AUTOMATION AND ELECTRICAL CONTROL OF A COMPRESSED AIR ENERGY STORAGE SYSTEM

AUTOMATICA ȘI CONTROLUL ELECTRIC AL UNUI SISTEM DE STOCARE ENERGIE ÎN AER COMPRIMAT

Cristian NECHIFOR[1], Claudia SĂVESCU[2,*], Iulian Vlăducă[3],
Remus STOICA[4], Adrian SĂVESCU[5], Eduard VASILE[6],
Mihaela ROMAN[7], Daniel UȘERIU[8]

Abstract: *This work aims to develop the automation system for the motor-compressor and expander-generator systems of a compressed air energy installation, henceforth referred to as ROCAES. Considering that the expander and compressor operate independently according to the scope of work, a solution comprising two separate automation systems that work together was chosen. The software programming was performed relying on the established parameter lists and in accordance with the project's piping and instrumentation diagram, as well as the equipment mounted on the skid and in the automation cabinets. Guidelines are provided for future development, emphasizing the strengths and weaknesses of the solution.*

Keywords: Compressed Air Energy Storage, Twin-Screw Compressor and Expander, Asynchronous Machines, Industrial Automation, Control System.

---

[1] Dr. Engr., Automation and Electrical Engineering Department, INCDT COMOTI, *ORCID ID 0009-0004-4937-3470*.

[2] Dr. Engr., Automation and Electrical Engineering Department, INCDT COMOTI, *ORCID ID 0000-0001-9578-1222* (*Corresponding author e-mail: claudia.borzea@comoti.ro).

[3] Engr., Aviation and Industrial Turbines Department, Romanian Research and Development Institute for Gas Turbines COMOTI, *ORCID ID* 0000-0002-3508-8941.

[4] Engr., Automation and Electrical Engineering Department, INCDT COMOTI, *ORCID ID 0009-0003-4515-0512*.

[5] Prog., Automation and Electrical Engineering Department, INCDT COMOTI, *ORCID ID 0000-0003-0559-1172*.

[6] Engr., Screw Compressors Packages, INCDT COMOTI, *ORCID ID 0009-0001-5260-7539*.

[7] Engr., Automation and Electrical Engineering Department, INCDT COMOTI, *ORCID ID 0000-0003-2694-9233*.

[8] Engr., Centrifugal Compressors and Blowers Department, INCDT COMOTI, *ORCID ID 0009-0000-1143-2077*.

Rezumat: *Această lucrare își propune să dezvolte sistemul de automatizare pentru sistemele motor-compresor și expander-generator ale unei instalații de aer comprimat, cu acronimul ROCAES. Dat fiind faptul că expanderul și compresorul funcționează independent conform caietului de sarcini al proiectului, a fost aleasă o soluție constând în două sisteme de automatizare separate, care pot opera atât împreună, cât și independent. Programarea software a fost realizată pe baza listei de parametri și în conformitate cu diagrama de instrumentare a sistemului, ținând cont de echipamentele montate pe skid și în dulapurile de automatizare. Lucrarea furnizează o serie de linii directoare pentru dezvoltări ulterioare, punând accent pe punctele forte și pe slăbiciunile acestei soluții.*

Cuvinte cheie: Stocare energie în aer comprimat; Compresor și expander cu șurub; Mașină electrică asincronă; Automatică industrială; Sistem de control.

1. Introduction

Electrical energy storage refers to a process of converting electrical energy from the grid into another form that can be stored and subsequently reconverted when needed [1, 2]. CAES (Compressed Air Energy Storage) installations, which store energy in the form of compressed air, represent a technique for conserving the electrical energy to meet consumption demands during peak periods. These installations are conceived as a backup solution for renewable energy sources, such as wind turbines and photovoltaic parks [3, 4]. Their major limitations are the low power density and intermittency, largely depending on the local site and unpredictable weather conditions [5].

High-capacity installations employing underground storage (Figure **1**) can use salt caverns, depleted oil or natural gas reservoirs, aquifers, hard rock mines, etc. CAES equipment uses compressors to store pressurized air into a reservoir, and the compressed air is subsequently released into an expander that drives an electric generator supplying into electric grid.

In a CAES power plant [7, 8], compression usually occurs during periods of low electricity demand and hence with lower prices per kWh. Large-scale installations have very low efficiency, being commercially viable only in regions where electricity prices fluctuate dramatically. The air compression and expansion cycles introduce losses through thermal effects, which limit the efficiency [5]. The feasibility of these installations is also limited by terrain topography, requiring specific geological structures [6, 9].

This paper presents a relatively small CAES station developed within a pilot project, with storage in an air reservoir.

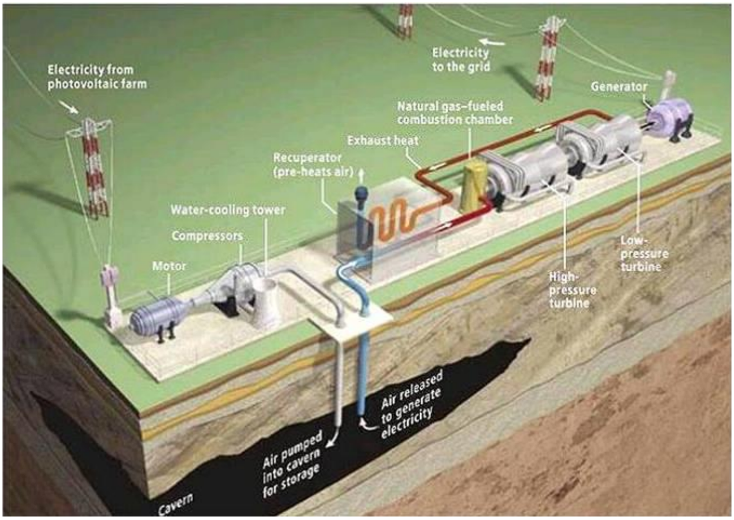

Figure 1. Schematic representation of a CAES installation [6]

2. Constructive solution

The ROCAES installation, whose block diagram is presented in Figure 2, uses a 100 kW screw compressor driven by a 110 kW three-phase asynchronous motor and a 132 kW screw expander that drives a 132 kW three-phase asynchronous generator [10–13].

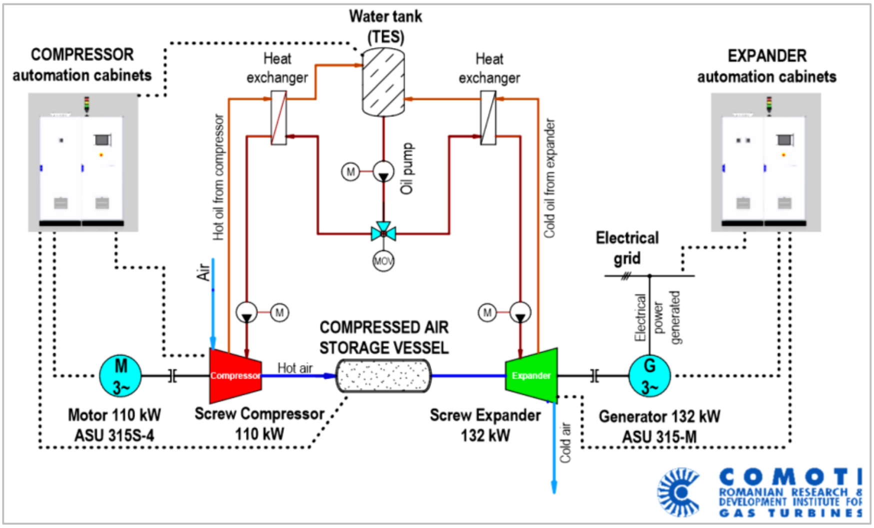

Figure 2. ROCAES block diagram

Both the motor and the electric generator are connected to the 50 Hz electrical grid, with the motor absorbing energy and the generator supplying electrical power into the grid. A 50 m^3 pressurized air reservoir and a 5 m^3 water storage tank for thermal energy storage (TES) complete the implemented solution installed in-situ.

The ROCAES energy storage installation makes use of a twin-screw compressor and a screw expander, both with oil injection. Due to their simple construction, reliability and decent efficiency (~74% in our case here), the equipment provides quite a viable solution for the considered application.

The compressor (Figure 3) and the expander (Figure 4) do not operate simultaneously.

Figure 3. Compressor skid

Figure 4. Expander skid

Therefore, the control is realised using two Programmable Logic Controllers (PLCs), one for expander, and one for compressor and other station elements including the compressed air reservoir and the water storage tank for oil’s thermal conditioning (cooling for the compressor and heating for the expander). When the compressor pumps, hot air accumulates in the compressed air storage reservoir. The lubricating and cooling oil exiting the compressor’s separator vessel passes through a thermal storage system, heating the thermal agent that transfers heat to the expander’s oil circuit.

Figure 5 shows the automation control cabinets designed and commissioned for compressor and expander skids, each of them comprising equipment split into two sections, namely the drives section – left, and the monitoring section – right. A modular solution was chosen for the cabinets, without separating walls between the drives and monitoring sections, for a better ventilation and cooling of the electrical equipment installed.

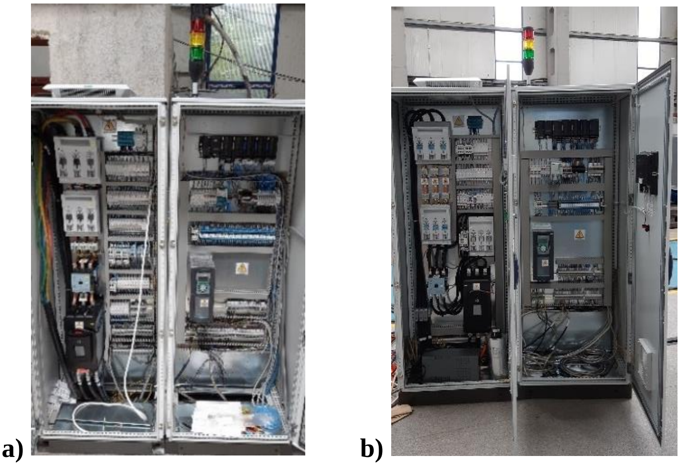

Figure 5. Control cabinets for: **a)** compressor and **b)** expander

For extended periods of time, neither the compressor nor the expander operates. The operation of the installation is related to certain optimal functioning periods: the compressor operates when there is a surplus of electrical energy, and the expander operates when there is shortage of energy. During standby periods, it would be ideal that the compressed air reservoirs to be full, ready to release the air into the expander-generator system. After opening the motor-operated valve before the intake, it takes maximum 20 seconds to start generating electrical energy.

Entering the generation mode is achieved by gradually opening the control valve, considering the instantaneous storage pressure. Fine-tuning of the injected power can be achieved, however limited by certain parameters such as the suction pressure, the discharge pressure, the air temperature, the oil temperature towards expander discharge, etc.

3. Automation System and Electric Drives

For the electric drive of the expander, a three-phase asynchronous machine with a rated power of 132 kW was chosen, ASU 315M-4 manufactured by UMEB. The compressor is driven by a 110 kW asynchronous motor type ASU 315S-4. In our application, the expander's electric machine is started up as motor and is accelerated to its synchronous speed (1500 rpm), moment when the valves open automatically and the compressed air from the reservoir is released into the expander, which spins the electric machine above its synchronous speed, in electric generator mode. The generated power is henceforth supplied into the electrical grid.

The software programming [14] was carried out relying on the established parameter lists and the designed electric diagrams, in accordance with the project's piping and instrumentation diagram, as well as considering the equipment mounted on the skid and in the automation and power cabinets.

Initially, the electric machine of the expander operates in asynchronous motor mode (started via softstarter) until it reaches the idle speed. It then automatically enters in generator mode, driven by the released compressed air, controlled by the implemented PLC software, and being able to generate electrical power up to approximately 138 kWe. The choice of asynchronous machines significantly simplifies grid connection, as they do not require additional synchronization manoeuvres with the grid's frequency.

The active electrical power output by the generator increases with the increase in power from the primary machine. The advantages of asynchronous machines are as follows:

- Simple construction and high safety in exploitation;
- Well-suited for a fully automated operation: start-up – loading – network operation, without human intervention.
- It has a high dynamic loading capacity, able to achieve a torque up to three times its rated torque and a high starting capacity, with torque up to two times the rated torque.
- Stability in operation, exploitation, manoeuvring, simple maintenance;
- Electrical supply directly from the three-phase alternating current grid;

- High technical performances – the asynchronous machines used herein, ASU 315S-4 and ASU 315M-4 have an efficiency η = 94,5%;

However, there are also several disadvantages, such as:

- High start-up shocks;
- In the current configuration, it can only operate on a network connected to the national system, unable to operate on an isolated network;
- For generator operation, reactive power is required, which is drawn from the grid or from a reactive power source. During operation, there is a continuous, oscillating exchange of reactive power between machine and grid, which can overload the grid with reactive component.

Reactive power can, however, be compensated using capacitive reactance. The reactive power issue was managed herein by providing a capacitors battery in the expander's drives cabinet. This prevents overloading the grid and consequently eliminates the need to increase the size of the connecting conductors, allowing them to be sized based on the active current output of the generator. For the analysis of energy parameters within the grid, a network analyser with a digital display is provided [15].

Table 1. Calculation formula used by the network analyser [15]

Phase variables	System variables	Energy metering
Instantaneous effective voltage $V_{1N} = \sqrt{\frac{1}{n} \cdot \sum_1^n (V_{1N})_i^2}$ Instantaneous active power $W_1 = \frac{1}{n} \cdot \sum_1^n (V_{1N})_i \cdot (A_1)_i$ Instantaneous power factor $\cos \varphi_1 = \frac{W_1}{VA_1}$ Instantaneous effective current $A_l = \sqrt{\frac{1}{n} \cdot \sum_1^n (A_1)_i^2}$ Instantaneous apparent power $VA_1 = V_{1N} \cdot A_1$ Instantaneous reactive power $\mathrm{var}_1 = \sqrt{(VA_1)^2 - (W_1)^2}$	Equivalent three-phase voltage $V_\Sigma = \frac{V_1+V_2+V_3}{3} \cdot \sqrt{3}$ Voltage asymmetry $ASY_{LL} = \frac{V_{LLmax} - V_{LLmin}}{V_{LL\Sigma}}$ $ASY_{LN} = \frac{V_{LNmax} - V_{LNmin}}{V_{LN\Sigma}}$ Three-phase reactive power $\mathrm{var}_\Sigma = (\mathrm{var}_1 + \mathrm{var}_2 + \mathrm{var}_3)$ Three-phase active power $W_\Sigma = W_1 + W_2 + W_3$ Three-phase apparent power $VA_\Sigma = \sqrt{W_\Sigma^2 + \mathrm{var}_\Sigma^2}$ Total harmonic distortion $THD_N = 100 \frac{\sqrt{\sum_{n=2}^N \lvert X_n \rvert^2}}{\lvert X_1 \rvert}$ Three-phase power factor $\cos \varphi_\Sigma = \frac{W_\Sigma}{VA_\Sigma}$	$k\ \mathrm{var}\ hi = \int_{t1}^{t2} Qi(t)dt \cong \Delta t \sum_{n1}^{n2} Qnj$ $kWhi = \int_{t1}^{t2} Pi(t)dt \cong \Delta t \sum_{n1}^{n2} Pnj$ where: *i* – phase (L1, L2 or L3); *P* – active power; *Q* – reactive power; t_1, t_2 – starting and ending time point of consumption recording; *n* – time unit Δ; Δ*t* – time interval between two successive power consumptions; n_1, n_2 – starting and ending points for consumption recording.

This device can provide the following information, as listed hereinafter. Among these parameters, those of interest, retrieved as 4-20 mA current signals by the PLC's analogue inputs include the three-phase apparent power and instantaneous effective current (generator's analyser), and the instantaneous active power and reactive power (network analyser).

4. Commissioning tests and experimental results

The operation of the expander-generator system was tested in-house by connecting the expander intake to a Compressor of High-Pressure (CHP) of rated power 250 kW. The CHP provided and maintained a discharge pressure of 12-14 bar, supplying air into the expander intake at a pressure of ~4 bar. The electric machine of the expander was started as motor by means of a softstarter, with the expander intake valve open.

It is crucial to start up the expander-generator system with the intake valve open towards the compressed air source. Insufficient air pressure on the intake may create vacuum during expansion, causing dangerous vibrations (shocks) in the equipment when the vacuum encounters higher atmospheric pressure outside at the outlet. A preliminary set of operational tests were conducted independently with the two sub-systems, namely the motor-compressor skid and the expander-generator skid. The power delivered to the grid (Wr) is lower than the generated power (Wg) because the generated power also has to supply the power needed for the 4 kW motor of the oil pump, as well as to power the electrical consumers in the control cabinets.

The recorded data from the expander-generator system was represented graphically in Figure 6, showing a maximum generated power of 66.1 kW, out of which 64.6 kW were supplied into the grid. An instantaneous power peak of 31.8 kW, absorbed from the grid, was recorded when the motor was reaching synchronous speed.

The temperatures recorded during this set of tests are plotted in Figure 7. Under normal operating conditions, it is crucial to ensure the heating of the air and oil entering the expander. The maximum achievable power output is limited by the air temperature inside the expander, which drops dramatically below -15 °C or lower after only 20 minutes of operation if the lube oil is not heated, according to the experiments in [13].

Since the maximum power which can be generated is limited by the temperatures of the expansion equipment, prolonged exposure to low temperatures is highly uncommendable, as it would degrade the lube oil quality and potentially damage the two screw rotors of the expander.

Additionally, ice needles may form due to the relative humidity of the air, which presents a very high risk of expander gripping.

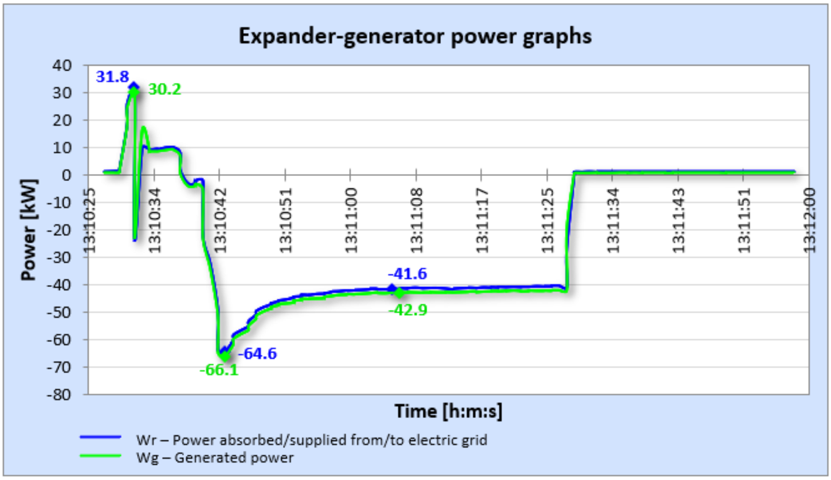

Figure 6. Power recorded during operation with continuous oil heating

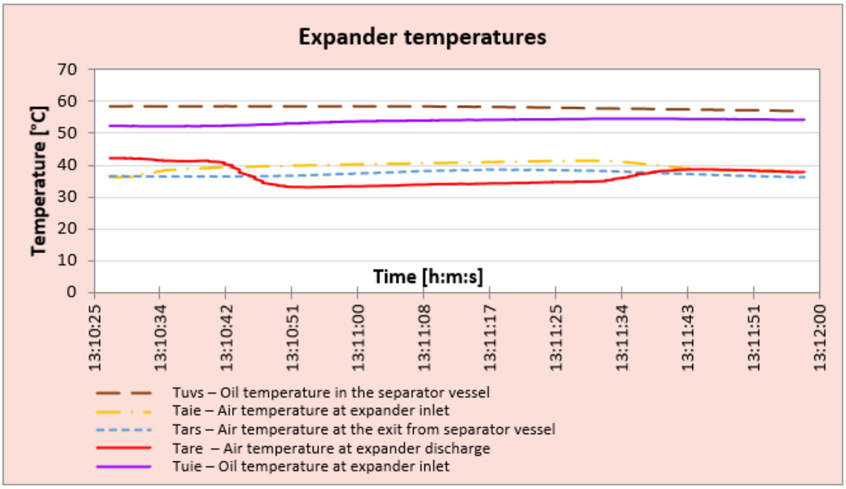

Figure 7. Temperatures recorded during operation with oil heating

5. Discussion and further considerations

It is important to consider that even though the two sub-systems work very well, the solution with twin-screw compressors and expanders is not the best for CAES. The commissioning with the whole installation (Figure 8), carried out in-situ at Popeci Utilaj Greu, Craiova, proved a reliable operation of the installation, but revealed significant losses and the expander being functional for a maximum of 10 minutes, as sustained by the pressure in the reservoir [13]. The small 50 m^3 pressurized air storage vessel showed thermal losses, the air temperature dropping with 1 °C per hour. This affected the air pressure in the storage reservoir, causing significant pressure drops.

Figure 8. ROCAES plant and air reservoir installed at Popeci, Craiova

The power graphs, which are correlated with the pressure trends, were plotted relying on the acquired data during the commissioning tests at Popeci, Craiova. Figure 9 shows the power consumed by the compressor and Figure 10 shows its discharge pressure, over a period of about 20 minutes.

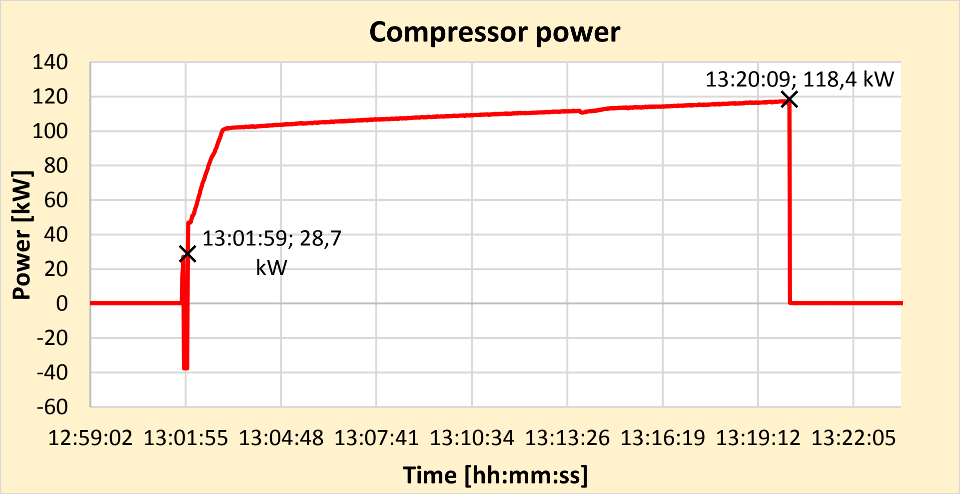

Figure 9. Compressor power consumed from the grid

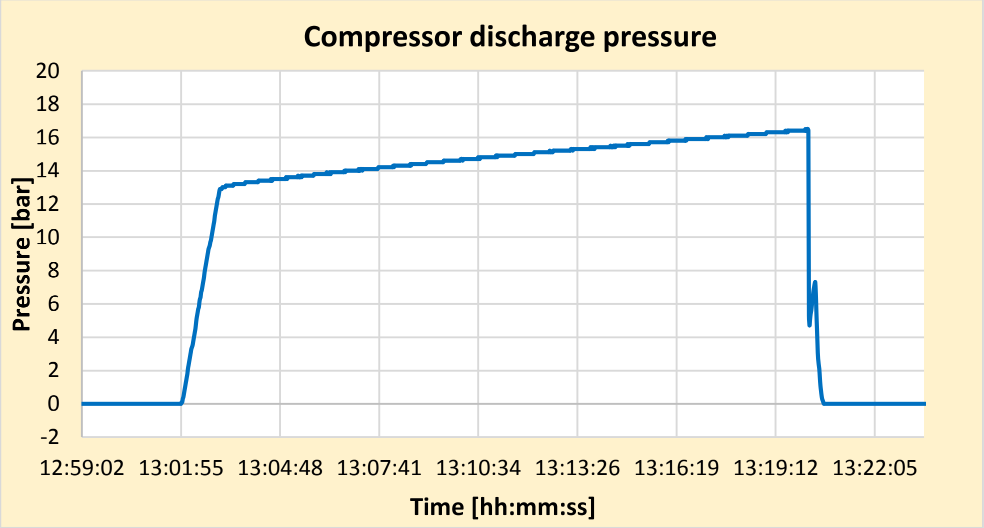

Figure 10. Air pressure at compressor discharge

In Figure 11 we plotted the power generated and power supplied to the grid. The expander-generator automatic shutdown sequence is performed when the pressure at its inlet, plotted in Figure 12, drops below a value capable of spinning the asynchronous machine above synchronous speed.

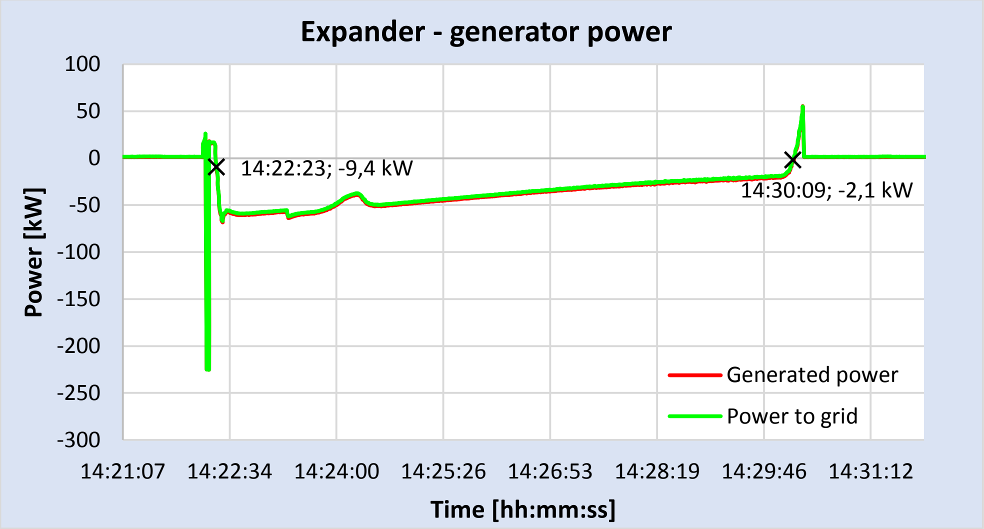

Figure 11. Generated power and power supplied into the grid

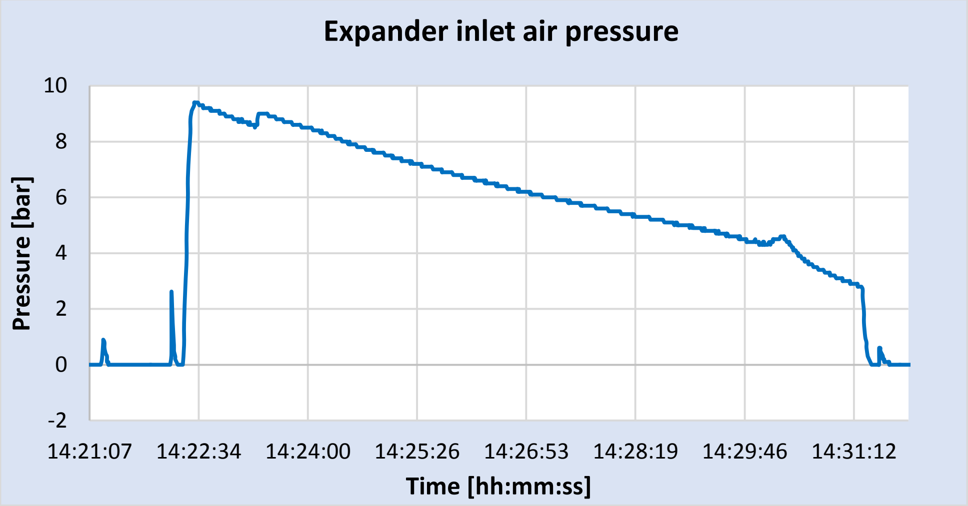

Figure 12. Air pressure at expander inlet

We calculated in [12] the theoretical efficiency of the expander-generator system, which was about 30%. Relying on the acquired data plotted in Figure 9 and Figure 11, we derived an average consumed power of 107.7 kW over a period of 20 min and 10 sec, and an average power supplied to the grid of 37 kW, for 7 min and 46 sec. commissioning tests revealed a real overall efficiency of the entire ROCAES system calculated to 13.5% with (1):

$$\eta_{sys} = \frac{\left|P_{grid} \cdot t_{gen}\right|}{P_{cons} \cdot t_{cons}} = \frac{4.88 \text{ kWh}}{36.17 \text{ kWh}} = 13.5\ \%, \qquad (1)$$

where: η_{sys} [%] – System efficiency; P_{grid} – Average power supplied to grid; t_{gen} – Power generation time; P_{cons} – Average consumed power; t_{cons} – Power consumption time.

The work presented represents a significant evolution of the compressed air energy storage technology initially developed within the ROCAES project. The solution proposed by COMOTI demonstrates not only the technological feasibility of using compressed air energy storage for modern energy applications, but also the scalability potential of this technology for higher power applications.

As for DOs and DON'Ts, we summarize our recommendations, that we deem crucial to be considered within potential future research projects:

- **The motor-compressor power should be higher than the power of the expander-generator**. Choosing a higher generator power does not mean that the rated power can be produced [16]. The generated power solely depends on the air pressure and amount in the storage reservoir, and its capacity to spin the expander. We recommend the compressor's driving motor power to be double than the generator's.

- **Asynchronous induction machines are a very reliable solution** that should be maintained. Synchronous machines necessitate additional manoeuvres for synchronization with the grid frequency at every start-up, that would require specialised personnel to be available for travelling to the installation spot(s) every time.
- **Oil heating is a must** for avoiding discharge air cooling much below freezing point, that could jeopardize the expander by forming ice chips and therefore damaging the expander.
- **A thermal energy storage is highly recommended to be provided along with the CAES**. The water tank did improve the efficiency, but another storage media like salts would be more effective [17].
- **A single electric machine connected to both compressor and expander shafts could be a reliable and cost-effective solution**, as the compressor and the expander are not expected to operate at the same time.
- **A better insulated and higher capacity air reservoir would be beneficial**, for sustaining the necessary pressure for a longer operation of the expander [18].

6. Conclusions

The main objective of the ROCAES project was to demonstrate the technological feasibility and economic efficiency of a low power energy storage solution using compressed air. This approach allowed for a research and development prototype, with the potential for a subsequent development of the technology in larger scale projects.

During the testing phase, the two main parts of the ROCAES installation, namely the screw compressor and expander driven by asynchronous three-phase machines, operated effectively. This is largely attributed to the electrical and automation components with the control, regulation, and monitoring system, ensuring continuous monitoring of critical parameters by means of PLCs. The installation was successfully commissioned and was handed in to the beneficiary, currently being found at Popeci Utilaj Greu hall in Craiova, Romania. Acoustic tests were carried out, proving the rubber puffers between the skid and ground an effective solution for reducing the operation noise under 85 dB from typically over 100 dB for our rotary screw compressors.

This research project regards a small-scale demonstrative prototype. Future works aim to use the accumulated knowledge in developing a larger scale CAES system. ROCAES project is a starting point for the integration of energy storage with compressed air on a wider scale, contributing to the stability and efficiency of electrical networks, in the context of increasing demand for renewable energy sources and the need for reliable energy storage solutions and efficient. However, we should first work on mitigating the risks and avoid making the main mistakes that were done in this first project.

REFERENCES

[1] E. Bazdar, M. Sameti, F. Nasiri, and F. Haghighat, ‘Compressed air energy storage in integrated energy systems: A review’, *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112701, Oct. 2022, DOI: 10.1016/j.rser.2022.112701.

[2] H. Chen, X. Zhang, J. Liu, C. Tan, and A. F. Zobaa, ‘Compressed Air Energy Storage’, in *Energy Storage - Technologies and Applications*, IntechOpen, 2013. DOI: 10.5772/52221.

[3] S. W. Yufenyuy, G. M. Mengata, L. Nneme Nneme, and U. M. Bongwirnso, ‘Indoor environment PV applications: Estimation of the maximum harvestable power’, *Renewable and Sustainable Energy Reviews*, vol. 193, p. 114287, Apr. 2024, DOI: 10.1016/j.rser.2024.114287.

[4] R. Maity, K. Sudhakar, and A. A. Razak, ‘Agri-solar water pumping design, energy, and environmental analysis: A comprehensive study in tropical humid climate’, *Heliyon*, vol. 10, no. 21, Nov. 2024, DOI: 10.1016/j.heliyon.2024.e39604.

[5] M. Saadat, A. Srivatsa, P. Y. Li, and T. Simon, ‘Air Compression Performance Improvement via Trajectory Optimization: Experimental Validation’, presented at the ASME 2016 Dynamic Systems and Control Conference, American Society of Mechanical Engineers Digital Collection, Feb. 2017. DOI: 10.1115/DSCC2016-9825.

[6] ‘Compressed Air Energy Storage - Energy Storage | CTCN’. Accessed: Jan. 22, 2025. [Online]. Available: https://www.ctc-n.org/technologies/compressed-air-energy-storage-caes.

[7] G. Dib, P. Haberschill, R. Rullière, and R. Revellin, ‘Thermodynamic investigation of quasi-isothermal air compression/expansion for energy storage’, *Energy Conversion and Management*, vol. 235, p. 114027, May 2021, DOI: 10.1016/ j.enconman.2021.114027.

[8] G. Dib, P. Haberschill, R. Rullière, and R. Revellin, ‘Modelling small-scale trigenerative advanced adiabatic compressed air energy storage for building application’, *Energy*, vol. 237, p. 121569, Dec. 2021, DOI: 10.1016/ j.energy.2021.121569.

[9] N. Wang, C. Kang, and D. Ren, Eds., *Large-Scale Wind Power Grid Integration*. Oxford: Academic Press, 2016. DOI: 10.1016/B978-0-12-849895-8.01001-0.

[10] C. Borzea, I. Vlăducă, D. Ionescu, V. Petrescu, F. Niculescu, C. Nechifor, G. Vătăşelu, and M. Hanek, ‘Compressed Air Energy Storage Installation for Renewable Energy

Generation', *E3S Web Conf.*, vol. 112, p. 02010, 2019, DOI: 10.1051/e3sconf/201911202010.

[11] C. Borzea, A. Savescu, I. Vladuca, and A. Stoicescu, 'Asynchronous Three-Phase Machine Driven as Generator by a Twin-Screw Expander', *Electric Machines, Materials and Drives - Present and Trends*, vol. 16, no. 1, Art. no. 1, 2020.

[12] I. Vlăducă, C. Borzea, D. Ionescu, A. Ţăranu, R. Ciobanu, V. Ringheanu, and R. Nedelcu, 'Compressed air energy storage facility with water tank for thermal recovery', *E3S Web Conf.*, vol. 180, p. 02002, 2020, DOI: 10.1051/e3sconf/202018002002.

[13] C. Borzea, A. Savescu, C. Haraguta, A. Gazdac, and R. Nedelcu, 'Automatizarea acționării electrice a unei instalații de stocare a energiei în aer comprimat (EN: „Automation and Electrical Actuation of a Compressed Air Energy Storage Installation")', *Electric Machines, Materials and Drives - Present and Trends*, vol. 15, no. 1, Art. no. 1, 2019.

[14] A. Mitru, 'Data Communication and Software Developing for the Automation of an Industrial Piston Compressor', *Revue Roumaine des Sciences Techniques, Série Électrotechnique et Énergétique*, vol. 70, no. 1, p. in press, 2025.

[15] Carlo Gavazzi, 'Energy Management Smart Modular Power Analyzer Type WM30 96', gavazzionline.com. [Online]. Available: https://www.gavazzionline.com/pdf/WM3096DSENG.pdf.

[16] W. He and J. Wang, 'Optimal selection of air expansion machine in Compressed Air Energy Storage: A review', *Renewable and Sustainable Energy Reviews*, vol. 87, pp. 77–95, May 2018, DOI: 10.1016/j.rser.2018.01.013.

[17] P. Mokhberi, P. Mokhberi, M. Izadi, M. Bagheri Nesaii, W. Yaici, and F. Minelli, 'Thermal regulation enhancement in multi-story office buildings: Integrating phase change materials into inter-floor void formers', *Case Studies in Thermal Engineering*, vol. 60, p. 104792, Aug. 2024, DOI: 10.1016/j.csite.2024.104792.

[18] N. Luo, B. Xiao, W. Liu, Y. Duan, and D. Niu, 'Design and Selection of Pipelines for Compressed Air Energy Storage Power Plants', *E3S Web Conf.*, vol. 441, p. 02005, 2023, DOI: 10.1051/e3sconf/202344102005.

Acknowledgements

The implementation works were funded by the Competitiveness Operational Program 2014-2020, Priority Axis 1 – Research, Technological Development and Innovation in Support of Economic Competitiveness and Business Development, Action 1.2.3, Partnerships for Knowledge Transfer, contract POC 79/08.09.2016, with the support of Romanian Ministry of European Funds.