A Novel Performance Analysis Method for Compressed Air Energy Storage Systems (Postprint)

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Date: 2017-11-07T00:00:00+00:00

Abstract

In response to the characteristics of compressed air energy storage systems, including symmetry in system processes, correspondence of process points, and strong physical correlations between corresponding points, this paper proposes a novel corresponding-point analysis method applicable to compressed air energy storage systems. Mathematical models for corresponding-point efficiency, corresponding-device exergy efficiency, equipment factor, and recovery coefficient are established, which can reflect the local and overall recovery capabilities of the system, the performance of corresponding devices, and the direction for system optimization and improvement. Furthermore, this paper employs a supercritical compressed air energy storage system as a typical case study, demonstrating the practicality and simplicity of this analysis method. The research in this paper provides a concise method for the analysis of compressed air energy storage systems and possesses certain research and engineering value.

Full Text

A New Method for Performance Analysis of Compressed Air Energy Storage Systems

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Abstract

Compressed Air Energy Storage (CAES) systems exhibit characteristic features of process symmetry, point-to-point correspondence, and strong physical correlations between corresponding points. This paper proposes a novel corresponding-point analysis method tailored for CAES systems and establishes mathematical models for corresponding-point efficiency, exergy efficiency of corresponding equipment, equipment factors, and recovery coefficients. These models effectively reflect the recovery capability of both local and overall system components, the performance of corresponding equipment, and directions for system optimization. Using a supercritical compressed air energy storage (SCAES) system as a typical case study, the practicality and simplicity of this analytical method are demonstrated. This research provides a concise approach for analyzing CAES systems and holds significant value for both research and engineering applications.

Keywords: Compressed Air Energy Storage System; Analysis Method; Corresponding Point

0 Introduction

Compressed Air Energy Storage (CAES) systems offer advantages of large storage capacity, long storage duration, and low specific investment, making them one of the most promising large-scale energy storage technologies and attracting considerable attention from researchers worldwide [?, ?]. Since Stal Laval first proposed utilizing underground caverns for compressed air storage in 1949, numerous CAES system variants have been developed, including conventional CAES, Advanced Adiabatic CAES (AA-CAES), Liquid Air Energy Storage (LAES), Humid Air Turbine CAES (CASH), Supercritical CAES (SCAES), Small-Scale CAES (SSCAES), and CAES systems coupled with other technologies [?, ?]. Although these systems differ in process configuration, all involve air compression and expansion processes, exhibiting certain process symmetry and parameter correspondence with strong physical interconnections.

Current CAES system analyses primarily employ traditional First Law energy balance methods and Second Law exergy balance approaches [?], which fail to account for the characteristic symmetry and parameter correspondence of CAES systems, resulting in complex analysis and optimization procedures. This paper proposes a corresponding-point analysis method specifically suited for CAES systems by examining these process characteristics, and demonstrates its application through a typical case study.

1 Characteristics of CAES Systems

[Figure 1: see original paper] illustrates the process flow diagram of a conventional CAES system. During charging, electricity drives compressors to pressurize air stored in underground caverns, thereby storing energy. During discharging, high-pressure air from the cavern enters a combustion chamber to mix with fuel, producing high-temperature gas that expands through a turbine. The process reveals corresponding points in the system flow, such as compressor outlet corresponding to turbine inlet, and compressor inlet corresponding to turbine outlet.

[Figure 2: see original paper] shows an AA-CAES system flow diagram. The primary difference from conventional CAES is the elimination of fossil fuels through recovery of compression heat for heating turbine inlet air. For the typical case where compressor and turbine stages are equal in number, process symmetry and point correspondence become more pronounced: each compressor inlet corresponds to a turbine outlet, each compressor outlet corresponds to a turbine inlet, and the storage cavern inlet corresponds to its outlet.

[Figure 3: see original paper] presents an SCAES system flow diagram. During charging, air is compressed to a supercritical state, liquefied after recovering compression heat and utilizing stored cold energy, and stored in a liquid air tank. During discharging, liquid air is pressurized, heated, and expanded through a turbine to drive a generator. The SCAES system also exhibits good process symmetry and point correspondence: compressor inlets/outlets correspond to turbine inlets/outlets; high-temperature inlet/outlet of the cold storage regenerator; low-temperature inlet/outlet of the cold storage regenerator; and outlet/inlet of the liquid air storage tank.

This paper defines two points that correspond in the process as "corresponding points." In the SCAES system shown in [Figure 3: see original paper], the corresponding point pairs are: 1-25; 2-24; 3-23; 4-22; 5-21; 6-20; 7-19; 8-18; 9/10-(16+17); 11-(15+14); 12-(13+14). The energy storage endpoint and release starting point are termed "storage corresponding points" (storage points) (when considering storage losses, a specific time must be defined). During charging, the working fluid undergoes various thermodynamic processes with changing states, ultimately reaching the storage point. During discharging, the fluid parameters are progressively restored through a series of corresponding processes. Due to energy losses, discharge process parameters cannot fully recover to their corresponding point values (without external energy input or excluding external energy effects). Therefore, this paper analyzes system performance by examining parameter recovery at corresponding points during discharge and exergy exchange between corresponding equipment and the environment.

2.1 Selection Principles for Corresponding Points and Equipment

The corresponding-point analysis method builds upon thermodynamic calculation results to determine system performance and optimization directions through parameter calculations. [Figure 4: see original paper] shows the model of corresponding points and equipment for CAES systems, dividing both charging and discharging processes into N equipment units that correspond one-to-one, forming N corresponding equipment units (the dashed box shows the i-th corresponding equipment) and N+1 corresponding points. The storage point serves as the link between charging and discharging processes, with its exergy value equal to the air exergy in the storage cavern (selected at a specific time based on actual conditions).

For effective system analysis and optimization, corresponding points and equipment should satisfy the following principles: enable comprehensive evaluation of overall and local "recovery" performance; preferably combine equipment of the same type; and enable focus on local losses and internal energy transfer.

The total exergy input to the i-th through N-th corresponding equipment during charging is described by the exergy value at the i-th corresponding point during charging, E_i^S, and the thermal exergy and work input from the environment to the i-th corresponding equipment during charging, $E_{Q,i}^S$ and W_i^S, respectively.

The total exergy output from the i-th through N-th corresponding equipment during discharging is described by the exergy value at the i-th corresponding point during discharging, E_i^N, and the thermal exergy and work output from the i-th corresponding equipment to the environment during discharging, $E_{Q,i}^N$ and W_i^N, respectively.

Treating the i-th through N-th corresponding equipment as an integrated unit, the performance of equipment downstream of the i-th corresponding point can be described by $\eta_{i\text{-dot}}$. We define $\eta_{i\text{-dot}}$ as the corresponding-point efficiency of point i. When i equals 1, the corresponding-point efficiency becomes the system exergy efficiency.

2.3 Recovery Coefficient and Equipment Factor

The recovery coefficient of corresponding equipment i is defined based on the relationship between equipment performance and storage point characteristics, where L_{storage} is the exergy value at the storage point. We define L_i as the equipment factor, which represents the relative impact of each equipment unit on system performance.

Additionally, based on equation (4), we can derive simplified relationships for system optimization. The equipment exergy efficiency, equipment factor, recovery coefficient, and other parameters provide directions for system optimization and improvement. In practice, the derived relationships generally hold, so the following analysis is based on this assumption.

Taking the derivative of $\Delta\eta_i$ with respect to L_i^N yields expressions that indicate $\Delta\eta_i$ is more sensitive to L_i^N. Further from the storage point, as $\eta_{i\text{-dot}}$ decreases and downstream input exergy increases, the sensitivity difference between $\Delta\eta_i$ to L_i and L_i^N becomes larger (described by their ratio), while the overall sensitivity to both decreases.

When m = N, the analysis shows that when L_i remains constant and mutual influence among ξ_i is small, the corresponding-point efficiency is more sensitive to equipment with larger equipment factors. Therefore, to improve system efficiency, particular attention should be paid to corresponding equipment with larger equipment factors.

2.4 Exergy Loss and Exergy Efficiency of Each Corresponding Equipment

The total exergy loss generated by the i-th through N-th corresponding equipment is calculated based on the difference between input and output exergy values. Substituting the appropriate relationships yields the total system exergy loss.

The exergy loss generated by the i-th corresponding equipment is determined by analyzing the specific processes within each equipment unit. The exergy efficiency of each corresponding equipment is defined as:

$$\eta_E = \frac{\text{benefit exergy}}{\text{cost exergy}} \tag{21}$$

According to this definition, the rationality of exergy efficiency depends on the selection of "benefit exergy" and "cost exergy," which should be carefully distinguished for different equipment. Unlike corresponding-point efficiency, which evaluates the performance of a local process segment including the storage point, the exergy loss and exergy efficiency of corresponding equipment can evaluate any local process segment within the system, providing complementary analysis capabilities.

Compared with traditional system energy balance and exergy balance analysis methods, the corresponding-point analysis method focuses on corresponding points and equipment in CAES systems, calculating corresponding-point efficiency, corresponding equipment exergy efficiency, equipment factors, and recovery coefficients to provide a concise analytical approach.

3 Case Study

This paper uses SCAES ([Figure 3: see original paper]) as a typical case for corresponding-point analysis. The basic system parameters are shown in . The pressure reduction device in the liquefaction section employs a liquid expander. Based on the actual configuration of corresponding equipment (compressor-turbine, intercooler-reheater, cold storage regenerator, liquid expander-cryogenic pump), the exergy efficiencies are defined as follows:

For compressor-turbine equipment: cost exergy is compressor power consumption; benefit exergy is the sum of turbine output work and unrecovered air exergy (or cost exergy minus exergy loss).

For intercooler-reheater equipment: cost exergy is the exergy decrease of air in the intercooler; benefit exergy is the exergy increase of air in the reheater (or cost exergy minus exergy loss).

For cold storage regenerator equipment: cost exergy is the exergy decrease of air during discharging; benefit exergy is the exergy increase of air during charging.

For liquid expander-cryogenic pump equipment: cost exergy is the exergy value at the liquid expander inlet; benefit exergy is the sum of cryogenic pump outlet exergy, total output work, and the difference between liquid expander outlet exergy and cryogenic pump inlet exergy (representing exergy loss recoverable in other equipment), which equals cost exergy minus exergy loss.

System Calculation Basic Parameters - Charging pressure: kPa - Discharging pressure: kPa - Intercooler/reheater temperature difference: K - Intercooler/reheater pressure loss: kPa - Cold storage regenerator minimum temperature difference: K - Cold storage regenerator pressure loss: kPa - Compressor isentropic efficiency - Turbine isentropic efficiency - Liquid expander isentropic efficiency - Cryogenic pump isentropic efficiency

This case study neglects losses in the low-temperature liquid storage tank, so the air state within the tank represents the storage point state. Based on these exergy efficiency definitions, the corresponding-point analysis results are presented in , where point 25' represents the state after exergy dissipation from the final turbine exhaust. Corresponding equipment is numbered 1S-1N through 11S-11N from the starting point to the storage point.

shows that corresponding-point efficiency decreases progressively from the storage point to the starting point (points 1-25'). The efficiency at corresponding point 1-25' represents the system exergy efficiency at 0.6227. The efficiency reduction values caused by each compressor-turbine stage are 0.0585, 0.0504, 0.0438, and 0.0376, respectively, showing a decreasing trend. This occurs because although exergy losses are similar across stages, $E_{i\text{-SINPUT}}$ differs, with larger values near the starting point making efficiency changes less sensitive to identical exergy losses. This phenomenon can also be explained by equation (11).

The efficiency reduction values caused by each intercooler-reheater stage are 0.0029, 0.0059, 0.0099, and 0.0269, respectively, showing an increasing trend. This indicates that although $E_{i\text{-SINPUT}}$ is larger near the input end, intercooler-reheater losses increase more rapidly. The liquid expander-cryogenic pump reduces corresponding-point efficiency by 0.0335, while the cold storage regenerator reduces it by 0.103, demonstrating significant exergy loss in the cold storage liquefaction section that warrants performance improvement.

Exergy loss coefficients for each compressor-turbine stage are approximately 4.68% with similar exergy efficiencies around 0.815. Moving from storage to starting point, intercooler-reheater exergy loss coefficients are 0.98%, 1.54%, 2.33%, and 4.78%, with exergy efficiencies of 0.8277, 0.7162, 0.5966, and 0.3215, respectively. This shows increasing exergy loss and decreasing efficiency, particularly for the low-pressure intercooler-reheater, indicating that parameter improvements should focus on reducing losses in this section. The cold storage regenerator and liquid expander-cryogenic pump have exergy loss coefficients of 5.09% and 3.80%, with efficiencies of 0.9049 and 0.9665, respectively. The relatively high loss coefficients stem from the value of cold exergy, where losses are more pronounced even at similar component efficiencies.

Comparing equipment factors reveals that intercooler-reheater factors are 2-2.5 times those of compressor-turbine units. The cold storage liquefaction section exergy efficiency (corresponding-point efficiency) is approximately 0.8635. Compressor-turbine exergy efficiencies remain around 0.815, while intercooler-reheater efficiencies are 0.3215, 0.5966, 0.7162, and 0.8277. System efficiency can be improved by reducing losses in low-pressure intercooler-reheaters and the cold storage liquefaction section.

Equation (17) indicates that improving intercooler-reheater exergy efficiency (recovery coefficient) is more effective than improving compressor-turbine recovery coefficients. The cold storage regenerator has a large equipment factor and recovery coefficient greater than 1 (ideally 1). Equation (11) shows that to prevent excessive efficiency reduction across the regenerator, the corresponding-point efficiency at its low-temperature end should remain high and close to 1. Therefore, liquid expander-cryogenic pump performance significantly impacts system efficiency, as demonstrated by the notable efficiency drop when throttling valves are used for pressure reduction in SCAES systems [**?**].

Recovery coefficients affect the magnitude of corresponding-point efficiencies. In this system, the numerical relationship of recovery coefficients causes corresponding-point efficiency to decrease progressively from storage point to starting point.

Since SCAES can be viewed as a combination of compression-expansion sections (compressors, turbines, intercoolers, reheaters) and cold storage liquefaction sections (cold storage regenerator, liquid expander/throttling valve, cryogenic pump, low-temperature storage tank), system research can be divided accordingly. Based on , the cold storage liquefaction section exergy efficiency (corresponding-point efficiency) is approximately 0.8635. In practice, since work exchange between the cryogenic pump and liquid expander with the environment is minimal, the ratio of exergy at point 16 to point 10 can approximate the cold storage liquefaction section exergy efficiency.

Beyond the computational analysis, equations (15) and (16) reveal that for compressor-turbine equipment, reducing turbine exergy loss is more effective for improving system efficiency than reducing compressor exergy loss. For intercooler-reheater equipment, reducing reheater exergy loss is more effective than reducing intercooler exergy loss.

4 Conclusions

Addressing the characteristics of process symmetry, point correspondence, and strong physical correlations in CAES systems, this paper proposes a corresponding-point analysis method for CAES.

1. Mathematical models for corresponding-point efficiency, corresponding equipment exergy efficiency, equipment factors, and recovery coefficients

were established. Corresponding-point efficiency reflects overall and local recovery capability, while corresponding equipment exergy efficiency reflects equipment and local performance. The analysis method provides direction for system improvement and optimization.

2. The relationship between efficiency reduction values and recovery coefficients/equipment factors shows that efficiency reduction correlates with the proportion of downstream input exergy occupied by equipment factors and the difference between downstream point efficiency and equipment recovery coefficient. Under certain conditions, system efficiency is more sensitive to recovery coefficients of equipment with larger equipment factors.
3. SCAES corresponding-point analysis reveals that the cold storage regenerator high-temperature end corresponding-point efficiency is 0.8635, indicating significant room for improvement in the cold storage liquefaction section. The analysis demonstrates the method’ s effectiveness in identifying optimization opportunities.

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