International Conference on Applied Energy 2019
Aug 12–15, 2019, Västerås, Sweden
Paper ID: 734

ENERGY ANALYSIS OF MULTISTAGE COMPRESSED AIR ENERGY STORAGE SYSTEM

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ABSTRACT

To satisfy the demands for fast-response peak regulation in power grids, the development of multistage compressed air energy storage (MCAES) system has accelerated in recent years. However, because of system imperfections, such as redundant structures, excessive numbers of energy conversion stages, and lower total utilization rate, it is necessary to identify and mitigate the weaknesses of the system. Consequently, this study conducts the thermodynamic analysis of MCAES. First, the efficiency losses in the working processes of the MCAES are considered, and a system node is added based on existing modular models, making the model more robust. Second, the effects of process parameters on system performance metrics, including power generation efficiency and residual heat, are studied. Finally, the weighted correlation network analysis (WGCNA) is used to analyze the sensitivity of various equipment and process parameters to system efficiency under different structures. Through the weight comparison, the weak points are located, which provides detailed theoretical guidance for the structural design and equipment parameter selection of MCAES.

Keywords: Compressed air energy storage system, Thermodynamic analysis, Correlation relationship analysis

NOMENCLATURE

Abbreviations	
com	Compression
ec	Heat exchange
ef	Efficiency
ex	Expansion
thr	Throttle
TES	Thermal Energy Storage
Symbols	
P	Power
p	Pressure
Q	Quantity of heat
W	work
R_g	Ideal gas constant
T	Temperature
t	Time
η	Efficiency
λ	Energy grade factor

1. INTRODUCTION

Access to efficient and large-scale energy storage systems is an effective manner to solve the problem of renewable energy fluctuations and improve the reliability of electrical power distribution systems [1]. The multi-stage compressed air energy storage (MCAES) system, which is a new type of energy storage method, can realize the large-capacity, long-term storage of energy, and has been rapidly developed in recent years [2].

However, owing to several energy conversion stages in the system, the overall energy utilization efficiency is low, and that has become a key factor limiting the large-scale deployment of compressed air storage power stations. To identify the system's weaknesses and optimize the system structure, domestic and foreign scholars have conducted research on the technical and economic performance of MCAES. Audrius Bagdanavicius et al. studied the energy conversion characteristics of MCAES in [3]. The results show that the energy utilization efficiency of MCAES is increased from 48% to 66% by recovering the heat generated by compression. Erren Yao studied the performance of

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

adiabatic compressed air energy storage (A-CAES) connected to a combined cooling, heating, and power (CCHP) system in [4]. A sensitivity analysis results show that the heat exchanger energy efficiency value, turbine inlet temperature, and inlet pressure have a great influence on the thermal performance of the A-CAES system. In the literature [5] which compared the effects of structure parameters on the exergy loss of the A-CAES process. In the literature [6–7] which analyzed the influence of key equipment parameters on system energy conversion efficiency. The above literature has advanced progress on the performance of the A-CAES system. However, most of the existing literature analyzed the sensitivity of single parameter changes, which ignored the coupling relationship between various parameters and cannot fully describe the system performance parameters. Meanwhile, single parameter sensitivity analysis cannot intuitively compare the correlation between parameters and system performance.

To solve the above problems, based on the established model, the effects of structure and process parameters on system power generation efficiency and residual heat of the heat storage tank are studied. To perform the multi-parameter sensitivity analysis, this study (1) uses the WGCNA method to analyze the influence of various input parameters on system performance, (2) studies the relationship between various parameters, (3) views the interaction network of different parameters, and (4) draws the correlation graph which clearly analyzes the correlation between the parameters and the efficiency. The specific research content is as follows.

2. THERMODYNAMIC MODULAR MODELING

The MCAES structure is shown in Figure 1. The system includes five subsystems: compression, expansion, heat exchange, gas storage, and heat storage.

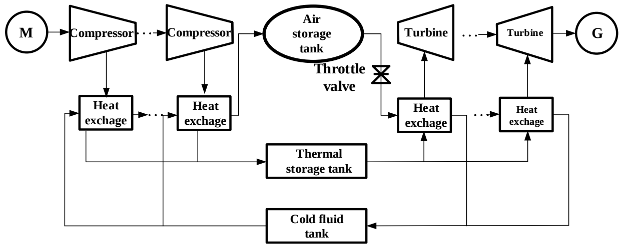


Figure 1. Structure of MCAES

The modular model has been described in detail in the literature [8–9]. Based on the modular model, this study adds the overpressure loss and throttling loss model to make the model more robust.

The overpressure loss is

$$\Delta P_{com} = R_g T_{n,out} \ln \frac{p_{\max}}{p_{stor}(t)} . \tag{1}$$

The throttle loss is

$$\Delta P_{\mathrm{thr}} = R_{\mathrm{g}} T_{\mathrm{stor}} \ln \frac{p_{\mathrm{stor}}(t)}{p_{\min}} . \tag{2}$$

The entire power generation efficiency of the system can be calculated as follows.

$$\eta_1 = \frac{W_{\mathrm{ex}}}{W_{\mathrm{com}}} , \tag{3}$$

Considering the residual heat in the heat storage tank, the total efficiency of the system is defined as follows.

$$\eta_2 = \frac{W_{\mathrm{ex}} + \lambda Q_{TES}}{W_{\mathrm{com}}} , \tag{4}$$

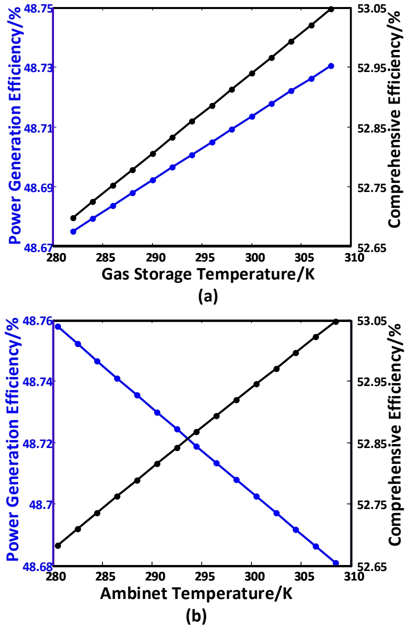
Because of the different grade of heat and electric energy, the energy grade factor λ is equal to 0.1[9].

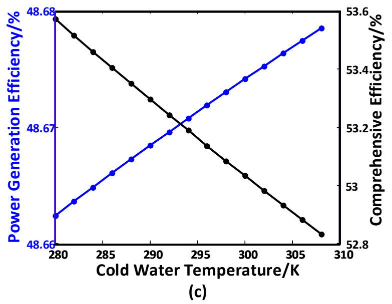
3. THERMODYNAMIC CHARACTERISTIC ANALYSIS

Thermodynamic analysis is an important prerequisite for structural optimization and efficient control of MCAES. To compare and verify the sensitivity analysis presented in the following text, this section studies the thermal characteristics of MCAES based on the previously mentioned model.

3.1 Influence of Process Parameters

Figure 2 is the simulation result of the influence of process temperatures on system performance.



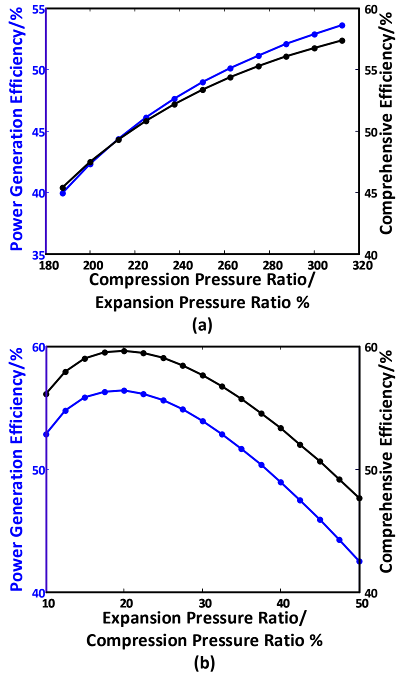


(c)

Fig.2 Impact of temperature parameters on system efficiency

According to the model, as the gas storage temperature increases, the node loss of the gas storage and throttling process decreases, which leads to the increase of the system efficiency; as the ambient temperature and cold water temperature increase, the inlet and outlet temperatures of the compression process will increase, resulting in an increase in both compression work and system heat storage. However, the simulation results show that the ambient temperature and cold-water temperature have opposite effects on the two evaluation indices of the system, and the trend is close to linear. In general, temperature has less effect on system efficiency.

Figure 3 shows the effect of changes in pressure ratio and expansion ratio on system performance under simulated structural levels.



(a)

(b)

Figure 3. Impact of pressure parameters on system performance

The increase in pressure ratio will inevitably lead to an increase in compression work, as well as in the inlet and outlet temperature of the compressor. Correspondingly, the heat storage temperature will also rise, which will drive the rise of expansion work. As shown in the simulation results, as the pressure ratio increases, the expansion power increment is greater than the compression power increment, and the system power generation efficiency and the total efficiency increases with the compression pressure ratio.

When the total expansion ratio of the system is increased, the single-stage expansion ratio and the system expansion power will increase, and the throttling loss will decrease. Simultaneously, the system expansion time will be reduced, and the heat storage tank heat consumption will increase. The simulation results show that when the expansion ratio changes, the system efficiency first rises and then falls, and the optimal total expansion pressure is approximately 22% of the maximum pressure.

At the simulation level, the flow change has no effect on system performance. However, during the operation of the system, due to the loss of resistance along the pipeline, the flow rate change will change the working temperature and process pressure loss, thus reducing the system efficiency.

3.2 Influence of Equipment Parameters

The obvious impact of compression and expansion equipment efficiency on system performance is not discussed here. This section focuses on the impact of heat exchanger efficiency of the compression heat exchanger on system performance.

Figure 4 shows the simulation results of the effect of heat transfer efficiency on system performance.

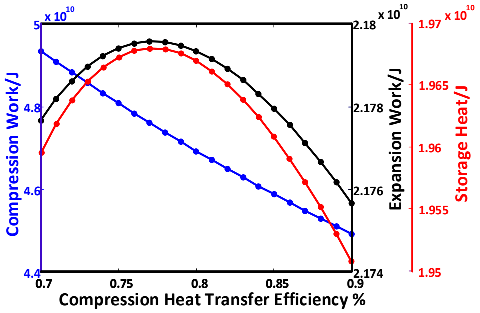
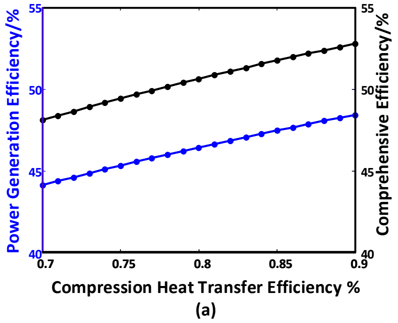
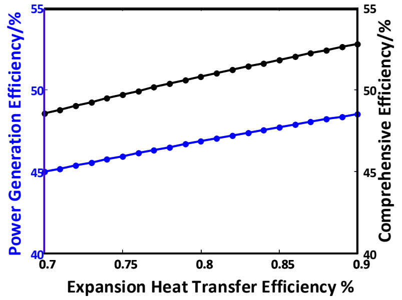


Figure 4. Impact of compression heat exchanger efficiency on compression work, expansion work and storage heat



(a)



(b)

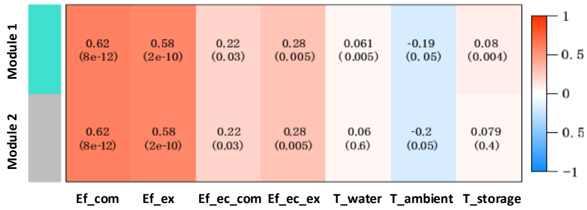
Figure 5. Impact of heat exchanger efficiency on system efficiency

It can be seen from the analysis of the results in Figure 4 that as the heat exchanger efficiency increases during the compression process and the inlet temperature of each stage's compressor decreases, which leads to the decrease of compression work. In terms of the change of stored heat, the increase of heat exchange efficiency will increase the relative heat transfer amount of each stage. On the other hand, the increase in the efficiency of the pre-heat exchanger will reduce the hot fluid inlet temperature of the after-stage heat exchanger, resulting in the decrease of the heat transfer in the subsequent stage. From the overall simulation results, the system storage heat follows an upward and then downward tendency; correspondingly, the system expansion work also shows a similar trend due to changes of the heating temperature.

The expansion stage heat exchanger has a single influence on the system performance due to decoupling from the compression process. As can be seen from Figure 5, as the heat transfer efficiency increases, the system efficiency increases approximately linearly.

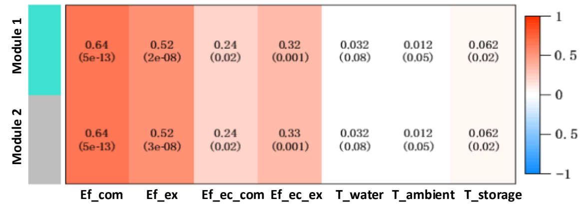
4. SYSTEM PARAMETER CORRELATION ANALYSIS

The single parameter analysis method has certain limitations which make it impossible to intuitively compare the importance of different parameters on system performance. Weighted gene co-expression network analysis (WGCNA) is a statistical method used to describe the relevance between different samples. The positive and negative correlation and the degree of correlation between samples and targets are determined by the color of each sample parameter in the phenotype diagram [10]. The advantage of WGCNA is that it makes full use of information to convert the association of thousands of target parameters and phenotype into the association of several target sets and phenotypes, and intuitively obtain the correlation between the target and each sample. In this section, WGCNA was used for engineering analysis for the first time. This study takes 50 different combinations of parameters and calculates the system efficiency of 2000 sampling points under the combination, and it obtains several efficiency sets (gene sets). The analysis results are shown in Figure 6 and Figure 7.



	Ef_com	Ef_ex	Ef_ec_com	Ef_ec_ex	T_water	T_ambient	T_storage
Module 1	0.62 (8e-12)	0.58 (2e-10)	0.22 (0. 03)	0.28 (0.005)	0.061 (0.005)	-0.19 (0. 05)	0.08 (0.004)
Module 2	0.62 (8e-12)	0.58 (2e-10)	0.22 (0.03)	0.28 (0.005)	0.06 (0.6)	-0.2 (0.05)	0.079 (0.4)

Figure 6. Generation efficiency correlation analysis by WGCNA



	Ef_com	Ef_ex	Ef_ec_com	Ef_ec_ex	T_water	T_ambient	T_storage
Module 1	0.64 (5e-13)	0.52 (2e-08)	0.24 (0.02)	0.32 (0.001)	0.032 (0.08)	0.012 (0.05)	0.062 (0.02)
Module 2	0.64 (5e-13)	0.52 (3e-08)	0.24 (0.02)	0.33 (0.001)	0.032 (0.08)	0.012 (0.05)	0.062 (0.02)

Figure 7. Comprehensive efficiency analysis by WGCNA

The numbers outside the parentheses in the table describe the correlation, and the numbers in parentheses represent the credibility of the correlation result (the result is credible only if the number is less than 0.05,). The rows in the phenotype diagram represent highly inlined efficiency sets. There is no artificial classification of efficiency data in this study. Module 1 in each figure contains 99.1% of the total efficiency concentration, so only the correlation results of the first row need to be consulted. Among them, the change of equipment parameters has a considerable influence on the efficiency, and the influence of compressor and expander efficiency is obviously greater than that of heat exchanger efficiency. The influence of temperature parameters is basically negligible. The experimental results are consistent with the analysis results in the second section.

5. CONCLUSION

In this paper, the energy conversion process and node loss of MCAES are considered comprehensively, and the modular model is improved. On this basis, the influence of process parameters and equipment parameters on the thermal performance of MCAES was studied. To address the shortcomings of the single parameter analysis method, this study applies the WGCNA to the engineering field analysis for the first time. Through the phenotype chart, the influences of equipment efficiency, temperature, and other parameters on system efficiency are compared. The results show that equipment performance is the key factor determining the conversion efficiency of MCAES. Moreover, the conversion efficiency of compressor and expander has the most severe impact on system power generation efficiency and total efficiency.

ACKNOWLEDGEMENT

This work is supported by the Foundation for Innovative Research Groups of NSFC (61821004), National Natural Science Foundation of China (61573223, 61733010), and fundamental research funds of Shandong University (2018JC032)

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