Exergetic analysis of integrated layout for liquid air energy storage applied to APR1400 using mechanical drive steam turbines

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1. Introduction

To combat global warming as part of a worldwide mission, many nations have declared their initiatives to increase clean energy portfolio significantly. There are two challenges, of many, to overcome in making the energy transition possible: grid support in accompanying more intermittent energy sources and enhanced flexibility in the conventional baseload sources.

As a vital baseload power, nuclear energy is currently providing about 11% of the world's electricity. However, increase in renewable energy, mainly solar and wind, has raised concerns that the conventional power such as nuclear would need to curtail production during period of over-generation and to provide energy at a significant ramp rate [1]. The phenomenon has been identified in the 'duck chart', and the concern has ramifications for how the conventional nuclear plants should change.

More specifically, the period of over-generation in an hourly curve leads to negative price of electricity, harming the economic return on power generation and thus forcing the conventional plants to reduce their load. In such probable scenarios, the demand for large-scale energy storage systems as well as the need for load-following capabilities have been presented.

Recently, a concept of the liquid air energy storage (LAES) system has received attention for its advantages over other candidates for grid-scale storage [2]. Compared to pumped hydro storage or compressed air energy storage, LAES has high energy density, has no geological constraints, and can be easily integrated with other thermal systems. For such potential, Li et al. has first presented a concept of integrating a 250MWe nuclear plant with LAES [3].

When considering possible layouts for integration, three categories can be suggested. As shown in Figure 1, the steam provided to the secondary side in a PWR can be integrated with the LAES by electric, thermal, or mechanical coupling. While the previous reference in [3] suggests the pathway of integrating steam with the discharging cycle of the LAES, mentioned as option 2, its performance would be limited because using steam during the discharge leads to the reduction of power. Instead, the integration with the LAES charging cycle can reduce the power load to the grid during charge and increase the output during discharge.

Considering the required sizing of the LAES air compressors suitable for large PWR integration such as APR1400, the integrated system can consider mechanical drive steam turbines (MDST). Commercially available in large-scale petrochemical plants, these turbomachines can offer direct mechanical output to operate the heavy duty air compressors by utilizing the steam from the nuclear secondary side. They can be directly coupled on a shaft or linked through gears.

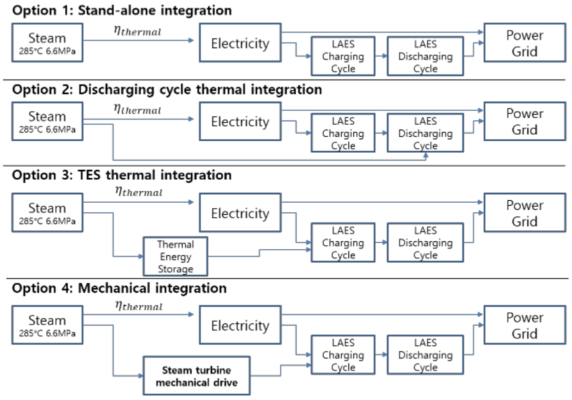

Fig. 1. LAES integration options for PWR applications

This paper analyzes the performance potential using MDST in the integration of the LAES with the APR1400, Korean PWR plant reference. The exergy analysis is implemented to analyze the losses incurred in the option 4 layout.

2. Methodology

To calculate the exergetic performance of the LAES integration layout to the APR1400, the framework for analysis is introduced. The in-house code is developed for LAES steady-state design, built in MATLAB environment and using NIST REFPROP 10 database for air properties [4]. The properties of hot storage material, Therminol VP1, are obtained from the database offered from the Eastman Chemical Company [5].

To obtain the state points for the integrated layout shown in Fig. 2, genetic algorithm is adopted in the code to find the optimal solution for the multi-variable problem. The operators of the algorithm include elite selection, crossover, and mutation. The design code is optimized for maximum round-trip efficiency.

After the optimal design has been obtained, the layout is analyzed for how much exergy destruction has occurred for each component. The equations for each component are listed below.

$$\text{Flow exergy: } x = h - h_0 - T_0(s - s_0) \qquad (1)$$

$$\text{Exergy destroyed: } \dot{W}_{lost} = T_0\dot{S}_{gen} \qquad (2)$$

$$\text{Round-trip efficiency: } \eta_{RT} = \frac{Energy\ released\ during\ discharge}{Energy\ consumed\ for\ charge}$$

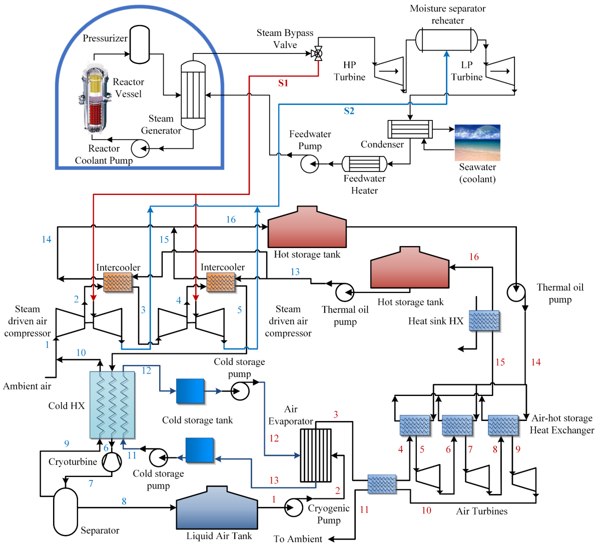

Fig. 2. Schematic of LAES integrated layout using MDST

3. Analysis results

The results of the analysis for the integrated layout are shown. In Table 1, the input parameters selected for design are represented for both charging and discharging cycles, along with the steam bypass flow inlet and outlet conditions. The steam flow conditions are derived from the APR1400 steam generator outlet conditions, and the MDST outlet pressure is matched for the original APR1400 high pressure turbine outlet condition.

The outcome of the optimization is also listed in the figure as optimal values selected for the highest round-trip efficiency. The genetic algorithm is adopted and run for 30 initial sets under 30 generations. At the optimal design, exergy destruction profile is calculated for each component, along with the relative exergy percentage.

Table 1. Design parameters and results for calculating the integrated layout

General design values	
Ambient temperature(°C)	25
Ambient pressure (kPa)	100
LAES Tank (kPa)	100
HX pressure drop (%)	1

Charging cycle design values	
Maximum charging pressure (MPa)	18.8
Air compressor efficiency (%)	85
Pinch point hot storage intercooler (K)	10
Cold box HX pinch point (K)	5
Cryoturbine efficiency (%)	70
Cold storage mass flow rate (kg/s)	273
Steam inlet temperature (°C)	285
Steam inlet pressure (MPa)	6.6
Steam outlet pressure (MPa)	1.5
MDST isentropic efficiency (%)	90

Discharging cycle design values	
Maximum discharging pressure (MPa)	14.5
Cryogenic pump efficiency (%)	70
Air evaporator pinch point (K)	5
Air recovery HX pinch point (K)	5
Air-hot storage HX pinch point (K)	10
Air turbine efficiency (%)	85

Design results	
Cold storage inlet temperature (K)	103
Cold storage outlet temperature (K)	299
Cold storage pressure (MPa)	14
Charging mass flow rate (kg/s)	347
Discharging mass flow rate (kg/s)	255
Hot storage mass flow rate (kg/s)	455
Liquid yield (%)	73.5
Air compressor work (MWe)	288
Cryoturbine work (MWe)	7
Cryopump work (MWe)	6
Air turbine work (MWe)	153
Heat rejection (MWth)	76
Round trip efficiency (%)	52.5
Required steam mass flow rate (kg/s)	1245

Table 2. Exergy destruction for each component of the integrated layout (top: charging cycle, bottom: discharging cycle)

Component	**Exergy Destruction (MW)**	**Percent of total (%)**
Compressor 1	9	5.8
Air-hot storage intercooler 1	3	1.9
Compressor 2	10	6.4
Air-hot storage intercooler 2	9	5.8
Mixing tee - hot storage	4	2.6
Cold box HX	14	9.0
Cryoturbine	12	7.7
MDST (total)	32	20.5

Component	**Exergy Destruction (MW)**	**Percent of total (%)**
Cryogenic pump	6	3.8
Air evaporator	13	8.3
Air HX	1	0.6
Air-hot storage HXs	7	4.5
Air turbines	20	12.8
Heat sink	16	10.3
Ambient loss at turbine exit	0.01	0.01

4. Conclusions

To integrate the LAES to increase flexibility of the existing nuclear plant, a technically feasible layout is suggested using MDST to drive the air compressors. The optimized results for maximum round-trip efficiency are presented, along with the exergy destruction profile for each component to observe the potential area of improvement. It can be concluded that the layout can make better use of the waste heat released to the ambient by modifying the discharging cycle layout.

Further works include the safety analysis of the steam bypass back to the secondary side merge point and the preliminary design of each component.

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