Design of a System Coupling Liquid Air Energy Storage System with Thermal Power Unit

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Abstract. In recent decades, the market share of new energy resources is increasing rapidly; the intermittency of new energy resources became an issue to power grids. One prevailing solution is to install large scale energy storage systems. To make energy storage systems participate better in peak shaving without geographical constraints, the paper put forward a new design of a system that couples liquid air energy system with a thermal power unit to utilize waste heat from the condenser of the thermal power unit; the system is also independent from electricity input when producing electricity.

Keywords: Liquid Air Energy Storage System, Thermal Power Unit, System Coupling

1. Research context
In recent decades, renewable energy sources are having increasing share in the global power market. In 2008, new renewables represented about 229 gigawatts of the electricity generating capacity, which is nearly 5% of total global power capacity (about 4700 GW); renewable energy increased by about 50% in installed capacity[1]. Global investment in the development and utilization of renewable sources of power was 244 billion dollars in 2012[2]. Such an increasing share may cause issues to power grid systems due to instability of power production of renewable energy sources: for example, windmills may be affected by weather patterns, photovoltaic plants may be affected by day-night cycles, etc.

Consequently, energy storage systems are considered to be a potential solution to buffer production swings of renewable energy sources. Energy storage systems transform electricity into other forms of energy and utilize them at a later time. For example, a battery transforms electricity into electrochemical energy, compressed air energy storage transforms electricity into potential energy of air, etc. Change in production and demand in the power grid cannot be accommodated without traditional grid management or participation of energy storage systems. Energy storage systems may also function in smoothing voltage fluctuation in modern power grid and levelling the loads. Energy storage produce flexibility gains to benefit customers and producers, but also causes loss of a fraction of energy whenever energy is stored or transported; hence, we need to consider benefits of energy storage systems in terms of flexibility and reliability, as well as energy and efficiency loss.

From the perspective of energy production, energy storage systems can replace traditional grid management to some extent. Applications of energy storage include counterbalancing intermittency of renewable energy sources, regulating power plants, and peak shaving[3]. As mentioned before, the share of intermittent energy source is likely to increase in the following years, but many current grid infrastructures struggle to handle such huge swing, and they are even in danger of grid collapse. According to Czech grid operator ČEPS, a.s., aging power grids in countries in eastern Europe are in their limit to hold gulf of electricity produced by wind turbines in northern Germany and the Baltic Sea regions, and face potential grid collapse; Czech Republic themselves are also planning to construct security switches near borders to disconnect from western Europe to avoid critical overload.
Other alternatives to deal with intermittency include locational dispersion of wind and solar plants to avoid weather effects, or disconnecting customers.

Like energy production, energy consumption fluctuates as well; it is effected by habits of local society, climate patterns and social trends. A reliable power grid is expected to cater for intermittency caused not only by factors above but also unexpected factors like natural disasters and accidents. For the benefit of both producers and consumers, energy storage systems is capable to deal with the fluctuation.

Energy storage systems are divided into two major categories according to their energy capacity. One type can deliver a precise amount of energy in a short period of time, such as capacitors and flywheels; the other type stores huge amount of energy but take longer to collect and release it, such as pumped hydro energy storage (PHES), compressed air energy storage (CAES), and chemical battery energy storage, which are technologically more mature and play a more important role in dealing with intermittency of power production[4]. Energy storage can also be easily characterized by their specific energy (energy stored per volume or mass) and peak power (the maximum rate of energy delivery by the device).

CAES system uses an existing underground site such as a cave or an abandoned mine site to store gas at approximately 4–8Mpa[4-6]. Built in 1978, the Hundorf plant is the first ever CAES facility, whose stores compressed air at around 46 atm in two salt caverns with a total volume of 310,000m³. The latest large scale CAES was built in McIntosh, USA, where heat flow of CAES system is enhanced[7]. CAES is currently considered a proper way to deal with high penetration in smart grid and energy internet[8]; as a matter of fact, power capacity of global compressed air energy storage systems sum up to 400MW[5]. However, as CAES shows lower cycle efficiency than PHES or batteries, and CAES is highly limited by geological constrains[8], CAES may not be a major solution in energy storage in near future.

PHES is a well-established and commercially acceptable technology for utility-scale electricity storage and has been applied since 19th century[2]. PHES stores gravitational potential energy from height differences in water levels. In this system, low-cost electricity in off-peak time is used to run the pumps to lift water from a low reservoir to a high reservoir; they will then be released to low reservoir through generator to produce electricity in peak time and be sold in high price. With 104 GW of installed capacity in total PHES now contributed 97% of total global storage capacity, where United States contributed 22GW, and Europe contributed 44GW in total[2,4]. However, PHS require specific large volume water reservoirs in different heights, which is a strong geographical constraint to large scale application of PHES.

Launched by Hitachi Ltd. and Mitsubishi Heavy Industries, Ltd. built prototypes of LAES to test practicality of LAES[10]. In 2015, Highview Power Storage Ltd. started to construct a pre-commercial level plant, and operation has started since 2018.

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Based on the need of participation of energy storage systems in peak shaving to support renewable energy sources, the paper put forward and designed a system that combines thermal power unit with LAES system which utilizes excess heat produced by thermal power unit to improve the ability to output work. The paper also introduces in detail the composition and working fluid of the system coupling CES with thermal power unit.
2. The Basic mechanics of system coupling LAES with thermal power unit

2.1. System composition
A system coupling CES with thermal power unit consists of pressurizing subsystem, heat storage subsystem, packed bed regenerator, air liquefaction subsystem, expansion generation system, and thermal power unit, shown in figure 1.

2.2. Introduction of subsystems

2.2.1. Pressurizing subsystem. Pressurizing subsystem consists of four screw compressors and corresponding intercoolers. Screw compressors consume electricity to decrease the volume of air; by doing so, the pressure of air will increase. When air is compressed, its temperature will increase, so when air enters heat exchangers, its temperature increases, and it will give heat to low temperature heat storage fluid. Four compressors pressurize air in the same pressurizing ratio (the ratio of pressure of output air versus pressure of input air). Low temperature heat storage fluid will enter intercoolers and absorb heat from high temperature pressurized air. Intercoolers receive a type of high temperature work fluid (which is air in the system) and a type of low temperature work fluid (which is heat storage fluid in the system), and conduct fluids close to each other, so that the temperature of the high temperature fluid (air) will decrease, and the temperature of the low temperature fluid (heat storage fluid) will increase, until the temperature of two different fluids are exactly the same. Heat storage fluid from intercoolers will then be sent to heat storage tank in which heat is stored, or to the condenser of thermal power unit to collect excess heat produced by thermal power unit.

2.2.2. Heat storage subsystem. Heat storage subsystem is composed of the final intercooler, heat storage tank, and reheater. The final intercooler cool pressurized high temperature air by using low temperature heat storage fluid to collect heat from the high temperature compressed air; it then conducts the fluid to heat storage tank or to condenser as other intercoolers do. Heat storage tank stores heat storage fluid, which is the major medium to deliver excess heat produced by components in the system. Heat storage fluid delivers high temperature heat storage fluid to reheater and interheaters in the expansion subsystem to heat low temperature air which produces work in expanders.
2.2.3. Packed bed regenerator. Packed bed regenerator uses small spherical rocks as filler to retain low temperature. When high temperature liquid air from pressurizing subsystem enters the packed bed regenerator, small rocks absorb heat from air, so the temperature of air decreases to a very low point, and the temperature of rocks will correspondingly increase; when low temperature gas air from cryogenic liquid pump enters the packed bed regenerator, the rocks give heat to low temperature air, so temperature of air will increase, and temperature of rocks will decrease.

2.2.4. Air liquefaction subsystem. Air liquefaction system consists of throttle valve, gas-liquid separator, liquid air storage tank, and cryogenic liquid pump. Throttle valve decreases pressure of low temperature gas air and cause them to liquefy. Pressurized air decreases flow rate and temperature when entering throttle valve, some in which liquefies; throttle valve send a mixture of gas and liquid air to the gas-liquid separator. The gas-liquid separator utilizes different properties of gas air and liquid air to separate them; gas air is conducted back to packed bed regenerator to be reheated and then to pressurizing subsystem to be pressurized again; the liquid air is then conducted to liquid air storage tank, the liquid air storage tank sends liquid air to cryogenic liquid pump; the pump increases the pressure of liquid air and cause it to vaporize into gas air. Gas air is then conducted to packed bed regenerator again to be reheated, and then to expansion generation subsystem to produce electricity.

2.2.5. Expansion generation subsystem. Expansion generation subsystem consists of three expanders, generators and interheaters. The reheater and interheaters use high temperature heat storage fluid from heat storage tank as heat source to heat cryogenic air to normal temperature. Expanders expand the volume of gas so that they produce mechanical work to the machine, which will be conveyed to generator to produce electricity. Three expanders depressurize air in the same ratio (the pressure of output air versus the pressure of input air).

2.2.6. Thermal Power Unit. Thermal power unit consists of boiler, turbine, condenser, and valve. It functions separately with LAES normally, but when required, it uses heat storage fluid as cooling fluid in the condenser; when high temperature vapor enters condenser, it gives heat to low temperature heat storage fluid and cools down; temperature of heat storage fluid will increase, and the fluid will then be conducted from condenser to heat storage tank.

2.3. System working process
In the system, pressurizing subsystem, air liquefaction subsystem, heat storage subsystem and expansion generation subsystem can work both separately or simultaneously. In the whole process, air with normal temperature and pressure is first purified so that water, carbon dioxide and solid impurities are excluded. Then air goes through pressurizing subsystem and get pressurized; intercooler between and after compressors functions to cool the air and send the heat to heat storage tank; condenser send excess heat from coupled thermal power unit to heat storage tank simultaneously. Next, cold air enters packed bed regenerator and turn into cryogenic air. Air is depressurized when passing throttle valve, and is separated into two flows; gas air returns exergy to packed bed regenerator and is conducted to pressurizing subsystem, while liquid air enters liquid air storage tank. In the above process electricity turns into internal energy of liquid air. When outputting work, the system conducts liquid air out of liquid air storage tank. Air first goes through cryogenic liquid pump to be pressurized, then enters reheater to receive heat from heat storage tank. Finally, it enters expansion generation system to be depressurized to atmospheric pressure. In the above process, internal energy of liquid air transferred into electricity.
3. Future Perspective
The paper has put forward an idea to enhance LAES system, but the feasibility of the system has not been examined yet; little is known about its working efficiency and durability. Furthermore, as a product that can reach industrial level and is feasible to be put into actual use, the system needs to determine fundamental parameters such as pressurizing ratio and working temperature of air. Additionally, what fluid should be selected as the heat storage fluid in the system is still undetermined. As for future expectations, basic thermodynamical models of the system should be created, and simulation via computer could be applied.

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