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Techno-economic analysis of using battolyser for primary frequency control in power system with wind power

Zilong Wang[1,*] and Ang Li[2]

[1] Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong SAR
Pokfulam, Hong Kong Island (Hong Kong)
Phone number: 00852 53481095

[2] Asset Management Department, CLP Power Hong Kong Limited, Hong Kong SAR, and Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong SAR
Pokfulam, Hong Kong Island (Hong Kong)

Abstract. Large-scale integration of wind power brings new challenges to the frequency stability of traditional power systems. The use of battery has become increasingly mature for frequency control. Recently, battolyser as a brand-new technology that combines the functions of battery and electrolyser, shows higher technical and economic potential owing to its hydrogen production ability. Regarding this, the authors conduct detailed calculation and simulation to quantify its performance in primary frequency control. Results are compared with battery under various wind power penetration ratios and state-of-charge (SoC) conditions. It is shown that battolysers are more competitive in primary frequency control with high share of wind power when it operates at a higher SoC with more expensive electricity.

Key words. Battolyser, primary frequency control, power system, wind power, battery.

1. Introduction

The climate change and energy crisis increase the need for renewable energy, which leads to the comprehensive installation of wind turbines in power systems. According to the International Energy Agency, in 2022, wind electricity generation increased by a record 265 TWh, reaching more than 2100 TWh. China continues to lead regarding wind capacity additions, with 37 GW added in 2022. The European Union is accelerating wind deployment in response to the energy crisis, with 13 GW added, and wind energy covered 16% of the EU electricity demand in 2022. Wind power accounted for 22% of new electricity capacity installed in the United States in 2022, with the help of new funding for wind power in the Inflation Reduction Act introduced in the same year [1-3].

The large-scale deployment of wind power brings issues to the power system. On the one hand, the wind power output is uncertain due to the wind speed variation. It will take a lot of work to forecast the real-time wind power output and control it for the need. On the other hand, with the increasing penetration of renewable generation in power systems, a considerable part of conventional synchronous units providing inertia response are displaced by renewable units. However, wind and solar units typically offer low to zero inertia response because of their non-synchronous connection to a power system [4]. This intensifies the imbalance between active power production and demand, causing more severe frequency fluctuations, which may affect power system stability.

Handling power imbalance issues at the second level generally relies on primary frequency control by the speed regulator of the synchronous generator. While the fast and high-frequency fluctuation of frequency caused by the variation of wind power output makes the traditional primary frequency regulation units harder to achieve the goal and less cost-effective.

Battolyser is a newly developing technology based on the original battery with the added function of an electrolyser. Paper [5] introduces the essential characteristics of battolyser. A battolyser operates in the discharge mode when there is no voltage on the electrodes, or the voltage is less than the charging threshold. On the contrary, a voltage higher than the threshold will cause it to charge. When the voltage further exceeds the threshold voltage of the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) of the electrodes, the above reactions will occur to generate oxygen and hydrogen in sync with charging. If the electrode voltage is maintained at fully charged and the battolyser continues being charged, it can produce hydrogen and oxygen at the highest rate. Because the battolyser has the similar ability of fast input or output power energy and energy storage like battery, it can smooth wind power generation output while produce hydrogen.

Regarding the use of batteries for primary frequency control (PFC) with wind power, both academia and industry have conducted studies and applications [6-23]. Various schemes have been developed to control and optimize the adaptability of battery output to wind power fluctuations.

Battolysers have begun to receive more and more attention in recent years of research. Scholars from the Delft Institute of Technology and the UK have conducted relevant research on its chemical properties [5, 24-26]. Scholars of paper [5] are the first to study the electric and chemical characteristics of battolyser based on Ni-Fe batteries. Paper [24] analyses the influence of the internal resistance and structure of the battolyser based on the Ni-Fe battery. The availability of lead-acid battolyser is tested in the paper [25]. Physical and actual models of the battolyser are built in paper [26] to gain the operation features for up-scale cell design. This analysis is focused on the low-voltage circuit level and is unrelated to the power system. Some scholars have studied the economics of battolyser working with wind power to output electricity and hydrogen [27]. In summary, although research on battolysers is in its infancy, it has shown great application prospects in large scale power systems given its proven technical performance in chemical characteristics and low-voltage level performance.

For the first time, this article analyses the performance of battolyser for primary frequency regulation in power systems with wind power. The required rated power of battolyser for contingency in different wind energy penetration rates is summarized. This article proposes cost formulas for using battolysers in PFC and calculates the PFC energy cost based on different electricity and hydrogen prices. The technical performance and economics of battolysers are quantitively compared with that of batteries. The proposed analysis method can be applied to other power systems using the battolyser for PFC.

2. Electrical characteristics of battolyser

The electrical characteristics of battolyser are similar but different from batteries. The electrical characteristics of the battolyser made by Ni-Fe battery used for analysis in this report are summarized from the literature [5, 24, 26]. The lithium battery, which is currently the most frequently used battery, is used for comparison. The energy loss and temperature changes of the battolyser and battery are not considered in operation. Energy loss is accounted for in the cost calculation.

A. Charging characteristics

Charging characteristics influence the energy distribution of the battolyser operating in power system. During the charge and discharge process, the SoC of the lithium battery changes linearly [28]. All the charging energy of the lithium battery is used to improve the SoC, and all the discharge energy reduces the SoC.

During the discharge process, the SoC change of battolyser is linear. But during the charging process, the SoC change of the battolyser is non-linear. When the SoC of the battolyser is low, a high proportion of the charging energy is used to increase its SoC and a low ratio is used to produce hydrogen; when the SoC of the battolyser is higher, a lower proportion of its energy is used to increase the SoC, and a higher ratio is used to produce hydrogen during the charging process.

Based on the analysis of the charging and discharging process of battolyser in [5], this paper derives the formula for charging energy distribution during the charging process of battolyser, which is formulated as (1)~(2).

$$E_{ba}(x) = \frac{\frac{2}{1+e^{-2\cdot x}} - 1}{x} \tag{1}$$

$$E_{el}(x) = 1 - E_{ba}(x) \tag{2}$$

E_{ba} is the proportion of energy used to charge the battery part of the battolyser. x is SoC. E_{el} is the proportion of energy used to charge the electrolyser part of the battolyser.

B. Discharging rate

Discharging rate influences the output power of the battolyser operating in power system.

Discharging rate means the maximum operating current for a battery or battolyser in charging and discharging. This rate is often expressed as C. A battery charging or discharging rate of 1 C means the stored energy takes 1 hour to charge or discharge fully. Based on the chemical characteristics of Ni-Fe batteries, their charging and discharging rate are less than 1 C [24]. This results in lower charging and discharging power under the same conditions. The charging and discharging rate of lithium batteries is faster, above 2 C [29]. That is, its charging and discharging power is higher. The battolyser and battery is supposed to operate in its maximum current and rated voltage in the study. This paper uses 1 C and 2 C as the charging and discharging rate of the battolyser and lithium batteries.

3. Methods of using battolyser for PFC

Based on the analyzed scenarios, this paper formulates the PFC operation strategy of the battolyser and establishes a standard for evaluating its PFC effect. The battery is set up with the same parameters as a control group.

A. Analysis scenarios

The battolyser and battery is connected to the power system with speed governors and wind power to provide PFC service automatically according to the operation strategy. The thermal generator units are synchronous generators with speed regulators, which can perform PFC automatically, while wind power generators cannot provide PFC service. The power generation of all generators and demand is constant that the increase of wind power penetration will decrease the generation share of synchronous units. Despite the charging characteristics and discharging rate, the lithium battery has the same setting as the battolyser.

B. Battolyser operation strategy

The actual PFC power of the battolyser is related to the power limit by SoC and the reference PFC power, which is set by the power signal obtained through the virtual droop control.

1) Reference PFC power

The PFC signal of the battolyser is obtained through the virtual droop control. When there is an imbalance between active power supply and demand in the system, frequency deviation, Δf, will occur. If Δf exceeds the PFC dead zone, the battolyser performs PFC. The reference PFC power, ΔP, for battolyser is formulated as (3)~(6).

$$\Delta P = P_m \cdot \frac{\Delta f - f_{db}}{f_0} \cdot \frac{1}{R} \quad (3)$$

$$\Delta f - f_{db} > 0 \quad (4)$$

$$f_{db} > 0 \quad (5)$$

$$\Delta P < \Delta P_{max} \quad (6)$$

P_m is the rated power of the battolyser; f_{db} is the PFC dead zone of the system; f_0 is the standard frequency of the system; R is the droop control coefficient of the battolyser, which determines the power ramping speed of the battolyser used for PFC; ΔP_{max} is the power limit by SoC.

2) Power limit for PFC

Specific protection measures are required to prevent equipment damage caused by excessive charging and discharging when the battery and battolyser are charged and discharged in the power system. The strategy adopted in this paper is to linearly reduce the maximal discharging power of the battolyser when its SoC is low. When the battolyser gradually reduces its SoC from a low value during the discharge process, its output power upper limit is gradually reduced from 100% of the rated power to 0. Its charging process is unlimited.

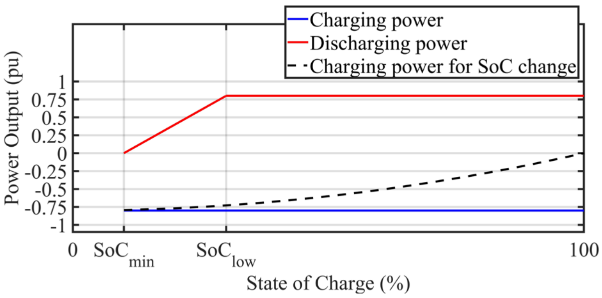

Fig. 1 Output power limits of battolyser

Compared with battolyser, the lithium battery has extra power limit that reduces its charging power when the SoC is high.

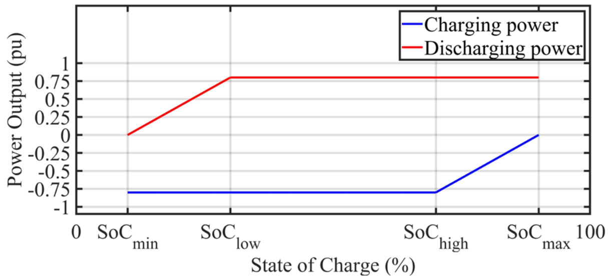

Fig. 2 Output power limits of battery.

C. Evaluation of PFC effect

This paper measures the PFC effect of battolyser and battery from two perspectives: handling system contingency and PFC energy cost. This article only considers PFC and does not consider the impact of secondary frequency regulation.

1) Handling system contingency

The most severe contingency for PFC is the instantaneous massive fluctuation of the active power of the system, due to the variation from the wind power, thermal units generation and load. According to the N-1 reliability rule, the worst instantaneous fluctuation happens when the largest generator or load is disconnected.

This paper evaluates the PFC effect of the battolyser by determining its minimum power capacity that can secure the frequency deviations below the maximum values when system contingency occurs. According to [30], the PFC dead zone is 20 mHz; the maximum quasi-stable frequency deviation is 200 mHz; the maximum instantaneous frequency deviation is 800 mHz.

2) PFC energy cost

The calculation of PFC energy cost is based on the following assumptions: the battery or battolyser only serves for the PFC in its lifetime; the price paid to the battolyser for PFC in discharging is the electricity price; for PFC demand on power supply, which is discharging mode for battolyser or battery, the capital cost, operation cost and electricity revenue are considered; for PFC demand on power consumption, the battery can be charged by free electricity and only has the capital and operation cost; the battolyser can earn extra profit by producing and selling hydrogen; the charging process and discharging process account for 50% respectively in the total operation time; the cost of water for electrolysis and revenue from selling oxygen is ignored.

When other conditions are the same, this PFC cost differs for battolyser in different SoC. C_{bl}, the normalized PFC cost of battolyser for each MWh operation, is formulated as (7).

$$C_{bl} = \frac{C_{cap,bl} + C_{ope,bl}}{L_{bl}} - 0.5 \cdot \left(\frac{p_{elec} \cdot 1\,MWh}{E_{ba}(x) \cdot \gamma_{bl}} + \frac{p_{hydr} \cdot 1\,MWh \cdot E_{el}(x)}{[E_{ba}(x)]^2 \cdot \gamma_{bl} \cdot r_{elec-hydr}}\right) \quad (7)$$

x is SoC; $C_{cap,bl}$ is the fixed cost of battolyser per unit, in £/MW for one-hour storage; $C_{ope,bl}$ is the unit operating cost of the entire life cycle of battolyser, in £/MW for one-hour storage; L_{bl} is the life cycle times of battolyser; p_{elec} is the electricity price in £/MWh; γ_{bl} is the charging energy utilization efficiency of battolyser; E_{ba} is the proportion of energy used to charge the battery part of battolyser; p_{hydr} is the price of hydrogen, the unit is £/kg; E_{el} is the proportion of energy used to charge the electrolyser part of the battolyser; $r_{elec-hydr}$ is the conversion ratio of the battolyser using electricity to produce hydrogen, the unit is MWh/kg Hydrogen.

The normalized PFC cost of battery for each MWh operation, C_{br}, is formulated as (8)

$$C_{br} = \frac{C_{cap,br} + C_{ope,br}}{L_{br}} - 0.5 \cdot \frac{p_{elec} \cdot 1\,MWh}{\gamma_{br}} \quad (8)$$

$C_{cap,br}$ is the fixed cost of battolyser per unit, in £/MW for one-hour storage; $C_{ope,br}$ is the unit operating cost of the battery throughout its life cycle in £/MW for one-hour storage; L_{br} is the life cycle times of the battery;γ_{br} is the charging energy utilization efficiency of the battery.

4. Case study

This article simulates the PFC effect of the battolyser in an IEEE 30-node power system with six generators in the Simulink. The configuration of wind energy penetration rate and contingency is shown in the Table I. The standard system frequency is 50Hz. The negative wind energy penetration rate represents system contingency of insufficient active power; the positive wind energy penetration rate represents system contingency of excess active power.

Table I. - Configuration of wind energy penetration rate and contingency

Wind energy penetration rate		-60%~+60%
Contingency	Disconnected generator	50 MW
	Disconnected load	30 MW
	Max wind power variation	7%

A. PFC for contingency

The minimum rated power required by the battolyser and battery to perform PFC by SoC can be obtained in different wind energy penetration rates. Table II shows the minimum power required for PFC using battolyser and battery at different wind energy penetration rates.

1) *Influence of SoC*

The distribution characteristics of the power required by the battolyser and the battery to conduct PFC is the same for each wind energy penetration rate. The 30% case is selected for analysis, see Fig. 3. The ordinate value is the ratio of the power required by the battery or battery to the installed wind power capacity.

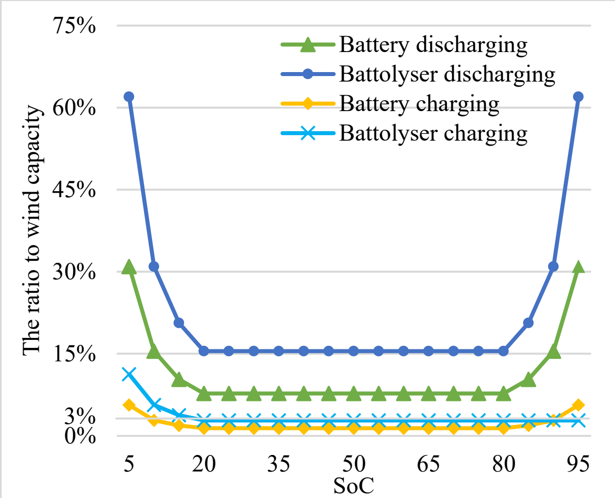

Fig 3. Distribution by SoC of power required by battolyser and battery for PF C in contingencies (wind energy penetration = 30%).

Curves in dark blue and green is above the other two. This means the required PFC power in discharging is higher than that in charging. More PFC power is required at low and high SoC. The battolyser and battery should better keep working in a SoC about 50 for the best PFC ability of handling contingency. The dark blue curve is above the green one and the light blue curve is above the yellow one at most SoC. This means the battolyser requires more PFC power capacity

Table II. - The minimum PFC power required for a battolyser or battery in power systems with different wind power penetration rates.

Wind energy penetration (%)	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
Wind power capacity (MW)	426	355	283	213	142	71	0	71	142	213	283	355	426
Battery power (MW)	24	21	19	17	14	12	0	0	1	3	6	8	11
Battolyser power (MW)	47	42	37	33	28	23	0	0	1	6	11	16	21

The negative penetration means downward variation occurs for wind power and system generation.

for handling the contingency at most SoC, except for being charged at the SoC of over 90.

2) *Influence of wind energy penetration rate*

Fig. 4 summarises the cases in the same absolute value of wind power penetration. The ordinate value is the ratio of the power capacity required by the battery or battery to the installed wind power capacity.

We can see from the figure that the charging power for PFC increases with higher wind power penetration and the discharging power decreases in contrast. While the required discharging power is more for all the wind penetration. This means the power requirements of discharging process in PFC is of more importance. And the effect of battery is always better than that of the battolyser. The difference between the charging and discharging power for the battolyser is far more than that of battery. The difference may be smaller with a higher wind penetration.

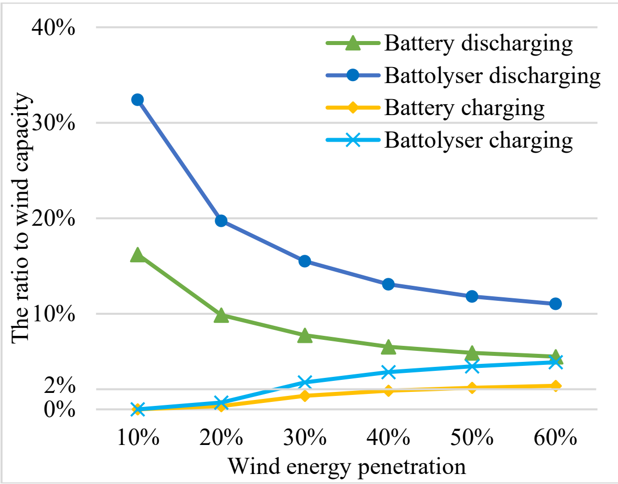

Fig. 4 The minimum PFC power required for a battolyser or battery in power systems with different wind energy penetration rates.

B. *PFC cost of battolyser*

The PFC costs of battolyser in different SoCs are different for various electricity and hydrogen prices. Four application scenarios are set based on the differences in hydrogen prices and electricity prices, as shown in Table III.

The PFC energy cost of the battolyser and battery can be calculated according to equation (1), (2), (4) and (5), and the results are shown in Fig. 5, based on the data in Table IV.

As is observed from Fig. 5, the PFC cost of battolyser decreases with the increase of SoC. If the battolyser works at a high SoC, its PFC cost may be lower than that of battery. The curves of current scenarios are under the those of future scenarios. This means current conditions on PFC are more cost-effective for the battolyser because the hydrogen revenue may be decrease due to the lower price in the future. The three curves on the top shows the off-work time may lead to higher PFC cost. This is due to the less PFC service need and lower service electricity price.

Table III. Application scenarios for PFC cost calculation

Scenarios	PFC tool	Electricity price	Hydrogen price
1	battery	Trough[b]	N/A
2	battery	Peak[a]	N/A
3	battolyser	Trough	Current[c]
4	battolyser	Peak	Current
5	battolyser	Trough	Future[d]
6	battolyser	Peak	Future

(a) Trough electricity price is 10 £/MWh.

(b) Peak electricity price is 60 £/MWh.

(c) 'Current' refers to the situation that hydrogen from electrolysis is still in the development stage, the price of green hydrogen produced is relatively high (10 £/kg)

(d) 'Future' refers to the time when electrolysis of water to produce hydrogen is fully developed, and the price of green hydrogen produced is relatively low (3 £/kg).

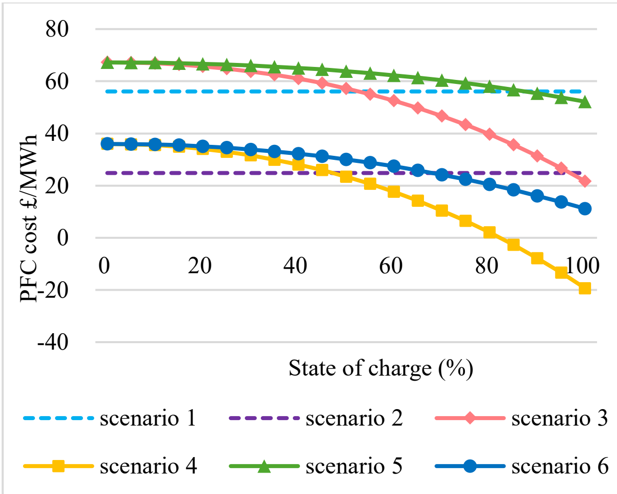

Fig. 5 The PFC cost by SoC in different scenarios.

Table IV. – Cost data of battery and battolyser [27]

	Battery	Battolyser	Unit
Capital cost	147	178.4	£k/MW for 1 h storage
Operation cost	40	42	£k/MW for 1 h storage for lifetime
Life cycles	3000	3000	N/A
Charging efficiency	80%	80%	N/A
Hydrogen production	N/A	17	kg H2/MWh

5. Conclusions

This article analyses the technical performance and economics of using battolysers for PFC in power systems with different wind power penetration rates.

Generally, batteries serve better than battolysers in handling the PFC contingency at most situations, except being charged at the SoC of over 90. The performance of battolysers will be better with a higher wind penetration.

If battolysers work at a high SoC, its PFC cost may be lower than that of batteries. Low prices of electricity and hydrogen leads to a high PFC cost for the battolyser.

In summary, battolysers are more competitive in primary frequency control with high share of wind power when it operates at a higher SOC with more expensive electricity.

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