Pneumatically Driven Generator for Use with Small-Scale Compressed Air Energy Storage System

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Abstract: *To cover the peak load in the energy systems, energy storage facilities are needed during periods when energy production is in excess. During sunny days, photovoltaic energy production can reach a level that exceeds the demand in the power grid. During these periods, battery storage systems, pumped storage hydroelectric plants or compressed air energy storage (CAES) can be used. CAES systems use compressors to store compressed air and air turbines coupled with generators to produce electricity. They can be large-scale with storage in caverns or former mines and small-scale (SS-CAES) with storage in air tanks. An SS-CAES uses a piston or screw compressor, and as an expander it can use an air turbine or a pneumatic motor coupled to an electric generator. The article presents the realization of a control system for an SS-CAES and of an electricity generation unit with a pneumatic motor and permanent magnet generator usable for SS-CAES in rural or isolated areas.*

Keywords: *Pneumatic drive, energy storage, control, SS-CAES*

1. Introduction

To support the transition toward a sustainable energy sector, energy storage systems are becoming indispensable, as they enable the efficient use of renewable sources with variable output, such as solar and wind energy.
The basic principle consists of compressing air into pressurized tanks when there is an energy surplus (usually from renewable sources such as solar or wind), and later, this compressed air is released and used to generate electricity during periods of high demand.
Unlike traditional CAES systems, which require large-scale infrastructures (geological cavities or underground reservoirs), SS-CAES is designed for smaller-scale applications, using commercial pressure tanks and modular components. Thus, these systems are suitable for:

- microgrids and isolated communities,
- integration of intermittent renewable sources.

The main advantages of SS-CAES include modularity, high reliability, durability, and lower environmental impact compared to electrochemical storage solutions. S-CAES also faces challenges related to energy efficiency (thermal losses during compression and expansion) and lower energy density compared to batteries.
Research and development in the field of SS-CAES aim to optimize components and processes to improve system performance and support its applicability in microgrids, isolated communities, and hybrid power generation systems.
Ghadi et al. [1] propose the use of SCAES units as aggregators in distribution networks for participation in day-ahead energy markets. A dual-agent model (aggregator + distribution operator) optimizes costs, losses, emissions, etc.
Congedo et al. [2] conduct a feasibility study on micro-CAES systems combined with thermal storage for a single-family home with 3 kW PV. They perform multi-objective optimization, performance analysis, and comparison with batteries. Result: low efficiency for CAES in this context, but exploitable advantages (lifetime, thermal recovery).
Rabi et al. [3] provide an updated overview of CAES variants (diabatic, adiabatic, isothermal), advantages and disadvantages at different scales; they discuss technical challenges, costs, applications integrated with renewable energy systems, and the inclusion of smaller/distributed storage concepts.

Luo et al. [4] give an overview of energy storage technologies and highlight that SS-CAES is particularly suitable for integration into microgrids and for balancing renewable generation.
Budt et al. [5] detail the operating principles of CAES, classify systems into adiabatic, diabatic, and isothermal, and highlight the potential for reducing energy losses in small-scale applications.
Raju & Khaitan [6] present a simulation model of compressed air storage in caverns, which can be scaled and applied for SS-CAES sizing at local or community levels.
Gupta & Saini [7] review the performance and challenges of SS-CAES, concluding that innovations in materials and thermal management are key to improving small-scale efficiency.
Mohammadi & Mehrpooya [8] analyze hybrid systems (e.g., CAES + solar/biomass plants), revealing that SS-CAES is attractive for decentralized and residential applications.
IRENA [9] reports costs and market projections, showing that SS-CAES has the potential for cost reduction by 2030, especially if standardized above-ground tanks are used.
Alami [10] presents a case study on integrating SS-CAES with photovoltaic panels, demonstrating that a hybrid system can ensure supply continuity in the absence of sunlight, at affordable costs.
Zakeri & Syri [11] compare life-cycle costs of different storage technologies and show that SS-CAES becomes competitive in long-term applications, where the number of cycles is high.

2. Thermodynamic equations for air storage and utilization

Ideal Gas Law

The fundamental relation is:

$$p \cdot V = n \cdot R \cdot T \tag{1}$$

where:

p = pressure (Pa),
V = volume (m^3),
n = number of moles of gas (mole),
R = universal gas constant (8.314 *J*/(*mole* · *K*)),
T = absolute temperature (*K*).

This relationship is used to relate the pressure, volume and temperature of air in pneumatic tanks.

Compression and expansion processes

Depending on the heat transfer, the isothermal model and the adiabatic model are distinguished:

• **Isothermal compression/expansion (T = const.)**

$$p \cdot V = const. \tag{2}$$

Energy stored in compressed air in an isothermal process:

$$E_{isot} = n \cdot R \cdot T \cdot ln\left(\frac{p_2}{p_1}\right) \tag{3}$$

where p_1 și p_2 are the initial and final pressures.
This model has a high theoretical efficiency and requires intense heat exchange with the environment.

• **Adiabatic compression/expansion (no heat exchange with the outside)**

$$p \cdot V^{\gamma} = const. \tag{4}$$

where $\gamma = \frac{c_p}{c_v}$ is the ratio of specific heats (≈ 1.4 for air)
Energy stored in an adiabatic process

$$E_{adiab} = \frac{p_2 \cdot V_2 - p_1 \cdot V_1}{\gamma - 1} \tag{5}$$

This model describes the real situation of rapid compression, where the temperature increases significantly, requiring cooling systems to avoid energy losses.

Efficiency and losses

The overall efficiency of the conventional CAES cycle varies between 40...60%, but by implementing the advanced adiabatic system (AA-CAES), where the heat of compression is stored and reused, values of 70% or even more can be achieved.

The efficiency of a compression and expansion system is influenced by:

- Heat losses through tank walls
- Internal friction in compressors and actuators
- Leakage losses through valves and connections

Calculating the energy stored in a tank

For a tank of constant volume V, charged from pressure p_1 to pressure p_2, the additional energy stored is approximated by:

$$E = \frac{(p_2 - p_1) \cdot V}{\gamma - 1} \tag{6}$$

This simplified formula is frequently used for sizing pneumatic accumulators and quickly assessing storage capacity.

3. Test stand for a small scale compressed air energy storage system

The system was developed for laboratory experiments and can use the maximum compressed air pressure of 10 bar, the tank being a standard one for compressors of maximum 10 bar. The system characteristics are found in table 1. For increased storage capacities, tanks and compressors of 35÷40 bar or higher can be used. High pressures involve the management of the heat generated when compressing the air and the low temperature from the expansion of the air through the turbine or pneumatic motor.

Table 1: Technical characteristics of the system

Compressor	Pneumatic motor	Generator	Air tank	Control system
• Power: 2200 W • Flow: 392 l/min • Max. pressure: 8 bar	• Max. power: 1.25 kW • Speed: 300÷3000 rev/min • Air consumption: 3÷30 l/s • Torque: max. 10 Nm	• Type: permanent magnets • Power: 1000 W • Speed: 750 rev/min • Voltage: 24 V	• Volume: 350 l • Max. pressure: 11 bar • Pressure transducer: 25 bar	• PLC based • Electric energy meter • PC application for control and data acquisition

3.1 Pneumatic diagram of the system

The pneumatic diagram of the system in figure 1 contains the compressor for charging the air storage tank with its pressure switch and safety valve. A pressure regulator is connected from the compressor tank followed by a directional valve for directing the air to the storage tank. In order to avoid air losses, a check valve was installed after the directional valve DV1. The air then reaches the storage tank through an isolation valve. A directional valve DV2 is connected to the tank pipe followed by a group with a filter, pressure regulator and lubricator, because the pneumatic motor has a working pressure of 6.5 bar and requires lubrication. The proportional flow regulator was installed to correct the speed of the pneumatic motor depending on load fluctuations, through the control unit made with a programmable logic controller (PLC). The diagram also includes temperature and pressure sensors, and a torque and rotary speed transducer is installed between the pneumatic motor and the generator (energy conversion device). To monitor electrical energy consumption, an EM energy meter is used that measures the power delivered to load resistors.

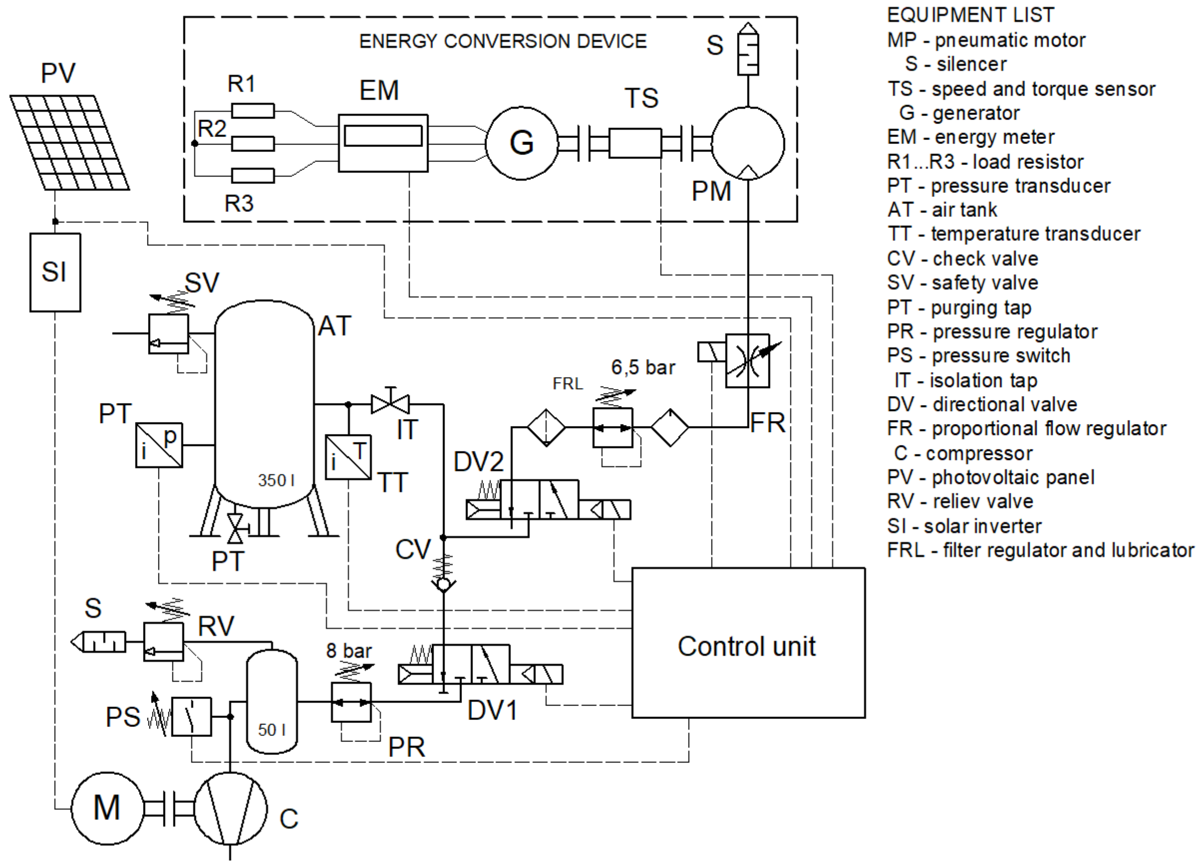

Fig. 1. Scheme of an SS-CAES system for research purposes

3.2 The control and data acquisition system

The control and data acquisition system is installed in an electrical cabinet (figure 2) containing: automatic circuit breaker, 24 Vdc power supply, PLC type TM221CE24T from Schneider Electric, module with 4 analog inputs (0…10V, 4…20mA) for transducers, 4 intermediate relays for commands and a three-phase energy meter, type A9MEM3155, for monitoring electrical energy. The controller has implemented a software for data acquisition regarding system parameters and for managing compressed air storage and consumption. The following elements are connected to the controller inputs: pressure transducer, temperature transducer, torque and rotation speed transducer and the signal regarding the voltage of the solar panels. The pressure switch is connected to a digital input, and the solenoids of the pneumatic directional valves and the contactor for powering the compressor electric motor are connected to the digital outputs.

The system control algorithm takes into account the pressure in the storage tank and the voltage present at the photovoltaic panels. If the voltage is within parameters, i.e. there is sufficient solar radiation, the compressor is started to charge the storage tank. If the solar radiation drops below a certain level or if the maximum pressure has been reached, the compressor stops. When the compressor starts, DV1 is also switched to direct the air to the tank.

To use the stored compressed air, DV2 is switched on and the pneumatic motor is started, which drives the generator. The generator speed can be corrected to maintain the delivered voltage by adjusting the control signal of the flow regulator within a range of values. If the pressure in the storage tank drops below the nominal working pressure of the pneumatic motor of 6.5 bar and the generator load is too high, the generator is disconnected and the system enters the compressed air recharge mode.

Fig. 2. Assembled control and data acquisition system

The system can communicate via Modbus TCP/IP protocol with a PC application that allows viewing of operating parameters.

3.3 Energy conversion device

The device can convert compressed air energy into electrical current and contains a permanent magnet generator, a torque and speed transducer, a pneumatic vane motor type AM4-NRV-22B from Gast and 2 rotary couplings. The physical implementation of the energy conversion device can be seen in the figure 3.

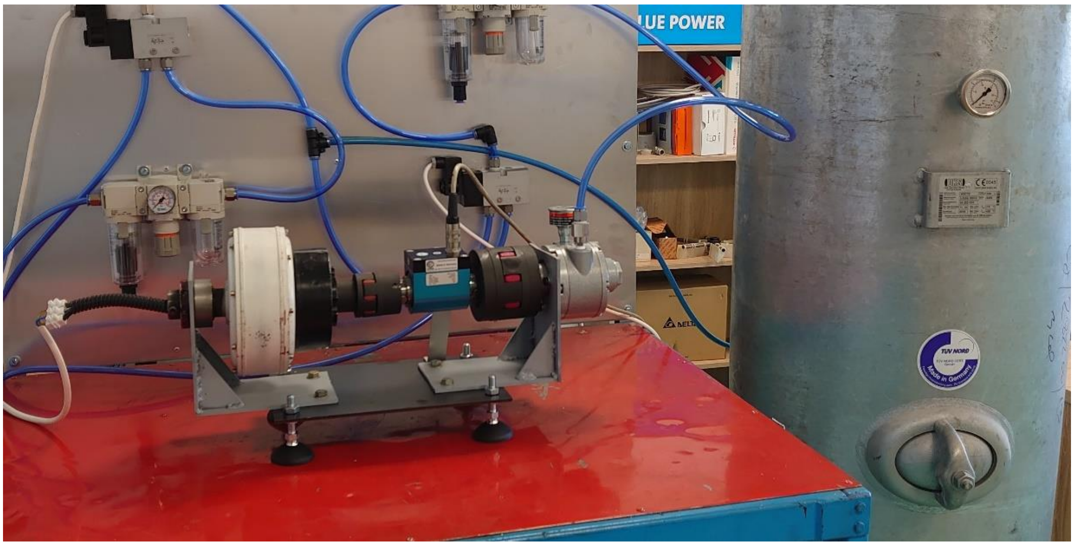

Fig. 3. Physical realization of the compressed air electricity generation device

4. Conclusions

The generator driven by a pneumatic motor allows the implementation of SS-CAES for isolated areas.
The stand designed to test the generator driven by a pneumatic motor allows testing of different control strategies for SS-CAES for use by beneficiaries in isolated areas.
Standard air tanks and modular components can be used to create SS-CAES.
SS-CAES allow integration with intermittent renewable energy sources and have a longer lifespan compared to battery storage for long-term applications.

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