ASYNCHRONOUS THREE-PHASE MACHINE DRIVEN AS GENERATOR BY A TWIN-SCREW EXPANDER

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Abstract. The paper presents the functioning regimes of a 132 kW asynchronous three-phase machine, used for the expander-generator system in a compressed air energy storage facility. The installation consists of a 110 kW twin-screw electro-compressor, which supplies pressurized air up to ~16 bar into a 50 m^3 storage vessel. The compressed air is afterwards released from the reservoir into expander's inlet, spinning its shaft. When the expander's shaft spins the electric machine over its synchronous speed, this one enters in generator mode, supplying electric power into the grid. Two power analysers installed on the automation control cabinet monitor the generated/absorbed power and the power supplied/consumed by the system from the grid. Using the data acquired by means of PLC during commissioning tests, we plotted the power curves, differential pressure and significant temperatures, as well as the electric machine's speed.

1. INTRODUCTION

The increasing use of the potential of renewable energy sources such as wind, biogas, solar, hydro and compressed air energy storage (CAES) encourages the use of low-cost generating systems, able to operate in remote areas, and driven by a diversity of prime movers [1]. With wind turbine generators [2] and hydro generators [3, 4] as an alternative energy source, the induction generators are being considered as an alternative choice to synchronous generators due to their simplicity, ruggedness, reduced maintenance necessary, lower price, brushless construction (for squirrel cage machines), absence of a separate direct current source, self-protection against severe overloads and short circuits etc. Squirrel cage induction generators with capacitor excitation, known as self-excited induction generators (SEIG), are very suited and used in isolated systems [1].

At the present moment, the emphasis falls on using renewable energy resources cost-effectively, for ensuring the quality and reliability of the power supply. Traditionally, synchronous generators have been used for power generation, but induction generations are increasingly being used in the present due to their advantageous features over the conventional synchronous generators. Self-excited induction generators have been a considerable research direction for a few decades until time being, due to their popularity as the simplest energy conversion devices to produce off-grid electricity, in standalone mode, with various prime movers and employing diverse conventional and renewable energy resources [1].

The major drawbacks of self-excited induction generators are the low voltage and frequency adjustments needed under the speed of the prime mover, as well as for load perturbations, or in other words the problem of regulating the voltage magnitude and voltage frequency under load variation. The main decision whether to use an induction generator or a synchronous one depends on a large number of variables. Not only the technical properties of the machines have to be considered, but also the application and the systems into which the generators will supply energy [5].

The paper focuses on the operation regimes of a 132 kW three-phase asynchronous machine used for the expander-generator system of ROCAES compressed air energy storage installation [6-8].

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2. COMPRESSED AIR ENERGY STORAGE PLANT

2.1. Overview

ROCAES installation (Figure 1) is a relatively low scale compressed air energy storage prototype [6-8], making use of a manufactured reservoir to store the compressed air, and a water tank for thermal conditioning. The demonstrative model makes use of a twin-screw compressor and a twin-screw expander, electrically actuated by three-phased asynchronous machines. The compressor is driven by a 110 kW asynchronous motor, supplying pressurized air into a 50 m^3 storage unit. The expander is driven by the pressurized air released from the reservoir. Its shaft spins a 132 kW asynchronous three-phase induction machine over its synchronous speed, injecting electric power to the grid. The compressor and the expander have not been designed for a simultaneous operation.

Fig. 1. ROCAES installation with automation and control room

During compressor's operation, pressurised hot air is accumulated in the storage reservoir. The lube oil tray passes through the thermal storage unit (5 m^3 water tank) and transfers heat to expander's oil circuit [8]. An oil injection pump recirculates the oil on a bypass circuit configured with a three-way MOV (Motor Operated Valve), thus ensuring the oil heating. After the compressor stops, oil recirculation also stops automatically for thermal energy conservation in the storage tank.

2.2. Advantages of using induction generator over synchronous generator

It can be stated without doubt that the synchronous motor has a difficult start-up, since it is not able to develop electromagnetic torque unless the synchronism condition is fulfilled. In order to start a synchronous motor, one can either use an auxiliary motor or asynchronous start-up. Using an auxiliary motor for driving the rotor up to synchronous speed is less practiced, since it rises the overall costs. Asynchronous start-up is possible only if the motor has an extra short-circuit winding that has the same role as the squirrel cage at the asynchronous motor.

For a 200 kW synchronous generator driven by an air/gas twin-screw expander, in a similar application [9], several manoeuvres are being required, along with a more complex automation system. The electric machine is driven up to its synchronous speed by the air/gas released into the expander, until reaching its synchronous speed, at the same frequency as the electric grid (50 Hz), with very tight allowed tolerances. Then, only when the phase of the machine and that of the electric grid are the same (the sinusoidal curves overlap), this one can be coupled to the grid. Any phase shift can yank the synchronous generator and cause shocks, sparks and overcurrents, which can harm the electric machine. The automation system ensures protection switches which disrupt the machine's circuit from the grid. For the 200 kW synchronous generator, when this happens, the power line may fall.

Induction generators have a simpler construction than synchronous generators [10, 11], are easier to operate, control, and maintain, and do not have synchronization problems [1]. Induction machines have been widely used in power generation and industrial applications [12] for decades due to their numerous advantages like robust design and lower cost as compared to synchronous machines. When a standalone induction generator is driven by a mechanical prime mover, the remanent magnetisation in the rotor induces an electromagnetic field in stator windings at a frequency proportional to rotor's speed [13].

The asynchronous machine used in our application is firstly coupled to the electric network, then started up as motor with a softstarter. The softstarter was chosen as a safer driver than frequency inverter, as speed variation is unnecessary, the installation being intended to generate at rated power (compressed air or electric power). Softstarters are a modern start-up method, ensuring current limitation, along with the necessary torque and start timer, so as to allow a smooth start-up and avoid mechanical and electrical shocks and strains. We provided ultra-rapid fuses for thyristors protection, in case of short-circuit, as well as thermal relays.

ASU 315M-4 [14] squirrel cage three-phase induction machine chosen has an active (shaft) power of 132 kW. Its characteristics are given in Table 1. At asynchronous generators, an extra reactive power component appears [15], relatively high, which is interchanged with the grid. For not putting an extra load on the grid, we provided a capacitor battery of 50 kVAr to ensure the necessary capacitive reactive power (compensating induction reactive power).

Table 1. Asynchronous machine specifications

Motor type	**Rated power**	**Rated speed**	**Rated current @400V**	η	**cos** φ	I_p/I_n	M_p/M_n	M_{max}/M_n	**Mass**
ASU 315M-4	132 kW	1470 rpm	225 A	95.0 %	0.89	7.4	2.0	3.0	820 kg

*Where: η – Efficiency; I_p – Start-up current; I_n – Rated current; M_p – Start-up torque; M_n – Rated torque; M_{max} – Maximum torque.

For the given application, asynchronous generators offer undeniable advantages: Simple construction and safe operation; Good technical performances (high start-up torque up to 2xM_n, high dynamic load capacity, good efficiency); Stability in operation, exploitation, manoeuvring, as well as simple maintenance; Power supply directly from the three-phased alternative current grid, connection to grid from start-up; Its operation can be fully automated: start-up – loading – grid functioning, without human operator's presence being necessary.

3. EXPANDER-GENERATOR SYSTEM

The electric power produced by the generator increases with the prime mover's power. The expander's induction machine initially functions as asynchronous motor (launched with softstarter) until reaching no-load speed $\left(\frac{dn}{dt} = 0\right)$, afterwards being driven by the pressurised air released, controllably, from the storage unit into the expander. When exceeding the synchronous speed, the asynchronous machine enters automatically in generator mode, which can generate a power of up to ~138 kVA. Choosing an asynchronous generator significantly eases the coupling to grid, as no manoeuvres are required for synchronisation with the electrical network's frequency. The expander-generator system (Figure 2) was commissioned at Popeci Heavy Equipment industrial hall in Craiova, Romania.

Fig. 2. Expander-generator system

The expander's asynchronous machine receives electric power from the AC three-phase network by connecting its stator to this one, energy that it converts in mechanical power to turn the shaft. When the shaft is spun mechanically over synchronous speed, by the compressed air released from the reservoir, the rotor will have a higher speed than the stator, pulling after it the stator's magnetic field, and thus becoming inductor.

Entering into generation regime is realised by opening the valve on expander's inlet at a certain angle, considering the instantaneous storage pressure. Subsequent finer adjustments of the injected power can be made, affected by a series of limitative parameters such as: inlet pressure, discharge pressure (differential pressure between inlet and outlet), air temperature, oil temperature etc.

The two power analysers installed on the automation control cabinet monitor the generated/absorbed power of the asynchronous machine (Figure 3 left), and the overall power supplied/consumed by the system into/from the electric grid (Figure 3 right). As it can be observed, the power is negative, indicating generation. The values displayed on the network analyser (right) are slightly lower, since a share of the generated power is used to power the electrical consumers within the automation cabinets.

Fig. 3. Power analysers displaying the generated power (left) and power supplied to grid (right)

4. COMMISSIONING TESTS AND ACQUIRED DATA ANALYSIS

The purpose of the automation Supervisory Control and Data Acquisition (SCADA) system, represented by two sets of drives and automation cabinets, one for compressor and one for expander automation, is to monitor, control and regulate the operation parameters of thermal, mechanical and electrical processes, in order to keep these ones within safe operation limits. The information from the transducers monitoring installation's important parameters is transmitted to the two separate VersaMax PLCs located in the automation cabinets, for the independent operation of expander and compressor skids [8]. The analogue I/O (inputs/outputs) signals for varying parameters are transmitted in 4-20 mA unified current signal, while digital I/O (open/close, on/off type) are transmitted in 0-24 VDC voltage signal.

The air reservoir was filled for about 2 hours of compressor operation, reaching a pressure of ~16 bar. Then, this one was shut down as the automation system was designed for not allowing a simultaneous operation with the expander. The twin-screw expander's air inlet valve was therefore opened, and the electric machine was started in motor regime, until reaching no load speed. Pressurised air from the storage unit was released, opening the reservoir valve towards the expander.

A minimum air pressure condition 2 bar was set at the inlet in the software program realised in Proficy Machine Edition, dedicated for VersaMax PLCs. If not meeting this condition, the expander goes through an automatic shutdown sequence. The condition was set considering minimum air pressure in the reservoir dropping down to 4-5 bar, considering the pressure losses until air reaches expander's inlet. As well, a similar software shutdown sequence occurs when the asynchronous machine enters again in motor regime and its consumed power exceeds 50 kW. Figure 4 shows the last shutdown cause (Wg over 50 kW) on the control panel.

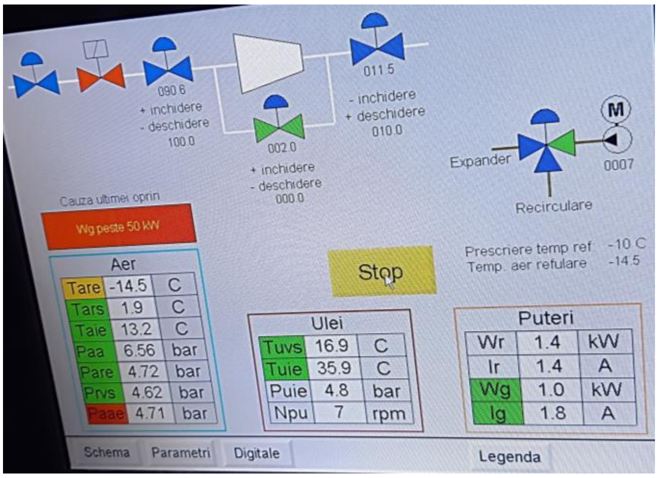

Fig. 4. Operator panel displaying last shutdown cause

The data about all important parameters requiring monitoring and control by means of PLC is acquired and saved through the DAQ (Data Acquisition) software. From these parameters, we chose the most relevant ones for the functioning of the system and represented graphically their evolution in time.

Hence, in Figure 5 hereinafter, we plotted the power curves. Positive power shows that the asynchronous electric machine functions as motor, absorbing power from the grid. Then, as the expander inlet suction valve gradually opens to let in pressurised air coming from the reservoir, the electric machine begins to spin over its synchronous speed, driven as generator. The launching generator current spike gives the high instantaneous power when entering in generator mode, passing very quickly through zero point, when the induction machine does neither consume, nor generate power. After the spike, it begins to stabilize, recording a generating peak power of 68.4 kW, which gradually decreases as the air in the storage unit begins to drain and air pressure on expander's inlet gradually decreases. Then the machine enters in motor regime again, and it is automatically shut down through a programmed PLC sequence, with the condition of exceeding 50 kW consumed power (see Figure 4 above).

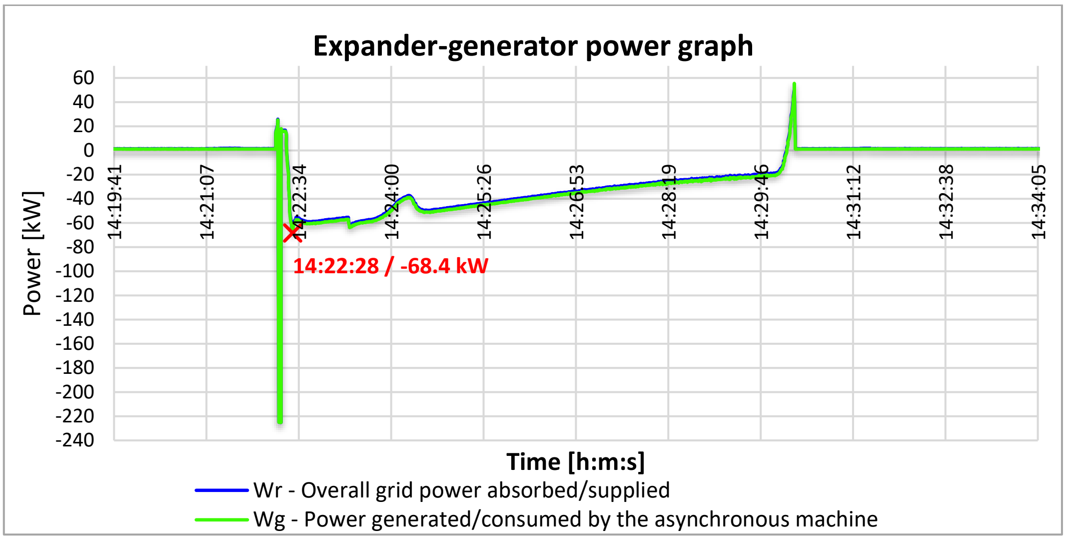

Fig. 5. Induction machine power curves

The power depends on the expander's inlet and discharge air pressures, more precisely on the differential pressure between inlet and outlet. It can be observed that the above power graph is tightly correlated with the differential pressure curve in Figure 6 below. The power decreases with pressure, until the asynchronous machine is shut down, and then the reservoir's valve is also closed, for preserving the little air pressure that has remained.

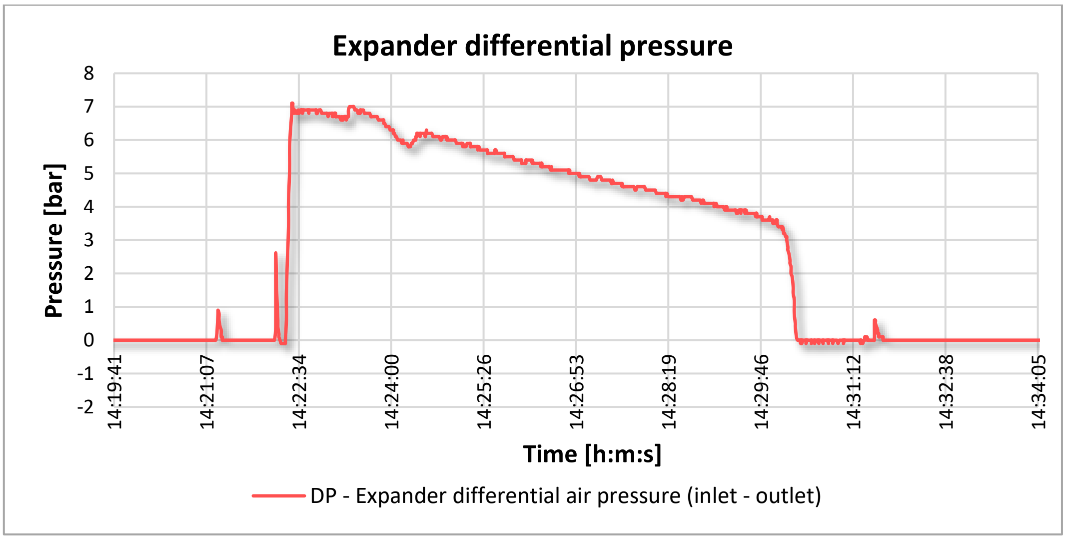

Fig. 6. Differential air pressure between expander's inlet and outlet

The maximum power that can be obtained is also limited drastically by air temperature. The thermal recovery water storage tank plays an important role in heating the pipes carrying the lubrication oil for the twin-screw expander's rotors. The heated oil consequently transfers heat to the decompressed air within the expander, whose temperature tends to decrease drastically. On the graph in Figure 7, one can see that the temperature at expander discharge still decreases below freezing point. However, using a heating resistance would add considerable power consumption to the system.

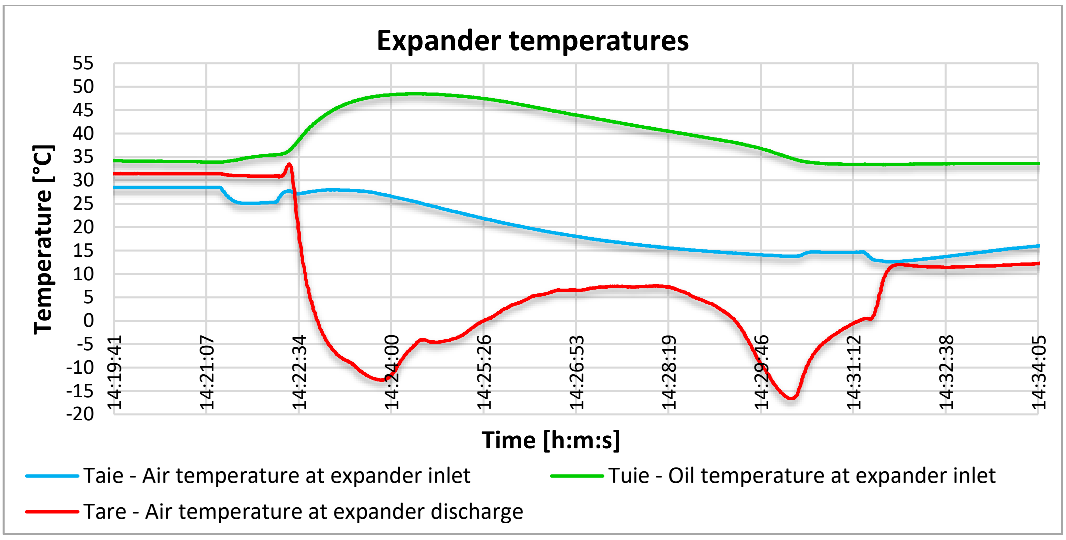

Fig. 7. Expander significant temperatures

Figure 8 shows the speed of the asynchronous machine, maintaining constant above synchronous speed (around 1595 rpm) during the generation regime and coinciding with the graphs above in terms of time periods. However, the speed measured determines a very high slip, which may be likely to show certain transducer misreading. Nevertheless, the curve evolution is reliable, respecting the other parameters' graphs.

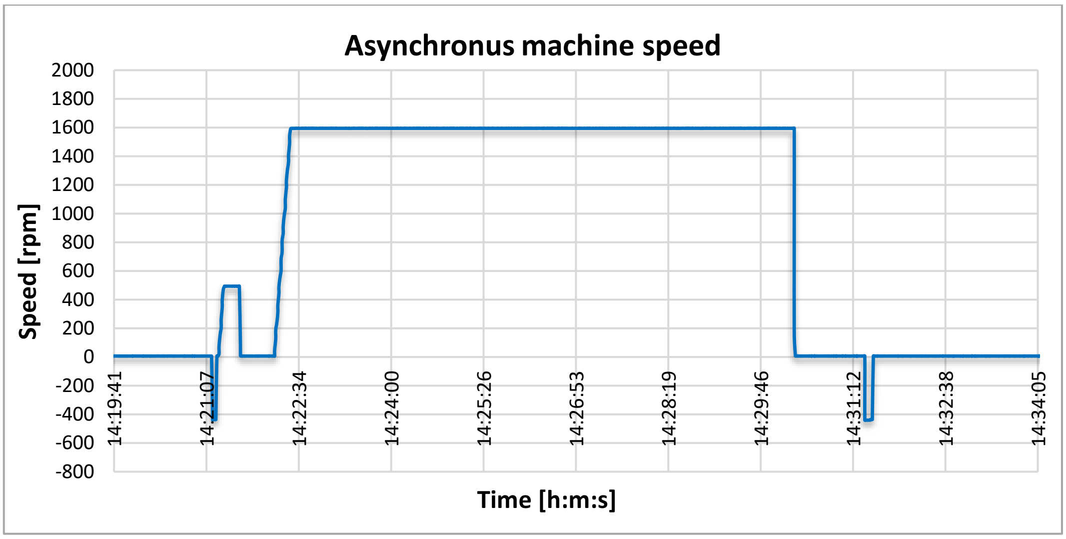

Fig. 8. Asynchronous machine speed graph

5. CONCLUSIONS

The paper presents the functioning regimes of an asynchronous three-phased machine driven by the compressed air released from a twin-screw expander. ROCAES installation is controlled by a customized automation SCADA system, which ensures the good operation parameters by means of PLCs and their embedded software programs. During commissioning tests, a good functioning of the equipment was noted, an important share being attributed to the reliability of the electronic and automation system. Graphs showing relevant parameters variation were plotted. The system, however, is overall inefficient, mainly due to the storage solution. Future research will try to find and exploit a gas deposit, already pressurised. The pressure and temperature decrease in the reservoir diminish the maximum power, but using another heating equipment would make the installation an even greater power consumer. The maximum pressure obtained in the vessel is actually limited by the compressor's motor power. Solutions for improving the efficiency through minimising losses shall be considered. As well, we aim to measure vibrations and temperature spectrums, for finding optimum mounting spots for an energy harvesting system comprising piezoelectric and thermoelectric transducers.

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