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# Design and dynamic behavior of large Ring Motors for grinding mills

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**Mining Technologies** 

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## 1 Introduction

The mining industry uses grinding mills to comminute tonnage.

Large grinding mills are driven by Gearless Drives, with the Ring Motor as its main component. The Ring Motor is wrapped around the mill and its rotor poles installed at an extension of the mill head.

The air gap between the rotor poles and the laminated core of the motor measures only some millimeters, the outer diameter of the rotor up to 14 meters and more. Deformations of the motor must be limited to avoid contact between rotor and stator. These deformations can be caused by acting operational forces but may also be caused by vibrations of the stator during operation.

A check of the designs is accomplished finite-elementmethod (FE) during which the relevant parts of the motor are divided into many small elements. All relevant influences like operational loads, manufacturing tolerances, temperature and magnetic field in the air gap are considered in the model.

The design goal is to assure a reliable operation of the motor for all operation conditions.

The paper describes the modeling of a large Ring Motor and the principal results of FE-calculations which such a model, the design goals for a Ring Motor and the evaluation of the FE-model by measurements at operating motors.



## 2 Design of Ring Motors

Siemens performs electrical and mechanical design of Ring motors in their Dynamowerk factory in Berlin.

Ring Motor drive a grinding mill without contact between rotating and fixed parts. This concept avoids girth gear and pinions, which are used for conventional mill drives. The stator of the Ring Motor is wrapped around the mill as a ring. Due to the large size, the stator is fabricated and transported in segments. At site, the stator segments are mounted together around the mill. Vertical anchor bolts fix the stator to two sole plates in the foundation. The rotor of this synchronous motor consists of poles installed at a flange of the grinding mill. A closed air circuit cooling system limits the operating temperature to permitted values.

Ring Motors vary the speed of the mill by changing the stator frequency. A cycloconverter provides variable frequency for start, stop and speed variation during operation.



Figure 1: Ring Motor of the 38' SAG-Mill of Rio Paracatú Mineraçao; Brazil

## **3** Design Verification

To assure reliability of operation the mechanical design must be verified.

The magnetic field and the motor torque deform the stator of the motor. The stator ovalization leads to additional air gap deformation, which must be kept between limit values. To avoid excessive vibrations, the cycloconverter frequency must not meet a lateral natural frequency of the stator. The stresses on the motor structure and the fastening elements must be within the permissible range during all operational conditions.

#### 3.1 Modeling

A check of the designs is accomplished finite-elementmethod (FE) during which the relevant parts of the motor are divided into many small elements. Besides the motor, the model considers also the major effects of mill body, foundation and soil. The mill is modeled as a rigid body. Spring elements at the center of the mill consider the stiffness of the mill and its bearings. The simplified foundation is modeled by volume elements and considers the weakness of foundation and soil.

The FE-model of stator takes into account:

- All relevant stator structural parts
- Stator core with reduced Young's modulus
- Negative linearized air gap springs
- All masses



Figure 2: 3D-FE-model of a Ring Motor, mill and foundation



#### 3.2 Load Cases

The following load cases must be calculated and documented for cold and hot condition:

To start-up the motor, the excitation of the rotor poles is necessary. During excitation build-up, the magnetic field between rotor poles and stator passes its highest stiffness value. For this load case, the model contains the concentric magnetic pull and stiffness for this operation mode, the maximum allowable initial mill eccentricity, stator assembly tolerances and the gravitational acceleration.

For the start-up of the motor, the rotor poles are full excited. Therefore, the magnetic pull between rotor poles and stator has its highest value. The motor stator provides the highest operational torque to the mill. For this load case, the model contains the concentric magnetic pull and stiffness for this operation mode, the maximum allowable initial mill eccentricity, stator assembly tolerances, the starting torque and the gravitational acceleration.

During normal operation, the mill operates in the speed range of about minus forty to plus ten percent of the nominal speed. Between rotor and stator acts the rated torque. The electrical damping effects in the stator winding reduce the magnetic pull and the stiffness of the magnetic field between rotor poles and stator. For this load case, the model contains the concentric magnetic pull and stiffness for this operation mode, the maximum allowable initial mill eccentricity, stator assembly tolerances, the rated torque and the gravitational acceleration.

According to international electrical standards, the motor must resist short circuits. The radial magnetic pull between rotor poles and stator disappears. The short circuit current causes a very high torque between rotor and stator. For this load case, the model contains the short circuit torque and the gravitational acceleration.

The Siemens Ring Motor is designed for installation in all earthquake areas. Customers specify the earthquake design accelerations according to standards like UBC, IBC, ASCE or NCh2369, the Chilean Standard. For this load case, the model contains all loads of normal operation and the specified earthquake acceleration loads.

### 4 Design Criteria

For reliable operation limits of air gap deformation and stress on material are defined.

#### 4.1 Stress on Material

In general, the stress level is low due to the high stiffness of the structure. The anchor bolts and shear pins are verified for allowable stress values.

#### 4.2 Air Gap Deformation

The deformation of the stator iron core and the related rotor part leads to the air-gap deformation.

The maximum air-gap reduction must not exceed a defined limit value.

The limit value depends on the size of the air-gap. The size of the air-gap depends on the size of the motor.



Figure 3: Typical air gap deformation, during start-up of Ring Motor; Calculated with FE-model



#### 4.3 Vibration Behavior

A Modal Analysis with the FE-model for the load case normal operation shows the mode shapes of the motor and its natural frequencies. There are axial and lateral mode shapes.

#### 4.3.1 Axial Mode Shapes

Axial mode shapes are movements of stator parts in axial direction of the mill. The magnetic forces between rotor and stator in axial direction of the mill are too small to excite axial mode shapes. The modal analysis shows the following axial mode shapes:



Figure 4: 1<sup>st</sup> axial mode shape; Bending of upper part of stator



Figure 5: 2<sup>nd</sup> axial mode shape; Bending of lower part of stator



Figure 6: 3<sup>rd</sup> axial mode shape; Twisting



Figure 7: 4th axial mode shape; Twisting of lower part of stator

The motor operation cannot excite the axial mode shapes, but an earthquake can, if an earthquake has the direction of the axis of the mill and meets the resonance frequency. Therefore the stator must be designed to resist the resulting stresses.

Additionally an earthquake detector, part of the Gearless Drive System will switch of the equipment, when the earthquake reaches a level near the design limits.



#### 4.3.2 Lateral Mode Shapes

Lateral mode shapes are movements of stator parts in directions lateral to the axis of the mill.



Figure 8: 1<sup>st</sup> lateral mode shape; Ovalization of upper part



Figure 9: 2<sup>nd</sup> lateral mode shape; Ovalization of lower part

The motor operation can excite the occurring lateral mode shapes of the stator, since the electromagnetic forces of the motor are in lateral direction. Therefore, the design task is to keep the corresponding resonance frequencies out of the operation frequency range of the Ring Motor.

#### 4.3.3 Campbell Diagram

A Campbell Diagram shows a good comparison of operation frequency and natural frequencies. The diagram in figure 10 shows the calculated natural frequencies for the lateral mode shapes and the converter output frequency, which can excite the lateral mode shapes. Due to the damping of the system, a resonance effect is already possible, when the exciting converter output frequency approaches close to a lateral natural frequency. Therefore the green area has to be free of lateral mode shapes to avoid critical resonance effects.



Figure 10: Campbell diagram: operation frequency and calculated natural frequencies



## 5 Verification of FE-Model

The accuracy of a FE-calculation depends mainly on the realistic assumption of characteristics of materials and of connection elements. Such values cannot be found in the literature or in standards, but can only be determined by measurements.

To evaluate and, if necessary to rectify the applied FE-Model, Siemens performed measurements detecting the real natural frequencies of a Ring Motor in a modal analysis. Normally users of grinding mills do not allow interruption of production for such measurements due to the high production of about 3,000 USD per minute. Therefore, the measurements were performed just after commissioning of a Ring Motor before the start-up of the Peñasquito plant in Mexico, where Siemens supplied a 19.3 MW Ring motor for a 38' SAG-Mill. The measurements resulted in a modal analysis detecting the real natural frequencies of the Ring Motor.

#### 5.1 Measurement Layout

The design engineers defined forty locations of measurement points in the stator of the Ring Motor. They designed a mechanical shaker to inject forces and movements to the stator housing.



Figure 11: Layout of measurement points (numbered) and exciting locations



Figure 12: Measurement value processing

#### 5.2 Realization of Measurements

Acceleration sensors at each location measure the acceleration in three orthogonal directions.



Figure 13: Three acceleration sensors at one measurement location

The mechanical shaker needs access to the excitation location without fastening of the shaker feet at the stator. The goal was to install it on a self-contained location independent from the stator. The engineers designed a steel structure for installation on the foundation.





Figure 14: Steel structure with installed shaker



Figure 15: Shaker, installed

The high inertia of the shakers decouples the shaker from the steel structure. A bar connects the shaker to the excitation points.

The test agenda specified measurements at three operation modes of the Ring Motor:

- Motor without stator current and without excitation current
- Motor with excitation current
- Motor in operation at 9 rpm

The team measured the acceleration at the three operation modes in X and Y direction and changed the direction of the shaker by  $90^{\circ}$  correspondingly.

#### 5.3 Results of Measurements

The Modal analysis of the Ring Motor was performed with the classical phase separation process. For all measurement configurations, the shaker excited the stator housing with a sine sweep of 2 Hz to 20 Hz with sine steps of 0.1 Hz. At each frequency step, an adjustable number of sine waves were applied, giving the test structure time for transients, to avoid running over any resonances.

They measured the following mode shapes:



Figure 16: 1st axial mode shape; Bending of upper part of stator



Figure 17: 2<sup>nd</sup> axial mode shape; Bending of lower part of stator





Figure 18: 3<sup>rd</sup> axial mode shape; Twisting



Figure 19: 4<sup>th</sup> axial mode shape; Twisting of lower part of stator



Figure 20: 1<sup>st</sup> lateral mode shape; Ovalization of upper part



Figure 21: 2<sup>nd</sup> lateral mode shape; Ovalization of lower part





#### 5.4 Comparison of Measured and Calculated Natural Frequencies

To evaluate the existing FE-model we compare its results with the measured values of natural frequencies. Natural frequencies must have a save distance to the operational frequencies of the motor to avoid a resonance when operational and natural frequencies meet.

At first, the comparison shows that the FE-model depicts all measured mode shapes. There were no mode shapes measured, additional to those calculated.

Comparing the values of the natural frequencies shows a good accuracy of the calculated values of the axial mode shapes. The measured values of these mode shapes are slightly higher than the results of the calculation. Motor operation cannot excite axial mode shapes, because the axial forces in the motor are too low to excite resonances.



Figure 22: Campbell diagram: operation frequency and measured natural frequencies

The measured values of the natural frequencies of the lateral mode shapes are much higher than the calculated ones. Therefore, the risk of excitation of these natural frequencies is low.

The finite element model provides very safe results, because it works with very conservative assumptions.

The natural frequency of a vibrating system depends on the modal mass and the stiffness of the system. In case of the Ring motor the stator mass and its distribution is well known and used for the FE model. Therefore, the stiffness of the stator and the anchoring system of the motor has to be higher than modeled. The most important conservative assumption is the stiffness of the stator core and the anchoring system. In reality, these values are much higher than modeled.

Due to this fact, all delivered Ring motors have a higher safety margin with regard to the dynamic stability and with regard to the air gap deformation, than expected.



## 6 Evaluation and Rectification

The stiffness of the motor stator is a combination of the stiffness of stator housing and the stiffness of stator core.

The stator housing consists of steel plates, beams and pipes. The dimensions and material properties of these parts are well known and already used in the FE-model. Therefore, the stiffness of the stator housing is very accurately modeled. Conservative assumptions were made regarding the characteristics of the laminated iron core of the stator.

The modeling of the stator core was investigated and rectified.

Until now, the stator core is modeled by a closed ring of volume elements with a low isotropic Young's modulus. Investigations on the basis of the measurements show, that the low Young's modulus is correct for the x-direction (direction of mill axes). But for the y- and z-directions (orthogonal to the mill axes) the Young's modulus are in reality about six times higher than assumed for the old FE-model. So the stator core is to model with an anisotropic Young's modulus.

The described rectification of the stator core modeling alone is not sufficient to have a good convergence of the calculated natural frequencies to the measured natural frequencies. Closer investigations showed that the modeling of the anchoring system must be rectified. Until now, the stator model is fixed to the foundation model by one beam element per foot bolt. The diameter of these beam elements corresponds to the diameter of the pressure cones around the preloaded foot bolts. The length of the beam elements corresponds to the clamping length of the foot bolts. Based on the measurements, further investigations with a detailed FE-model of the anchor bolts, foot bolts, sole plates and the surrounding concrete showed a more stiff behavior than the described old model. The stiffness values for a single bolt for all directions were calculated with this detailed FE-model. The beam elements in the old model were exchanged by spring elements, using the new calculated stiffness values.

The rectified FE-model calculates values of the natural frequencies nearby the actually measured values, but still on the save side.



Figure 23: Campbell diagram: comparison of measured and new calculated natural frequencies



## 7 Conclusion

The FE-model, which Siemens used to verify the design of Ring Motors for grinding mills, was very reliable due to its conservatively assumed values of those characteristics, which cannot be found in the literature or in standards and due to its precision of all other well-known characteristics.

The measurements at an existing Ring Motor confirmed as well the precision as the conservative approach and provided exact data for rectification of the model.

The rectified model calculates precisely all resonance modes and natural frequencies of the Ring Motor.

On a basis of highest scientific level and with the thoroughness of good engineering, Siemens' design tools provide Ring Motors of highest operational reliability.



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