balancing effect due to the combined plants operation reaches the maximum value for a WB equal to ±3.0m. The reached overall E_{be} is 66% of the overall E_{br}. The reduction of the WB to ±0.5m causes a reduction of the overall balancing performance to 23% of the overall E_{br}. The strategies outlined by M-Day are characterized by similar management strategy because E_{ue} is mainly due to a lack of production then by an excess of production.

For a detailed analysis, Tonstad hydropower plant with ±3.0m as operative working bands has been selected but similar considerations can be obtained for the other cases. Figure 3 shows the levels reached by the lower and upper reservoirs. The M-Day can perform an operating strategy that allows to work close to the bounds of the reservoirs plotted as red lines. The operative characteristics of the machineries are plotted in the Figure 4. The normal probability density function calculated for the daily flow rate variation and for the daily energy production stand that high values of change are required between two next days. The cumulative curves for the machineries can show how the balance is reached and it is possible to note similar shapes for the characteristics and limited working time. The operation outcomes are just a result due to the constraints on the historical levels and to the shape of the balancing request.

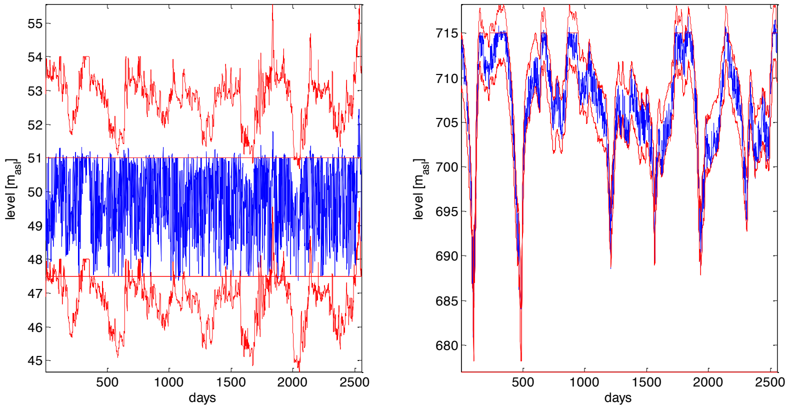

Figure 3.Water levels reached by Sirdaslsvatn reservoir (a) and by Nesjen reservoir (b).

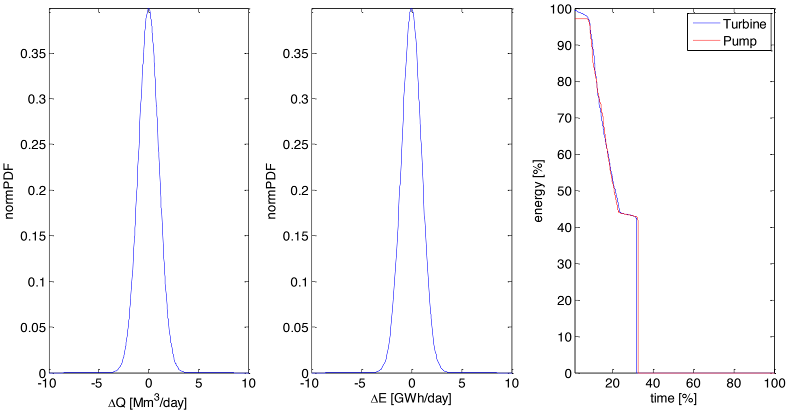

Figure 4. Normal probability density function for the daily flow rate variation (a), and for the daily energy variation (b). Cumulative curves for the machineries operations (c).

Other characteristics of the balancing capability can be seen from Figure 5, where balancing request and actual operation are plotted. From the graphs is possible to determine the minimum and the maximum power managed by the machineries. For every balanced requests from the North Sea, it is possible to analyse the selected strategy by the hydropower plant. Considering the Figure 5a, the yellows dots stand for perfect matching between the balancing request and plant operation while the blue dots stand for lack of managed energy by the hydropower plant and the reds dots stand for an excess of managed energy by the hydropower. In the Figure 5b, are plotted the same operating point from the reservoirs point of view. The yellows dots are operating points that fulfil the reservoirs bounds while the blues and reds dots outlined operating points that stress the lower reservoir (LR) or the upper reservoir (UR) operation. From the combined analysis of these two figure is possible to see that the yellow dots in Figure 5a are always coupled with yellow dots in Figure 5b. It means that the perfect matching between the balancing request and plant operation is always coupled with reservoirs operation in the allowable limits. The reds dots in Figure 5a are coupled with yellow dots in Figure 5b. These conditions mean that the critical component is the hydro machinery and not the reservoirs because the operating strategy forces the machinery to operate at low load causing an excess of production compare with the balancing request. The blue dots in Figure 5a associated with the machineries operations are mainly coupled with red and blue dots in the Figure 5b. It means that the limiting causes of these operations are the reservoirs that often reach the operating limits that prevent the full machinery operation.

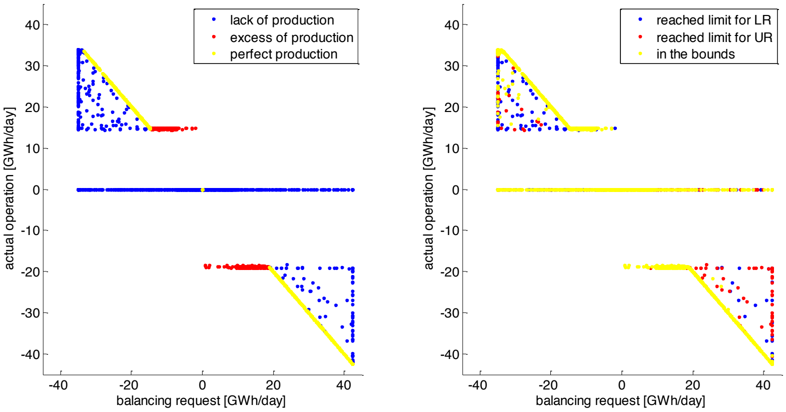

Figure 5. Balancing request versus actual operation highlighting unbalanced energy (a) and the reservoirs limitation (b).

5. Conclusions

This paper investigates how Norwegian pumped hydro can smooth out the North Sea offshore wind power production variations. Two optimization models with different time-horizons are developed for this purpose, and they have been applied on three realistic case studies. Every pumped hydro plant considered as case study was outlined on previous research works and the balanced power charged per every plant is just a percentage of the total forecasted balanced request from the North Sea. The models can manage up to seven years of balancing request from the North Sea and the natural inflows and outflows of the reservoirs. Historical levels of the reservoirs are considered as trajectory working curves taking into account three different working bands. The investigation showed a balancing potential close to 70% of the analysed wind power balancing request. The relative weights of constraints in the objective penalty function influences this number, and is a subject for further research.

Further studies will investigate the outcomes of an hourly optimization model and the effects of the return of investment of these refurbished plants in the Norwegian scenario. Further developments will also comprise evaluation of the electricity market value of the balancing capability, and improvements of the handling of environmental constraints.

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