

Giovanelli, Ambra; Tamasi, Luca; Salvini, Coriolano

Article

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Performance analysis of industrial steam turbines used as air expander in Compressed Air Energy Storage (CAES) systems

Ambra Giovannelli, Luca Tamasi, Coriolano Salvini*

Dipartimento di Ingegneria, Università degli Studi ROMA TRE, Italy

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Abstract

The Authors consider that as a mid-term storage technology (from some hours to some days), small/medium size CAES systems (1–10 MW) might be efficiently and profitably used for off-grid and self-consumption applications as well as for the provision of ancillary services on the lower grid levels. A crucial aspect related to the feasibility of the system concerns with the availability of efficient and affordable air expanders. For typical applications, suitable values for pressure at the air expander inlet range from 40 to 60 bar. Since such values are comparable with those featuring industrial steam turbines, an interesting option to reduce development efforts and costs is to take as a reference the common steam turbine engineering practice. The goal of the present paper is to explore the possibility of using existing modules developed by industrial steam turbines manufacturers to assemble the air expander. On the basis of available information, a possible arrangement for an air turbine has been set up and modeled. Results show a loss of performance in terms of efficiency in respect to steam operations. Nevertheless, the performance level in a really wide range of operation can be considered more than satisfactory. Therefore, the use of industrial steam turbines technology might be considered of interest for the intended applications.

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Keywords: Compressed Air Energy Storage (CAES); Industrial steam turbines; Turbomachinery modeling; Air expander

1. Introduction

The increasingly use of renewable energy sources (RES) significantly contributes to the reduction of CO₂ emission and to the sustainability of the overall energy system. On the other hand, the intermittency and the uncertainty in forecasting RES availability bring serious issues in managing electric networks. Electric Energy Storage (EES) can contribute to mitigate the above issues and, consequently, further promote the market penetration of RES. EES systems can generate additional electricity when RES availability is insufficient to meet the forecast production level or store energy in case of an excess of availability.

* Corresponding author.

E-mail address: coriolano.salvini@uniroma3.it (C. Salvini).

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Among the currently available EES solutions, Compressed Air Energy Storage (CAES) represents an interesting option. Basically, CAES systems operate according to a Brayton cycle in which compression and expansion processes do not take place simultaneously as in a Gas Turbine (GT) plant, but are decoupled and shifted along the time. During off-peak periods, electric power is absorbed from the grid to compress air, which is stored in a reservoir. During the peak demand periods, the stored air is heated and expanded to produce electricity.

Starting from the basic concept, a variety of solutions have been developed along the time. Such solutions can be grouped into three main classes: Diabatic CAES (D-CAES), Adiabatic CAES (A-CAES) and Isothermal CAES (I-CAES). At the present, only D-CAES can be regarded as a mature technology. In D-CAES, an external heat source is used to heat the stored air before the expansion. A fossil fuel (usually Natural Gas) represents the most common option. Nevertheless, alternative heat sources have been proposed and investigated as reported by Chen et al. [1], Li et al. [2] and Salvini [3].

D-CAES existing plants (Huntorf and McIntosh plants) are large-size ones (320 and 110 MW) with underground air storage. According to Budt et al. [4], the Authors of the present paper consider that as a mid-term storage technology (from some hours to some days), small/medium size CAES systems might be efficiently used for off-grid and self-consumption applications as well as for the provision of profitable ancillary services, e.g. secondary and tertiary reserve. Such applications call for plants suitably located on the electric grid and therefore, to overcome any restriction to the plant location arising from the unavailability of underground reservoirs, artificial storage tanks must be addressed [3,5].

According to above considerations, D-CAES plants capable of managing power in the megawatt range equipped with artificial storage tanks will be addressed in the present paper.

One of the point of strength of the proposed concept is the possibility to arrange the whole system by using proven and consolidated technologies and commercially available components. The compression train can be assembled by using commercial centrifugal compressors. The artificial air storage can be conveniently built by welding tube sections usually employed for Natural Gas pipelines [6]. If the heat source is a fuel, a combustion chamber derived from Gas Turbine technology or an industrial burner can be used, depending on fuel type. If the air is heated by using hot exhaust gases [2,3,7] the heat transfer device can be designed by adopting the same arrangement, equipment (tubing, manifolds, casing, etc.) and materials used for Heat Recovery Steam Generators [8].

A crucial aspect related to the feasibility of the system concerns with the availability of efficient and affordable air expanders. For applications under consideration, suitable values for pressure at the air expander inlet range from 40 to 60 bar [9,10]. Since such values are comparable with those featuring industrial steam turbines, an interesting option to reduce development efforts and costs is to take as a reference the common steam turbine engineering practice. The goal of the present paper is to explore the possibility of using existing modules developed by industrial steam turbines manufacturers to assemble the air expander.

2. Industrial steam turbine manufacturing

Industrial Steam Turbines applications span in a really wide range of design parameters: inlet steam conditions (pressure and temperature), inlet mass flows, number of steam extractions and extraction pressures, exhaust conditions, rotational speed and so on.

In order to speed up the design process, to reduce costs and to shorten time span for delivery, major Steam Turbine Manufacturers have developed standardized pre-designed building blocks to assemble the whole machine [11]. From these families of modular components, the designer can select the most suitable ones to meet the specific requirements of the customer. On the basis of the modular concept, different Manufacturers have developed similar but somewhat different approaches [12–15].

On the whole, the following building blocks are available to assemble an industrial steam turbine:

- bearing housing for live steam and exhaust sides of the turbine;
- actuators, control and trip valves;
- gear box and alternator;
- inlet casing, including valve chest and governing stage nozzles;
- turbine casing, featured by different lengths and inlet/outlet cross sections;
- extraction module, often integrating devices to control mass flow and pressure of the extracted steam;
- exhaust casing for condensing and backpressure turbines;

- base frames, including the oil system.

The shaft is usually a single piece forging with integral disks. The shaft is individually manufactured according to the required steam path.

Governing stages (impulse stages or Curtis wheels) are often adopted to control the delivered power and the extracted steam mass flows. High/medium pressure reaction stages are usually arranged in groups with constant hub diameter (see Fig. 1b). Different design options for low pressure reaction stages (constant hub diameter, constant mean diameter and so on) are preferred by different Manufacturers.

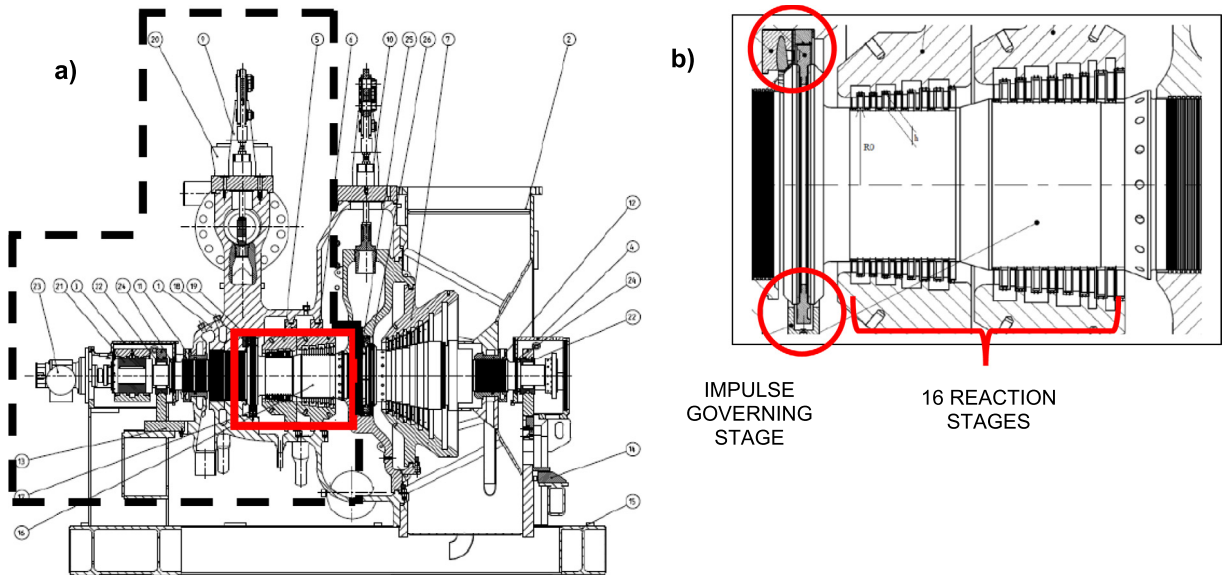


Fig. 1. (a) Reference Industrial Steam Turbine; (b) High Pressure section detail.

Standardized stator and rotor reaction blades are available in a variety of series featured by different sizes. Since for many applications part load operations are the rule, the blade leading edge is suitably shaped in order to minimize incidence losses over a wide range of inlet flow angle.

3. Air performance of an existing industrial steam turbine

The first step in assessing the air performance of a steam turbine is the implementation of a model capable of reproducing the behavior of the machine under condition of normal use.

Data required to properly define an industrial steam turbine assembly are, of course, proprietary. Therefore, to carry out the present study, an existing condensing steam turbine (depicted in Fig. 1a) manufactured by a renowned Company has been taken as a reference to collect realistic data.

The turbine is composed by a high pressure section (constituted by a partial admission regulating stage followed by sixteen reaction stages), an extraction module, a low pressure section equipped with an impulse regulating stage as well and, finally, an exhaust casing for condensing applications.

At reference condition (inlet steam at 60 bar and 470 °C, discharge pressure 6.4 bar, rotational speed 8600 rpm), the power transferred to the blading in the high pressure section stages is of some 5.4 MW, with a steam consumption of 10.8 kg/s. Such features suggest the use of the high pressure section to arrange an air expander for CAES applications analyzed by the Authors [9,10]. In such applications, the compressed air is heated at moderate temperature (around 500 °C) by using fuel or exhaust gases discharged by a Gas Turbine. According to results presented in the abovementioned works, air inlet pressure and temperature are assumed equal to 40 bar and 470 °C respectively, and exhaust pressure at 101.3 kPa. The air turbine can be assembled by using the same inlet casing and high pressure section of the reference steam turbine, as evidenced in Fig. 1a by the black dotted contour. The

machine can be completed by adding an exhaust casing for backpressure applications, selecting the most appropriate one to match the turbine casing and the discharged air volumetric flow.

3.1. Turbine model set up

In order to assess the air turbine performance, the following approach has been adopted:

- implementation of a general turbine model for off-design performance calculation;
- retrieval of the data set required to configure the reference steam turbine high pressure section. In order to do that, all available information about the reference turbine have been used and assumptions consistent with the industrial steam turbines state of the art have been made. The remaining unknown quantities (essentially constituted by blade angles), have been established by iteratively solving an inverse sizing problem aimed at minimizing the error between the model output and high pressure section design quantities, reported in Section 3.
- Investigation of air operation performance.

A row-by-row mean line model for off-design calculation has been realized. For both impulse and reaction stages, governing equations are applied to stator and rotor rows by assuming stationary operations.

The impulse governing stage (sketched in Fig. 2a) has been modeled by adopting a two streams approach: the first stream accounts for the steam flow passing through the fully opened distribution sectors, the second one for the flow through the partially opened one. A schematic qualitative representation of the expansion line of each stream in a h - s (enthalpy-entropy) diagram is given in Fig. 2b. For fully admitted sectors, it is assumed that the stagnation pressure at the stator vanes inlet equals the stagnation pressure upstream the trip valve p_0 , i.e. the pressure drop across both trip and fully opened admission valve are neglected. The expansion in stator row is therefore represented by the line 0–1.

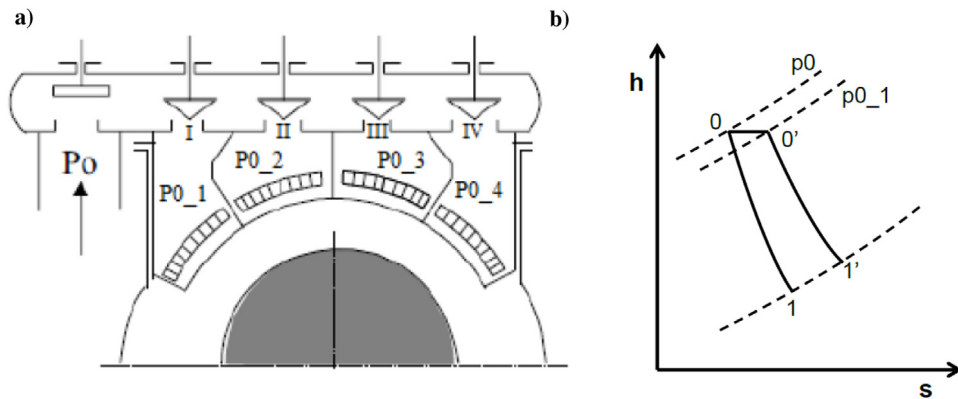


Fig. 2. (a) Impulse Regulating Stage cross section; (b) Schematic representation of the expansion lines on the h - s (enthalpy-entropy diagram): 0–1 fully opened distribution sectors, 0'–1' partially opened distribution sector.

For a partially admitted sector, the throttling across the admission valve causes a reduction of the steam mass flow and of the stagnation pressure upstream the stator vanes (line 0–0'–1' in Fig. 2b). Therefore, the two streams enter the rotor blades with different velocities and, consequently, different amounts of work are transferred to the moving blading. The specific work (per unit of mass of steam) is evaluated as the weighted average of works produced by each stream, being weights the corresponding mass flow rates. Steam conditions downstream the rotor blades are evaluated in the same way, assuming a perfect mixing between the two streams.

Losses have been evaluated by using typical well established formulations. Skin friction losses are estimated by using correlations accounting for flow deflection and acceleration according to Catania [16]. Incidence losses are calculated according to Kroon and Tobiasz [17]. If sonic conditions occur, losses are augmented by introducing a factor whose value depends on the Mach number at the exit of the row [18]. For the impulse regulating stage, disk friction and venting losses are evaluated by means of typical literature correlations [19].

On the basis of the high pressure section drawing reported in Fig. 1b, realistic values for some relevant geometric quantities (e.g. hub diameter, blade heights at leading and trailing edge, axial blade length) have been assumed for each blade row. The remaining unknown quantities required by the model have been determined according to the abovementioned approach. Main assumptions and results are discussed in the following.

With reference to the impulse stage, steam is admitted along an arc of circumference of 180° subdivided into four admission sectors. The stator exit angle α_1 has been set at 17° . A symmetric rotor blading has been assumed. At reference conditions, the stage operates with a velocity ratio (i.e. the ratio between the velocity of steam exiting the stator c_1 and the peripheral velocity u) equal to 1.8.

The sixteen reaction stages have been sized by assuming a reaction degree equal to 0.5, the conservation of the axial velocity, α_1 angle equal to 21° , similar blading (i.e. equal blade angles for each stage) and a velocity ratio equal to 1.3.

At reference rated conditions, the power transferred to the blading evaluated by the model is equal to 5.2 MW, in a satisfactory agreement with the Manufacturer datum (5.4 MW). A total-to-static isentropic efficiency of 0.88 has been found.

3.2. Air operation performance assessment

Subsequently, the model has been used to assess the turbine performance when fed with air at 40 bar and 470°C . Fig. 3a shows the air mass flow rate versus the power transferred to the turbine blading. At full admission condition, such a power is equal to 3.5 MW with an air consumption of about 9 kg/s. Mechanical losses in bearings and gear box, power absorbed by auxiliary equipment and power losses in the electric generator are accounted for by assuming a mechanic–electric efficiency equal to 0.94. As a result, at full admission condition, an electric power output of 3.3 MW is produced.

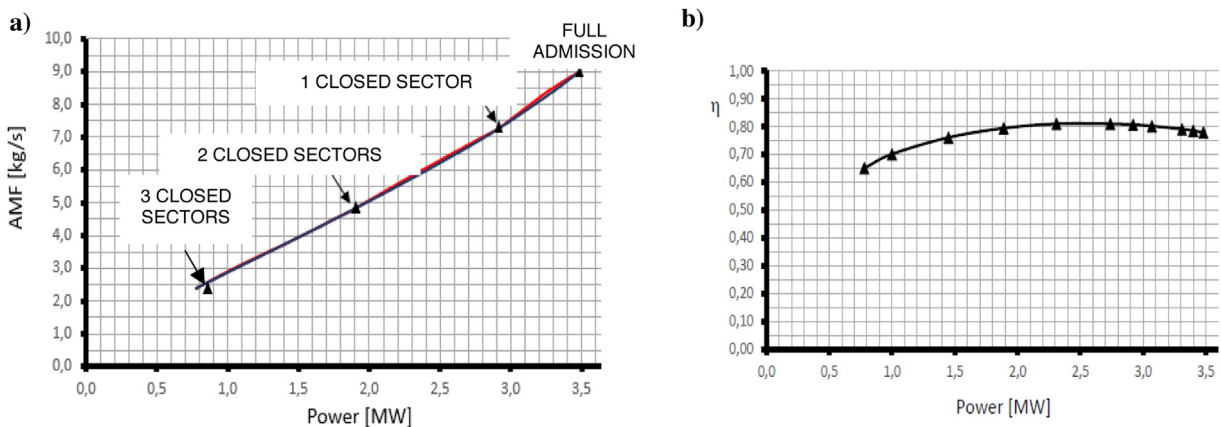


Fig. 3. (a) Air consumption versus power; (b) Isentropic efficiency versus power.

Finally, part load performance has been investigated. Load reductions are achieved by using the partial admission regulating stage, closing in sequence the four admission sectors, as shown in Fig. 3a. Isentropic efficiency versus power is given in Fig. 3b. It can be noticed as the efficiency value at full admission condition shows a significant reduction in respect to that evaluated in case of steam operation (0.88). However, a satisfactory behavior is observed in a wide range of operation. In fact, load reductions up to 50% can be obtained with efficiency values around 0.8, really close to the full admission value. Further load reductions imply an efficiency decrease up to 0.65 at 20% of full load.

4. Conclusions

The performance of an air expander for CAES applications assembled according to the industrial steam turbines manufacturing practice has been investigated. On the basis of available information, a possible arrangement for an

air turbine has been set up and modeled. Results show a loss of performance in terms of efficiency in respect to steam operations. Nevertheless, the performance level in a really wide range of operation can be considered more than satisfactory. Therefore, the use of industrial steam turbines technology might be considered of interest for the intended applications.

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