A comparative study of two liquid air energy storage systems with LNG cold energy recovery

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Abstract. Due to the nature of fluctuation and intermittency, the increasing penetration of wind and solar power will bring a huge impact to the power grid management. Therefore the concept of liquid air energy storage system was proposed. Compared to compressed air energy storage, liquid air energy storage has a larger storage capacity and no geographic constraints owing to the high density of liquid air. In order to obtain the optimum system design, two different liquid air energy storage systems with LNG cold energy recovery were studied. For one system, the LNG cold energy was used to precool the compressor inlet air to decrease the compression work. For another one, the LNG cold energy was applied to supplement the cold energy needed to liquefy the air and realize the decoupling between the energy storage and release processes. Thermodynamic analysis based on steady-state mathematical model was employed to evaluate the system performance difference.

1. Introduction

The increasing penetration of renewable energy, including wind and solar power, has promoted the carbon emission reduction in the energy consuming market. However, the randomness and volatility of renewable energy have brought huge impacts to the reliability, power quality and operation costs of power grid [1-2]. The application of large-scale energy storage technology can effectively solve the above problems. Among many energy storage technologies, pumped hydro energy storage and compressed air energy storage need to rely on special geographical conditions. And high power battery energy storage also needs to meet the challenges of safety, cycle life and waste battery treatment. Liquid air energy storage (LAES) is a large-scale and long-term energy storage technology for achieving the deep consumption of renewable energy, which has outstanding advantages of clean, low carbon, safety, long service life and no geographical restrictions. Electrical energy can be stored by the form of liquid air which can considerably improve the energy storage density and overcome the geographical constraints [3].

Many LAES systems have been proposed by different scholars from various countries [4]. Nevertheless, the production of liquid air needs a cryogenic liquefaction technology, which is a high energy-consumption process and has relatively low cycle efficiency. To further improve the energy storage efficiency of the LAES system, researchers have developed a number of hybrid LAES systems coupled with the cold energy utilization of liquefied nature gas (LNG). Park [5] proposed a LAES...
system which realizes air liquefaction by utilizing the cold energy during LNG gasification, and the energy storage efficiency of the overall integrated system can reach 95.2%. A hybrid LAES system combined with organic Rankine cycle based on the utilization of the LNG cold energy was proposed by Zhang [6], and the energy storage efficiency and exergy efficiency are 70.51% and 50.73%, respectively. Peng [7] compared the system performance of the traditional LAES system with the hybrid LAES-LNG system, indicating that the energy storage efficiency of the hybrid system increases by 15-35%. She [8] proposed the integration of the LAES with the LNG regasification process via a Brayton cycle, and the energy storage efficiency and exergy efficiency of the system can reach 70.6% and 57%, respectively. Guo [9] investigated the influence mechanism of introducing LNG to the LAES system, and compared the performance of four different LAES systems. With the decoupling between the energy storage and release processes, the energy storage efficiency is improved obviously. Gao [10] provided a hybrid LAES-LNG system realizing the cryogenic compression during the charging process and exploitation of the exhaust heat from the power station during the discharging process. The highest system efficiency can reach 99.39%.

However, there are few reports considering the difference of different technical routes for the LNG cold energy recovery in the LAES system. In order to obtain the optimum system performance, two different liquid air energy storage systems with LNG cold energy recovery were studied. For the low temperature compression (LTC) process, the LNG cold energy was used to precool the compressor inlet air to decrease the compression work. For the cold energy supplement (CES) process, the LNG cold energy was applied to supplement the cold energy needed to liquefy the air and realize the decoupling between the energy storage and release processes. Thermodynamic and parametric sensitivity analysis based on steady-state mathematical model was employed to evaluate the system performance difference.

2. System description

Figure 1 shows the schematic diagram of the two proposed LAES system with LNG cold energy recovery. The system is mainly composed of four units, including the compression unit, the liquefaction/ regasification unit, the cold energy storage unit, and the turbo-generation unit. In the CES process, an additional organic Rankine cycle (ORC) and a thermal energy storage unit are configured. The compression unit contains a compressor train (CP), precoolers (PR) or intercoolers (IC). The liquefaction/ regasification unit consists of air coolers (AC), air heaters (AH), a separator (SEP), an air expander, a liquid air pump and a liquid air tank. The cold energy storage unit includes solid phase packed beds (BED). The turbo-generation unit includes an air turbine train (ATB) and preheaters (PH). The ORC contains a propane pump, a propane evaporator, a propane turbine and the AH. The thermal energy storage unit contains a cold water tank (CWT) and a hot water tank (HWT).

As shown in Figure 1, during the energy storage process, the ambient air is compressed by the CPs to a high pressure, and enters the liquefaction unit. Specially, in the LTC process, the air is cooled by the LNG pressurized from the LNG tank (LT) by the LNG pump (LP) to a low temperature to decrease the compression work. While in the CES process, the air is cooled by the water to store compression heat. Then the air is further expanded to a near ambient pressure in the expander (AE) and stored in the liquid air tank (LAT), and the gaseous air flows back to supply the remaining cold energy. In the CES process, the air is firstly cooled by the LNG cold energy in the first stage, and then further cooled to a lower temperature by the packed bed.

During the energy release process, the air is pressurized by the liquid air pump (LAP) and heated in the air heaters (AH). Also, the cold energy of the liquid air is stored by the packed bed. In the CES process, the ORC cycle uses the cold energy of the liquid air and the compression heat to achieve power generation. Then the air expands in the ATBs to generate power. In the CES process, the air is further heated by the hot water to recover the compression heat. Meanwhile, the gasified LNG is transported to the user through the pipeline.
Figure 1. Schematic diagram of the two proposed LAES system with LNG cold energy recovery.
3. Thermodynamic analysis model
To simplify the analysis of the proposed LAES system, some assumptions were made as follows:
 a. The air properties are based on the Peng-Robinson equation;
 b. The pressure drop of each heat exchanger and pipe was neglected.
 c. All the operation processes reach steady state.

3.1. Energy analysis model
The power consumption of compressor train is:
\[
W_{CP} = \sum_i W_{CPl} = \sum_i m_a [h_{CPOut} - h_{CPin}]
\]
where \(m\) is the mass flow, \(h\) is the specific enthalpy, the subscripts \(a\) and \(i\) represent air and the sequence number for each stage of compressor, the \(in\) and \(out\) represent inlet and outlet, respectively.

The output power of low temperature air turbine is:
\[
W_{AE} = m_a (h_{AEin} - h_{AEout})
\]

The power consumption of liquid air pump is:
\[
W_{LAP} = m_a (h_{LAPout} - h_{LAPin})
\]

The output power of air turbine is:
\[
W_{ATB} = \sum_i W_{ATBi} = \sum_i m_a [h_{ATBin} - h_{ATBout}]
\]

For the propane pump in the CES process, the power consumption can be calculated as:
\[
W_{PP} = m_p (h_{PPout} - h_{PPin})
\]

where the subscripts \(p\) represent propane.

For the propane turbine in the CES process, the output power can be calculated as:
\[
W_{PTB} = m_p (h_{PTBin} - h_{PTBout})
\]

For all the heat exchangers, the unified energy balance equation is:
\[
m_H (h_{H,in} - h_{H,out}) = m_C (h_{C,out} - h_{C,in})
\]

3.2. Performance assessment indexes
The electric energy storage efficiency (ESE) can be used to measure the performance of a LAES system. It is expressed as a ratio of the net power output during energy release process to the net power input during energy storage process, which is:
\[
ESE = \frac{W_{net}}{W_{CP}}
\]

For the LTC process, the ESE is expressed as:
\[
ESE_{LTC} = \frac{W_{ATB} - W_{LAP}}{W_{CP} - W_{AE}}
\]

For the CES process, the ESE is expressed as:
\[
ESE_{CES} = \frac{W_{ATB} + W_{PTB} - W_{LAP} - W_{PP}}{W_{CP} - W_{AE}}
\]

4. Results and discussion
The thermodynamic simulation was carried out to analyze the proposed hybrid LAES-LNG system. All the components and streams in Figure 1 were calculated, and some key parameters were studied.
4.1. Thermodynamic simulation results
Table 1 shows the simulation results of the proposed LAES system. The pressure of LNG was chosen as 10 MPa with a temperature of -156°C for the requirement of long distance transportation. The adiabatic efficiency of the compressors and expanders were both set as 85%, while the efficiency of the pump was set as 75%. Besides, the environmental temperature is 25°C and the temperature of hot water is 111°C (4 bar). The minimum temperature approach of the cryogenic heat exchanger and high temperature heat exchanger was 1.5 K and 10 K, respectively. The outlet power of both the LTC and CES process is 50 MW. The ESE of the LTC process is 80.6%, which is higher than that of the CES process with an ESE of 56.2%. However, both the mass flow of air and LNG consumption for the LTC process are higher than that of the CES process.

| Term               | Unit   | Value   | Value   |
|--------------------|--------|---------|---------|
|                    |        | LTC     | CES     |
| **Power of CPs**   | kW     | 62050   | 88959   |
| **Power of ATBs**  | kW     | 50000   | 50000   |
| **Power of PTB**   | kW     | -       | 6898    |
| **Mass flow of air** | Nm³/h | 736900  | 486100  |
| **Pressure of LNG** | MPa   | 10      | 10      |
| **Outlet temperature of LNG** | °C   | -39     | -50     |
| **Mass flow of LNG** | t/h   | 538     | 358     |
| **ESE**            |        | 0.806   | 0.562   |

4.2. Parametric sensitivity analysis
Figure 2 shows the effect of LNG pressure on the energy storage efficiency. The ESE of the LTC process increases with the increasing LNG pressure, while the ESE of the CES process remains constant. This is because that in the LTC process, the inlet temperature of each stage compressor can be lower when the LNG pressure increase, which leads to the decrease of power of CPs. The maximum ESE of the LTC process is 0.806 and the ESE of the CES process is 0.562.

![Figure 2. Effect of LNG pressure on the energy storage efficiency.](image)

Figure 3 presents the effect of LNG pressure on the mass flow and outlet temperature of LNG. The mass flow of LNG of the LTC and CES process both increase with the increasing LNG pressure. And the mass flow of LNG of the LTC process is larger. The outlet temperature of gasified LNG after
utilization for the LTC process decreases with the increasing LNG pressure, while the CES process has an opposite trend. This is due to the limitation of constant minimum temperature approach of the heat exchangers. The heat capacity of the LNG changes with the LNG pressure, which can significantly affect the minimum temperature approach between the LNG and air.

![Figure 3. Effect of LNG pressure on the mass flow and outlet temperature of LNG.](image)

Figure 3. Effect of LNG pressure on the mass flow and outlet temperature of LNG.

Figure 4 shows the effect of compressor adiabatic efficiency on the compressor power and ESE. The power of CPs for both the LTC and CES process decreases with the increasing adiabatic efficiency. The ESE of the two processes both increase with the increasing adiabatic efficiency while the LTC process has a higher efficiency for its power of CPs is much smaller.

![Figure 4. Effect of compressor adiabatic efficiency on the compressor power and ESE.](image)

Figure 4. Effect of compressor adiabatic efficiency on the compressor power and ESE.

5. Conclusions
In order to improve the energy storage efficiency of the LAES system, cold energy utilization of LNG for the LAES system has been widely studied. To obtain the optimum system performance, two different liquid air energy storage systems with LNG cold energy recovery (LTC and CES process) were proposed. Both the thermodynamic and parametric sensitivity analysis was conducted to evaluate the system performance difference. The results show that the maximum ESE of the LTC and CES process can reach 0.806 and 0.562 under the design conditions, respectively. Also, the ESE of the LTC process and the mass flow of LNG of the LTC and CES process both increase with the increasing LNG pressure. More LNG cold energy is needed in the LTC process to achieve a 50 MW outlet power. Furthermore, the increase of compressor adiabatic efficiency brings a beneficial effect to the system
performance.

6. References

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