Performance analysis of the compressed-air power station with a constant volume storage battery

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Abstract. The considerations of compressor and gas-turbine equipment operation as a part of compressed air energy storage (CAES) during the work with variable-pressure accumulator affects on upstream efficiency all plant. Feature of operation of the constant volume storage battery is continuous pressure decrease during a discharge. In conditions when the maximum pressure in the accumulator exceeds admissible pressure in front of the gas turbine, process of selection of air is carried out in two stages: a throttling up to the maximum and admissible size in front of the turbine with the subsequent transition to the mode of the sliding pressure. The generalized method of calculation of indicators of the compressed-air power station with a constant volume storage battery is presented. The tests of the compressor and gas-turbine equipment as a part of CAES on the basis of the gas turbine GT-100-750-2 during the work with constant volume storage battery are constructed. For the accepted structure of the compressor and gas-turbine equipment which is a part of the compressed-air power station, the specific electric supply on unit of a consumption of the scooped air have made 0.004 kWh/kg; the net efficiency on electric supply of CAES – 18.8%.

1. Introduction
It is known that in schemes of compressed air energy storage (CAES) with a constant volume storage battery the damping container in the form of a reservoir is absent. The compressor, using surplus and economy night power, pumps air to an underground cavity. During peak of electricity load compressed air is selected from the underground cavity and used in the gas turbine for electrical generation.

Processes of air injection and bleed in storage proceed with its changing the parameters (pressure, density, discharge). It affects on change of characteristics of a compressor and gas-turbine power equipment as a part of CAES. Moreover, if characteristics’ change of the compressor while injecting is typical for CAES operation with different types accumulators characteristics’ change of gas turbine equipment while air bleeding takes place only when CAES operates with variable-pressure accumulator. Operation of this type accumulators of this type is characterized by constantly changing parameters of the stored compressed air in its selection.

Thus, considerations of compressor and gas-turbine equipment operation as a part of CAES during the work with variable-pressure accumulator affects on upstream efficiency all plant. Generalized design procedure of CAES while operating with variable-pressure accumulator is explained below.
2. Method of calculation

The gas-turbine compressor which is a part of CAES, as a rule, consists of several parts. As there is a strong functional connection between compressor speed, its weight output and developed pressure all follow-up calculations are carried out on the basis of characteristics of each part of the compressor, showing dependence of compressor pressure ratio, efficiency on the dimensionless quantity weight output. On characteristics these parameters are limited by lines of the pure number of speed, dividing a working zone of the compressor and a zone where compressor can’t work in (the surging begins).

Mass air flow rate:

\[ G_1 = G_{1n} \cdot \sqrt{\frac{T_{1n}}{T_1} \cdot \frac{P_1}{P_{1n}}} \]  

(1)

where \( G_1 \) – mass air flow rate of a low pressure compressor (LPC), kg/s; \( T_1 \) – air temperature in front of the compressor, K; \( P_1 \) – air pressure in front of the compressor, bar; similar parameters with the \( «n» \) index belong to nominal parameters of the compressor; \( G \) – the dimensionless mass air flow rate determined by the characteristic of the compressor.

The specified speed:

\[ n_1 = \sqrt{\frac{T_{1n}}{T_1}} \]  

(2)

On these values according to the characteristic of LPC there is compressor pressure ratio and efficiency. Further the following parameters are calculated.

The compressor specific work of LPC (\( L_1 \)):

\[ L_1 = C_p \cdot T_1 \cdot \left( \sigma_{kl}^m - 1 \right) \cdot \frac{1}{\eta_1} \]  

(3)

where \( C_p \) – air specific heat, kJ/(kg·K); \( \sigma_{kl} \) – compressor pressure ratio; \( m \) – index; \( \eta \) – compressor efficiency.

The air temperature behind the compressor:

\[ T_1' = T_1 + \frac{L_1}{C_p} \]  

(4)

The air pressure behind the compressor:

\[ P_1' = \sigma_{kl} \cdot P_1 \]  

(5)

The air temperature at the exit from the aftercooler of LPC:

\[ T_2' = T_1' - \psi \left( T_1' - T_n \right) \]  

(6)

where \( \psi \) – the efficiency of the aftercooler.

The pressure at the exit from the cooler behind the compressor:

\[ P_2' = P_1' \cdot \sigma_{pl} \]  

(7)

where \( \sigma_{pl} \) – the pressure loss factor in the aftercooler.
After that, according to the received temperature values and exit pressure, on the basis of conditions of constant mass flow, the similarity criterion according to the characteristic of the high pressure compressor (HPC) is calculated and compressor pressure ratio and efficiency of HPC are defined.

During air accumulator charging parameters on an entrance of the compressor remain constants, and at the exit – pressure of air increases. Therefore the working point on the compressor characteristic changes all the time, moving on curve n = const.

Calculation of process of downloading comes to an end at approach to the compressor surge line.

As the final pressure of air in storage is higher than admissible for the turbine, at the discharge pressure of compressed air decreases to maximum and admissible value of pressure in front of the turbine.

The pressure reduction is made until pressure of compressed air isn't equal in the accumulator:

\[ P_{ac} = \frac{P_{GT}^{\text{max}}}{\sigma_f \cdot \sigma_{ce} \cdot \sigma_{tv}} \]  \hspace{1cm} (8)

where \( P_{ac} \) – the pressure of compressed air in the accumulator, bar; \( P_{GT}^{\text{max}} \) – the maximum and admissible value of pressure of compressed air in front of the turbine, bar; \( \sigma_f \) – the efficiency of the air filter; \( \sigma_{ce} \) – the combustion efficiency; \( \sigma_{tv} \) – the size of pressure losses in the throttle valve.

After achievement of admissible value of compressed air pressure in front of the turbine, the throttle valve is completely opened, and the air accumulator begins to work in the mode of the sliding pressure. For obtaining the largest accuracy calculation is conducted by separate small periods to which there corresponds a certain value compressed air pressure in the accumulator.

On each new time span of \( \omega t \) of a discharge receiving new value of compressed air pressure in front of the turbine \( (P_{GT}) \), expansion rate is defined \( (\sigma_{GT}) \):

\[ \sigma_{GT} = \frac{P_{GT}}{P_{\text{exit}}} \]  \hspace{1cm} (9)

where \( P_{\text{exit}} \) – the combustion product pressure of at the exit from the gas turbine, bar.

Using characteristics of the gas turbine, on the basis of dimensionless criteria of similarity, on received \( \sigma_{GT} \) there is an efficiency of the turbine and a mass air flow rate.

After each selection of air the amount of the air stored in the accumulator decreases and is:

\[ m = m_0 \cdot \gamma_{\text{leak}} - G \cdot t \]  \hspace{1cm} (10)

where \( m_0 \) – initial amount of the compressed air stored in the accumulator, \( m^3/\text{day} \); \( G \) – the consumption of compressed air at selection, kg/h; \( t \) – production time, h/\text{days}, \( \gamma_{\text{leak}} \) – leak of compressed air which makes \( 1 \cdot 10^{-5} \% \div 1 \cdot 10^{-3} \% \) of amount of the compressed air stored within a day in the accumulator [1].

On the basis of the ideal gas equation compressed air pressure in the accumulator will be:

\[ P_{ac} = \frac{m \cdot R \cdot T_{ca}}{V_{ac}} \]  \hspace{1cm} (11)

where \( R \) – individual gas constant for air, J/(kg·K); \( T_{ca} \) – temperature of compressed air in the accumulator, K; \( V_{ac} \) – the volume of the air accumulator, \( m^3 \).

The accumulator operation in the sliding pressure mode will be continued until pressure of compressed air isn't fixed on minimum admissible, from operation view point, value. After that the CAES operation with a constant volume storage battery comes to an end.

As indicators of efficiency of the CAES operation with a constant volume storage battery it is possible to use the following indicators.

The specific amount of the scooped air is defined on unit of volume of the accumulated air:
where \( g_{ac} \) – the specific amount of the accumulated air, kg/m\(^3\); \( V_{st} \) – the volume of storage at the end of injection air, m\(^3\); \( G_{ac} \) – the amount of the accumulated (active) air, kg.

Quantitative assessment of the scooped air generation can be defined on the basis of a specific electric supply on unit of a consumption of the scooped air \( e \), (kWh/kg):

\[
e = \frac{P_{pr} - P_{com}}{G_{ac}}
\]

where \( P_{pr} \) – the amount of the produced electric power of the gas turbine CAES, kWh; \( P_{com} \) – electric energy consumption by the compressor in the course of CAES charging, kWh; \( G_{ac} \) – the amount of the accumulated air for one daily cycle, kg.

The net efficiency on electric supply of CAES can be determined as follows:

\[
\eta_{elas} = \frac{P_{pr} \cdot 3600 \cdot \left(1 - \beta_{apr}\right)}{C_{sp} \cdot \left(P_{com} + C_{GT}\right) \cdot Q}
\]

where \( C_{sp} \) – specific reference fuel consumption for electric supply for the compressor drive in the course of CAES charging, kgCE/(kWh); \( C_{GT} \) – fuel consumption for the compressor drive in the course of CAES charging, kgCE; \( Q \) – combustion value of fuel equivalent, kJ/(kg·K); \( \beta_{apr} \) – the auxiliary power requirements (without the compressor drive).

3. Results
As an example of calculation the scheme CAES submitted in the figure 1 has been chosen. The intercooled twin-cylinder compressor of axial-flow-type at rate of 197.4 kg/s is a part of CAES. The exducer in operating time of the compressor is completely open.

On the air filter there is a throttling. Therefore on an entrance of the compressor there are following parameters: \( T_1 = 288 \) K, \( p_1 = 0.97 \) bar, \( \sigma_p = 0.97 \).

Low and high compressor-capacity curve, it agrees [2], are shown respectively in figures 2 and 3. The efficiency and the compressor pressure ratio, according to these characteristics, increase at decrease in a mass air flow rate. And the high pressure compressor parameters change more considerably.

Originally for LPC at the accepted compressor pressure ratio – 2.8, according to the characteristic, the mass air flow rate has made 1.05; the LPC efficiency – 0.8.

As a result of calculations of LPC the following values have been received. The temperature at the exit from LPC – 163.9 °C; the air pressure – 2.71 bar. According to the characteristic of HPC the mass air flow rate has made 1.26; the compressor pressure ratio – 2.5; the HPC efficiency – 0.66.

As a result of calculations of HPC the following values have been received. The temperature at the exit from HPC – 204.9 °C; the air pressure – 6.3 bar; the air consumption – 202.9 kg/s. Further increase pressure of the pumped air is possible only to value of 9.8 bars. Further increase in pressure of air leads to hit of characteristics of the compressor in a surge zone. The working point on characteristics of compressors moved on curve \( n = 1.05 \).

At a mass air flow rate of HPC air equal to 1.063; the compressor pressure ratio has made 3.34 bars; the HPC efficiency – 0.845; the air temperature at the exit from HPC – 485.45 K, the consumption of air was cut at the same time up to 197.8 kg/s.
Figure 1. The simple CAES scheme
1 – the engine; 2 – the low-pressure compressor (LPC), 3 – the high pressure compressor (HPC);
4 – the aftercooler; 5 – the air accumulator; 6 – the air filter; 7 – the throttle valve; 8 – the combustor;
9 – the gas turbine; 10 – the electrical generator unit.

Figure 2. The characteristic of the low pressure compressor.
Figure 3. The characteristic of the high pressure compressor.

In the figure 4 the power characteristics of compressors of high and low pressure of CAES constructed depending on pressure of compressed air in the accumulator are shown during its charging. From the figure 4 it is visible that during charging, increase in pressure of compressed air in the accumulator from 6.3 bars to 9.8 bars is followed, first of all, by increase of the compressor pressure ratio: at the compressor of low pressure with 2.8 to 3.25 (16%); at the compressor of high pressure with 2.5 to 3.34 (33.6%). Other parameters change as follows. Air temperature for HPC increases on 16.6 ºС (8.1%), temperature behind the aftercooler of LPC – on 1.8 ºС (4.8%); the LPC efficiency increases by 0.041%, the HPC efficiency – 0.185%; the consumption of air was cut on 5.1 kg/s (2.5%). In general, taking into account timed charging of 3.4 hours, the quantity of the consumed electric power was 293.62 MWh/days.

As the peak gas turbine the single-cylinder design like GT-100-750-2 with inlet temperature of gases 750 º and with a maximum pressure of 7.8 bars is accepted. Characteristics of the gas turbine, according to [3], are presented in the figure 5.

Feature of operation of the constant volume storage battery is continuous pressure decrease during a discharge.

The maximum pressure is equal in the accumulator 9.8 bars. It exceeds admissible pressure in front of the gas turbine, it needs to be throttle. The air throttling is carried out up to the maximum and admissible pressure of compressed air in front of the turbine at the level of 6.8 bars. Losses in the throttle valve are accepted by 3 %. Temperature of the compressed air stored in constant volume storage battery is accepted 70 ºC.
Figure 4. Power characteristics of the CAES compressors, depending on pressure in the air accumulator during charging.

After a throttling stage operation of the accumulator switches over to the mode of the sliding pressure. This stage will proceed until pressure in the accumulator is established at the level of the air accumulator, minimum admissible from the point of view of operation, pressure of 4.4 bars. Losses on a throttling at this stage of a discharge are absent.

For obtaining the largest accuracy the calculation of air extraction is carried out by separate small periods. The certain value of compressed air pressure in the storage battery is corresponded to these intervals. So, calculation of the throttling stage of air in front of the turbine is performed in two stages, with pressure decrease of air in the accumulator up to 8.3 bars, and up to 6.8 bars. Calculation of turbine operation on the sliding pressure is performed also in 2 stages, with pressure decrease to 5.3 bars and up to 4.4 bars.
At each stage of air selection is set by new value of compressed air pressure in the accumulator. Further the new value of expansion rate is defined, and according to the characteristic of the turbine the efficiency corresponding value of the turbine and a mass consumption of air is calculated. Then using (10 and 11) is found time of a discharge and the amount of the produced electric power, on this time span. In the figure 6 the power characteristics of the gas turbine of CAES constructed depending on pressure of compressed air in the storage battery during his discharge are submitted.

These characteristics are constructed for the 0.45 million m$^3$ air accumulator. The shaded area belongs to the throttling time of compressed air in front of the turbine.

Abscissa axis, in the figure 6, is presented by 2 parameters: pressure of compressed air at each stage of air extraction in the storage battery $P_{ac}$ and the corresponding value of time of a discharge $\tau_{dis}$. On ordinate axes the following parameters are postponed: the expansion rate $\sigma_{GT}$, the mass air flow rate via the turbine $G$, the temperature of gases behind the gas turbine $t_{GT}$, the electric power of the gas turbine $N_{GT}$, the mass of compressed air at extraction $M_{extr}$, the remained mass of compressed air in the accumulator $M_{rem}$, the efficiency of the gas turbine $\eta_{GT}$, quantity of the amount of the produced electric power of the gas turbine $P_{pr}$.

Apparently from the figure 6, the compressed air extraction from the constant volume storage battery accompanied with pressure decrease from 9.8 bars to 8.3 and up to 4.4 bars leads to reduction of extent of expansion rate with 8.0 to 4.23 (47%); the temperature of gases behind the gas turbine increases with 385 °C to 476 °C (23%), the electric power falls from 99.8 MW to 76.6 MW (23.2%). Besides, the mass of the selected compressed air fluctuates in the range of 0.68÷ 0.43 thousand tons per day.

The indicators of work of compressed air energy storage with the a constant volume storage battery, for the accepted set of the equipment are presented in the table.
Figure 6. The power characteristics of the gas turbine of the station, depending on pressure in the storage battery during a discharge
Table. Performance indicators of CAES with the constant volume storage battery.

| The indicator                                               | The value |
|-------------------------------------------------------------|-----------|
| The amount of the scooped (active) air for a daily cycle, thousand tons | 2.4       |
| The total of the air stored in the accumulator, thousand tons  | 4.48      |
| The electric power consumption by the compressor in the course of CAES charging, $P_{com}$, kWh | 293.62    |
| The charging time, $\tau_{ch}$, hours a day                  | 3.4       |
| The electrical supply by the gas turbine in the course of CAES discharge, $P_{gt}$, kWh | 302.97    |
| The discharge time, $\tau_{disch}$, hours a day               |           |
| The specific amount of the scooped air, $g_{ac}$, kg/m$^3$    | 5.2       |
| The specific electric supply on unit of a consumption of the scooped air, $e$, kWh/kg | 0.004     |
| The net efficiency on electric supply of CAES, $\eta$, %     | 18.8      |

4. Conclusions

1) The generalized method of calculation of indicators of the compressed-air power station with a constant volume storage battery is presented. The tests of the compressor and gas-turbine equipment as a part of CAES on the basis of the gas turbine GT-100-750-2 during the work with constant volume storage battery are constructed.

2) The storage battery charging by compressed air is carried out by the compressor in the mode of the sliding pressure. For the accepted conditions at increase in pressure of compressed air from 6.3 bars to 9.8 bars compressor pressure ratio at the low pressure compressor increases in the accumulator for 16%, at the high pressure compressor – for 33.6%; air temperature for HPC increases on 16.6 °C, temperature behind the cooler after LPC – on 1.8 °C; LPC efficiency increases by 0.041%, HPC efficiency – for 0.185%; the consumption of air is cut for 2.3%. Increase in pressure of air in the accumulator is carried out at an exception of hit of characteristics of the compressor in a surge zone.

3) In conditions when the maximum pressure in the accumulator exceeds admissible pressure in front of the gas turbine, process of selection of air is carried out in two stages: a throttling up to the maximum and admissible size in front of the turbine with the subsequent transition to the mode of the sliding pressure. The throttling time, is followed by pressure decrease of air from 9.8 bars to 8.3 bars, and up to 6.8 bars, a stage of operation of the turbine on the sliding pressure – up to 5.3 bars and 4.4 bars. In general bleed compressed air from constant volume storage battery, is followed by pressure decrease from 8.3 to 4.4 bars. It leads to reduction of expansion rate by 47%, temperature of gases behind the gas turbine increases on 91 °C, electric power falls for 23.2%. For the accepted structure of the compressor and gas-turbine equipment which is a part of the compressed-air power station, the specific electric supply on unit of a consumption of the scooped air have made 0.004 kWh/kg; the net efficiency on electric supply of CAES – 18.8%.

References

[1] Olkhovsky G G, Kazaryan V A and Stolyarevsky A.Ya 2011 Compressed-air power station (Moscow: Gubkin Russian State University of Oil and Gas) p 358 [in Russian]
[2] Olkhovsky G G 1971 Thermal test of stationary installation (Moscow: Energy) p 408 [in Russian]
[3] Measurements of gas turbines GT-100 (A FT-100 gázturbina mérései) 1975 (Budapest: VEIKI Közlemények) p 25
[4] Aminov R Z and Novichkov S V 2017 Use of the absorption lithium bromide refrigerating machine for increase in overall performance of compressed-air power station Izvestya Vuzov. Problemy energetiki 19 62–72 [in Russian]
[5] Aminov R Z and Novichkov S V 2017 The modification of gas turbine installation at the air-storage gas turbine plant *Transaction of Academenergo* 2 84–92 [in Russian]

[6] Guo Ch, Pan L, Zhang K, Oldenburg C M, Li C and Li Y 2016 Comparison of compressed air energy storage process in aquifers and caverns based on the Huntorf CAES plant *Applied Energy* 181(1) 342–56 DOI: 10.1016/j.apenergy. 2016.08.105

[7] Buffa F, S. Kemble, Manfrida G and Milazzo A 2013 Exergy and Exergoeconomic Model of a Ground-Based CAES Plant for Peak-Load Energy Production *Energies* 6 (2) 1050–67 DOI: 10.3390/en6021050

[8] Lv S, He W, Zhang A, Li G, Luo B and Liu X 2017 Modelling and analysis of a novel compressed air energy storage system for trigeneration based on electrical energy peak load shifting *Energy Conversion and Management* 135 (1) 394–401 DOI: 10.1016/j.enconman. 2016.12.089.

[9] Mazloum Y, Sayah H and Nemer M 2017 Dynamic modeling and simulation of an Isobaric Adiabatic Compressed Air Energy Storage (IA-CAES) system *Journal of Energy Storage* 11 178–90 DOI: 10.3390/j.est.2017.03.006

[10] Liu W, Liu L, Zhou L, Huang J, Zhang Y, Xu G and Yang Y 2014 Analysis and optimization of a compressed air energy storage – combined cycle system *Entropy* 16 (6) 3103–20 DOI: 10.3390/e16063103

[11] Tsiruleva N N, Khlynin A S, Sorokina N A, Khozin AM and Lavrov V N 2013 Development of a low-emission fuel combustion system in gas turbine plants *Gas industry* 10 26–8 [in Russian]