Development of the 4th Generation Vertical Roller Mill Drives

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Abstract — The Vertical Roller Mill (VRM) has proven a universal tool for grinding limestone, clinker and slag in the cement industry. The maximum mill powers doubled from 2500 kW in the mid-seventies to 5000 kW in the nineties. Today, another 20 years later, we see 10 MW with a tendency to grow further. As in other industries, unit sizes increase and with this the requirement for equipment availability. Gear technology developed in synchrony with mill power. Starting with the first generation drives featuring bevel parallel shaft gears, the torque passing 1 Mio Nm required torque split. In 1979 forming the second generation of drives emerged featuring a planetary output stage. The current state of the art three stage bevel - planetary gear is the third generation of VRM drives.

New fourth generation gear concepts have been proposed and tested to cope with the increasing torques – always with the goal to further improve key performance features.

I. NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>DOL</td>
<td>direct on line (referring to the start of an electric motor)</td>
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<td>HP</td>
<td>High Pressure (system used for hydrostatic lubrication)</td>
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<td>i</td>
<td>ratio (input speed / output speed)</td>
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<td>LV</td>
<td>Low Voltage, i.e. 690 V</td>
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<td>MV</td>
<td>Medium Voltage, i.e. 3 kV to 6.6 kV (regarding motors) and/or 13 kV</td>
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<td>SCS</td>
<td>Sub Control System built from standard PLC hardware e.g. SIEMENS S7</td>
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<td>TCO</td>
<td>Total Cost of Ownership = f(purchase price, maintenance cost, spares cost, power loss cost, stand still cost)</td>
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<tr>
<td>Tin</td>
<td>Input torque</td>
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<tr>
<td>Tout</td>
<td>Output torque</td>
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<td>VRM</td>
<td>Vertical Roller Mill</td>
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<tr>
<td>VSDS</td>
<td>Variable Speed Drive System - i.e. motor feed via cycle converters</td>
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<tr>
<td>za</td>
<td>Number of teeth of the annulus</td>
</tr>
<tr>
<td>zs</td>
<td>Number of teeth of the sun</td>
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II. INTRODUCTION

When developing technical systems to higher maturity, engineers use two different approaches -- always with the goal to improve performance:

As long as it is feasible we adapt the size of the machine using the existing solution with detail improvements. When reaching feasibility limits, we adapt the technical approach and develop new solutions that aspire to overcome shortcomings of the existing solution.

Moreover, successful innovation considers customer demands. New technical generations of mechanical systems are born every 20 years with a clear tendency to ever-shorter innovation cycles. The 3rd generation drive has been introduced 1998. After 17 years, it is time for innovation.
The innovation targets followed always are:

- Higher capacity/production
- Higher reliability
- Lower Total Cost of Ownership (TCO)
- Less and easier maintenance
- Improved safety
- Less space/weight/noise (depending on application)
- Product-specific customer demands

Even though TCO is still not systematically established in the decision making process of machinery for the cement industry, the goal of lowering total cost of ownership has penetrated deeply into the thinking of the engineering community: No one would accept a cost increase if such an increase would not pay back shortly. So it can clearly be stated that the development of technical systems is driven by economical needs.

Technical change by size adaption or change of the approach brings different results. Back to the VRM: It is time to cope with increasing demands for torque and system availability with a new 4th drive generation.
III. POWER UP!

Fig. 2. A “curve of innovation” monitoring the torque increase of VRM-drives over the decades

The first three generations all have in common that an angle drive is applied to connect a horizontal axis motor with a vertical axis mill.

The change from generation one to generation two was that load was no longer distributed on one torque path, but was spread over three torque paths by introducing a planetary gear set in the output stage.

The change from generation two to three was to duplicate the number of the planet wheels in the output stage and the introduction of a third gear stage allowing more torque and more ratio. The challenge of the past decade was the dawn of the feasibility limit of large size bevel gears: The list of world-wide makers shrunk to two or three companies and one gear maker experienced severe bearing problems on the bevel pinions. The bevel gear became a cost driver and a major lead-time criterion for the third generation of VRM drives.
After having evaluated different design ideas, it became obvious that parting from the single motor drive is an indispensable requirement for achieving a majority of above targets. The most enforcing requirement was the given design height of existing mills in combination with the other indispensable requirement “no bevel gear”. With this in mind, vertical motors had to be arranged on a pitch circle defined by the mill tunnel size. The motor torques thus had to be collected in a first gear stage. As the pitch diameter of the motor axis was not small, the central wheel with which the motors had to engage was equally large – so (fortunately) the ratio of the first gear stage could be brought up to 14 easily.

When rating this first stage gearing, it was a necessity to feature a through hardened and tempered bull gear, both for cost and feasibility reasons. Another indispensable requirement was to enable an assembly of the motor/drive pinion assembly (drive set) without alignment. This resulted in an evaluation of the feasible runout – and rectangularity tolerances. As a consequence the necessary pinion lead modification resulted in a gear load distribution factor $\kappa_\beta$ of 1.2.

As this first stage featured a ratio of 14 the second stage could become a low ratio planetary stage with as many as possible planets. This was the reasonable way to complete the drive train under the focus of the development targets.

An alternative design with three parallel shaft stages and with no rotating planet carrier had been checked, patented, evaluated and rejected for various reasons. The most important one was the one of its kind efficiency of a low ratio, low speed planetary output stage. The ratio is defined as:

$$\frac{1}{1 + \frac{2.5}{z_p}} = 1 + 2.5$$

and respectively:

$$\text{Tout} = \text{Tin} \cdot (1 + 2.5)$$
The “1+” is what provides extra ratio by the so called “coupling effect” of the co-rotating planetary gear drive. This “1+” is transmitted without any loss – i.e., this second stage has 30% less loss than, e.g., a parallel shaft stage. Those 30% are not transmitted over the gear mesh.

From a customer acceptance perspective, it was important to note that this final stage had always been used with the best experiences in the customary gears of the third generation. Consequently, there was no reason to deviate from a proven concept that is still far from its technical and production-wise limits.

Figure 3 shows the physical difference between a parallel shaft stage with six pinions and a planetary stage with six planets. Both top views are at the same scale, both designs have a through hardened and tempered bull gear and/or annulus. The example is based on the assumption of 10 MW @ 20 mill rpm:

![Fig. 3. The scaled physical difference between parallel shaft and a planetary arrangement for the same torque](image)

Taking the tooth width into account one can easily calculate the geared surface to:

- Parallel shaft stage, 6 pinions: 15 m²
- Planetary stage, 6 planets: 10 m²

When adding the geared surface of the first stage connecting the motors using one big wheel – however on the high speed stage side - 3,35 m² have to be added which brings the entire drive to a geared surface of 13,4 m² – less than just the output stage of a solution using a parallel shaft stage to drive the mill.
This yielded the basic design of the new 4th generation drive.

- Motors featuring 900 – 1000 rpm
- Pinions driving a central wheel with a high ratio (e.g. 14)
- Output to the mill via a planetary stage featuring 6 planets

A VRM-drive however is more than just the drive train. The mill axial and radial bearings had to be located and supported by a rigid and economical casing design. Along with the casing design, the number of vertical axis motors had to be established, considering motor diameter and length, the makers of water jacket cooled cage induction motors were offering.

The OEM development partner has stringent mill standardization in terms of power, speed and physical size. The 4th generation drive was required to fit under the mills just as the 3rd generation drive.

V. DRIVE MOTOR SELECTION

The single motor slip ring design in combination with liquid rheostats of the large size drivers is a necessity for the cement industry as most plants have limited grid capacities – be it due to their access to a remote branch of the high voltage grid, or due to the limited capacity of the site operated power plant. In any case it is not normal practice to start a motor of more than 2 MW DOL.

The slip ring and rheostat is the least expensive way to start a motor with limited starting current. However, this implies the transfer of the entire runner current to the shorting contactor (and/or the starting resistance) outside the runner where a mechanically driven bridge forms the short circuit point. In this set-up, the current slip ring single motor mill drives and rheostat are subject to wear and maintenance much more than a cage induction motor.

Another important step forward that is associated with a multi motor solution is that the 4th generation can be equipped with cage induction motors. As the startup requires much less than nominal torque, it is possible to start one or two of the motors DOL and just slightly exceed the nominal current of the mill drive.

As for the cooling there was no real choice: The most compact and dust proof motor was required and this is a water jacket cooled design. Fortunately there is a selection of companies with substantial reference lists – also in the cement industry.
The chosen two-stage drive train did not allow for a wide selection of motor speeds: As the target of an uncomplicated drive with a minimum number of components was ruling the selection process, a 6-pole motor was the only choice for 50 Hz grids. 4 poles, despite a little lower in €/kW required a gear ratio of 80 which could not be featured in 2 stages. 8 poles at 50 Hz was physically too large and too expensive. However, 8 poles can be selected for 60 Hz applications featuring the same motor dimensions at a certain power thanks to the fact that 60 Hz gives 20% more power at the same physics than at 50 Hz.

Torque motors have not been taken into consideration simply because of the fact that they would have counteracted a major design target: no mandatory VSDS. Another reason not to opt for torque motors was the high price of this technology. The price is currently more than double of the customary cage induction technology.

Motor voltage was another concern: It became evident soon that the 4th generation drives system motors were below 2 MW. For this power range, LV as well as MV is a choice. Evaluating cost for
- The motors,
- The cables,
- The circuit breakers,
- Phase condensation modules,
- Possible VSDS,

It became obvious that > 1 MW (per motor) MV is the more economic choice and < 1 MW LV provides lower investment cost. In case a VSDS would be involved, the cost advantage of LV VSDS is so overwhelming that a variable speed application would have to be designed in LV even an the ultimate power of 1,6 MW per motor.

For the selection of a motor manufacturer, a bundle of requirements thus had to be met:
- Cage induction motor, compact and thus insulation class H
- Water-jacket cooling
- Availability of 690 V – 6,6 kV, 6 pole 50 Hz and 8 pole 60 Hz in the same casing
- Sinus as well as VSDS operation
- Precision abilities as displayed below

Fig. 5. Drive unit is composed of the motor and the pinion drive shaft in its cartridge.
VI. CASING DESIGN

Once the motors were defined, we tackled the casing. The essential question here was how to support a sufficient number of motors and have a casing that is stiff enough for the mill loads and the torque support. The number of motors was decided considering the following influences:

<table>
<thead>
<tr>
<th>Number of Motors</th>
<th>Target power 13 MW</th>
<th>Two mill thrust pads per motor, 4 HP pumps</th>
<th>Target: height &amp; diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3,3 MW/motor-too high</td>
<td>8 pads-too large</td>
<td>Too high</td>
</tr>
<tr>
<td>5</td>
<td>2,6 MW/motor-too high</td>
<td>10 pads-too large</td>
<td>Too high</td>
</tr>
<tr>
<td>6</td>
<td>2,2 MW/motor-too high</td>
<td>12 pads-ok but 3 pumps</td>
<td>Too high</td>
</tr>
<tr>
<td>7</td>
<td>1,9 MW/motor-too high</td>
<td>14 pads-ok but no pump</td>
<td>Too high</td>
</tr>
<tr>
<td>8</td>
<td>1,6 MW/motor-ok</td>
<td>16 pads-ok, 4 pumps-ok</td>
<td>ok</td>
</tr>
<tr>
<td>9</td>
<td>1,4 MW/motor-ok</td>
<td>18 pads-ok, but no pump</td>
<td>ok</td>
</tr>
<tr>
<td>10</td>
<td>1,3 MW/motor-ok</td>
<td>20 pads-ok, 4 pumps-ok</td>
<td>Too large diameter</td>
</tr>
</tbody>
</table>

From the above table it can be seen that there was no real choice in terms of the number of motors. Fortunately, the eight motors allowed 16 thrust pads supported with exactly equal support stiffness as shown in Fig 6. The identical support stiffness for all pads is a crucial design criterion for VRM drives. Any violation against this rule has undesired consequences. Regarding customer acceptance, it is an advantage that, for the last 25 years, most gear drives had 16 pads thrust bearings with four HP pumps—a design that allows one pump to fail without any restriction to the grinding process. This design has thus proven to be failure free.

Fig. 6. Casing section with a motor mounted and a neighbor motor removed to illustrate the thrust bearing support

Because a fabricated casing for the form required, to bear 8 motors was not an option, casting was chosen at an early stage of the development. Casting provided the freedom to design a structure featuring soft direction of loads. The structure was designed, FE analyzed and optimized in stress and weight.
An important target had been reached already with the first attempt: the motors moved (between unloaded and loaded mill) without important disturbance of their axis. This is an important prerequisite to warrant proper tooth contact at any load and torque from the mill. The (little) disturbance found was another contribution to determine the proper drive pinion lead modification.

The OEM development partner has stringent mill standardization in terms of power, speed and physical size. The 4th generation drive was required to fit under the mills with no adaptation versus a 3rd generation drive.

VII. MOTOR HANDLING AND FIXATION

Once the drive’s basics were fixed as displayed above, the remaining development targets were addressed. One major point was to ensure maintenance without (single) motor and gear removal. It became evident quickly that the drive unit as shown in Fig. 5 is to be handled as an assembly. This drive unit formed by the driver and the first reduction stage pinion is multi-redundant. Thus it was a requirement to handle this unit under the mill in an efficient way. Two options to handle the drive units had to be considered:

For the quick disengagement, the motor flange had to be prepared in a way to fix the unit in disengaged position and seal the radial gap to the casing. Quick disengagement with a target time frame of two hours was implemented where all motor connections remain in place.
For the complete removal and/or replacement of one drive unit, a system was developed and certified that allows the drive unit to be easily assembled and retrieved from the gear unit with a target time frame of half a day.

Once retrieved from the gear unit as shown in Fig. 9, a solution for handling the heavy drive unit under the mill was required. Fig. 9 shows the track system used for assembly and retrieving of the drive unit.

Figure 10 displays how accessible and maintenance friendly the entire mill surrounding is due to the compactness of the drive system. The lack of obstruction by oil pipes is just one positive aspect of the design.
VIII. MULTI BODY SIMULATION OF THE MECHANICAL AND ELECTRICAL SYSTEM

The industry increasingly realizes that a dependable and efficient drive system is more than a driver (purchased by someone somewhere at the lowest cost), a gear purchased by an OEM at the lowest price and a VRM driven by this haphazard assembly. A multi-million business requires a *professional system approach with the latest analytical tools.*

![Diagram of the multi body simulation](image)

Fig. 11. Mechanical system schematic of the multi body simulation

Therefore, the 4th generation drive requires an analytical approach that takes the driven equipment, the mechanical drive system, the electrical drive system and the power supply into consideration. For this a complex model has been established where the manufacturers of the VRM, the gear, the motors and the power supply elements have cooperated in an implicit way.

The target of the dynamic simulation of the system operation was to find out which stress, deflection, electric current and which mutual impact the system components will show under possible operation conditions. A design software package was used for this approach Fig. 11 gives an impression of how the system was built up.
The redundant motors require a redundant power supply system that needs to be installed between the motor terminal and the site power supply. The electrical system is an integral part of the entire drive system. It has to be ensured that the components properly communicate and that the interlocking considers all the operational and system requirements. Fig. 12 shows the system components, the communication lines and the system boundary.

We developed an SCS, which is system tested together with the entire drive prior to delivery. This will greatly reduce site work and the potential danger of faulty operation. Such an SCS can be designed and tested only when taking into account that there is a drive system responsibility and not arbitrariness with regard to hardware selection and communication.

As pointed out earlier in section 3, the choice between several motor options is necessary to provide an optimum solution for the individual mill drive:

For medium voltage up to 6.6 kV (MV) and constant speed, as systems as shown in Fig. 13 is proposed:
Depending on the mill rated power one or two ingoing circuit breakers and one circuit breaker per motor is ensuring maximum system availability – even if individual components would fail. The equipment was constructed in accordance with IEC 62271.

The motors are started direct on line (DOL). Two motors provide sufficient starting torque without exceeding the nominal current of the mill power supply. Upon reach of the nominal speed the remaining (already spinning) motors are energized one after the other before grinding begins (see Fig. 16).

For slow rotation, a “welding mode” operation is available. This mode can be selected on the PLC/SCS without any work on the equipment – like installing a chain drive, a cycle converter or a geared motor.
Transformer(s) provide low voltage if no LV-grid is available. Depending on the mill rated power, one or two (redundant) cycle converters provide variable frequency and voltage to one or two motors that are accelerating the mill. Upon reaching the nominal speed, the remaining (already spinning) motors are energized one after the other before the grinding begins. Finally the cycle converter(s) are de-energized and the motors that started the mill are directly connected to the grid.

Fig. 13. Electrical diagram for MV grids with constant speed depending on the rated mill power

Fig. 14. Electrical diagrams for Low Voltage applications with constant speed depending on the rated mill power
One circuit breaker per motor ensures maximum system availability – even if individual components were to fail. The equipment is constructed in accordance with IEC 61439.

For higher than 6.6 kV grids or low voltage grids (LV) and variable speed, a system as shown in Fig. 14 is proposed: Cycle converters allow a speed variation in accordance with parameter changes, e.g., to produce different products on a VRM with their ideal speed. However, it is important to take into consideration that a variable speed drive system causes approximately a 4% drop in system efficiency.

One converter per motor is ensuring maximum system availability – even if individual components were to fail. All converters follow the same set point of frequency. This set-up ensures that the system function is the same as it is directly on the grid, while allowing for variable speed. The equipment is constructed in accordance with IEC 61439.

Fig. 15. Electric diagram of a variable speed option of the drive system depending on the rated mill power
As mentioned in the mechanical simulation section VIII, the entire drive system underwent a system analysis during which the handling of a synchronized multi motor drive was carefully checked.

Fig. 16. Torque output of the individual motors during a start with two MV motors DOL, other motors cut in one after the other after rev up.

During prototype testing, the calculated current curve as shown in will be verified with the option to adjust the model.
As the cement industry - same as all branches where expensive investments with long lead times are operated – asks for innovation but at the same time limits novelties: Technologies applied shall be experienced. This is an inherent contradiction that innovating companies have to deal with.

Fig. 17. Tunnel boring machine, driven by a multi motor arrangement

Early in the project development, the motor manufacturer related his experience with multi-motor drives. Fig. 17. shows a tunnel boring machine. Similar to the presented 4th generation VRM-drive, a multitude of motors are driving the cutter head of a tunnel boring machine via one planetary drive per motor and a common annulus. Both, motor and cutter head are in the same axis direction. The service factor of the drive is 50% above the VRM application. Constant speed and variable speed applications have been built in hundreds.

The developed drive system features an input stage that is a novelty for the cement industry, but has been built before in other applications. It will be full load tested during the prototype qualification. The output stage is unchanged compared to existing references in vertical and horizontal mills.

The developing company conducted a multitude of design reviews with the engineering groups of leading cement producers, the partnering VRM producer, and our engineers over the entire developing period from late 2011 onwards. All up-to-date means of analysis have been employed. The prototype will be equipped with an Advanced Condition Monitoring System developed by the engineering group which has developed the drive system and the SCS. A multitude of monitoring equipment will be installed which will provide more information of the drive train than ever before in the application of a prototype.

The system test on the developing company’s test stand has already given certainty of the unit’s maturity. An online condition monitoring system allows further observing the operation of the drive after commissioning. This ensures a maximum of product maturity at the earliest time possible.

More information regarding the prototype operation will be presented in the future.
XI. CONCLUSION

After more than 3 years of development, a compact solution for VRM-drives is available, opening new horizons regarding higher torques, more efficient maintainability, and redundancy. A prototype application is under construction. The drive is presented to the market together with one mill manufacturer in an OEM partnering agreement. The mill and the drive are forming a system with a minimum of interfaces and a maximum of dependability.

REFERENCES

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