Industrial High Speed Turbogenerator System For Energy Recovery

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Abstract: The developed turbogenerator system is designed for process gas expansion producing a maximum of mechanical turbine power of about 70 kW that is fed as electrical power into the grid. In this arrangement the radial inflow expander turbine is mounted on the shaft of a permanent magnet excited high speed synchronous generator, supported by 5 axis active magnetic bearings. This arrangement eliminates the gearbox and is absolutely oil free. A novel static frequency inverter using flexible closed loop vector control improves machine application and allows a very wide range of speed with a nominal value of 45,000 rpm. On the grid output, pure sine currents with a power factor of 1 is fed to the grid. Active magnetic bearings prevent every type of process fluid contamination and seals are only to prevent excessive loss of process fluid. In the first test phase the proposed package was tuned and tested in steady state and transient conditions on a specially developed test stand using an identical second machine as a motor linked to the generator package under test via a flexible high speed coupling. In a second phase, the turboexpander-generator package was tested in nominal conditions in an open loop with pressurized air, connected to a 460 VAC, 60 Hz grid.

1 Introduction

Radial inflow turboexpander design dates back to the late 1930's in air separation application. Since then gas dynamics design and manufacturing of parts have been refined to the extent that its high isentropic efficiency is attracting more application for process industries. Application of radial inflow turboexpanders have extended to include hydrogen purification, helium liquefaction and natural gas process.

Bearing technology has also improved to accommodate turbomachine industry requirements. Oil lubricated bearings, gas bearings, air foil bearings, and active magnetic bearings have been utilised by turboexpander manufacturers.

In application where turboexpander is used exclusively for refrigeration and the mechanical power is not significant, air or oil brake are utilised. In latter applications, the cryogenic process is extremely sensitive to contaminants, particularly oil contamination. In spite of considerable advances in sealing technology, cryogenic process industries have their eyes on oil free turbomachines i.e., active magnetic bearings.

Advancements in active magnetic bearing technologies in the eighties and availability of reliable high frequency generators with power range of 50–70 kW in the early nineties provided turboexpander manufacturers and cryogenic process industries with another option. This option is turboexpander with active magnetic bearings and loaded with high frequency generator. This option is absolutely oil free.

2 The Expander High Speed Motor–Generator

This expander is designed to expand any pure (nitrogen, hydrogen, helium, etc.) or mixed process gas (air, natural gas, hydrogen rich natural gas, etc.) up to twelve to one (12/1) pressure ratio. The design is suitable for hazardous or non–hazardous environment. Variable inlet guide vanes is an important feature for expanders. It would provide an effective mean of process control and improving expander efficiency over a wide range of process fluid flow. The expander high speed motor–generator is equipped with variable inlet guide vanes.

Since this package is oil free, there are no concerns about process fluid contamination. Therefore, seals are to prevent excessive loss of process fluid. This package is designed to accommodate labyrinth or carbon floating ring seals. Power of this expander is limited to 75 kW. Power limitation is mostly due to high–speed–motor–generator and associated frequency inverter electronics.

Considering an average cost of energy, i.e., $.O5/kWh, additional investment for expander high–speed–motor–generator is paid back in less than three years.

3 Magnetic Suspension And Controller

The stator parts of the magnetic bearing consist of two identical cartridges mounted on each end into the generator housing (Fig. 1). Each cartridge contains a set of 4 radial electromagnets as well as the necessary inductive type position sensors for 2 axis radial position control. Each cartridge further contains a coil producing an attractive axial force on the corresponding ferro–magnetic rotor faces. The back up bearings are also a part of the cartridge; The turbine side cartridge additionally contains the axial position sensor. A special inductive angular position transducer used for the machine control is mounted on the opposite cartridge. The radial magnets as well as the position sensors are acting on a stack of thin laminations shrunk on the rotor shaft.

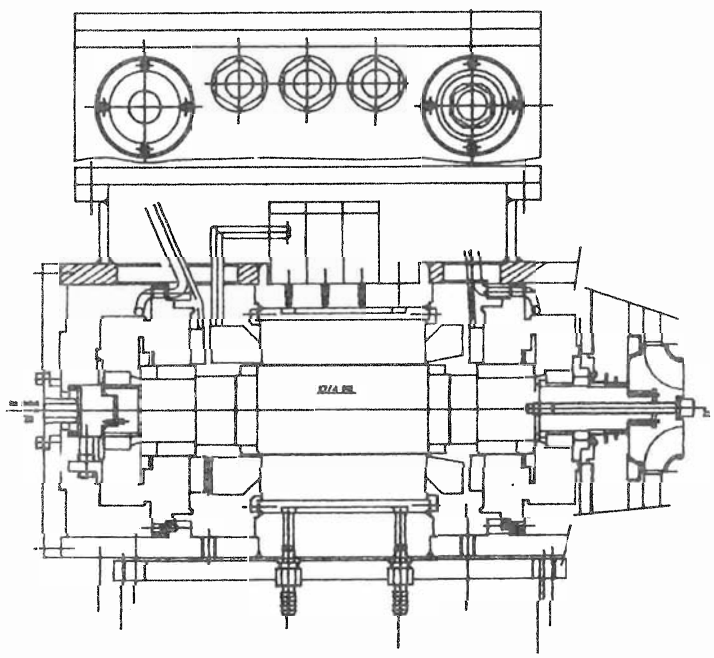

Fig. 1 Turbogenerator unit

Fig. 2 shows the complete rotor model and the computer generated mode shapes of the 1st and 2nd bending modes. The nominal generator operating speed of 45,000 rpm (750 Hz) lies far below the bending critical speed at standstill of 56,000 rpm (933 Hz). Due to the gyroscopic effects, the modes at standstill split to a forward and a backward mode (see Fig. 1). The 1st backward mode decreases to about 870 Hz at 45,000 rpm (750 Hz). The remaining security margin is high enough to guarantee stable operation even in overspeed conditions.

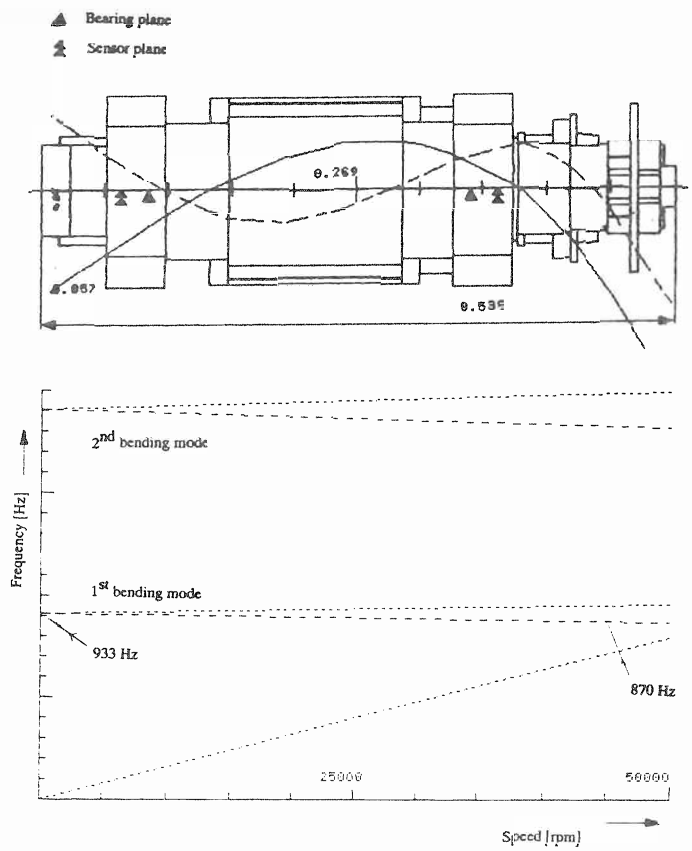

Fig. 2 Mode shapes and Campbell diagram

A standard E120/6 control cabinet is used for the 5 axis active position control of the turbogenerator shaft. It consists of 10 120V/6A switch–mode power amplifiers in MOSFET technology. The amplifiers are flux–controlled, in order to improve the disturbance force response in the low frequency region. The 5 position controllers are of analog type using our standard closed loop ABS system for unbalance force cancellation. The system allows the rotor to rotate around its natural axis of inertia and therefore no synchronous vibrations are transmitted to the generator housing. The control cabinet further includes a battery back–upped power supply, which can be adapted easily to different grid voltages and frequencies (460V, 60Hz is this case). The maximum power consumption of the cabinet is less than 300W. The size of the IP54 protected cabinet is 1,000 x 600 x 400 mm.

Measurements carried out with the levitated rotor have shown slightly higher mode values than the computed ones.

4 Permanent Magnet Excited High Speed Synchronous Machine

Especially for high speed applications the synchronous generator with permanent magnet excitation represents several advantages compared to the asynchronous machine:

- The rotor losses which are critical in high speed applications, are very low due to the synchronous operation and a very large magnetic "air gap".

- The permanent excitation allows easy braking operation with resistors. This feature can be used to avoid turbine runaway in case of an inverter failure or load drop of the electrical energy recovery system.
- The efficiency of the machine is very high, especially when the machine is controlled by an adequate frequency inverter using modern "vector control".
- The achievable volumetric power is high. This allows to build a short, stiff rotor and to keep the nominal speed far away from the first bending mode.
- The disturbance forces which are exerted by the machine on the magnetic bearing under load conditions are very low.

The construction of the 70 kW/45,000 rpm synchronous generator is based on S2M experience with AMB spindles using a similar synchronous machine concept.

Fig. 3 shows a cross section of the 2 pole synchronous machine with permanent magnet excitation. The permanent magnets are directly mounted on the rotor shaft. They are representing two magnetic poles, generating the excitation flux which rotates synchronously with the rotor. The direct axis (d–axis) indicates the direction of the flux vector. The magnetic field reacts with the currents in the stator slots creating the desired mechanical torque. A special carbon fibre sleeve is used to fix the magnets on the rotor. The sleeve design allows nominal peripheral speeds up to 250m/s.

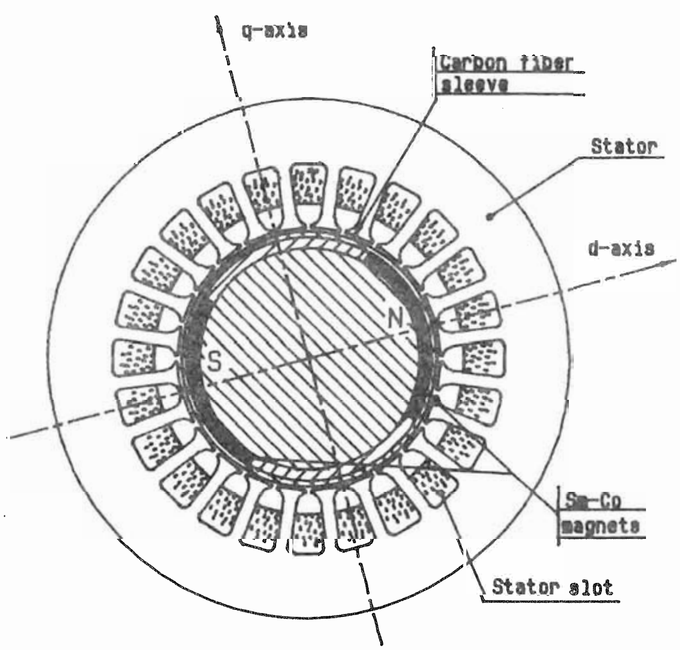

Fig. 3 Cross section of the permanent magnet excited synchronous machine

Rare–earth samarium–cobalt magnets have been chosen here. They have a high flux density of more than 1 T and a very large coercive force. Further, they allow an operating temperature up to 200°C and, with proper design, there is no danger of accidental demagnetisation through short–circuits.

For external magnetic fields, the magnets may be viewed as a part of air gap ($\mu r \approx 1$). From that the machine is characterised by a constant wide magnetic air gap of about 10 mm. The result is relatively small synchronous reactance and reduced armature reaction.

5 Static AC–AC Inverter System

In the present design the expander turbine and the rotor parts of the generator are mounted on a common shaft which is supported by active magnetic bearings. When the shaft rotates, a variable frequency source voltage appears at the power terminals of the generator, induced in the stator windings by the permanent magnets. A static frequency inverter is used to convert the electric power of the generator to the mains of constant voltage and frequency.

Such inverter system generally converts the generator AC power to an intermediate DC link and then the DC power to the AC grid. In [1] an uncontrolled rectifier bridge is used on the machine side. This is a very simple arrangement but it has important drawbacks: The intermediate DC link voltage depends on the generator speed and also on load. Even when using a pulse–width modulated DC–AC converter on the line side the practical operating speed range is limited when using an uncontrolled rectifier. Furthermore, the generator output power is limited to a maximum value determined by the synchronous inductance of the machine. Motor mode is impossible.

We chose a new, more complex machine control concept, which is characterised by a constant intermediate DC link voltage, a very large working speed range and an optimised machine exploitation.

The rapid progress in the field of power electronics, offering powerful high speed switching IGBT modules, and in digital signal control allowed to realise this new static inverter concept as sketched in Fig. 4. A machine side IGBT bridge (bridge 1) replaces the uncontrolled rectifier

This leads to a symmetrical design referring to the intermediate DC link, allowing power flow in both

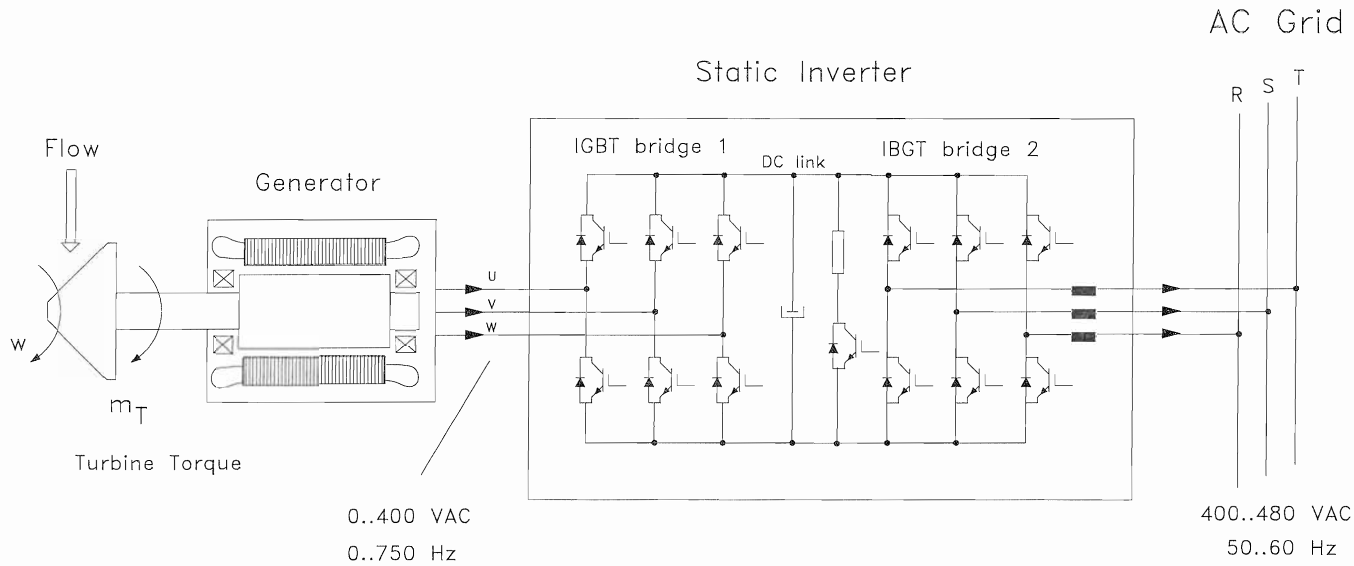

Fig. 4 Energy recovery system

directions, from the machine to mains and from the mains to the machine. A fully digital unit controls the switching of the transistors (10 kHz on machine side, 5 kHz on line side) operating in pulse–width modulation mode.

The principle of controlling the generator currents consists in orientating the phase angle between the stator current vector and the excitation flux vector to a value for which the generator produces maximum torque. A patented high speed angular transducer supplies the control unit with the necessary rotor angle information. This new, resolver compatible transducer has no rotating windings and his rotor part can be integrated easily on the shaft.

The main features of the realized recovery system for the 70 kW/45,000 rpm generator can be summarised as follows :

- The generator is operated in a very flexible « vector control » mode. This results in an improved machine exploitation. In case of the developed machine the obtained output power is about 50% higher than the maximum achievable value with uncontrolled rectifier operation. Pulse–width modulation and high speed switching produce quasi sinusoidal phase currents.
- The rated generator torque is available in a speed range from 0 to 45,000 rpm. A fast torque and speed control loop is included in the control unit so that the turbine can be operated with its optimal speed and according to the process conditions.
- The system allows to drive the machine as a motor without any modification, this additional feature can be of interest for future developments.
- The inverter control unit operates fully digital. The machine side vector control is performed by a DSP with a sampling rate of 10 kHz. All supervisor and interface functions are realized around a powerful micro–controller.
- The line side PWM converter feeds sine currents with a power factor of 1 to the mains. A special filter protects the grid from high frequency harmonics, due to IGBT switching, in order to fulfil today's standards.
- Synchronisation of the line side converter is done automatically when the inverter cabinet is connected to the grid
- An in–built braking resistor, connected through an IGBT–chopper to the intermediate DC link, protects the turbine from "runaway" in case of short grid interruptions and other failures. However, a fast acting "quick shut–off" valve stops the gas flow when there is any malfunction or a mains interruption for more than 1.5 second.

All power and control electronics of the static inverter, including the cooling system and power filters, are installed in a cabinet with the dimensions 1,800 x 600 x 400 mm. The IGBT power modules are mounted on water–cooled heat sinks, connected in a closed loop with a water/air heat exchanger. Exchanger and associated fans are included in the cabinet. In future it is planned to connect the inverter and generator cooling system to a common exchanger.

6 Vector Controlled Synchronous Machine

For a better understanding of the realized machine control, it is necessary to discuss the electrical machine model. The one phase equivalent circuit of the machine is shown in Fig.5 a.

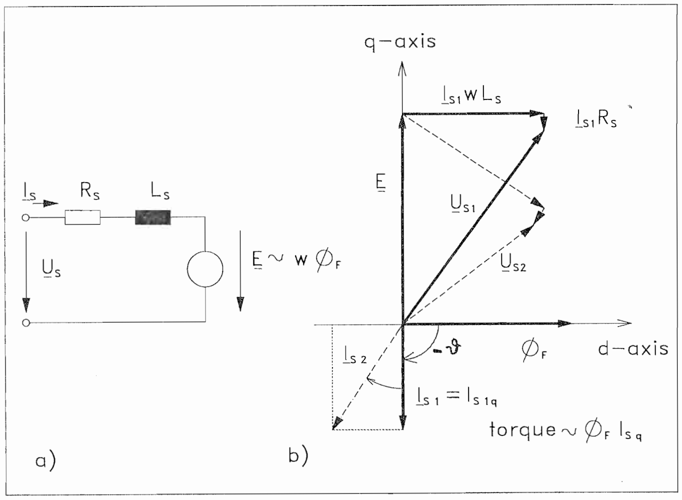

Fig. 5 Equivalent circuit (a) and vector diagram (b) of the vector controlled permanent magnet excited synchronous machine.

E is the source voltage, its amplitude is proportional to the product of angular speed ω and the constant rotor flux $\varnothing_F$.L_S represents the synchronous reactance and R_S stays for the winding (and cable) resistance. The frequency of the source voltage E is always equal to the rotational speed (2 pole–machine). In the vector diagram shown in fig. 4 the stator current vector $\underline{I}$, the source voltage vector $\underline{E}$ and the rotor flux vector $\varnothing_F$ are represented in a rotor coordinate frame. This orientation corresponds to the d–q (or park–) transformation, commonly used with synchronous machines. The rotor flux $\varnothing_F$ vector lies in the direction of the direct axis, d–axis. Then the source voltage vector $\underline{E}$ has a phase lead of 90° and lies in the direction of the quadrature axis, q–axis. The d–q coordinate frame rotates with the rotor. The principle of controlling the generator consists in orientating the phase angle between the *stator current vector* $\underline{Is}$ and the flux vector $\varnothing_F$. From the machine point of view, the optimal angle is $\delta = -90°$ (Isd = 0) in generator mode ($\delta = +90°$ in motor mode). This optimal generator operation where the generator produces maximum torque for a given stator current is depicted in fig. 4. The machine torque is constant and proportional to the rotor flux $\varnothing_F$ and the quadrature current component Isq.

Compared to a classical synchronous generator working on a constant frequency line, the above discussed operation would correspond to the stability limit, but with an adequate frequency inverter control this is without any consequence, the machine is self–controlled.

The inverter has to supply the vector $\underline{U}_{S1}$ in order to compensate the voltage drops across the synchronous inductance Ls and the stator resistance R_S. In cases where the inverter cannot supply the necessary voltage (voltage saturation), it is possible to introduce a negative d–component of the stator current vector, as sketched in Fig. 5 in dashed lines.

7 Test Facilities With Two Flexible Coupled Machines

In order to tune and to test the package under steady state and transient load conditions a special test stand has been developed and built. It consists of 2 identical machines linked with a flexible high speed coupling. One machine is the generator under test and the other machine is used in a motor mode (like a torque generator).

Both machines are using an identical magnetic bearing and frequency inverter system. The power flow is from the grid via the frequency inverter to the motor, from the motor via the mechanical coupling to the generator and then back to the grid via the 2nd static inverter. The grid supplies only the total losses. The machine and inverter losses have been measured by means of electrical power analyzers, placed between the 1st inverter and the motor, the generator and the 2nd inverter and between the 2nd inverter and the grid. This configuration allows to measure the machines and the inverter losses for every combination of speed and torque within the limit valves (45,000 rpm, 15 Nm).

Fig. 6 shows the measured generator and static frequency inverter efficiency versus speed. The measurements have been made with constant torque. The corresponding shaft power is also indicated in Fig. 6. The generator (machine) efficiency has a maximum value of 95 %; The static inverter system reaches the maximum efficiency of 92 % at full load.

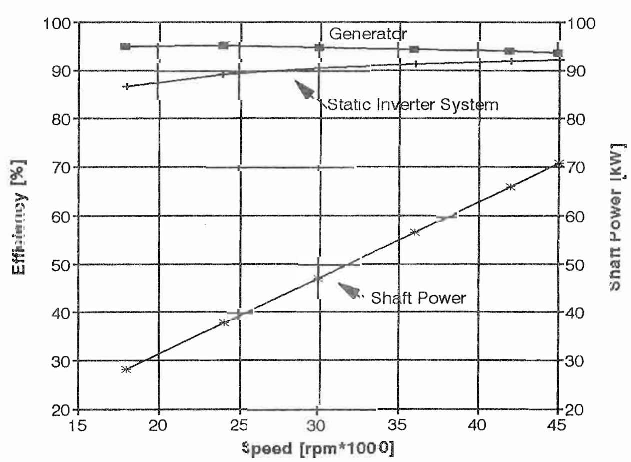

Fig. 6 Generator and inverter efficiency (test results)

Fig. 7 shows an oscillogram of the generator output current wave form.

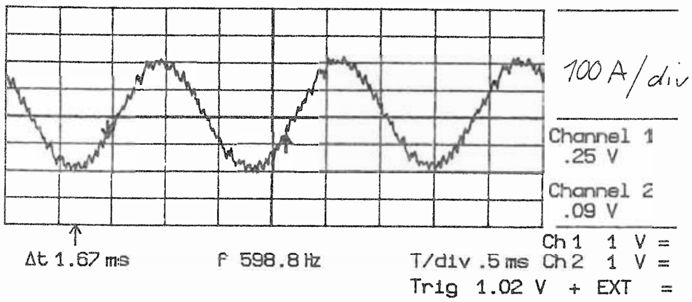

Fig. 7 Generator output current wave form

The wave form and the harmonics of a current fed to the grid is shown in Fig. 8.

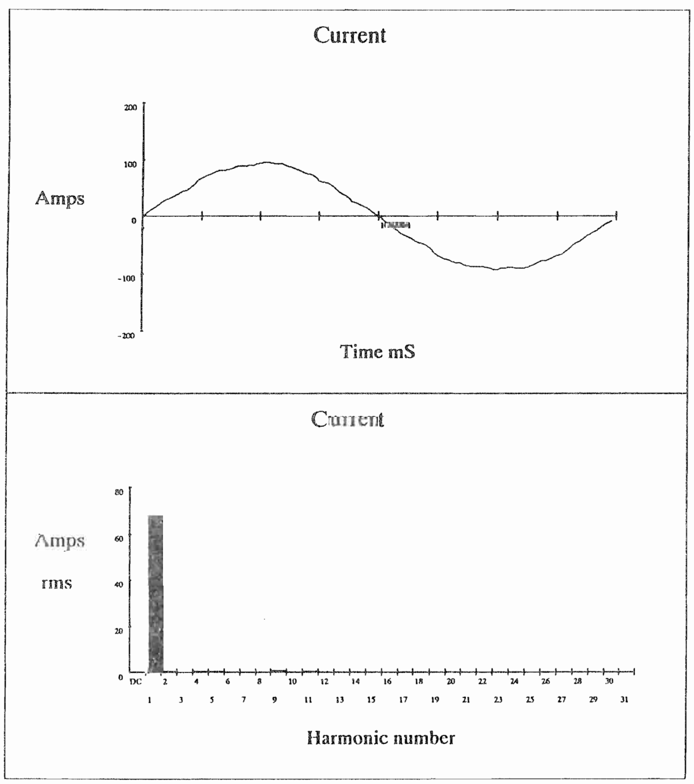

Fig. 8 Wave form and harmonics of current fed to the grid.

8 Shop test

The turboexpander–generator was tested at full power and full speed with pressurized air in an open loop arrangement. The generator output was connected to the grid (60 cycle, 460 Volt). The load was absorbed by a load-bank rated at 200 kW. A pneumatic actuator was used to adjust expander inlet guide vanes and hence controlling turboexpander–generator speed. A quick acting shutdown valve (1/2 sec. Closing time) was used to protect the unit in case of overspeed.

The pressure of inlet air was regulated to provide desired head coefficient. The variable inlet guide vanes were set in such a position to provide the required flow coefficient. The expander efficiency is measured versus velocity ratio (U/co) and the pick efficiency is determined by comparing the design velocity ratio (0.667) to the actual test results. U is the wheel peripheral speed and Co is the gas velocity equivalent to the enthalpy drop across the turboexpander.

The turboexpander was tested with two types of shaft seals. The shaft seals, depending on the application are labyrinth type or carbon ring seal. Since magnetic bearing turbo–expanders require larger seal clearances, floating carbon ring seal reduces the shaft seal leakage.

The turboexpander performance is shown in Fig. 9. The turboexpander pick efficiency with carbon ring seal is 88% and with the labyrinth seal is 87%.

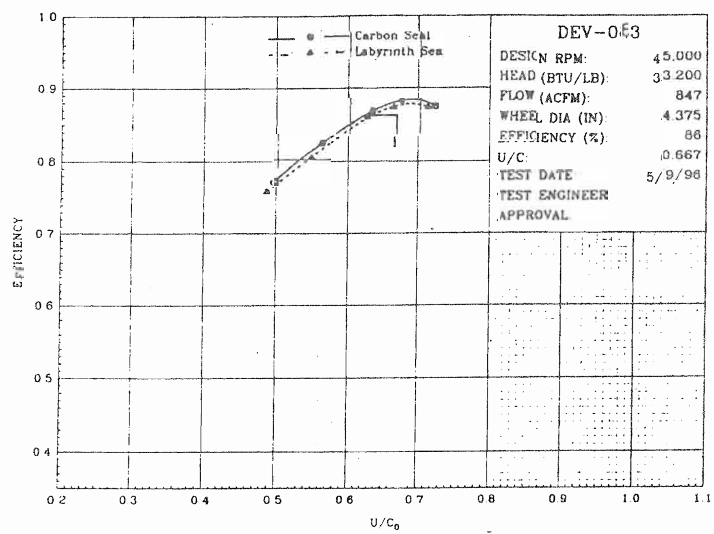

Fig. 9 Expander performance

9 Conclusion

Process industry in general and cryogenic industry in particular are demanding oil free turbomachines ([3], [4]). Turboexpander generator with magnetic bearing, i.e. absolutely oil free and gearless equipment, is now a mature product for energy recovery application.

This 70 kW machine that is therefore now a viable industrial product, opens the way to more powerful units already in advanced stages of development.

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