CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis
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ISBN 978-88-95608-26-6; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1335014

Optimisation of Pumped-Hydro Storage System for Hybrid Power System Using Power Pinch Analysis

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Storage technology in Hybrid Power System (HPS) is urgently required to adapt with the mismatch between the renewable energy (RE) production and the time distribution of load demands. Different storage systems incur different types and amount of losses depending on the power conditioning as well as storage system efficiencies. This work focuses on the design of HPS with pumped hydro storage systems using Power Pinch Analysis (PoPA). The previously developed modified Storage Cascade Table (SCT) for HPS with battery storage is adapted to calculate losses associated with the pumped hydro storage system. The demonstration of the method on an Illustrative Case Study shows that the application of pumped hydro storage in HPS yield lower total losses in the system. The maximum power demand target is reduced while the targeted maximum storage capacity is increased compared to when battery storage is applied.

1. Introduction

Storage technology has become a major issue with the increase penetration of renewable energy (RE) sources into power networks. It is seen as a key element for energy systems located in remote area which are not connected to the electricity grid. This is because, uncertainty exist due to the stochastic nature of RE to satisfy the demand at any instant. This uncertainty can be reduced by installing energy storage system. Storage system application does not only ensure real-time load levelling, but it is also a mean of better utilising RE by avoiding load shedding in times of overproduction (Ibrahim et al., 2008).

Pumped hydro storage system is currently the most practical storage on a large scale (Krajačić et al., 2013). It stores energy in the form of water, which is pumped from a lower to an upper reservoir (Bayón et al., 2013). In periods of low demand, excess electricity production is used to pump water to a deposit (upper reservoir) situated at a certain height. The water is recovered and released back into the lower reservoir at a later time through a turbine when it is required to cover peak load periods (Bueno and Carta, 2006).

Size optimisation of a pumped storage power plant for the recovery of wind-farms rejected energy was presented by Anagnostopoulos and Papantonis (2008). The authors determine the well optimised design using a combined evaluation algorithm that simulates the plant operation, with an automated optimisation software based on evolutionary algorithms. Vieira and Ramos (2009) proposed an optimisation tool using linear and non-linear programming approach. The best hourly operation according to the electricity tariff is obtained for a pump storage system supplied by wind energy. Hessami and Bowly (2011) developed a computer model to simulate the operation of several energy storage systems including the pumped hydro storage systems. The results show that pumped hydro storage application is very economical when there exists a natural system of rivers in a mountainous topography. Recently, Bayón et al. (2013) presented a

Please cite this article as: Mohammad Rozali N.E., Wan Alwi S.R., Manan Z.A., Klemes J.J., Hassan M.Y., 2013, Optimisation of pumped-hydro storage system for hybrid power system using power pinch analysis, Chemical Engineering Transactions, 35, 85-90 DOI:10.3303/CET1335014

numerical tool to design an optimal configuration of a wind farm combined with a pumped hydro storage plant. Mathematical modelling of the problem is first developed before Optimal Control techniques are applied to analyse the best preferable configuration in each specific real situation of the electricity market.

Power Pinch Analysis (PoPA) method for design of HPS with pumped hydro storage has not yet presented. The previous PoPA methods are specifically developed for HPS with battery storage without consideration of power losses (Wan Alwi et al., 2012). Mohammad Rozali et al. (2012) later extended the PoPA approach to include energy losses in the analysis. The losses that have been taken into account are those, which occur during power system's conversion (inverter and rectifier efficiencies), transfer (lead-acid battery charging and discharging) and storage (battery's self-discharge rate). This work therefore aims to design a HPS with pumped hydro storage systems using PoPA technique. This is because, this storage technology is seen as an innovative alternative to battery storage (Manolakos et al., 2004). In addition, the generating equipment is highly reliable and the power output can be extensively regulated maintaining a practically constant efficiency within the generated power range (Bueno and Carta, 2006).

The losses occur in HPS with pumped hydro storage is significantly different from those which involve in battery storage systems. First, the charging process in pumped hydro storage is affected by the pump efficiency that pumps the water into the upper reservoir at times of low electrical demand. The losses during discharging process on the other hand are caused by the turbine operation to generate electricity at peak load periods. The total charging and discharging rate is given by calculating the product of the efficiencies of pipe (friction losses) and the mechanical equipments (Wilde, 2011). Analogous to the self-discharge rate as in battery, evaporation losses occurs during storage period in pumped hydro storage. Table 1 summarises the comparison between the characteristics of batteries and pumped hydro storage.

Table 1: Characteristics of batteries and pumped hydro storage (Komor and Glassmire, 2012)

	Batteries	Pumped hydro
Storage forms	Electrochemical	Potential energy
Roundtrip efficiency, %	70 – 95	75 – 85
Self-discharge rate	Battery self-discharge rate (0.004%)	Evaporation losses
Charging rate	Battery charging efficiency (90%)	Pump and pipe efficiencies (90 %)
Discharging rate	Battery discharging efficiency (90%)	Turbine and pipe efficiencies (90 %)
Storage capacity, MW	≤ 10	≥ 200
Lifetime, y	3 – 15	25+
Capital cost, $/kW	150 – 1,500	100 – 4,000

2. Methodology

The modified Storage Cascade Table presented by Mohammad Rozali et al. (2012) is applied to investigate the energy losses effects in a HPS with pumped hydro storage system. The charging efficiency is the product of the pump and pipe efficiencies, while the product of turbine and pipe efficiencies are the discharging efficiency. Both efficiencies (charging and discharging) are assumed as 90 % (Wilde, 2011). The hourly evaporation losses is assumed to be negligible because the amount of water evaporated is far too small compared to the total water volume in the reservoir (Schoppe, 2010). Besides, conversion losses when converting between AC and DC electricity are also included in the calculation and are assumed as 95 % (Burger and Ruther, 2005).

A reversible AC pump-turbine unit is used in the system, i.e. using single reversible machine as both a pump and a turbine (Liang and Harley, 2010). Therefore, any excess in DC electricity is converted to AC before it can be pumped to the upper reservoir. In addition, the discharged electricity from the storage has to be converted from AC to DC before it can be supplied to the DC demand. The total volume of water in the upper reservoir represented the energy storage capacity at a given time in kWh. The designed technique is performed in two key steps i.e. (1) Specify the limiting power data, and (2) Determine the optimal power allocation and minimum electricity targets.

Step 1: Specify the limiting power data

The limiting power data consists of the minimum available power sources and maximum load demand for every time intervals (Mohammad Rozali et al., 2012). The limiting power sources and demands data as represented in Tables 2 and 3 are derived from Mohammad Rozali et al. (2012) to demonstrate the methodology.

Table 2: Limiting power sources for Illustrative Case Study 1

Power sources		Time, h		Time interval, h	Power generated, kW	Electricity generation, kWh
AC	DC	From	To			
Wind		2	10	8	50	400
Biomass		0	24	24	70	1,680
	Solar	8	18	10	60	600

Table 3: Limiting power demands for Illustrative Case Study 1

Power demand appliances		Time, h		Time interval, h	Power demands, kW	Electricity consumption, kWh
AC	DC	From	To			
	Appliance 1	0	24	24	30	720
Appliance 2		8	18	10	50	500
	Appliance 3	0	24	24	20	480
Appliance 4		8	18	10	50	500
Appliance 5		8	20	12	40	480

Step 2: Determine the optimal power allocation and minimum electricity targets

This is done by constructing the modified SCT (Tables 4a and 4b) for HPS operating with pumped hydro storage. Table 4a is constructed using the procedure described by Mohammad Rozali et al. (2012). Its step-wise construction is:

1) Column 1 lists the time for power sources and demands in ascending order, while the duration between two adjacent time intervals is listed in Columns 2.
2) Using the PCT technique, total sum of ratings for power sources and demands for each time interval are determined and are given in Columns 3 and 4.
3) Columns 5 and 6 listed the quantities of electricity sources and demands between time intervals which calculated with Eq (1).

$$\sum \textit{Electricity Source/ Demand} = \sum \textit{Power Rating} \times \textit{Time interval duration} \qquad (1)$$

4) The demands are satisfied by the sources accordingly for AC and DC. Any surpluses and deficits between time intervals are calculated separately for AC and DC using Eq (2) and listed in Column 7.

$$\textit{Electricity surplus/ deficit} = \sum \textit{Electricity Source} - \sum \textit{Electricity Demand} \qquad (2)$$

A positive value represents electricity surplus while negative value indicates electricity deficit.

Table 4a: Modified Storage Cascade Table for Illustrative Case Study 1

1	2	3		4		5		6		7	
Time, h	Time interval h	∑ Power source rating kW		∑ Power demand rating kW		∑ Electricity source kWh		∑ Electricity demand, kWh		Electricity surplus/ deficit, kWh	
		AC	DC	AC	DC	AC	DC	AC	DC	AC	DC
0											
	2	70	0	0	50	140	0	0	100	140	-100
2											
	6	120	0	0	50	720	0	0	300	720	-300
8											
	2	120	60	140	50	240	120	280	100	-40	20
10											
	8	70	60	140	50	560	480	1,120	400	-560	80
18											
	2	70	0	40	50	140	0	80	100	60	-100
20											
	4	70	0	0	50	280	0	0	200	280	-200
24											

The difference between the power allocation and electricity targets when using battery and pumped hydro storage can be visualised by constructing Table 4b. Different occurrences when converting between AC and DC electricity as well as different efficiencies of these two storage technologies yield different results and are described next (see Table 4b):

1) Eq (3) is used to calculate the amount of converted DC electricity surplus and listed in Column 8. For AC surplus, similar equation as Eq (3) can be used if the amount of surplus is less than the DC deficit. However, if the AC surplus is higher, only the exact amount of the required DC load is converted from the available AC surplus. Eq (4) is therefore derived to calculate the amount of AC surplus to be converted to DC if this event occurs. This is because converting all AC surpluses to DC would lead to higher losses as the DC electricity has to be converted back to AC before it can be pumped to the upper reservoir. This energy management is done by a controller to ensure an optimal operation of the system (Manolakos et al., 2004).

$$\text{Amount of converted DC electricity to AC} = \text{DC electricity surplus} \times \text{Inverter efficiency} \quad (3)$$

$$\text{Amount of AC electricity surplus to be converted to DC} = \frac{\text{Amount of DC deficit}}{\text{Rectifier efficiency}} \quad (4)$$

2) The amount of AC electricity available for storage after load utilisation is obtained via Eq (5) and listed in Column 9. The positive value indicates the charging quantity while the negative value represents the discharging quantity.

$$\text{Charging/Discharging quantity (AC)} = DC_{converted} + AC_{s/d} - AC_{converted} \quad (5)$$

Where
$DC_{converted}$ = amount of AC converted from DC surplus; $AC_{s/d}$ = AC surplus/deficit; $AC_{converted}$ = amount of DC converted from AC surplus.

3) Step 2 only provides the discharging quantity for AC deficit. Eq (6) is therefore derived to calculate the discharge quantity for DC deficit and listed in Column 10.

$$\text{Discharging quantity for DC deficit} = \frac{\text{Converted AC surplus + DC deficit}}{\text{Inverter efficiency}} \quad (6)$$

If the storage capacity is less than the AC discharge requirement to meet the deficit, the storage is discharged to the depth of discharge (DoD) of hydro storage. The DoD is assumed as 80% of the maximum storage capacity (Notton et al., 2011). In this scenario, Eq (7) is required to calculate the amount of the available AC electricity from storage to supply the deficit in demand. For example, between time 10 and 18 h, 484 kWh (560 – 76 = 484 kWh) of AC deficit is still not satisfied, which is higher than the amount of storage (371.72 kWh). Taking into account the discharging efficiency, the amount of electricity that can be supplied for AC deficit by the storage is obtained with Eq (7) to give 334.55 kWh. If the deficit is DC instead of AC, the conversion efficiency term is included in Eq (7).

$$\text{AC electricity available from storage [kWh]} = S_{t-1} \times \eta_d \quad (7)$$

Where
S_{t-1} = storage capacity at previous time interval [kWh]; t = time [h]; η_d = discharging efficiency (0.9).

4) The cumulative storage capacity is listed in Column 11. Eq (8) is used in the calculation which is based on the charging and discharging amount in Columns 9 and 10.

$$S_t = S_{t-1} + (C_t \times \eta_c) + D_t / \eta_d \quad (8)$$

Where
S_t= storage capacity [kWh]; C_t = charging quantity [kWh]; D_t = discharging quantity [kWh; t = time [h]; η_c = charging efficiency; η_d = discharging efficiency

Eq(8) has to be carefully applied because positive value in Column 9 represents the C_t while negative value indicates the D_t. The electricity cascade for the following time interval resumes at zero if the hydro storage has been discharged to its DoD (e.g. between time 10 and 18 h).

5) The largest value in Column 9 is divided by the DoD to obtain the actual maximum storage capacity via Eq (9).

$$S_{(t)actual} = S_{(t)} / DoD \tag{9}$$

6) If the amount of storage is still insufficient to satisfy the demand, the alternative solution is by importing electricity from the grid. The required amount of outsourced electricity is the remaining electricity demand which has not yet satisfied by the storage discharged quantity and listed in Column 12. The kW instantaneous external power demand is calculated with Eq (10).

$$\text{Outsourced power rating} = \frac{\text{Outsourced electricity}}{\text{Time interval}} \tag{10}$$

For this Illustrative Case Study 1, 18.68 kW of electricity need to be outsourced to supply the AC demand between time 10 and 18 h. Between time 18 and 20 h, 22.63 kW of external electricity is required to be sent to DC demand. Note that the 22.63 kWh is obtained after the conversion (DC-AC) losses of 5% are taking into account because the grid provides electricity in AC.

7) The excess power stored in the storage at t = 24 h during startup is brought to the following day (normal 24 h) operation and set as the storage capacity at t=0 h (62.53 kWh). The cumulative storage capacity for the 24 h operation is then calculated via Eq (8) and listed in Column 13. The actual maximum storage capacity of 571.98 kWh is obtained by Eq (9) using the amount of the largest value in Column 13 (457.58 kWh).

8) Column 14 lists the amount of outsourced electricity required for each AC and DC demand during 24 h operation. Between time 10 and 18 h, 11.65 kW of AC demand occurs, while 22.63 kW of electricity is required to be outsourced for DC demand between time 18 and 20 h.

Table 4b: Modified Storage Cascade Table for Illustrative Case Study 1

8		9	10	11	12		13	14	
Converted surplus, kWh		Charging/ Discharging quantity (AC), kWh	Discharge for DC deficit, kWh	Start up			Operation		
				Storage capacity, kWh	Outsourced electricity, kWh		Storage capacity, kWh	Outsourced electricity, kWh	
AC	DC				AC	DC		AC	DC
				0			62.53		
105.26	0	34.74	0	31.26	0	0	93.79	0	0
315.79	0	404.21	0	395.05	0	0	457.58	0	0
0	0	-21	0	371.72	0	0	434.25	0	0
0	0	-334.57	0	0	149.45	0	0	93.18	0
57	0	0	0	0	0	43	0	0	43
210.53	0	69.47	0	62.53	0	0	62.53	0	0

The results obtained are compared with those obtained by Mohammad Rozali et al. (2012) that applied the battery storage. For startup, the actual maximum storage capacity obtained in this study is increased to 493.81 kWh from 469.11 kWh, while an increase from 543.34 kWh to 571.98 kWh is obtained for 24 h operation. The increase in storage capacity has further reduced the maximum demand of the system. Maximum demand of 22.63 kW occurs in this study compared to 23.03 kW in the system with battery storage.

Table 5 highlights the difference between the procedure and equations involve in this paper with those used in the previous method with battery storage. As can be seen, the main difference between these two storage technologies is the form of the electricity of the storage. While the electricity surpluses have to be in DC for battery charging, the electricity in pumped hydro storage on the other hand need to be converted to AC before it can be pumped to the deposit. This subsequently affects the total AC-DC conversion losses of the system. Apart from that, the charging and discharging of battery depends only on the battery efficiency. On the contrary, charging and discharging processes in pumped hydro storage are affected by the efficiencies of pump and turbine as well as the friction losses in penstock pipe.

Table 5: Comparisons of methodology procedure and equations

	Battery	Pumped hydro
Charging/ discharging quantity (Column 9)	$AC_{converted} + DC_{s/d} – DC_{converted}$	$DC_{converted} + AC_{s/d} – AC_{converted}$
Discharge for AC (or DC) deficit (Column 10)	$\frac{\text{Converted DC surplus + AC deficit}}{\text{Rectifier efficiency}}$	$\frac{\text{Converted AC surplus + DC deficit}}{\text{Inverter efficiency}}$
Storage capacity (Columns 11 and 13)	$B_t = B_{t-1}(1-\sigma\times T) + (C_t\times \eta_c) + D_t/\eta_d$	$S_t = S_{t-1} + (C_t\times \eta_c) + D_t/\eta_d$

3. Conclusions

The optimal power allocation for HPS with pumped hydro storage system has been presented. The overall results show that the total losses in HPS with pumped hydro storage application are less than those that occur in battery storage. However, this result is influenced by various factors, for instance the trend of the power sources and power data of a location. Changes in the trend may results in different outcome. Besides, the best storage technology for a HPS is not only based on the efficiencies and the power trend, but the total cost as well. Therefore, further study on the total losses as well as the cost analysis for other types of electrical energy storage systems on various power trends is currently in progress. Besides, a Total Site PoPA for Smart Grid system planning is also currently being studied.

Acknowledgement

The authors would like to thank the Ministry of Higher Education of Malaysia and UTM in providing the research fund for this project under Vote No. Q.J130000.2544.03H44 and to the Hungarian State and the European Union under the TAMOP-4.2.2.A-11/1/KONV-2012-0072.

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