# MTG400: A MAGNETICALLY LEVITATED 400 KW TURBO GENERATOR SYSTEM FOR NATURAL GAS EXPANSION

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## ABSTRACT

Electrical energy is one of the most important bases of today's modern societies and, at the same time, opens new horizons for the development of new and future-oriented technologies. However, since it has become clear that energy resources are limited, more efficient, intelligent and ecologically beneficial concepts of power generation must be found in order to cope with the world-wide growing energy consumption.

Apart from the substantial potential of *reducing* energy consumption there is also a strong interest in *new* methods of power generation, even unconventional ones, if they are economically justifiable on a long term basis. In this context, the transformation of natural gas energy into electrical energy at the nodes between high pressure gas pipeline and low pressure consumer network has gained important significance. One reason for this is the fact that this energy recovery can be achieved with a high overall efficiency of approximately 80 %.

Conventional turbo machines with gear-box and mains-driven generator are already installed and generate electrical power of up to 3 MW per unit. However, there is a fast growing interest in smaller and more flexibly applicable units that can be manufactured in higher numbers.

For this purpose the MTG concept (magnetically levitated turbo generator) has been developed. It incorporates a gearless direct drive generator in active magnetic bearings (AMB) as well as a modern static inverter concept. A first 400 kW prototype has been extensively tested since autumn 1993, and two more machines are in service in a customer installation since April 1994.

## 1. INTRODUCTION

The common way of expanding natural gas from high pipeline pressure to the low consumer network pressure is to use conventional throttle valves. 100% loss of gas pressure energy is the consequence. A more clever solution is to take advantage of the pressure difference by applying expansion machines that provide at least partial energy recovery. Conventional piston- or turbine-driven machines with gear-box and generator are already in use in some European gas pumping stations. The new magnetically levitated turbo generator concept (MTG), however, incorporates a number of advantages over these conventional machines, such as

- high degree of availability
- pulsation-free gas flow
- oil-free and contact-free operation
- no gas leakage through capsular housing
- non-polluting operation
- vibration suppression by active magnetic bearings
- compact design
- low maintenance

The thermodynamics of the gas expansion process as well as the mechanical and electrical design of the turbo generator system will be discussed in the next sections.

## 2. THERMODYNAMIC ASPECTS OF THE EXPANSION PROCESS

A fundamental condition of the natural gas expansion process is to keep the gas temperature *constant*, i.e. to maintain the surrounding earth temperature at the gas inlet as well as at the outlet. Otherwise, unnecessary power loss at higher temperatures or environmental damages at lower temperatures may occur.

### 2.1 Expansion by Throttling

The standard approach of natural gas expansion by throttling down from high to low pressure is an *isenthalpic* process with an increase of entropy but without any mechanical power generation. The process can easily be described by means of the enthalpy-entropy diagram for natural gas (see figure 1, curve a) [1,2]. Due to the negative Joule-Thompson effect (gas cooling) the gas flow must be pre-heated (at constant pressure) in order to achieve the correct gas outlet temperature.

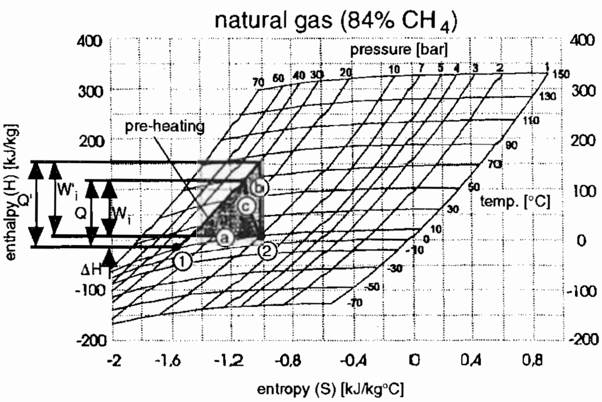


**FIGURE 1:** Enthalpy-entropy diagram for natural gas

### 2.2 Expansion with Power Generation

From both the economical and the ecological point of view gas expansion *with* mechanical power generation must be clearly favoured [1,2,3]. For this type of gas processing an even higher amount of pre-heating as compared with conventional throttling is necessary in order to fulfil the above mentioned gas outlet conditions (see figure 1, curve b).

The *real* expansion process is always accompanied by an increase of entropy. Thus, a so-called *polytropic* expansion must be considered (figure 1, curve c). The energy balance between gas inlet and gas outlet can be described by the following equation [4]:

$$Q = \Delta H + W_i + \Delta E_k + \Delta E_p \qquad (1)$$

In case of a real polytropic process the heat energy $Q$ transferred to the gas flow results in mechanical work $W_i$ as well as in an irreversible increase in gas enthalpy $\Delta H$. The latter corresponds exactly to the amount of heat necessary in the case of pure throttling. Increase in kinetic resp. potential gas energy $\Delta E_k$, $\Delta E_p$ is small and can be neglected.

Due to the polytropic expansion process importance must be attributed to the isentropic efficiency of the machine: the higher this efficiency the better the available energy potential is used. However, the previously mentioned boundary conditions of the process make it necessary to increase the amount of gas pre-heating for best energy exploitation.

If one subtracts the amount of heat necessary for the pure throttling process ($\Delta H$, see figure 1) from the total heat $Q$ transferred to the gas, one obtains the amazing result that every Joule of additional heat is completely transformed into mechanical resp. electrical energy [2]. In terms of actual cost and benefit, every 0.03 DM/kWh for pre-heating is paid back by 0.12 DM/kWh electrical energy, which stresses the profitability of the natural gas expansion process.

### 2.3 Comparison of Different Gas Expansion Mechanisms

Basically all machines that transform thermal into mechanical energy can be considered suitable for natural gas expansion:

- piston-driven machine
- screw type expander
- turbo expander

However, a comparison of the different machine types, under consideration of mechanical properties, production costs, efficiency and adaptability to different volume flow rates, rotation speeds and pressure ratios, shows that the Francis turbine with controlled guide blades is clearly advantageous for compressible media [4,5,6]. Moreover, the continuous and pulsation-free operation principle of turbo machines substantially reduces vibration and, at the same time, facilitates measurement of gas quantities such as flow rate and pressure.

## 3. A NATURAL GAS EXPANSION PLANT FEATURING A MAGNETICALLY LEVITATED TURBO GENERATOR

In 1991 PILLER started the development of natural gas expansion plants in the power range below 1 MW. This development was carried out in close co-operation with BOC-CRYOSTAR as turbine manufacturer and MECOS Traxler AG as magnetic bearing manufacturer. After consideration of the market situation the power range between 400 and 500 kW per unit was considered most advantageous. In addition, by applying a turbo expander in this power range, the disadvantages of conventional piston-driven machines can be completely overcome (see section 1).

The new natural gas expansion concept features a turbine with a direct drive generator in active magnetic bearings (see figure 2) and combines the latest engineering progress from fields such as mechatronics, power electronics and material technology. The novel machine design provides so many significant advantages that investment cost is easily compensated despite the comparably low power range under 1 MW. Moreover, the MTG system concept allows for a combination of independent machine units in series or in parallel to process high pressure ratios respectively high volume flow rates. In the following the most important advantages of the new MTG concept over conventional natural gas expansion machines are listed:

- The gear-box which must be considered a substantial cost factor, can be omitted by applying a direct drive mid-frequency generator. The amount of machine volume and, consequently, installation costs are drastically reduced. Installation of the new machine into existing plants is substantially simplified.
- The electrical energy recovery system allows for operation of the Francis turbine in its optimum speed range. The electrical power generation unit consists of an uncontrolled rectifier and a mains side static inverter.
- The problem of turbine run away in case of a load drop can be solved effectively by applying electrical power resistors within the inverter's D.C. circuit to brake the turbine to stand still.
- A most important advantage of the MTG system is the application of contact-free active magnetic bearings instead of conventional oil-film bearings. Thus, the cost-intensive oil supply system becomes altogether obsolete. Due to the capsular generator housing there is no need for any sealing between magnetic bearings and natural gas flow. The natural gas can even be used to cool generator and magnetic bearings [7]. Thanks to the capsular design the entire generator with turbine and magnetic bearings can be considered part of the expansion plant's pipe system, and there is no need to lead any rotating parts through the housing. Consequently, all danger of gas contamination by oil is eliminated.
- Due to the active magnetic bearing suspension generator operation is completely vibration-free, which allows for a simple machine founding.
- Thanks to the turbine the gas flow is continuous and pulsation-free. Hence, simple and low cost measurement arrangements for gas quantities such as flow rate and pressure can be used.

In the following sections the main components of the MTG system, magnetically levitated rotor with turbine and mid-frequency generator as well as static inverter, are presented, and their most important characteristics will be discussed.

### 3.1 Magnetically Levitated Turbo Generator

In 1984 PILLER started to investigate into magnetically levitated high speed generators for energy recovery in the liquefaction process of nitrogen. A first prototype (35 kW at 45'000 rpm resp. 50 kW at 65'000 rpm) was developed. The generator frequency was 1000 Hz [8].

**3.1.1 Mechanical machine design.** The machine concept used for that prototype, a synchronous machine with permanent magnetic induction, was consequently improved and finally applied for the natural gas turbo expander system (MTG, see figure 2). The most important advantages of this design are:

- The rotor with permanent magnets shows low loss and, therefore, little elongation due to warming.
- The overall concept allows for a mechanically stiff rotor design so that operation below the first bending critical speed is achieved.
- Thanks to a carbon fibre bandage for fixing the high energy density permanent magnets on the rotor, which was especially developed by PILLER, very high circumferential speeds can be reached (up to 280 m/sec) which allows for a large diameter of the generator part.

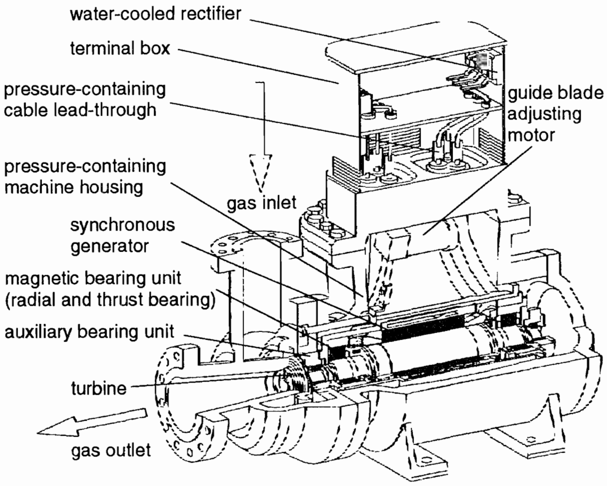


FIGURE 2: Magnetically levitated turbo generator

**3.1.2 Active Magnetic Bearing and Controller Design.** The suspension system for the turbo generator features full five axes active magnetic bearings with switched power amplifiers (310 V, 8 A). Feedback control is entirely digital using one single digital signal processor (DSP) running at a sampling rate of 5 kHz. The controller is implemented using state space description with an overall controller order of 28.

Since operating speed (32'000 rpm) is very close to the first bending critical speed (620 Hz, see figure 3) active damping even in this high frequency range is compulsory. Furthermore, each magnetic axis is equipped with a so-called *feedforward compensation* scheme (FFC) for unbalance force cancellation. Hence, the rotor rotates about its principal axis, and absolutely no rotation synchronous vibration forces are transmitted to the machine founding. Feedforward unbalance compensation schemes have a number of advantages over conventional implementations based on tracking notch-filters. In addition, the FFC implementation used for this application is quite exceptional due to its non-linear and time-variant structure which allows for an extremely *narrow-banded* operation required for this application (see section 4). A detailed description of the FFC unbalance compensation structure is found in [9].

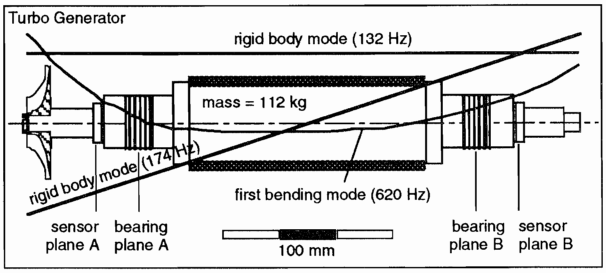


FIGURE 3: Mode shapes of AMB levitated rotor

The entire digital control system developed by MECOS is embedded in the world-wide known software package MATLAB[1] for controller design and signal processing. This link between hardware and powerful software makes it possible to design and download sophisticated controllers on the one hand and to monitor and analyse any system variable at run time on the other hand. The active magnetic bearings can be used *simultaneously* for levitation *and* as actuators for special test signals (impulse, step, sine). Hence, to give an example, transfer functions between any system variables can be measured using the same DSP as for levitation and *without* any additional measurement hardware in the loop. This allows for time-efficient plant and controller analysis and, thus, for a significant reduction of tuning time. Moreover, important insights into plant properties not exactly known at modelling time, e.g. fluid-structure interactions, can be gained using these built-in measurement and analysis capabilities of the magnetic bearing system. A survey of the entire software system is given in [10], and some measurement results are presented in section 4.

[1] MATLAB® is a trademark of MathWorks Inc.

### 3.2 Recovery of Electrical Energy, Process Control and Static D.C.-to-A.C. Inverter

The mechanical energy recovered from the magnetically levitated turbo generator (MTG) shall be fed back into the public power supply system with a high efficiency. For this purpose, optimum operating conditions must be achieved for the turbo generator as well as for the static inverter. An overview over the entire natural gas expansion system is given in figure 4.

**3.2.1 Control of Gas Flow.** The speed and gas flow conditions for the turbine can be controlled by adjusting the angle of the guide blades at the gas inlet. This control function is provided by a digital micro controller.

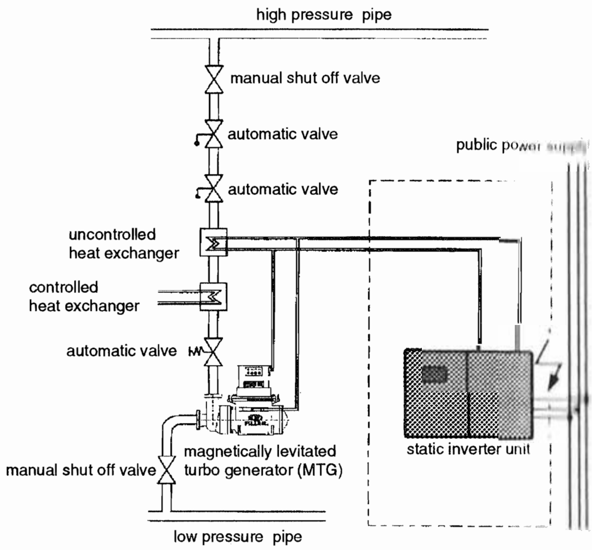


FIGURE 4: Natural gas expansion system overview

**3.2.2 Process Control.** All high level measurement and supervision functions necessary for the natural gas expansion system (figure 4) are realised using a digital micro controller. Apart from the above mentioned gas flow control the micro controller software comprises tasks such as visualisation of the system's operating conditions on a display and communication with the magnetic bearing controller (DSP) as well as with the central process control unit of the gas pumping station. All relevant system states are digitally stored and can be made available at any time. Moreover, similarly to the magnetic bearing control software, the time-history of several process variables can be reconstructed by built-in storage oscilloscope functions realised in software.

The digital implementation of all monitoring functions allows for connection to a digital information network. Thus, login by modem and remote diagnosis of all system conditions are possible. The system is even capable of *automatically* informing a service centre in case a technical problem occurs. This technique is state of the art in modern uninterruptable power supply systems (UPS) and helps to save important cost and time, since "the machine comes to the expert" instead of vice versa.

3.2.3 **Static D.C.-to-A.C. Inverter.** Two basic design approaches are possible:

- mains-driven inverter in thyristor technique
- pulse-width modulated inverter in IGBT technique (insulated gate bipolar transistor)

After rectification of the generator voltage the intermediate D.C. circuit voltage ranges from 360 V to 650 V. Due to this large voltage range a mains-driven inverter comes up with a poor power factor. Consequently, the inverter's overall efficiency is low and the back current on the mains side is substantial. Furthermore, isolated operation of the inverter without connection to a public power supply system is impossible.

As a consequence, a pulse-width modulated inverter in IGBT technique was chosen for the turbo generator system. The inverter's digital control runs at approximately 3 kHz and allows for feeding a *pure sine current* into the power supply system. No voltage or current distortions on the mains side occur. The most important characteristic of the PWM inverter, however, is that the power factor can be kept *near 1* without any reactive currents as is the case with thyristor based inverters.

The mechanical design of the static inverter unit features aluminium cooling attachments for the water-cooled power transistors. Since the thermodynamic process of natural gas expansion requires pre-heating of the gas (see section 2.2) the inverter cooling system is directly connected to the turbo generator for gas pre-heating (see figure 4). Thus, an important part of the electrical losses can be recycled in an ideal way so that the overall system's efficiency can be kept over 80 %.

If a load drop occurs the energy obtained from the turbo generator cannot be recovered any more. In order to avoid a turbine run away the generator output is automatically shorted by means of power resistors, and the turbo generator is brought from 32'000 rpm to standstill in about 25 seconds. The same effective and extremely reliable braking technique is applied in case of any other system malfunction (e.g. magnetic bearing failure), so that most rotor energy is dissipated through the electrical power resistors. Consequently, forces in the auxiliary ball-bearings can be kept small in case of an emergency halt.

## 4. EXPERIMENTAL RESULTS

In October 1993 a first demonstration and experimental turbo generator unit with a nominal output power of 400 kW was taken into service at PILLER in Osterode/Germany. The following machine requirements were successfully verified:

- overall monitoring and control functions
- security system function (e.g. D.C.-braking)
- static inverter function
- generator function (no-load voltage, open-circuit loss, short-circuit current)
- function of the combined gas and water cooling
- function of the active magnetic bearing system
- mechanically correct design of the rotor (bending criticals, material strength, etc.)

Due to the limited gas flow capacity of the compressor required for the experimental test stand the maximum energy recovery rate to the external power supply system was 50 kW. In April 1994, two machines were installed at a customer (see figure 5). In this plant two machines in series of 275 kW each expand an average natural gas flow rate of 20'000 $m^3$ (norm) from an input pressure of 25 bar to an output pressure of 3 bar. Until now the machines were able to produce electrical energy of up to 260 kW. Due to the seasonally low natural gas demand nominal energy production of totally 550 kW is expected for the end of the year.

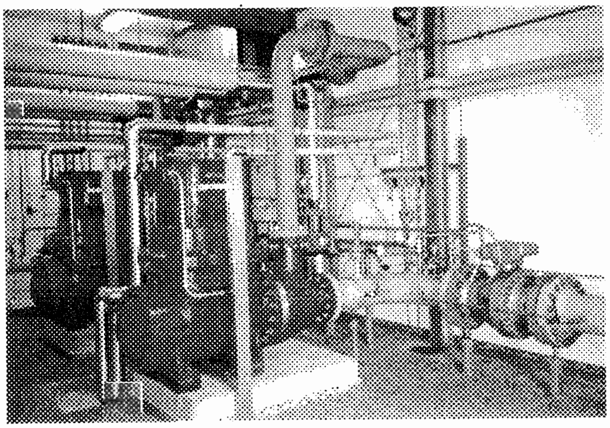

FIGURE 5: Turbo generators in a customer installation

Extended measurement series with the MTG prototype have been carried out since the end of 1993. Apart from temperature and gas flow measurements emphasis was put on frequency domain measurements of the magnetically levitated turbo generator. The built-in software functions of the digital magnetic bearing control for excitation and analysis (see section 3.1.2 and [10]) turned out to be an extremely valuable tool for verifying plant and controller characteristics as well as for identifying non-modelled or not exactly predictable plant characteristics such as fluid-structure interactions or gyroscopic effects.

Concerning these gyroscopic effects special interest was attributed to the question on *how near* to the rotation frequency the eigenfrequency of the first *backward* bending mode would come. Only approximate results could be obtained from Finite Element modelling. Hence, so-called *open-loop* transfer functions of the magnetically levitated rotor were measured at different rotating speeds without any additional measurement hardware in the loop using the built-in software tools. Figure 6 shows plant transfer functions at three different rotational speeds plotted as so-called waterfall diagram.

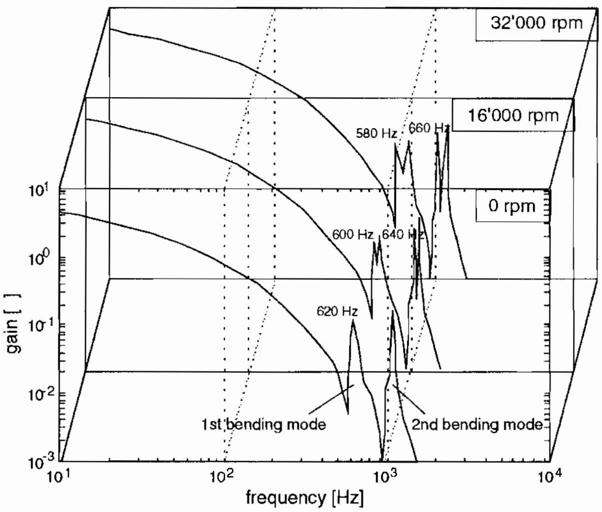


FIGURE 6: Measured plant transfer functions

As can be clearly seen in figure 6 the first bending mode of the turbo generator rotor (620 Hz at stand-still) *splits up*, due to the gyroscopic effects, into to modes (*forward* and *backward*) with increasing rotational speed. At operating speed (32'000 rpm resp. 533 Hz) the backward eigenfrequency of the 1st bending mode has come down to 580 Hz which only leaves a span of 50 Hz to the rotational frequency. However, as mentioned in section 3.1.2, operation of the feedforward unbalance compensation is so narrow-banded that absolutely no interference with the nearby backward bending eigenfrequency occurs. This was verified by a Fourier transform of the radial bearing current signal which shows no peak at rotation frequency. The digital feedback control provides enough damping even at the high frequencies of the 1st and 2nd bending modes so that smooth operation results. Moreover, sufficient damping is necessary for the transfer function measurement as well, since sine sweep excitation is applied even at the resonant frequencies of the closed-loop system.

## 5. SUMMARY

A magnetically levitated 400 kW turbo generator system for energy recovery in natural gas pumping stations with an overall efficiency of more than 80 % was developed. Due to the consequent application of digital control for the magnetic bearings as well as for process monitoring development and tuning time could be kept short. In October 1993, a prototype machine was taken into service, and two first units are in operation in a customer installation since April 1994

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