Design development of a full scale AA-CAES plant

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Abstract

Looking at the rising shares of renewables foreseen to aid the decarbonization of several economies and the increasing digitalization to support the bloom of smart grids, the investment on electric energy storage facilities is strongly desirable. The future electric networks will account for a widespread dissemination of energy producers where affordable and reliable energy storage systems are essential to optimize their management. This transition will be even more stressed in nations like Germany and Switzerland, which issued energy policies oriented to shut down coal-fired power plants by mid-late 2030s [1] and to phase out from the nuclear power by 2050 [2], respectively. Among the many energy storage technologies available nowadays, Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) plants can be comparable to pumped hydro systems (PHS) in terms of capacities and efficiencies. Therefore, a numerical model was developed in Matlab-Simscape to simulate the dynamics of AA-CAES plants and lately used to forecast the expected behavior of different designs. The final layout is the most promising one in terms of efficiency, reliability and availability of components.

Keywords

AA-CAES, dynamic model, energy storage, turbomachinery, TES

1. Introduction

In order to properly integrate and optimize the electric infrastructure towards the concept of sustainable smart grids, many energy storage technologies are under investigation. Nonetheless, traditional pumped hydro storage (PHS) still represents the performance benchmark for efficiency, reliability and lifespan. Despite its numerous benefits, its environmental impact is not negligible and the availability of adequate sites for additional plants is limited to specific sites with sufficient elevation differences. Moreover, the worsening of the climate changes might be reflected in water shortages which would place PHS plants in dispute with other fundamental needs besides energy storage, such as agricultural or industrial processes.

Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) plants are a promising candidate and a complementary alternative to PHS, in terms of both power and capacity. These systems can store electric energy via both thermal and mechanical energy storages by pressurizing air and storing it in underground caverns: electric energy feeds a motor coupled with a compressor, providing a high-pressure flow of hot air. This is cooled within a thermal energy storage (TES) and pressurized air is stored into a cavern. Electric energy can be recovered later by expanding the high-pressure air in the turbine- generator power block, after having recovered the thermal energy in the TES.

AA-CAES technology rose as an improvement of CAES plants, which found their first installations in Huntorf (Germany, 1978) and in McIntosh (United States, 1991), whose efficiencies are limited to 42% and 54% respectively [3], because the thermal energy content of air due to its compression is

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discarded. Therefore, fossil fuels are required during discharge phases to guarantee an adequate expansion of the pressurized air. In the AA-CAES concept, the need of fossil fuels is erased by storing the thermal energy content of the hot air exiting the compressor and recovering it before air expansion. Fig. 1 depicts two key advantages of the AA- CAES and PHS plants, with respect to other energy storage technologies: on the left-hand side [4], the economic competitiveness of AA-CAES plant in medium time scale is remarked. On the right-hand side of Fig. 1 [5], the ESOI index (the ratio of total electrical energy stored over the lifespan of a storage technology to its embodied primary energy) is reported. Technologies with the higher values are the less energy intensive. Since the index refers to CAES plants, AA-CAES ones are expected to be better thanks to the removal of fossil fuel needs.

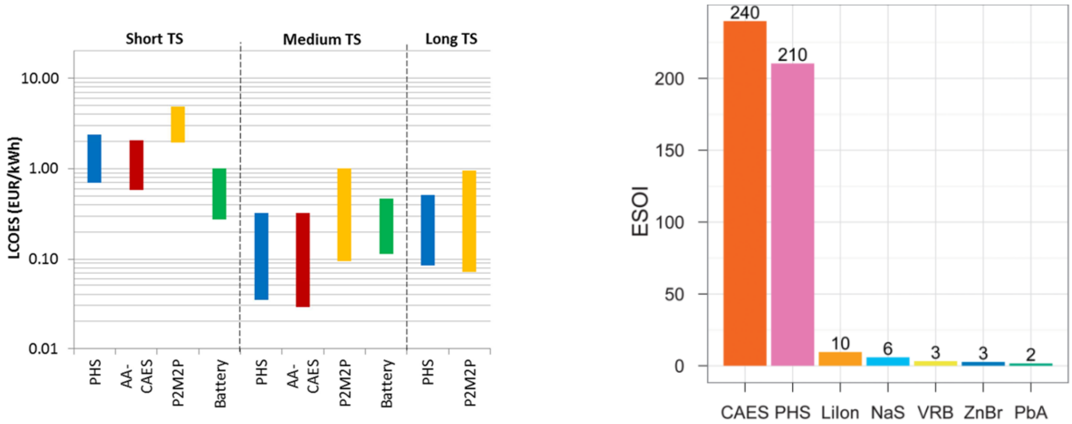

Figure 1: On the left LCOES for 100 MW storage systems with cost, efficiency, lifetime and electricity price variation [4], on the right ESOI index for load-balancing storage technologies [5].

2. Physical model

The AA-CAES plant model was built in Matlab-Simscape, an object-oriented software to simulate transients in physical networks, with customized blocks founded on the gas domain. Air was assumed as an ideal dry gas with temperature dependent properties: good accuracy was expected at high temperatures (reduced temperature T_R>2) regardless of pressure (except for $p_R \gg 1$), where T_R and p_R are the reduced temperature and pressure respectively (the critical point for air is T_{cr}=132.4 K, p_{cr}= 37.25 atm) [6].

The constitutive equations of each component of the AA-CAES plant were defined in order to model its dynamics: components in the gas domain can be modelled using control volumes which encompass the gas inside the component and separates it from the surrounding environment and other components. Components with big internal volume, for instance the cavern, were represented using an internal node, while other components with relatively small gas volumes, like turbomachinery, were considered quasi-steady-state and they do not have an internal node.

The compressor and turbine constitutive equations describe the thermodynamic transformations of air. The compression and expansion can be modelled either with isentropic or polytropic efficiencies. These were both implemented as efficiency maps, function of the volumetric flow rate or of the reduced mass flow and the pressure ratio upon the component. Assuming a power scheduling for the plant, the electric power from the grid is shared between the compressor stages, determining the mass flow rates during the plant charge. Similarly, during the discharging phases, one or more turbines feed a generator to deliver the scheduled power to the grid. Since the specific heat ratio of air varies with temperature, during the compressions and expansions an average of its initial and final values was adopted [7]

The dynamics of the caverns was described implementing the conservation of mass and energy. The former determines the mass variation within the volumes by summating the incoming and outgoing mass flows. The latter models the cavern energy variation in time accounting for the enthalpies associated to the aforementioned mass flow rates, the heat transfer occurring between the stored air and the cavern walls (by means of Newton's law of cooling with constant wall temperature and constant convective heat transfer coefficient) including also the TES thermal losses towards pressurized air. Indeed, the common idea behind the AA-CAES plant layouts presented in this paper was to exploit the cavern where pressurized air is stored to accommodate also the TESs. Thus, TES structure does not need to withstand high pressure differences, simplifying its design and reducing its costs. The TES is a packed bed of rocks in direct contact with the warm compressed air, which flows downwards to cool down and upwards to warm up. Having the hottest region on the top allows to stabilize the temperature stratification, since buoyancy forces avoid the detrimental onset of convective motions. Moreover, the low air conductivity together with the small contact areas among the rocks provide a high thermal resistance against the thermocline diffusion. The TES were designed as truncated cones, a shape that limits the ratcheting effect, caused by the different thermal expansions of rocks and structure, which generates high mechanical stresses with the risk of deformations and even cracks the walls themselves: the tilted storage walls re-direct these forces upwards, limiting lateral stresses. The reversed truncated cone also ensures a higher volume-to-surface ratio and a more uniform air velocity throughout the storage [8]. The AA-CAES model embeds a 1D code developed in FORTRAN to properly describe the TES physics and its thermocline evolution once its characteristics (i.e. geometries, insulation and rock properties) are defined [9], [10].

The physical model simulations can be either scheduled as series of cycles, either identical or different in amplitude and duration, or imported as hourly defined week. During the simulations feedback controls were necessary to cut the compressor train out if the maximum pressure was reached or to turn the turbine off when the cavern was emptied to its minimum.

The model was validated against the Huntorf CAES plant [11] and the Pollegio AA-CAES pilot plant built in Pollegio, Switzerland by ALACAES SA [12].

3. Exploring plant configurations

The model was used to verify the performance of different plant configurations, characterized by a high temperature TES and exploiting underground rock caverns in order to extend the availability of sites for the construction of AA-CAES systems.

3.1. First plant configuration

In the first plant configuration, depicted in Fig. 2, a LP compressor is connected to a LP TES, placed within a small airtight cavern (cavern 1) kept at 33 bar. An after-cooler, placed after the HP compressor stage, cools down the pressurized air flow before it is stored in the main cavern (cavern 2), in order to maximize the capacity with respect to cavern size and pressure limits, which were set from 80 to 100 bar. The discharging section of the plant includes a turbine where air expands after exiting the TES. Since the TES is place within cavern 1, a pressure equilibration between the two caverns is necessary: this is supposed to be done by connecting the two caverns and letting the air flow until pressure equilibrium. Namely, cavern 1 pressure increases from 33 to about 95 bar while cavern 2 pressure decreases from 100 to 95 bar. During the discharge phase of the A-CAES, the two caverns remain connected and the common pressure decreases from 95 to 80 bar. Before the subsequent charge phase, the two caverns are disconnected again. Analogously, at the end of a discharge phase, pressure in cavern 1 has to be reduced from 80 to 33 bar so that the LP compressor can operate without stalling. The expulsion of air from a nozzle towards the external ambient was reputed inefficient, since a sensible fraction of the stored mechanical energy would be discarded. Moreover, the thermal energy stored in the TES during charging phases would not be completely recovered since the total mass flowing through the TES during plant charges would be greater than the one during the discharging phases, due to the mass expelled from cavern 1. Therefore, an auxiliary turbine was implemented to guarantee the complete exploitation of the stored energy (both mechanical and thermal) during the depressurization phase.

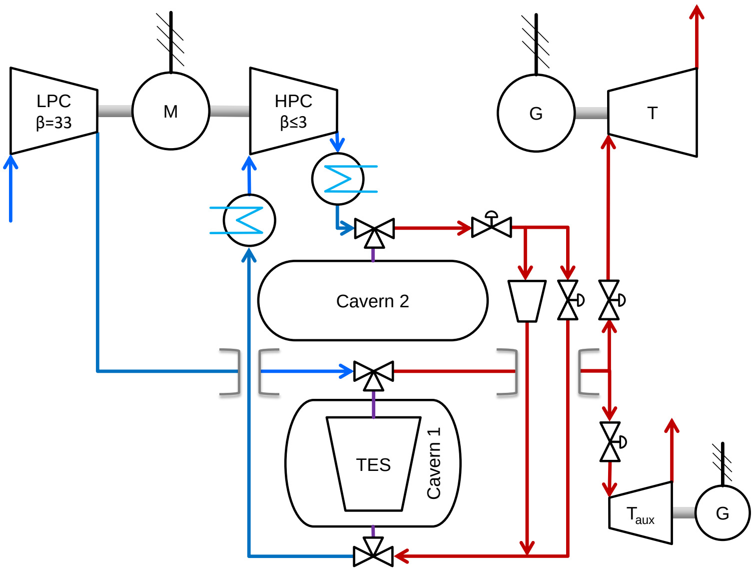

Figure 2: Schematic of the first plant configuration.

3.2. Second plant configuration

In the second plant configuration, illustrated in Fig. 3, an additional HP TES was accommodated within cavern 2, to replace the after-cooler and recover also the thermal energy of the HP compressor. To balance the system, a HP turbine is placed between the two caverns allowing the air pressure in cavern 1 to be kept constant and confining the pressure sliding in cavern 2.

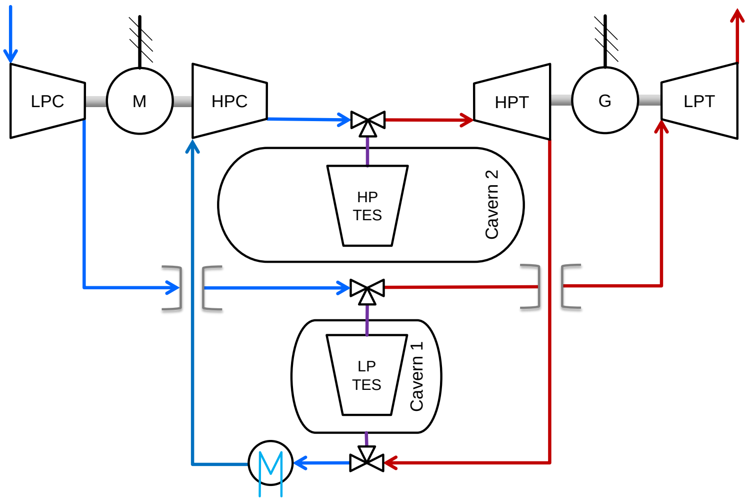

Figure 3: Schematic of the second plant configuration

3.3. Comparison

Looking at the two configurations, the main advantage of PC1 was the requirement of only one TES. However, the equilibrium and depressurization phases add idle times and operational complexity to the power plant, with the risk of a reduction of its responsiveness. These effects were evaluated with the model, which confirmed that the dynamics of cavern 1 was characterized by large temperature variations and dead-times associated to pressure adjustments [13]. Both of the effects are highly undesirable constrains for the AA-CAES plant: the former would likely affect the components life while the additional times to be accounted for pressurization and depressurization of the cavern 1 (at least 1 hour and 2.25 hour, respectively) would be detrimental for the plant responsiveness to the grid power demand. In the second plant configuration instead, both temperature and pressure variations in cavern 1 were limited. This goal can only be achieved if an adequate regulation of the mass flow rate of both compressors and turbines is possible. Transients of turbomachinery and their characteristics, especially their flexibility, play an important role in the plant operation. Finally, looking at the AA-CAES plant efficiency, defined as the ratio of the energy provided from the generator (connected to the turbines) over the one consumed in the motor (running the compressors), under regular cycling conditions the second plant configuration has a higher efficiency, 79% against 75% of the former.

4. Integration of available components

The promising good results of the previous simulations had to be verified by the availability of off-the-shelf machines: the influence of real turbomachinery behavior, the impact of their transients and energy requirements on the plant efficiency were the objectives of the following analysis.

Since AA-CAES technology is comparable to PHS in terms of energy capacity, power and expected round-trip efficiency, availability of adequate turbomachinery and their reaction times is of paramount importance to understand if and how the plant can compete in the storage markets. Start-up times are generally limited by thermal stresses: for high-temperature AA-CAES plants (> 400°C) reaction times are expected to be as flexible as gas-turbines plants (approximately 10-15 min; for PHS plants these are a maximum of 2 minutes [3]).

In order to investigate both the effects of real efficiency maps of compressors and turbines and of their transients on the plant grid-to-grid performance, MAN Energy Solutions Schweiz AG and ALACAES SA improved the AA-CAES plant depicted in Fig. 3. In the updated layout, the overall pressure ratio was evenly divided between the LP and HP components, combining commercially available state-of-the-art turbomachinery while balancing the effects of high temperatures [14].

4.1. Model update

The physical model was updated to properly include the energy required for turbomachinery transients (start-ups and shut-downs) and the integration of their efficiency maps. Compressor efficiency maps were defined as function of the volumetric flow rate and the pressure ratio while in the turbine ones as a function of the reduced mass flow rate and the pressure ratio [14].

Variable speed components would be more expensive and require dedicated electronics equipment, such as Variable Frequency Drivers, therefore constant speed machines were chosen as most suitable turbomachinery for both compressors and turbines. Their performance flexibility, whenever possible, is guaranteed by variable valve opening and variable inlet guide vanes.

The turbomachinery transients can be simplified in two phases:

1. a mechanical start-up phase, during which the turbomachinery speed accelerates from 0 rpm to a nominal speed at off-design process conditions;
2. a process/thermodynamic start-up phase, during which the turbomachinery, at constant rpm, reaches the operating point starting from off-design conditions. The duration of this phase is machine-specific.

To avoid frequent and costly machines starts and stops, the possibility of letting the compressor or turbine train rotate during idle (i.e., when the plant is neither storing nor producing electric energy) was examined. Unfortunately, the energy necessary for a turbomachinery train that rotates synchronously with the grid (3000 rpm for 50 Hz) during an idle phase was considered neither sustainable nor profitable. A more suitable option for idle phases in an AA-CAES plant was to keep both compressors and expanders warm and in slow rotation with a relatively small power consumption. In this way, too-long transients, strictly connected to the thermal inertia of the components and of the lubricating oil system, were avoided, with a beneficial impact on plant responsiveness of the plant. The transients were modelled accounting for the energy spent and the time required for typical turbomachine start-ups [14].

4.2. Simulation setup

The full-scale AA-CAES plant was tested under regular cycling 50 identical cycles composed of 5 hours of charge and 5 hours of discharge, separated by 0.1 hour of idle [14]. An initial pre-charge was introduced to foster the achievement of the stable periodic condition. The mechanical efficiencies of the electric motor and generator were set to 0.98. Cavern 2 had a volume of 177’000 m^3 and a wall area of 18’150 m^2. The 15 m height TESs (adiabatic) had a truncated cone shape with a top diameter of 32 m and a bottom one of 24.5 m. Cavern 1 dimensions were 34 x 34 x 16 m to accommodate the LP TES. A constant convective heat-transfer coefficient of 20 W/m^2K was assumed for both caverns. The power absorbed by the plant during the charging phases was set to 140 MW. The outlet temperature of the intercooler before the HP compressor was set to do not exceed 20°C.

4.3. Results

At the end of the 50 cycles, the AA-CAES plant was operating in stable periodic conditions. The grid-to-grid efficiency was around 75%, calculated as the ratio of the energy delivered by the generator over the one consumed by the motor and accounting for the energy required for turbomachinery transients and stops. Due to the sliding pressure operating condition, during the plant discharge the turbine train power delivered from 114.4 MW to 102.4 MW (due to the cavern 2 emptying and the corresponding pressure decreasing).

During the simulation the turbomachinery operated for most of the time (>96%) within their efficiency maps boundaries. The few exceptions occurred during the transients since they were affected by some simplifications in order to preserve the model robustness and complexity [14].

5. Conclusions

Two AA-CAES plant configurations were initially investigated: the former was characterized by a single high temperature TES after the LP compressor. In the latter plant configuration, an additional TES was placed after the HP compressor and consequently the turbine was split into LP and HP expanders. A numerical model was developed in Matlab-Simscape to create the digital twins of the proposed plant layouts and analyses their performance. Due to the importance of the TES to store the thermal energy, a 1D FORTRAN code was embedded to properly model the thermocline evolution during the plant operation. The first plant configuration required two additional phases, namely an equilibrium one, lasting around 1 hour to flatten cavern 1 and 2 pressure differences, and a depressurization phase, lasting around 2.25 hour to restore the nominal charging pressure in cavern 1. The second plant configuration overcame these limitations, increasing the plant flexibility and gathering higher plant efficiency under regular cycling conditions. Therefore, it was selected to include real turbomachinery efficiency maps and auxiliary energy consumption (due to transients and stand-by). The simulation was satisfactory since the selected turbomachinery worked most of the time within the nominal operating regions of the components. Moreover, the calculated plant efficiency reached 75% (grid-to-grid) confirming that this technology can play a relevant role with the other energy storages in guaranteeing a reliable electricity supply in future smart grids. Start-up energies influence on the AA-CAES plant efficiency was secondary but they can become more significant the shorter the cycles and the lower the turbomachinery power [14]. The best choice of the compressor and turbine operating modes during idles is therefore an outcome of the specific simulations and optimizations.

6. Acknowledgements

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