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The next generation
Power distribution gears

As the current generation of turbo gearboxes approach their operating limits, an innovative design provides new levels of performance and the potential to debottleneck entire drive trains.

As the power and power density of rotating machines continue to increase, turbo gearboxes are approaching their limits in terms of safe and reliable operation. Some radical re-thinking in gearbox design is called for if future machinery trains are not to be compromised by the capacity of their gear units.

Gearboxes are widely used to reduce or increase the speed of prime movers to match these to the driven machinery. Especially in critical operations where redundant equipment is not installed, the gearbox is just as key to reliability and safety as any other link in the power train.

Yet perhaps not surprisingly, many engineers are more interested in the driver or the driven equipment – gas turbines, electric motors, compressors, and pumps – than in the gearbox, which is often treated as a commodity item.

The fact that this is possible is a fine tribute to the reliability of standard turbo gearboxes, which operate under punishing conditions of stress, impact and wear. Even gear experts cannot work miracles, however, and the turbo gearbox as we know it is rapidly reaching the limits of performance. It is time for something new.

Limits of convention

Traditional gear designs for turbomachinery fall into two types: parallel shaft and epicyclic.

Parallel shaft gearboxes have two shafts, each carrying a single gear. They are available in power ratings up to 140 MW for small gear ratios < 6 when installed, for instance, between a gas turbine and a generator. As the name suggests, the input and output shafts do not share the same axis.

Epicyclic gearboxes split the power between several "planet" gears which move around a central "sun" gear while also mes-hing with a surrounding "ring" gear. Epicyclic gears are com-pact and provide co-axial input and output, but are limited to a power rating of 45 MW in the demand for a gear ratio > 6. To understand the limiting factors in gear design we need to translate external operating characteristics – power ratings and speeds – into gear-specific design parameters.

The main factors controlling power and speed limits are:

- **pitchline velocity (PLV) – the linear velocity of the gear teeth**
- **elastic deflection produced by torques and bending moments on all parts of the gearbox, especially as it applies to the pinion (the smaller of the two gears in a parallel shaft gearbox)**
- **desired input and output speeds**
- **operating limits of the bearings (loads and journal velocities)**
- **factor of safety chosen for the application**

The job of the gear designer is to find the best balance between these limiting factors, which sometimes conflict. For instance, taking advantage of the increased speed capacity of a high-performance bearing implies an increase in the PLV, which in turn raises both the circumferential forces within the gears and the tendency for oil flow to be interrupted. In a parallel shaft gearbox the solution is to increase the center line distance (and hence the overall gear size) to create a larger lever effect.

Currently the maximum physical achievable PLV is 200 m/s and the maximum journal velocity is 100 m/s. The maximum bearing load is 3.45 MPa if we refer to API 613 (paragraph 2.7.2.4), the gear standard applicable to high-speed gear-boxes in the oil and gas industry.

These limits mean that in some cases the gear unit becomes the determining link in the drive train. Turbocompressors, for instance, are currently restricted to approximately 35 MW by their gearboxes, depending to some extent on the input and output speeds required.

Outside the box

Incremental design improvements, such as the use of high-grade steels to withstand high PLVs, or an improved bearing design for higher journal velocities, boost the capabilities of conventional gear units. The resulting improvements are small, however, and the “tweaked” gearbox is still operating at its limits. Also, of course, it is a bad idea to be using what are essentially prototype gear units running in unproven areas of the speed-power chart.

An alternative to waiting for incremental improvements in materials science is to use an alternative gear design with a split power path. Such an approach overcomes the limiting parameters controlling the teeth and bearings of conventional gear types. Most importantly from the point of view of the plant designer, it removes the bottleneck imposed by current gear designs on the power limits of entire turbomachinery chains.

Splitting the power path to create a “power distribution gearbox” (PDG) allows the speed limit for a given transmission power to be increased and considerably eases the bearing problem. The limiting factor in the design of a PDG becomes the toothing: the speeds at which the teeth mesh and the heat generated there, mainly through compression of a mixture of oil and air. PDGs can currently be designed for power ratings up to 170 MW, output speeds up to 100 000 rpm, and gear ratios up to 10.

PDG design and function

The PDG combines the simple and robust construction of parallel shaft gears with the load-splitting ability of epicyclic gears (Figure 1). The result is a gear unit which offers high power ratings, speeds and speed ratios while remaining well within critical technical limits and so providing excellent safety margins.

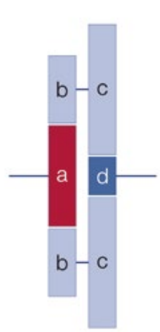
The PDG contains three or more planet gears arrayed around a central sun pinion. Each planet gear is actually a compound design whose second set of teeth meshes with a second sun pinion on a separate shaft (Figure 2).

The whole arrangement acts like a two-stage parallel shaft gear, but with several advantages

- **+ distributing the power between several planet gears reduces tooth loads**
- **+ as with epicyclic gears, each sun pinion is supported by its planets, so no bearings are required on either the low-speed or the high-speed side**
- **+ the three planet gears are supported by six hydrodynamic bearings instead of the four used in parallel shaft gear units**
- **+ the input and output shafts are coaxial**
- **+ since there is no outer ring gear, as an epicyclic gearbox would require, the PDG is compact.**

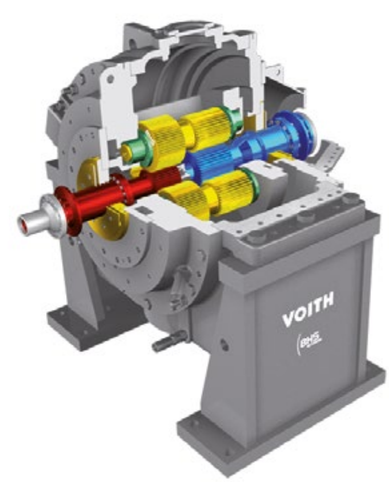
Integral double diaphragm couplings on the input and output shafts of the PDG accommodates axial, radial, and angular offsets to ensure optimal power transmission and rotordynamic performance. The short axial length of these couplings reduces the overall distance between shaft ends (DBSE) between the driver and the driven machine.

Figure 1:
The power distribution gear (PDG) uses a planetary arrangement to divide up the incoming shaft power, compound gears to further increase the peripheral velocity, and a second planetary arrangement to drive the output shaft. The result is a gear unit that can transmit more power at higher speeds than is possible with a conventional parallel shaft or epicyclic gearbox.



a: Sun pinion slow-speed side
b + c: Compound gear planet
d: Sun pinion high-speed side

Figure 2:
Because the two sun gears are supported by the planets, the main input and output shafts of the PDG need no bearings.



Performance in critical applications

An example of a typical gas-turbine-driven compressor shows how the PDG out-performs a parallel shaft gear unit in applications requiring high power density. The gas turbine speed is assumed to be 5 000 rpm and the compressor speed 12 500 rpm.

Pitchline velocity

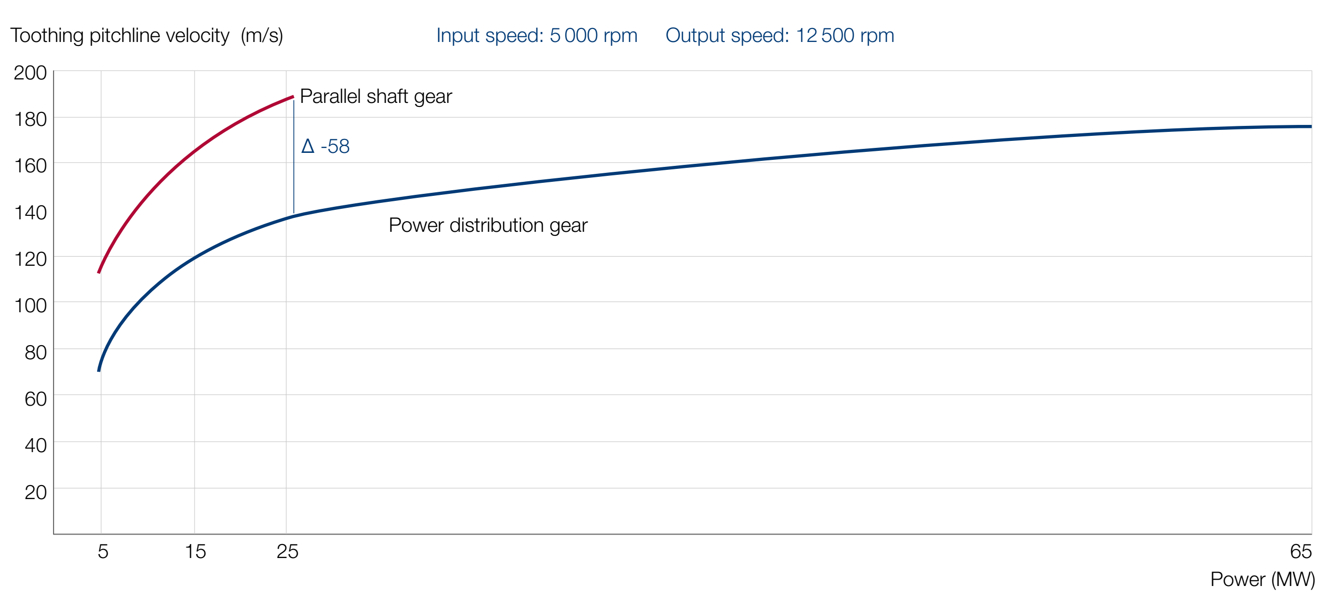
Figure 3 shows how the maximum PLV of the gear teeth varies as a function of transmitted power for the given input and output speeds.

A parallel shaft unit reaches in this case its maximum safe PLV of 190 m/s at a power rating of 26 MW. For the PDG, the PLV curve rises more slowly, and at 26 MW its PLV is with 132 m/s 30 % lower (58 m/s lower in absolute terms) compared to that of the parallel shaft unit. Even at power ratings up to 65 MW and beyond, the PDG still has a PLV below 180 m/s.

The reason for this improved performance is the smaller diameter of the planet gears in the PDG compared to the pinion gear in the parallel shaft unit. This increases the safety margin for centrifugal forces that is proportional to the square of the velocity divided by the diameter.

Figure 3: Gas turbine driven compressor

The PLV in a PDG remains below the 200 m/s safe limit for power ratings right up to 65 MW and more. The traditional parallel shaft gear, on the other hand, tops out at a power rating of 26 MW.



Journal velocity

The curves relating bearing journal velocity to power transmitted (Figure 4) are quite similar to those for PLV against power. The parallel shaft gear cannot handle more than 26 MW before the journal velocity reaches its safe limit of around 100 m/s. At this power rating, the PDG bearings are running at only 50 m/s – a 100 % safety margin – and even at 65 MW the journal velo city is no more than 65 m/s, still well below the safe limit.

The lower journal velocities arise because the pins (like stub axles) of the planet gears in the PDG are smaller in diameter than the radial bearings which support the pinion in the parallel shaft gear unit.

Bearing load

Along with pitchline and journal velocities, bearing load is the third main factor limiting gearbox performance. Figure 5 shows identical bearing loads for both gear designs in our compressor example.

Even at high powers, increasing the diameter of the planet pins keeps the PDG bearing nearly to the maximum of 3.45 N/mm^2 set by API 613. These pins function as fixed pro-file sleeve bearings, and are proven in the more that 8 000 BHS epicyclic gear units supplied by Voith. Bearing loads are also reduced because the PDG has six bearings (two for each planet gear shaft) compared to the four supporting the gear set of the parallel shaft gear.

Figure 4: Gas turbine driven compressor

Bearing journal velocities tell a similar story: where parallel shaft gears are limited to 26 MW in this application, the PDG maintains acceptable journal velocities up to 65 MW and more.

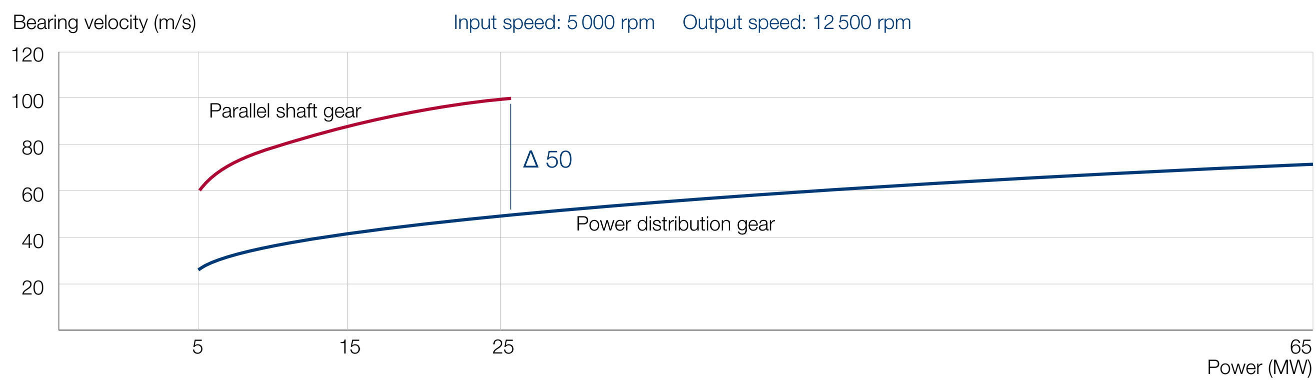
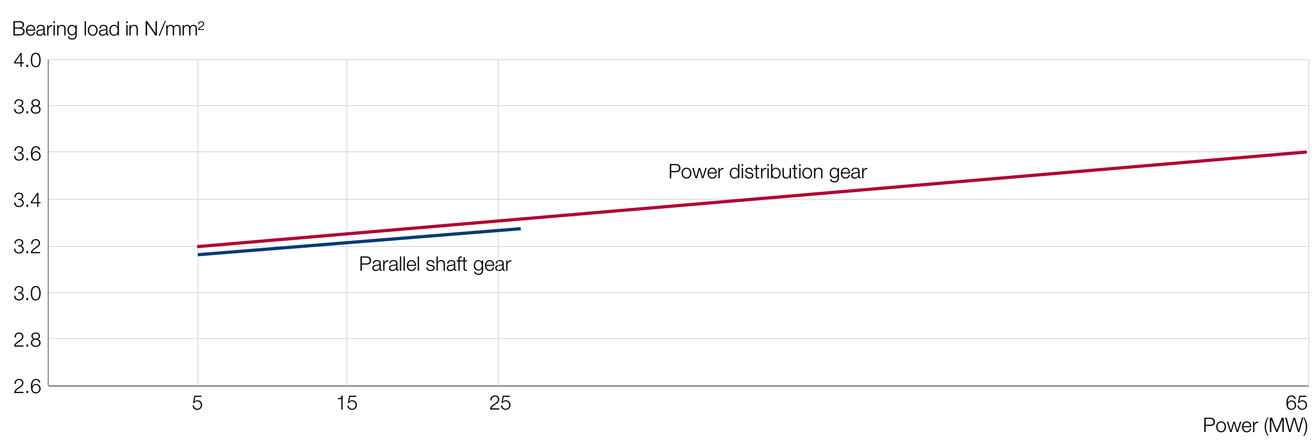


Figure 5: Gas turbine at 5 000 rpm to centrifugal compressor at 12 500 rpm

With the right choice of pin diameter for the planet gears, bearing loads in the PDG remain below the API limit even at high powers.



Efficiency

Especially in the oil and gas industry, reliability, safety and availability of machinery are rightly the most important operating characteristics. But as operators also come to focus on the cost of energy and cutting CO^2 emissions, efficiency also plays a role. As with the other criteria, in terms of efficiency the PDG rivals the parallel shaft design (Figure 6). As the parallel shaft gear approaches its limit of 26 MW, losses increase significantly, and at 26 MW the efficiency of the PDG is 0.7 % higher. Even more importantly, the PDG retains its efficiency of nearly 99 % even when transmitting 65 MW.

Oil consumption

Also interesting to compare is the oil consumption of both gear units, since this affects the capital cost of the lubrication system. At its power limit of 26 MW the parallel shaft gear uses more oil than the PDG (Figure 7) because of its high PLV and especially because of the higher bearing journal velocity.

Although the parallel shaft gear has fewer bearings than the PDG, one reason for its lower efficiency is the higher temperatures in the high-speed bearings of the pinion shaft, which in turn require more oil for cooling.

Figure 6: Gas turbine at 5 000 rpm to centrifugal compressor at 12 500 rpm

Close to its maximum power, the parallel shaft gear shows reduced efficiency.
The efficiency of the PDG remains higher even at power ratings up to 65 MW.

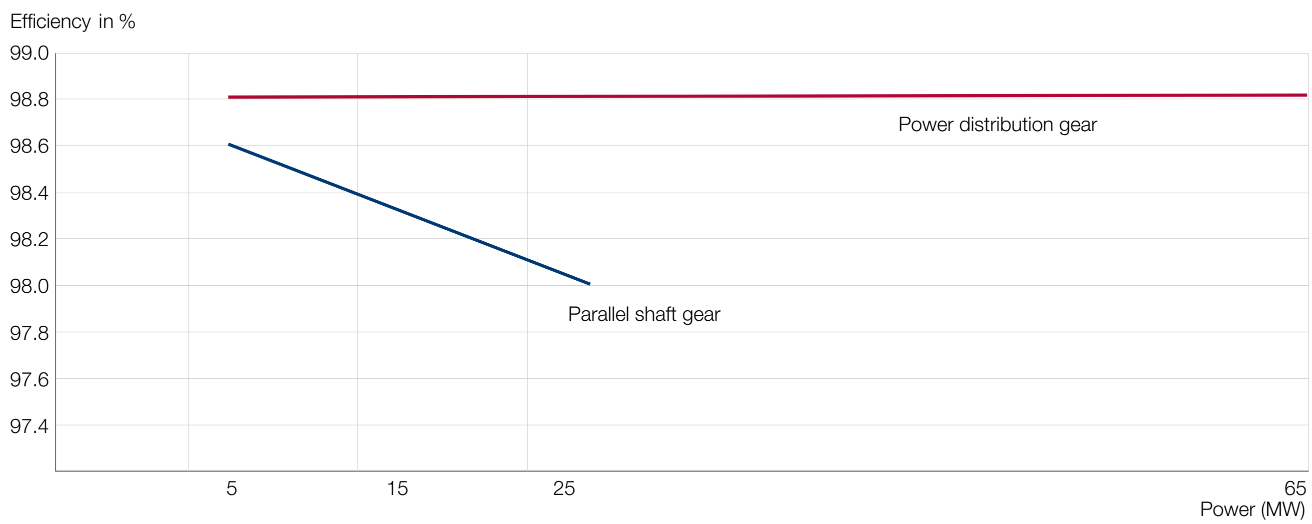
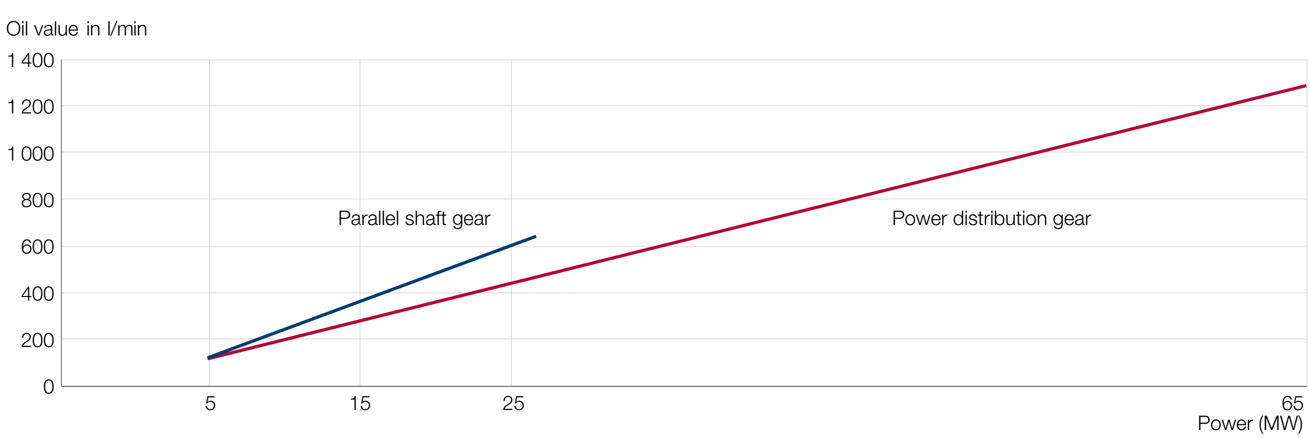


Figure 7: Gas turbine at 5 000 rpm to centrifugal compressor at 12 500 rpm

The PDG requires somewhat less oil than the parallel shaft gear, and oil consumption increases linearly with power rating.



When to use a PDG

As we have seen, splitting the power path gives the PDG more headroom in all three of the main parameters – PLVs, journal velocities, and bearing loads – which limit power transmission in conventional parallel shaft gears. Lower stresses and temperatures make the PDG more reliable, and its efficiency remains high.

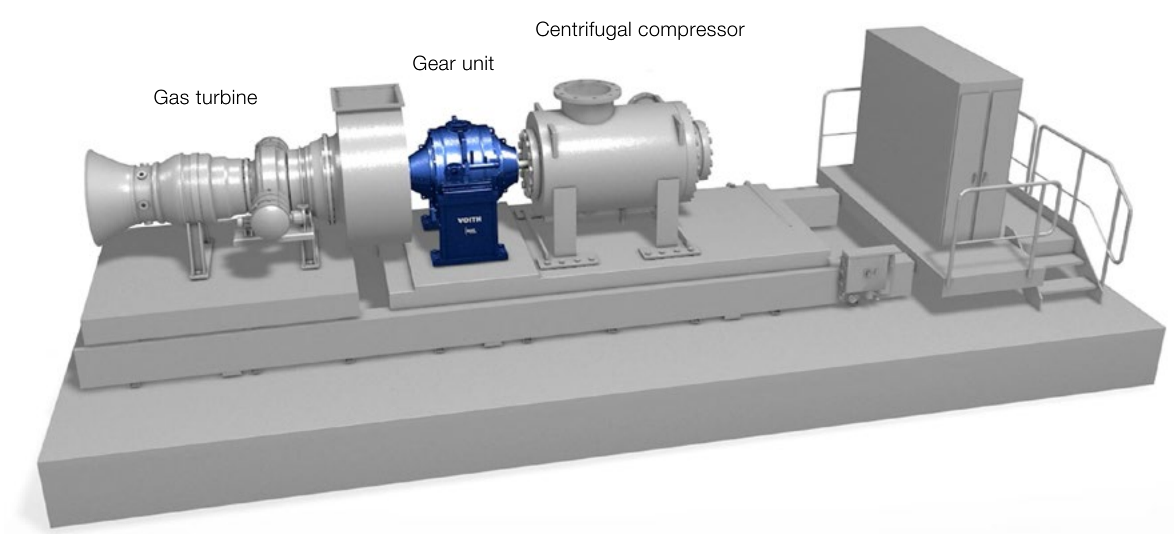
However, the higher complexity of a PDG compared to a parallel shaft gear unit means that some design aspects have to be considered carefully.

To ensure sufficient tooth lubrication, for instance, the planet gears require internal oilways as well as external flush lubrication. The relatively high ventilation within the gearbox created by the rotating suns and planets, which is at least proportional to the square of the velocity, also can disrupt external lubrication and prevent the sun gears from getting enough oil. Special oil baffles are needed to tackle this problem, and there is room for further improvement.

As a result, the PDG is best suited to applications requiring high power density, where traditional gear designs are approaching the limits of feasibility. In such cases it offers some compelling advantages.

In particular, this new gear design brings opportunities to debottleneck drive trains in which the gearbox has previously been the limiting factor. Gas-turbine-driven compressor trains, for instance, can now use larger compressors, and gas turbine models which up to now have been used mainly for power generation can find new applications as compressor drivers.

PDG – Ideal solution to transmit high speeds and high torques



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