EXPERIMENTAL RESULTS OF A MESOSCALE ELECTRIC POWER GENERATION SYSTEM FROM PRESSURIZED GAS FLOW

D. Krähenbühl[1], C. Zwyssig[2], H. Weser[3] and J. W. Kolar[1]
[1]Power Electronic System Laboratory, ETH Zurich, Switzerland
[2]Celeroton Ltd., Zurich, Switzerland
[3]High Speed Turbomaschinen GmbH, Wolfsburg, Germany

Abstract: In many process applications, where a pressure reduction is required, the energy is being dissipated as heat. Examples are throttling valves of gas pipelines and automotive engines or turbo expanders as used in cryogenic plants. With a new pressure reduction system that produces electricity while expanding the gas, this lost energy can be recovered. To achieve a high power density this energy generation system requires an increased operating speed of the electrical machine and the turbomachinery. Measurements of a compressed-air-to-electric-power system with a rotational speed of over 600 000 rpm, a maximum electric output power of 170 W, a maximum torque of 5.2 mNm and a turbine efficiency of 52% are presented.

Key words: radial turbine, turbomachinery, ultra high speed

1. INTRODUCTION

In pressure reduction devices, such as valves, conventional throttles or turbo expanders, the excess process energy is usually wasted as heat. However, this energy could be recovered by employing a system that removes the energy from pressurized gas flow and converts it into electrical energy.

One example is the replacement of the conventional throttle in automotive applications where a turbine in combination with a generator can actively throttle the intake air and thereby produce electrical power [1]. Measurements at constant speed have shown that up to 700 W electric power could be extracted (turbine Ø 40 mm) and an extrapolation with a 50% downsized turbine predicts that even more electric power could be produced.

While it is necessary to transport natural gas at high pressures, end-users require gas delivery at only a fraction of the main pipeline pressure. Therefore, energy can be recovered at pressure reduction stations if throttling valves are replaced by expanders driving electrical generators [2]. For power recovery, turbines are generally rated from 150 kW to 2.5 MW, however, the pressure reduction process is usually done in several stages, and an array of small turbine-generator modules could replace one large pressure reduction valve [3].

Also, the turbo expanders used today in cryogenic plants transfer the excess power (in the kW range) to a brake compressor where the energy is finally dissipated into cooling water. If a generator would be employed for the braking of the turbo expander, energy could be recovered, and therefore the efficiency of such plants could be increased [4].

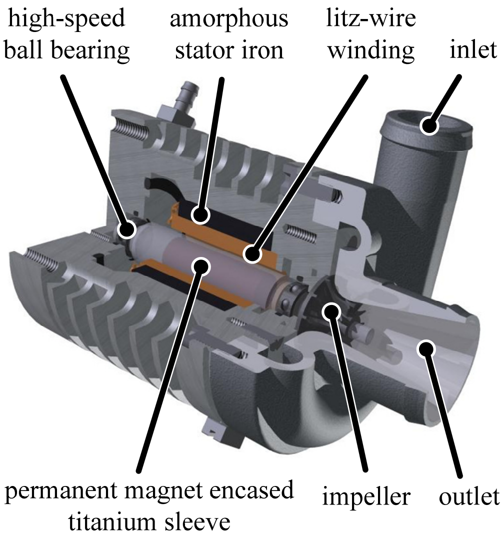

Fig. 1. Solid model of the turbo compressor system. Dimensions:33 x 43mm.

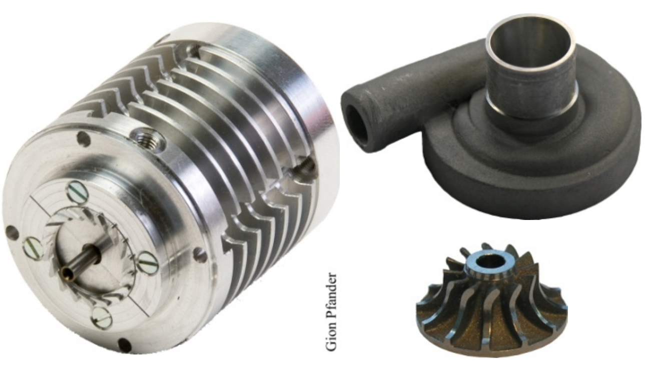
Gion Pfänder

Fig. 2. PM Generator with stator guide vanes, spiral casing and the radial turbine (d = 10.5 mm).

Several of the above mentioned applications, e.g. in automobiles, need ultra-compact power generation systems. Power density in both turbomachinery and electrical machines increases with increasing rotational speed [5], [6]. Therefore, for highest power density, these systems are operating at speeds between 100 000 rpm and 1 Mrpm at power levels of up to several kilowatts.

Besides higher power applications, micro-turbines with less than 100 W power output and very high speeds have been reported in literature. In [7], a PM generator, capable of supplying 8 W of dc power to a resistive load at a rotational speed of 305 000 rpm is shown. The stator uses interleaved, electroplated copper windings on a magnetically soft substrate. The rotor consists of an 8-pole SmCo PM, back iron and a titanium sleeve, because of the high centrifugal forces. The machine was characterized using an air-driven spindle. To provide a dc voltage, the ac generator voltages were first stepped up using a three-phase transformer and then converted to dc using a three-phase Schottky diode bridge rectifier. The dimensions of the device are chosen with reference to a future integration into a micro turbine engine. This leads to a power density of only the generator of 59 W/cm^3 and to a generator efficiency of 28%.

A planar generator with an diameter of 8 mm consisting of a permanent magnet disc rotor cut out of bulk SmCo or NdFeB protected by a titanium sleeve, and a silicon stator with electroplated three-phase planar coils is presented in [8]. The generator is driven by a planar turbine, etched into the opposite side of the rotor. Due to the turbine construction, the speed is limited to 100 000 rpm with 5 bar compressed air supply. A maximum power output of 14.6 mW was measured at 58 000 rpm with three Y-connected 50 Ω resistors. Using a turbine of a dental drill, the rotor reached a maximum speed of 420 000 rpm. With this setup, the highest electric power output of 5 W (three Y-connected 12 Ω resistors) was reached at 380 000 rpm with an electrical efficiency of 66%.

In [9], an ultra compact and fully integrated compressed-air-to-electric-power system with a rated rotational speed of 350 000 rpm and a rated power output of 60 W is presented. This compressed-air-to-electric-power system comprises of a single-stage axial impulse turbine (Laval turbine) and a PM-generator. Before the pressurized inlet air reaches the nozzle guide vanes and the impulse turbine, it is first diverted into eight channels that are arranged symmetrically around the generator. This leads to higher effort in the construction of the casing, but the generator and the ball bearings can be cooled. Measurements show that the system has a maximum power output of 124 W at 370 000 rpm and 6 bar supply pressure and a maximum system efficiency (turbine and generator) of 24% at 350 000 rpm. The integrated system has a total volume of 22.8 cm^3 ($d = 2.2$ cm $l = 6$ cm) which leads to a generator and turbine power density of 5.4 W/cm^3.

In this paper, experimental results of a mesoscale electric power generation system are presented. The design of the system has previously been described in [10].

2. SYSTEM DESCRIPTION

The compressed-air-to-electric-power system under investigation has a rated rotational speed of 490 000 rpm and a power output of 150 W. It is based on the reversal of an existing turbocompressor system, which reaches a maximal pressure ratio of 1.6 at a maximal rotational speed of 550 000 rpm and a power input of 150 W. It is driven by a low voltage electronics with 28 V dc input. With new and specially designed guide vanes, the turbo compressor system can be reversed and operated as a turbine system. This new, compressed-air-to-electric-power system comprises of an inward-flow radial (IFR) turbine and a PM generator. The PM generator and turbine have a total volume of 36.8 cm^3 ($d = 3.3$ cm, $l = 4.3$ cm), which leads to a power density of 4 W/cm^3. The theoretical design and description of the generator and turbine system have been presented in [10], while in this paper measurements of electric output power, torque and efficiency are presented.

The calculated electrical and thermodynamic data is summarized in Table I.

Table I: Electrical and Thermodynamic Data

Electrical Data	
rated speed n_r	490 000 rpm
rated electric output P_{el}	150 W
magnet flux linkage Ψ_{PM}	0.22 mVs
back EMF at rated speed	11.2 V
stator inductance L_S	2.25 μH
stator resistance R_S	0.125 Ω
machine efficiency η_{mr}	87%
Thermodynamic Data	
inlet temperature T_0	300 K
inlet pressure p_0	3.5 bar
outlet pressure p_2	1.12 bar
guide vane efficiency η_n	90.25%
isentropic efficiency η_{is}	70%

3. TEST BENCH SETUP

In order to verify theoretical considerations and the compressed-air-to-power system concept an experimental test bench, shown in Fig. 3, is built. It includes a mass flow sensor and several temperature and pressure sensors and a three phase variable resistive load. The system has been tested up to an inlet pressure of 3 bar and a maximal outlet electric

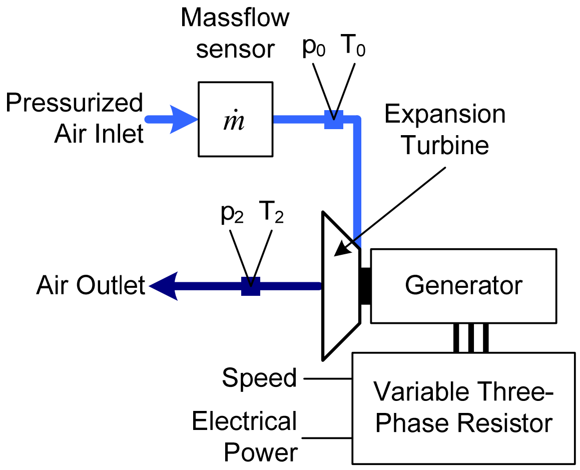

Fig. 3. Test bench setup.

power of 170 W. For the measurements, the operating point could be changed by varying the resistive three-phase load and the supply pressure. Additionally to input and output pressure the input and output temperature of the air flow has been measured. As expected, the efficiency could not be measured depending on the temperature drop, because the turbine is not isolated enough from the thermal losses of generator and the ball bearings. The turbine and generator speed can be determined from the current in the resistor load. Similarly, with a three-phase power analyzer the electric power can be measured.

Assuming adiabatic flow through the turbine, the pressurized air to electric power efficiency has been calculated using

$$\eta_{system} = \frac{P_{el}}{\dot{m}\cdot\Delta T_{(0-2s)}\cdot c_p} \tag{1}$$

where c_p is the specific heat capacity and P_{el} the electric output power. The corresponding temperature drop $\Delta T_{(0\text{-}2s)}$ can be calculated with

$$\Delta T_{(0-2s)} = T_0\left(1-\frac{p_0}{p_2}^{\left(\frac{1}{\kappa}-1\right)}\right) \tag{2}$$

where p_0 is the inlet pressure, p_2 the outlet pressure and T_0 the inlet temperature. With the knowledge of the generator efficiency, the isentropic efficiency of the turbine can now be calculated with

$$\eta_{turbine} = \frac{\eta_{system}}{\eta_{generator}}. \tag{3}$$

The generator efficiency is determined with the measured losses shown in Fig. 4 plus the calculated copper losses.

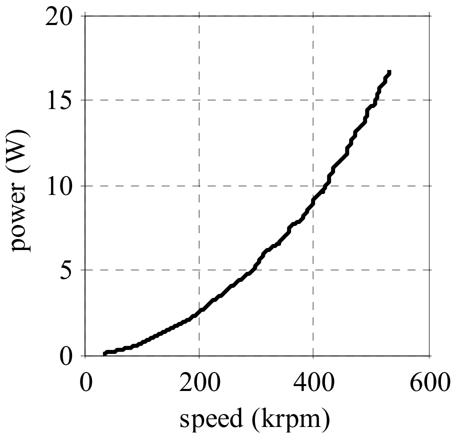

Fig. 4. Measured losses of the high speed motor versus speed. The measured power losses include the bearing losses, windage losses and core losses. For the total generator losses, the calculated copper losses are added.

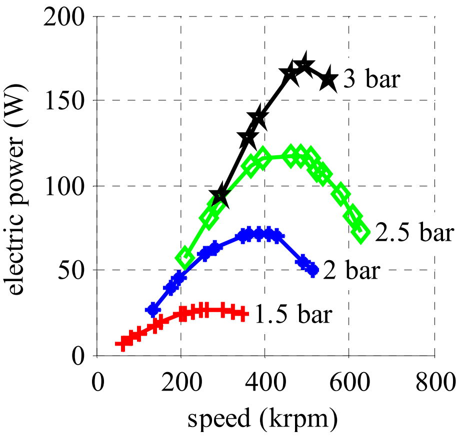

Fig. 5. Electrical power generated by the turbine and generator system as a function of speed and supply pressure.

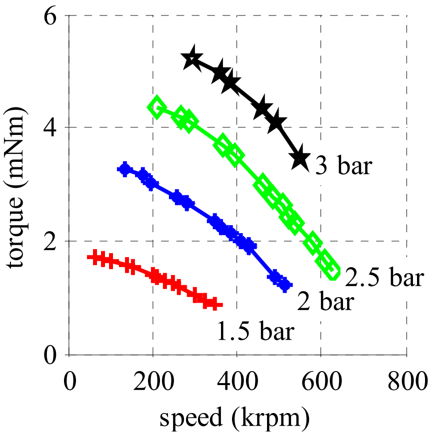

Fig. 6. Torque generated by the turbine as a function of speed and supply pressure.

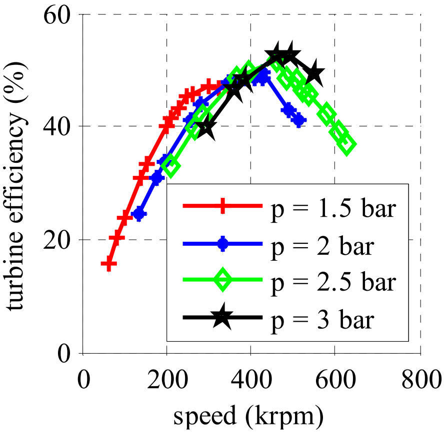

Fig. 7. Turbine efficiency as a function of speed and inlet pressure.

4. MEASUREMENTS

First, the motor has been tested without load up to a speed of 550 000 rpm and for measuring the bearing, windage and core losses the deceleration test was used (Fig. 4). Not included in the deceleration test are the copper losses depending on the phase currents, but they can be calculated accurately and added to the measured generator losses.

In a second step, the impeller and inlet housing are mounted. Fig. 5 and Fig. 6 show the electric output power and torque as a function of speed and supply pressure. The maximal electric power output is around 170 W at 495 000 rpm and the maximal measured torque is 5.2 mNm at 295 000 rpm. An increase of the three phase resistance causes a decrease of the torque and therefore an increasing speed at a constant supply pressure.

Fig. 7 shows the turbine efficiency as a function of speed and supply pressure. The maximal turbine efficiency lies around 52%, while the maximal system efficiency (turbine plus generator) is 43% The maximal generator efficiency (83%) is significantly higher compared to [7] (28%). Comparing this radial turbine with an axial turbine such as in [9], the turbine efficiency (52% versus 28%) as well as the system efficiency (43% versus 24%) is higher for the radial turbine, but the manufacturing and controlling the tolerances is more difficult.

5. COMPARISON

In [7] and [8] the μ-generators are driven with simple air-driven turbines and therefore only the generator power density is presented. Therefore, comparing the generator power density of the different systems, it can be recognised that the traditionally fabricated systems, like in [9] and the system presented in this paper, have power density in the same range (11 W/cm^3 versus 6 W/cm^3), while systems that have electroplated surface windings and are made used deep lithography or silicon etching, like in [7] and [8], have power densities up to 59 W/cm^3. But on the other hand the maximum electric output is clearly higher with traditionally fabricated systems (124 W and 170 W versus 5 W and 8 W). Also the generator efficiencies of [7] and [8] (28% and 66%) are lower than in the high-speed generator used in the presented system (83%).

6. CONCLUSION

This paper investigates an existing high-speed radial turbo compressor system that is reversed to a compressed-air-to-power system. Measurements show that the system has a maximum power output of 170 W at 495 000 rpm and a maximum efficiency of 52%. Compared to other system published in literature such as [7] - [9], the presented compressed-air-to-electric-power system has a significantly higher electric output power and a higher system efficiency.

REFERENCES

[1] L. Guzzella, M. Betschart, T. Fluri, R. De Santis, C. Onder, T. Auckenthaler. *Recuperative Throttling of SI Engines for Improved Fuel Economy.* SAE 2004 World Congress & Exhibition, March 2004, Detroit, MI, USA.

[2] A. Mirandola and L. Minca. *Energy Recovery by Expansion of High Pressure Natural Gas*. Proc. of the 21st Intersociety Energy Conversion Engineering Conference, Vol. 1, pp. 16-21, San Diego, California, Aug. 25-29, 1986.

[3] B. Lehman and E. Worrell. *Electricity Production from Natural Gas Pressure Recovery Using Expansion Turbines.* Proc. 2001 ACEEE Summer Study on Energy Efficiency in Industry, Vol. 2, Tarrytown, NY, July 24-27th, 2001, pp. 43-54.

[4] P. R. LeGoy. Utility Requirements for Power Recovery in the Cryogenic and Chemical Industry Using Variable Frequency Drives in the Regenerative Mode. The 1999 IEEE Power Engineering Society Summer Meeting, July 1999, Edmonton Alberta Canada.

[5] A. Binder, T. Schneider. *High-Speed Inverter-Fed AC Drives.* International Aegean Conference on Electrical Machines and Power Electronics, Electromotion 2007, Bodrum, Turkey, Sept. 10-12, 2007.

[6] S. Kang, S.-J.J. Lee, F.B. Prinz. *Size does matter, the pros and cons of miniaturization.* ABB Rev. 2 (2001) 54–62.

[7] D. P. Arnold, F. Herrault, I. Zana, P. Galle, J.-W. Park, S. Das, J. H. Lang, and M. G. Allen. *Design optimization of an 8-Watt, microscale, axial-flux, permanent-magnet generator.* J. Micromech. Microeng., vol. 16, no. 9, pp. S290–S296, Sep. 2006.

[8] H. Raisigel, O. Cugat, and J. Delamare. *Permanent magnet planar micro-generators.* Sensors and Actuators A: Volume 130–131, pp. 438–444, August 2006.

[9] D. Krähenbühl, C Zwyssig, H. Hörler and J. W. Kolar. *Design Considerations and Experimental Results of a 60 W Compressed-Air-to-Electric-Power System.* 2008 IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA), Beijing, China, Oct. 12 – 15, to be published.

[10] D. Krähenbühl, C. Zwyssig, H. Weser and J. W. Kolar. *Mesoscale electric power generation from pressurized gas flow.* Proceedings of the 7th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2007), Freiburg, Deutschland, Nov. 28 - 39, pp. 289 - 292 (2007).