ORIGINAL

HIGH EFFICIENCY TURBOGEARS FOR GAS TURBINES
FIRST OPERATING EXPERIENCES

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ABSTRACT

A new type of gas turbine gear, running in a partial vacuum, is placed into operation in two power stations for the first time after an extended testing of function and protective equipment on the test bed. The High Efficiency Turbogear (HET) Technology will be basically explained in a short outline including special aspects of design and construction. The new gear technology and its integration into the control circuit of a 65 MW gas turbine train will be discussed including technical details of the protection system. The calculated saving of power losses had been verified by measurement at a power station which will be presented together with general aspects of cost saving.

NOMENCLATURE

HET	High Efficiency Turbogear, i.e. the system of increasing the efficiency of a power plant by reducing gearbox losses
HKW 2	**"Heizkraftwerk" - thermal power station**
MW	megawatt
v'	pitch line velocity (m/s)

INTRODUCTION

Within the effort to improve the efficiency of heavy-duty gas turbines attention is given to each component of the gas turbine train. Thus, an improvement of the efficiency of gas turbine turbogears was developed to a marketable commodity showing remarkable reduction on fuel consumption and CO_2-emission in case of constant power output. The power losses could be reduced to more than 45 per cent compared to a conventional turbogear.

It is well known that losses in turbogears can be reduced by an optimization of two components:

- bearing
- toothing.

The improvement of bearing design concerning loss reduction is continuously going on whereas the reduction of toothing losses which make the main part of the total gear losses could clearly be reduced by the generation of a partial vacuum around the toothing for the first time. This technology is called High Efficiency Turbogear (HET®).

Along with several constructive details which are required to produce a partial vacuum a complex control system is needed to integrate this technology into the gas turbine protective control unit. It has to be assured that there is no restriction in availability for the gas turbine train and that there is an automatic switch over into conventional mode in case of any trouble concerning the vacuum system. In any case it should be customer's decision to switch between vacuum and conventional mode at any time.

IMPROVEMENT OF THE EFFICIENCY OF GEARS BY THE HET-TECHNOLOGY

Principle

The aim of the HET-Technology is a reduction of the gearbox losses.

Gearbox losses have their origin in toothing and bearing because of the friction and aerodynamic effects. This power losses heat up the lube oil and the gear itself and has to be carried off as heat.

Figure 1 gives an overview of the origin of relative power losses for a typical high-speed gear with a power of more than 30 MW. For gears with a pitch line velocity of 150 m/s and more the losses in toothing, originated from the gear mesh and the rotation of the rotors, are caused at about 80 % by aerodynamic effects known as "churning" and "windage" (as shown in figure 2). The detailled process of aerodynamic toothing losses is described in a VGB publication [1].

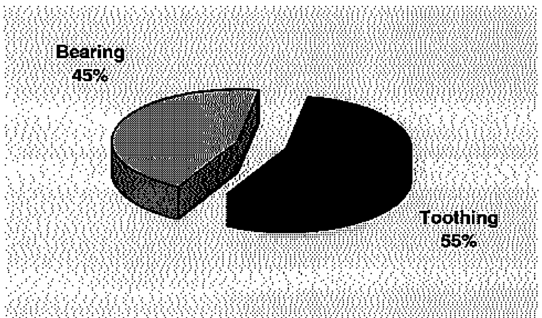

Fig. 1: Origin of gearbox losses

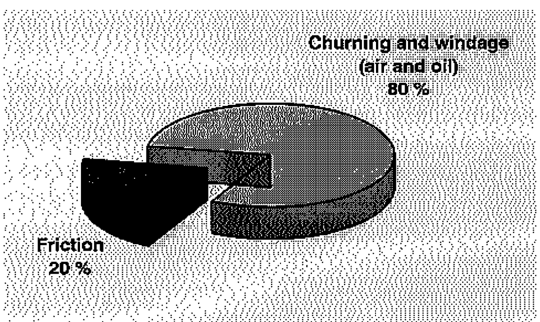

Fig. 2: Origin of toothing losses

Based on these information the approach of reducing gearbox losses is simple and logical: the sources of power losses have to be optimized. With stress on the toothing, the aerodynamic toothing losses can be reduced by

- taking out as much as possible of the air that causes windage and churning
- reducing the oil flow to the gearmesh to the minimum required for good lubrication and cooling.

In addition, the oil consumtion of the bearings has to be minimized and the circumferential bearing speed has to be increased.

Constructive Details

The pioneering solution for a considerable reduction in gearbox losses is to run the gearwheels under vacuum. The detailled design, for which MAAG has a patent, is explained in figure 3.

The HET-gearbox has in addition to the main casing (2) an inner casing (4) which encloses as closely as possible the gearwheels (1). From the so created interior space (9) the air and also most of the the lube oil can be removed. To evacuate the air and the lube oil from the inner casing a combined oil and air pump (6) is used. In addition, the aerodynamic surronding in the inner casing has been optimized in a specific way to drain off the cooling oil for the toothing.

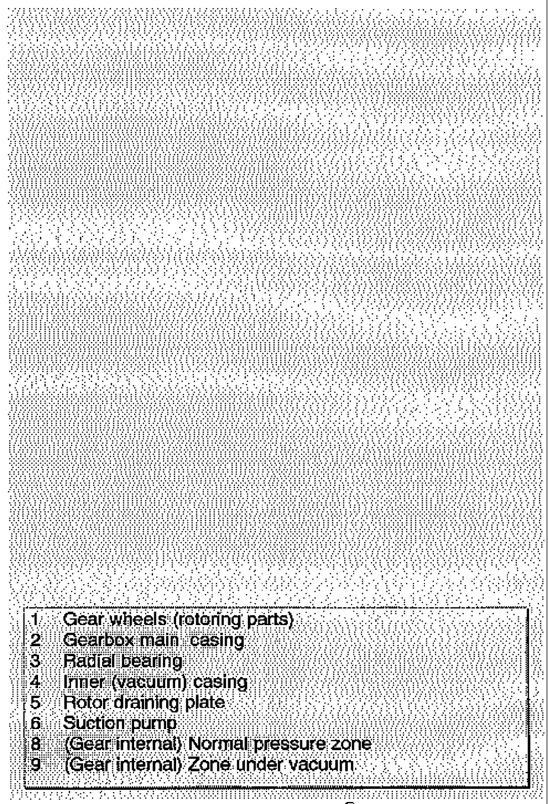

Fig. 3: Patented MAAG HET® gear design

INTEGRATION OF THE HET GEARBOX INTO THE GAS TURBINE TRAIN

The integration of the HET-Technology into the gas turbine shaft train requires reliability as well as easy maintenance. Thus, the following demands were made on the HET-Technology before it started operation in a power station for the first time:

- Guaranteed operation in two modes alternatively, vacuum as well as conventional, without any restrictions on life time and maintenance
- Switch over between vacuum and conventional mode without any restriction on the operating mode of the gas turbine
- Endurance test of new components such as the vacuum pump
- Elaboration of a protective control logic to guarantee trouble free operation of the gas turbine
- Testing of the protective control logic.

Protective Control Logic

The new HET-Technology was taken into use on condition that both operating modes, vacuum mode as well as conventional mode, can be switched over without any limitation on operation of the gas turbine. The HET-Technology is controlled by a redundant oil-level detection. If the oil level exceeds a defined limit the inner casing is flooded by nitrogen and further operation is possible in conventional mode taking into account higher gear losses, only. The protection equipment can basically be explained according to Figure 4.

Vacuum is generated in the inner casing of the gear (1 of Fig. 3) by means of a vacuum pump (2 of Fig. 3) which sucks off the mixture of oil and air. A second vacuum pump can be installed as an option. The oil-level is controlled by a redundant oil level detection (3). This control unit forces a switch over from vacuum to conventional mode if a defined level is reached. Trip of the gas turbine is released in case of a further, unexpected increase up to a second oil level. After release of the trip rotor revolution is reduced to an uncritical speed in case of a further increase of the oil level up to a contact between oil and gearing.

The inner casing is flooded with nitrogen via two valves (4) supplied by the nitrogen gas tank on top of the gear (5). It is controlled by two pressure transducers (6) and one pressure gage (7). This nitrogen gas tank has to be equipped with a safety valve (8). The tank is supplied by an array of nitrogen-bottles (9) and the pressure level of these bottles is controlled by a pressure transducer (10) as well. An isolating valve (11) enables the exchange of each bottle separately. The system pressure is adjusted by reducing valves (12) and a minimum pressure level for at least one final flooding of the inner casing is guaranteed.

If the inner casing is flooded by nitrogen the vacuum pump is switched off and two swing check valves (13) open to release the injected nitrogen to the drain. Each swing check valve is equipped with a proximity switch (14) with a redundant design of each swing check valve. Two exchange valves (15) are designed to avoid a bottleneck effect which leads to the development of a vacuum due to the oil running out of the inner (isolated) casing.

As explained above a switch over from vacuum to conventional mode is forced by an unexpected increase of the oil level. At the same time it is possible to switch over between both modes by hand.

System availability and reliability

Apart from the inner casing and the operation under vacuum mode the design of a HET gearboxes is based on well proved technology.

The gearwheels and toothing are designed based on the same know-how applied also for conventional applications. Especially the longitudinal modification on the toothing follows the same rule and is made with the same precision. The reliability of the toothing is therefore given and proved in practical experience.

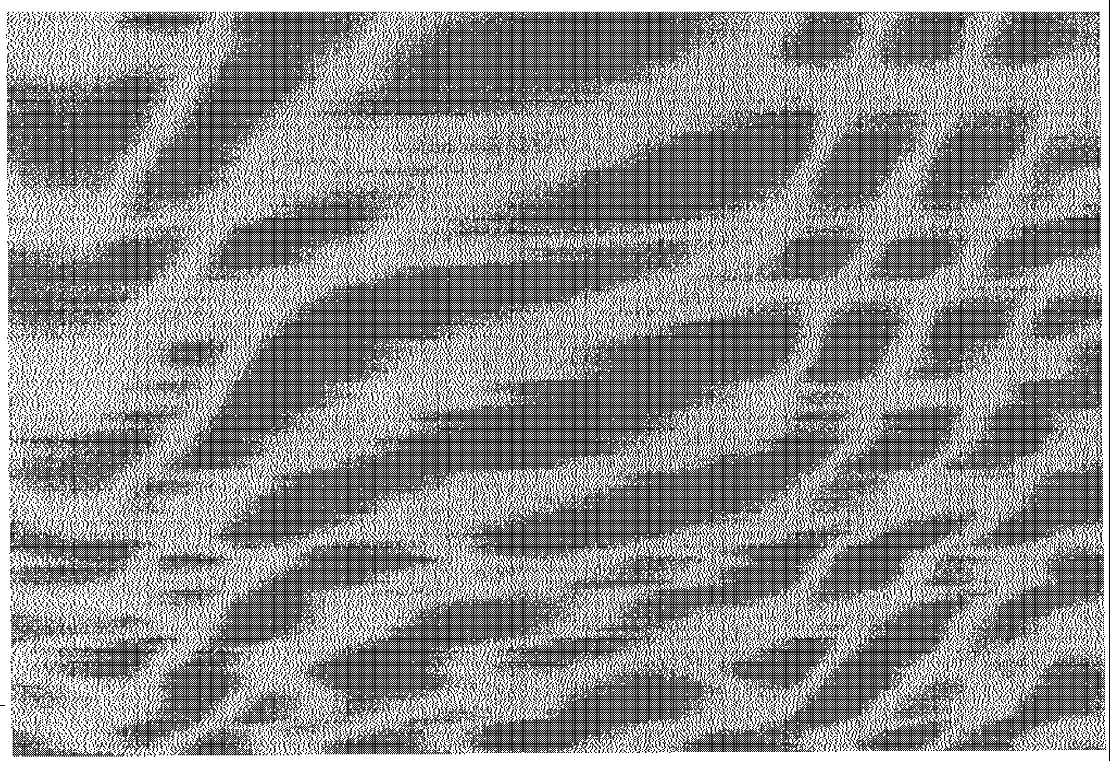

Fig. 4: HET Protective Control Logic

Furthermore, there is no difference in dimension and construction of the main gearbox casing. Also the centerline distance of a HET gearbox correspond normally with that one of a conventional gear with the same rated power. These two constructional details allow an easy replacement of conventional gearboxes in already operating power plants.

The availability of the HET gearbox depends consequently only on the ability to maintain the vacuum in the inner casing. This is ensured by a specific protective control system (as described before) and by using only reliable and well-tried parts. In addition it is possible to run the HET gearbox both on conventional and vaccum mode. Therefore the availability of the HET gearbox in view of its prime function (driving a generator e.g.) is at least as high as for a convetional gear.

FIRST OPERATING EXPERIENCES

The proof of the new HET-Technology is given in two power plants, Neckarwerke Elektrizitätsversorgungs AG's Altbach/Deizisau in Germany as well as SK Power's thermal power station at Hillerød in Denmark. In these power stations a MAAG gear GD-72,5 HET is combined to a Siemens (KWU) gas turbine V64.3 at Hillerød and a V64.3A at Altbach with cumulated operating hours of about 4'000 h at the time of writing this article. The availabilty of the HET-Technology in these two plants is 100 %, i.e. there was no shut down due to a defective vacuum system or the HET-Technology/gearbox itselves.

Review of the HET-Technology

Although the design of the gearwheels and the bearings are based on longtime technical experience the operating in a vacuum mode required an adaptation of some parameters and a new control and safty system.

Before introducing the HET-Technology in the market, a back-to-back test with 70 000 kW gears was made. The arrangement of this test has also been published in a VGB publication [1]. This test gave first indications to verify the design under full and partial load. But all these result were based on test conditions and not an real operating condition. For the design review it was therefore important to compare the data from the practical experience of the HET-Technology with the theoretical design approach.

The information based on two HET gearboxes with cumulated operating hours of more than 4'000 h proves the basic design and the reliability of the HET-Technology. But it shows also the possibility to optimize the system. In consequence, two major improvements were made:

- It was known that the thermal deformation in operating under vacuum mode would be different. This deformation was considered in the longitudinal modification and proved in praxis. In addition, the absence of air circulation causes a partial hot spot in the gap of the toothing . The degree of this heating could only be defined in the operating process. It is now controlled by optimizing the cooling of this area.
- The second improvement was made by optimizing the protective control system. This was done both in redisgning the arrangement of the instruments and in defining new requirements for the vacuum system.

Determination of the Gear Power Losses

Acceptance test measurements will be carried out at the test bed of the gear manufacturer in principle. The gear power losses are determined under no-load conditions by a determination of the volumetric flow rate as well as oil inlet and outlet temperature. Radiation is determined by calculation 18 kW at an ambient temperature of 25 °C. 2.5 kW power consumption of the vacuum pump has to be added to these power losses to come to an accurate valuation of the HET-Technology. The power losses under load conditions can be calculated or even be determined by a back-to-back configuration [1]. In addition, acceptance test measurement of the new HKW 2 parallel combined cycle power station at Altbach confirmed the guaranteed loss reduction of the HET-Technology under load conditions. This measurement was carried out according to the power loss measurement on the test bed which is described above. A comparison of the power losses under no-load, calculated load conditions as well as load conditions measured at the power station is shown in Figure 5.

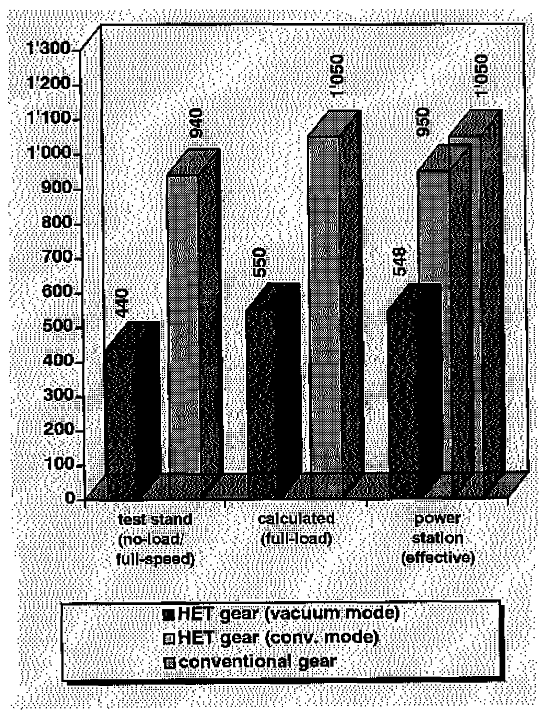

Fig. 5.: Comparision of gearbox losses HET versus conventional gearbox

Figure 5 significantly confirms the importance of gear power losses generated by the toothing , es-

pecially by churning and windage as it is described above. These toothing losses can be reduced by about 500 kW to a minimum if the vacuum mode is switched on.

Nowadays, the power loss of comparable turbogears is about 1050 kW. Thus, a saving of power loss was achieved for both modes of operation, HET-Technology as well as conventional operation. The power loss is clearly reduced to 600 kW under load conditions if the HET-Technology is switched on. The measurement carried out at the power station well fits to the calculated power loss which was measured during the no-load test run. According to the pitch line velocity (v') the coefficient for calculating the power losses for convetnional gearboxes on full speed can be read out of Figure 6 witch is based on longterm experience of MAAG. This correlation can be described by the following equation:

$$\text{Power losses}_{\text{FULL LOAD}} = \frac{\text{Power losses}_{\text{FULL SPEED/NO LOAD}}}{\text{Power losses ratio (Fig. 6)}}$$

The calculation for HET gearboxes follows in prinicple the same rule, but it is because of the vacuum system more complex, i.e. the ratios are different.

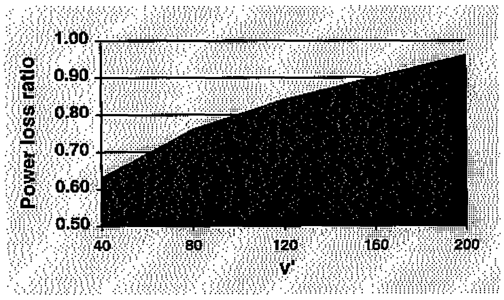

Fig. 6: Power losses ratio at a given pitch line velocity for conventional gearboxes

In addition, a power saving of 100 kW was also determined for the High Efficiency Turbogear running in conventional mode. This can be explained by the optimisation of the gearing oil cooling system which was developed in preparation for the HET-Technology, i.e. the gearbox losses of a conventional gearbox without the HET- provisions would be as mentioned in Fig. 5 about 1'050 kW.

Acceptance test measurements were also carried out at the Altbach/Deizisau power station to confirm gear losses under real load conditions. This power station is designed for a broad range of operating possibilities. A detailed description including the design concept - the connection of a gas turbine with waste heat boiler feeding the steam turbine to a conventional steam generation process on the water vapour side - is given in [2] and [3].

The gear losses measured at the power station well fit to the predicted losses which had been determined based on test measurements at the manufacturer's test bed under no-load condition as it is compared in Figure 5.

Improving of net efficiency due to the reduction of the gear power losses are shown in Figure 7 comparing the net efficiency of the gas turbine and the parallel operation with and without vacuum mode. **A good valuation of the improvement in efficiency of 0.3 points of percent can be given if a closer look is given at the development of gas turbine efficiency in general. Simple cycle gas turbine efficiency of 30 per cent can be given for the early 1970's as a basis. Thus, the new HET-Technology well supplements geared gas turbines and makes a good contribution to eco-friendly power supply and cost reduction.**

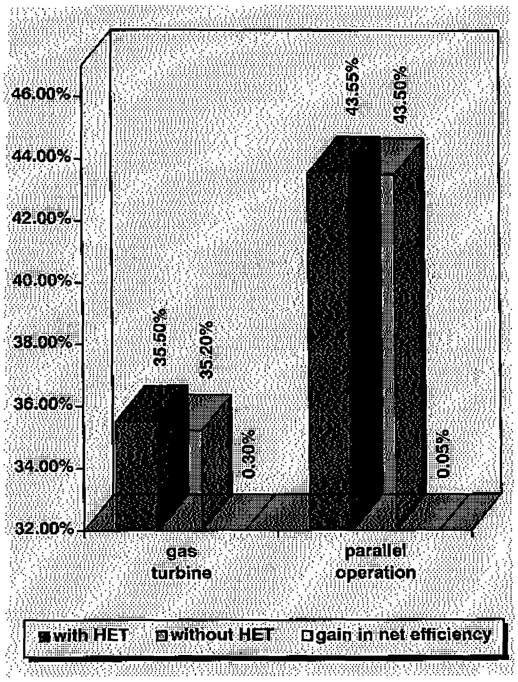

Fig. 7: Gain in net efficiency in %

The profit which can be achieved if the gear is running under vacuum mode on individual aspects of each customer and therefore it cannot be given in general. Nevertheless, the benefit of the HET-Technology can basically be described assuming a range of electricity generation costs from 0.04 to 0.06 $\$/kWh_{el}$. Cost saving per annum can be determined as a product of electricity generation costs, reduced power losses due to the vacuum mode and operating hours. These cost savings as a function of operating hours and electricity generation costs are plottet in Figure 8.

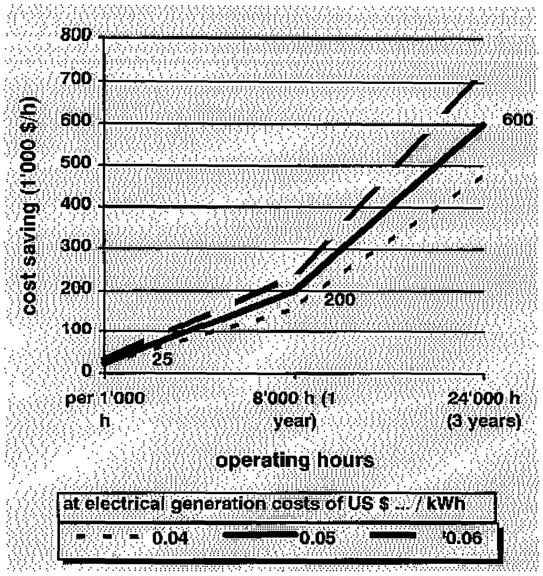

Fig. 8: cost saving of the HET technology

CONCLUSIONS

The new technology of High Efficiency Turbogears successfully started operation in two power stations for the first time. This new technology of gears, running in partial vacuum, was developed from first test runs at the gear manufacturer's test bad to the reliable operation in a 65 MW gas turbine train including all demands on a safe operation of the gas turbine train.

First experiences confirmed the trouble-free operation in two modes, vacuum and conventional. The gas turbine protective equipment which was developed for this new HET-Technology was successfully tested at the power station and a switch between vacuum and conventional mode was verified as well.

Power loss measurements of the gear had been carried out under no-load and load conditions. In addition to the usual determination of power losses at the manufacturer's facility the power losses had been measured at the power station, too. A power loss reduction of about 500 kW compared to conventional designed gears could be affirmed. Thus, the design of the new HET-Technology could be affirmed in efficiency improvement and operation experience implemented in the control and safety circuit of a 65 MW gas turbine train.

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