Lubricant evaluation for bearing operation in rotating electric machines

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Abstract - Poor lubrication is one major cause of bearing failures, including bearings for electric machines. This paper describes good practices for lubricant specification in order to maximize bearing life beyond the calculated expectation. Some factors can determine the choice of the most suitable lubricant for each bearing and its application.

1 INTRODUCTION

A rotating electric machine has a rotor, in which there is a laminated core mounted onto the shaft. The bearings are intended to allow the rotation of the rotor within a thin air gap between it and the stator, and with a minimized friction, by connecting the dynamic portion into the static.

Considering the particularities of electric machines, such as mounting positions, rotation speed, shaft diameters, different radial and axial loads, it is possible to understand the reason for many bearings types and different lubricants, as for their purpose or even the lubrication method.

This paper considers the main bearings types used by WEG, which are hydrodynamic and rolling-elements bearings. Hydrodynamic bearings are oil lubricated, and the rolling bearings (anti-friction bearings) can be oil or grease lubricated.

Proper lubrication is important to avoid premature bearing failure and in some cases to maximize bearing life beyond the calculated expectation. Bearing faults are the most frequent failures in electric motors (41%), according to a motor reliability study for large motors above 200 HP [1].

2 HYDRODYNAMIC BEARINGS

State-of-the-art hydrodynamic lubrication indicates that an inclined plane with an angle "*α*" relative to a horizontal plane, carries a load "*F*" and has horizontal velocity, "*U*", relative to a stationary horizontal plane surface. If the contact between the surfaces would be dry, that would result in significant friction and wear. However, if a sufficient lubricant quantity is provided and the sliding velocity is sufficiently high, the surfaces would be completely separated by a very thin lubrication film. In this case, the full hydrodynamic lubrication is obtained.

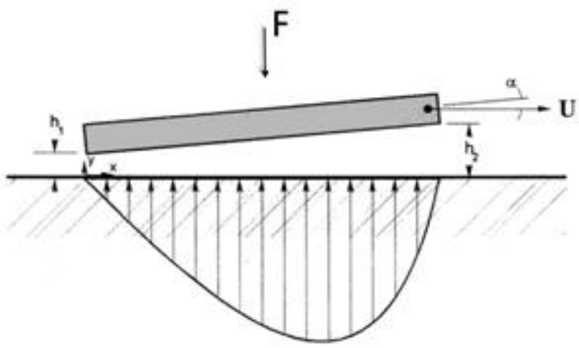

Figure 1: *Hydrodynamic lubrication of plane-slider. Figure adapted from the book "Bearing Design in Machinery - Engineering Tribology and Lubrication"* [2]

For hydrodynamic lubrication, the viscosity "µ" is the most important characteristic of a fluid because the bearing load capacity is proportional to oil viscosity during the desired rotations.

Viscosity is sensitive to changes in temperature. For mineral and synthetic oils, viscosity decreases (oil becomes thinner) when its temperature raises. However, the synthetic oil viscosity is relatively less sensitive to temperature variations when compared with mineral oils (higher *Viscosity Index*, VI).

The greatest concern in a hydrodynamic bearing project and lubrication is the complexity of the tribology, which is a coupled problem. It means that for a specific load, rotation speed and oil viscosity, the temperature increment decreases the viscosity and then the film thickness, which affects the shape of pressure and again affects the temperature. In a complete thermal elastohydrodynamic lubrication analysis (TEHL), the variables of bearing strain due to thermal and elastic loads also need to be considered on the calculation. The calculus must cycle through all variables many times until its convergence.

2.1 OIL LUBRICANT FOR HYDRODYNAMIC BEARINGS

The viscosity "μ" is a proportionality coefficient in a viscous fluid. Bearing oil is a Newtonian fluid, and a linear relationship between shear stress and the shear rate is given by below equation:

$$\tau = \mu \frac{du}{dy} \qquad \text{Eq. 1}$$

Where:
τ: shear stress
μ: absolut viscosity
du/dy: velocity gradient

Figure 2 shows the relative movement between two particles in the fluid and the shear stress existence.

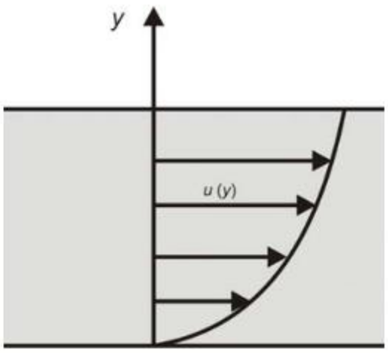

Figure 2: *Shear stress during the fluid movement*

Oils are practically incompressible; this property simplifies some equations because the fluid density "ρ", can be assumed constant. Many of the fluid mechanics equations, such as Reynolds equation, includes the ratio of viscosity to density. This ratio has been given the name kinematic viscosity "v":

$$v = \frac{\mu}{\rho} \qquad \text{Eq. 2}$$

The kinematic viscosity has the SI Units given by *m²/s*. However, it is very common to find it in the cgs Units, which gives it *cm²/s* or Stokes (St). In addition, a smaller unit used is centi-Stokes (cSt), equivalent to *mm²/s.*
In order to organize these details some members of lubrication oil organization decided to create the ISO VG system.
The purpose of this classification system is to establish a series of definite kinematic-viscosity levels, thus the lubricant suppliers, lubricant users and equipment designers will have a uniform and common basis for designating or selecting industrial liquid lubricants according to the kinematic viscosity required in a particular application. This viscosity classification is based on kinematic viscosity at 40 °C, and it is desirable that the viscosity grade width be no more than 10 % on either side of the nominal value, according to ISO 3448 [3].
Other relevant characteristic for a correct oil specification is the oil VI. It is a common empirical measure of the level of decreasing viscosity when the oil temperature increases. The viscosity index of any type of oil is determined by the following equation:

$$\text{VI} = 100 \text{ x } \frac{L - U}{L - H} \qquad \text{Eq. 3}$$

Where:
L: kinematic viscosity at 100°F of VI = 0
H: kinematic viscosity at 100°F of VI = 100
U: kinematic viscosity at 100°F of the tested oil

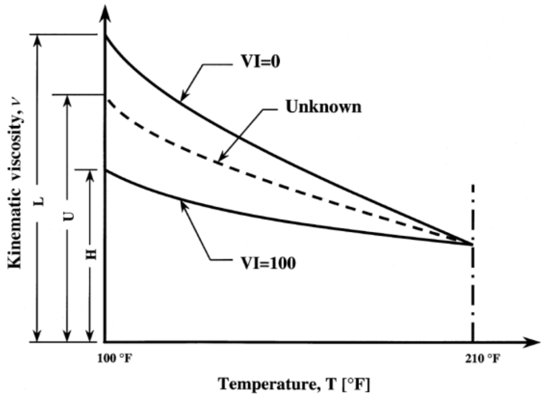

Figure 3: *Viscosity index illustration. Figure reprinted from the book "Bearing Design in Machinery - Engineering Tribology and Lubrication"* [2]

Thus, it becomes obvious that a higher viscosity index oil is desirable in hydrodynamic bearings, because it does not change significantly the viscosity during operation. Synthetic oils have higher VI than mineral oils, which makes it indispensable when viscosity stability in high temperature is necessary.
According Harnoy [2], some of synthetic oils advantages are:

- The viscosity is less sensitive to temperature variations (high VI);
- They have a relatively low pour point;
- They have relatively good oxidation and aging resistances;
- They have the desired low volatility.

On the other hand, these synthetic lubricants are more expensive and should be used only where higher cost can be financially justified.

WEG recommends mineral and synthetic oil in accordance with DIN 51524-1 HL [4] and/or DIN 51517-2 CL [5], which specifies lubricants that have additives protecting from corrosion and oxidation, and are recommended for use in low-pressure internal hydraulic systems. Oils according to DIN 51524-2 HLP [6] and/or DIN 51517- 3 CLP [7] are also allowed, but the anti-wear additive (AW) must be zinc free.
Other relevant information about oil for WEG's hydrodynamic bearings is the presence of extreme pressure additives (EP), which are prohibited due to solid components that can damage the white metal material (Babbitt). The EP's additives also are irrelevant on a hydrodynamic bearing because there is no contact between shaft and bearing in a high specific pressure.

3 ROLLING-ELEMENT BEARINGS

Rolling-element bearings are also called antifriction bearings since they have much lower friction when compared to sliding bearings. There are many types of rolling bearings in order to support radial and axial thrust loads in different operation conditions. The most common types used by WEG are deep groove ball bearing (DGBB); angular contact ball bearing (ACBB); cylindrical roller bearing (CRB), spherical roller thrust bearing (SRTB); spherical roller bearing (SRB); and tapered roller bearing (TRB).
The main advantage of rolling bearings, as mentioned, is the lower friction when compared to sliding bearings for the same operation condition. In addition to friction, the rolling action causes much less wear than the sliding bearing when applied in an electrical machine with daily start and stop operation cycle, i.e., when the hydrodynamic film cannot be formed due to low speed, even under a low specific pressure.
A major disadvantage of rolling bearings is the fatigue life limitation caused by high alternating stresses at the rolling contacts. Every rolling bearing has a lifetime calculation referenced in International Standard ISO 281 [8], which specifies methods of calculating the basic dynamic load rating of rolling bearings and methods of calculating the basic rating life (L10), which is the life associated with 90 % reliability, with commonly used high quality material, good manufacturing quality and with conventional operating conditions. In the last version this ISO, methods were added to calculate the modified rating life, including reliability factors, lubrication condition, contamination and fatigue load of the bearing. The modification factors could increase or reduce more than 10 times the basic bearing life.

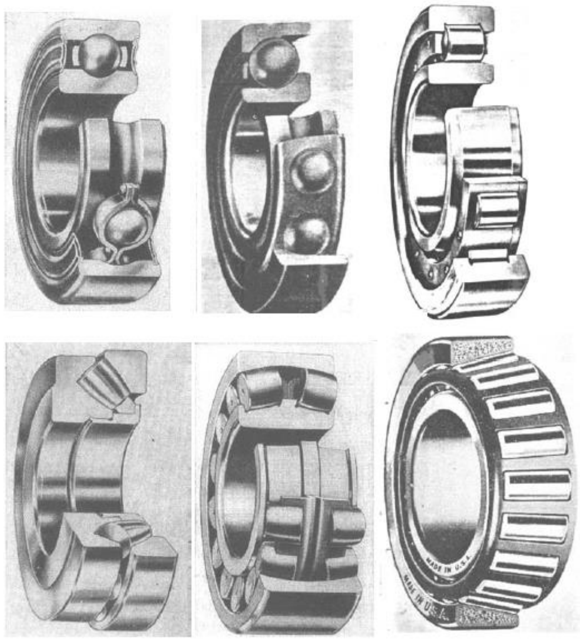

Figure 4: *WEG's standards rolling bearing. From left to right and up to down DGBB; ACBB; CRB, SRTB, SRB, and TRB. Figures reprinted from the book "Bearing Design in Machinery - Engineering Tribology and Lubrication"* [2]

3.1 ROLLING BEARINGS LUBRICATION

As hydrodynamic bearings, rolling-element bearings requires a thin fluid film at the contact area and a full elastohydrodynamic film between the rolling element and raceway, resulting in significant wear reduction. Consequently, much longer bearing lifetime is expected when comparing it to dry bearings.
According to Tallian [9], a predominant surface fatigue, that can be followed by a premature onset of spalling means poor lubrication, i.e. that the EHD and/or boundary lubrication parameters are inadequate for the operating conditions and for the surface geometry selected. Some tests indicated that the fatigue life is significantly improved for rolling bearings operating with a full EHD film.
It is important to explore the Herzt contact theory for rolling bearings, which considers the elastic deformation and stress distribution near the contact between rolling elements and raceways. ISO 281 [8] refers to the limiting static load (C_0) of rolling bearings and some manufacturers included it on their catalogues. It is important check any transient and momentary overload on the same rolling element during start-up and steady operation. The Hertz contact and EHD pressure distribution is similar under high loads and low speeds, due to the influence of the elastic deformation. On the other hand, at high speed the hydrodynamic effect

overcomes, and the full EHD fluid film can be created. Some theoretical numerical solution for EHD problem using Newtonian lubricant was studied by B.J.Hamrock [10] and the results are displayed below:

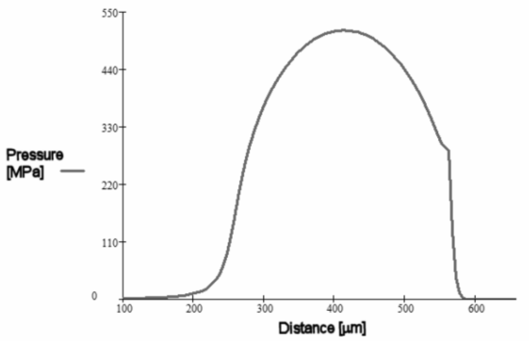

***Figure 5:** Pressure wave distribution. Figure reprinted from the book "Fundamentals of Fluid Film Lubrication"* [10]

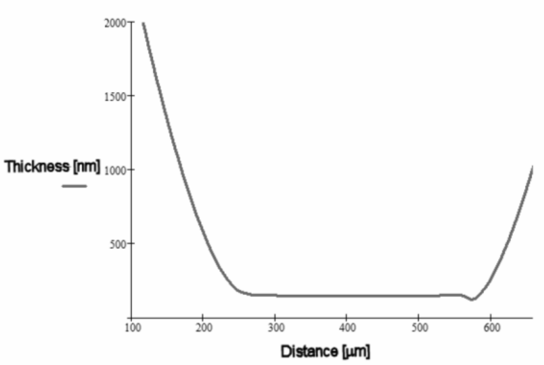

***Figure 6:** Film thickness in an EHD lubrication. Figure reprinted from the book "Fundamentals of Fluid Film Lubrication"* [10]

In order to achieve the full elastohydrodynamic lubrication it is important to control some parameters, as *lambda* ratio (λ) and *kappa* ratio (*k*). The λ is the ratio of the minimum oil film thickness (h_{min}) to the size of surface roughness (R_s) in the root-mean-square of the two individual surfaces in contact (RMS), the equation below presents *lambda* ratio:

$$\lambda = \frac{h_{min}}{R_s} \qquad \text{Eq. 4}$$

The *kappa* (*k*) is the viscosity ratio defined by the equation below:

$$\kappa = \frac{v}{v_1} \qquad \text{Eq. 5}$$

Where:

v: lubricant viscosity at operating temperature

v_1: lubricant minimum viscosity required

The minimum lubricant viscosity required is a function of rolling bearing mean diameter $d_m = 0{,}5(d + D)$ [mm], and the rotational speed of the bearing, *n* [rpm]. According to SKF catalogue [11], in a 500 rpm shaft speed rotation using a DGBB 6352 M ($d_m = 400$ mm), the minimum kinematic viscosity required is 11 mm²/s (cSt).

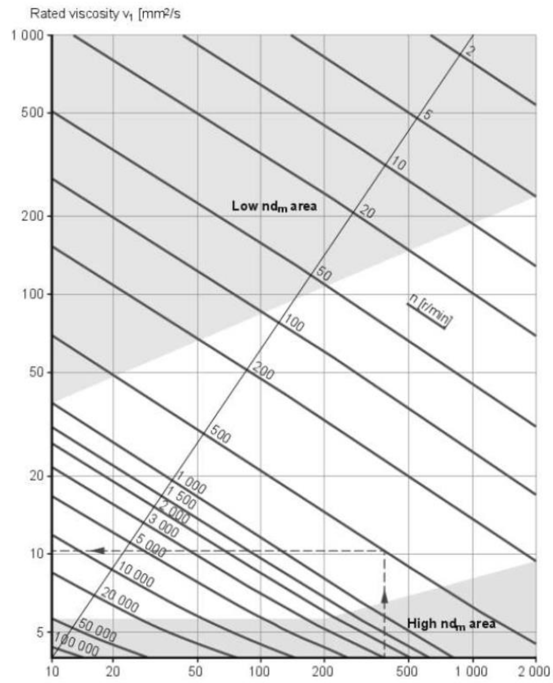

***Figure 7:** Minimum lubricant viscosity required*

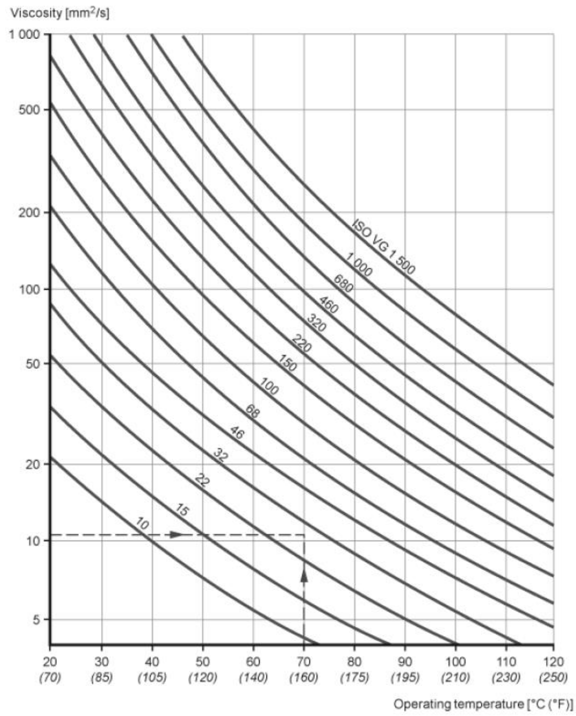

***Figure 8:** Viscosity-temperature diagram for ISO viscosity grades (Mineral oils, viscosity index 95)*

In order to achieve a kappa ratio > 1, a lubricant must have kinematic viscosity at operating temperature greater than 11 cSt. Figure 8 indicates that the oil lubricant must be ISO VG 32 or higher.
According to ISO 281 [8], the life adjustment factor has an improvement in fatigue-life due to improvement in EHD lubrication at higher viscosity. However, there is a limit on the benefits obtained from increasing oil viscosity. Generally, the *kappa* ratio below 4 is recommended as limit for grease or oil lubricated bearings [12], as further kappa increase also increases oil shear stress, resulting in higher friction from lubricant and bearing operation temperature. In some applications the kappa ratio can be out of general recommended limits, at this type of equipment make sure about lubricants with additives or evaluate the thickener and base oil combination in order to improve lubrication condition.

3.2 LUBRICANT SELECTION FOR ROLLING BEARINGS OF ELECTRICAL MACHINES

In case of rolling-element bearings, it is essential to select the correct lubricant type, considering its relation with bearing performance, costs, maintenance, sealing system, environment aspects, and obviously, customer requesting (market availability). However, the electrical machine manufacturer should advise in case of technical possible issues or different performance about bearing lubricant selected by customer.
Generally, grease lubrication is preferred rather than oil because it has some benefits such as: lower cost of complete bearing solution, lower oil leakage risk, better overall protection for corrosion and in start-stop condition, easier maintenance, and it is possible to use more complex additives formulation and noncontact labyrinth seal, which eliminates or reduce any additional friction, noise and wear. Important factors for grease lubrication are contaminated environments and rotational speed combined with bearing size, i.e., dmN factor, as it increases, the heat generation also increases. New technologies and high speed greases are available, but special attention should be considered due overheating possibility. In case of increase speed requirements, a complete analysis of vibration and temperature is recommended. The bearing design can be changed in order to attend higher temperature levels or increase bearing heat exchange capacity.
Oil lubricant is used in large and/or high-speed rolling bearings, and when requires increasing bearing cooling. Its main advantage is the possibility to run it through an external heat exchanger, including a filter to remove wear debris and the oil can return cooled and directly towards the bearing heating location to maximize the bearing lubrication efficiency. The oil lubrication disadvantages are the potential oil leakage and some losses generated by the mechanism responsible for supply the oil in the arrangement, called churning losses, which could increase significantly the oil sump temperature due oil shear.

3.3 ROLLING BEARINGS GREASE LUBRICATED

Grease selection for electric machines should be done based on overall performance requirements, grease formulation analysis and extensive experimental validation. The main characteristics recommended are the thickener type and general grease formulation, evaluated though grease data sheet properties. The additives in the composition, the base oil type, viscosity, consistency, temperature limits and VI are important parameters used in the grease initial definition.
WEG defines the most appropriate grease for each different application considering design requirements and strongly recommends to never mix different greases or change previous specified lubricant without previous analysis. It can be referenced that all lubricants have different behavior and the final lubrication performance will be a combination of many characteristics, resulting in better or poor lubrication condition. The incorrect lubrication application could affect significantly in the bearing life and cause premature failure.

3.4 GREASE PROPERTIES GENERAL EVALUATION

Greases data sheets comparison have to be the starting point to select an alternative grease. Relevant or immediate impacts due grease change can be evaluated using complete data sheet analysis. The Table 1 should be used as reference for properties or results for comparison and related standards. Some typical characteristics presented are in general used for ensure grease batch-to-batch quality, and it could not related directly to the operational performance at rated speed. Nonetheless, the storage and transportation conditions should be considered in a complete comparison analysis.
Different standards from DIN, ASTM, ISO and others are used for each different grease manufacturer, making sometimes more complex the direct comparison.

Table 1: *Summary of main grease properties*

Typical characteristics	
Description	Reference standard
Oil type or base oil	-
Thickener type	-
NGLI grade (Consistency)	DIN 51818
Viscosity class (ISO VG)	ISO3448
Density at 20°C	-
Cone penetration worked	ASTM D 217 / DIN 51825
Cone penetration unworked	ASTM D 217
Viscosity index (VI)	ASTM D2270
Apparent viscosity	ASTM D 1092
Kinematic viscosity of base oil	ASTM D 445
Temperature range	DIN 51825
Flow pressure	DIN 51805
Low temperature torque (Starting / running)	ASTM D 1478
Drop point	DIN ISO 2176
Pour point	ASTM D 97 (oil)
Oil separation	FED-STD-791. 321
Water resistance test loss	ASTM D 1264
Mean Hertz load - kg	ASTM D 2596
Copper corrosion	ASTM D 4048
Bearing rust test	ASTM D 1743-73
Evaporation in 22hours	ASTM D 2595
Anti-friction bearing performance	ASTM D 3336
High temperature bearing life	ASTM D 3336
Four ball wear test, welding load	DIN 51350

3.5 BASE OIL

The grease lubrication efficiency is primarily determined by the degree of separation between the rolling and contact surfaces, due to base oil viscosity. For proper lubrication, the lubricant must have a minimum viscosity when the application reaches its operating speed and temperature. The lubrication condition at normal operating temperature considers the *k* viscosity ratio. The discussion about the kappa (*k)* is described at item 3.1 of this paper. The VI and apparent viscosity analysis could help in the performance prediction.
The oil type is referenced according to the oil origin, which can be ester, polyalphaolefin (PAO), Mineral and others. In summary, synthetic oil are costly but have longer life when compared with mineral oil. Some characteristics that influences in grease oil releasing such as vibration, load, and temperature must be evaluate.

Limits of temperature are in general considered by parameters like dropping point, starting torque, running torque, consistency and pumpability. The results comparison from standardized tests have taken into account to estimate better or worst performance.

- Starting torque and running torque according ASTM D 1478 [13] are safe when starting torque has ≤10000g.cm and running torque ≤1000g.cm at required low-temperature.
- Flow pressure according DIN 51805-2 [14] is safe when it has ≤1400hPa at required low-temperature.
- Low-temperature penetrability ISO 13737 [15] according the minimum cone penetration required at low-temperature.

3.6 GREASE CONSISTENCY

Greases are lubricants manufactured with additives and mineral, synthetic or oil blend added in a formulated thickener suspension. The finished product should have fairly uniform consistency. Different from oil lubricated bearings, that in general present oil circulation, grease should have a formulation able to supply the additives and oil in the contact area. Therefore, other parameters of the grease should be considered as relevant such as base oil viscosity for proper lubrication along of each lubrication interval.
The NLGI (National Lubricating Grease Institute) grade classifies the grease consistency through by cone penetration tests for worked and unworked condition. These results are important in the evaluation of thickener and grease formulation. The base oil used in the grease formulation determines the oil viscosity and both characteristics are not directly related. Two greases can have the same NLGI grade but completely different base oil viscosities, and vice versa. The NLGI grade classifies the grease consistency, ranging from 0 (00 and 000) for very softer grease to 6, for extremely hard consistency. The greater grease consistency also indicates more resistance to flow under a given pressure. On the other hand, low consistency greases will flow easily, which means that grease consistency, or NLGI grade, is important to estimate or compare grease flow pressure or pumpability, that is one of the most important characteristics of the grease in the lubrication performance.
The grease consistency should not change dramatically when in operation, mainly for high speed or vibration application. Vertical electric motors using greases with low consistency can result in excessive detachment of the lubricant, which can flow through the seals, reaching the

internal parts of the electric motor and consequently resulting in poor bearing lubrication.

3.7 THICKENER EVALUATION

The grease thickeners act as sponges, releasing the base oil and additives.
Many of the characteristics of greases, such as operating temperature limit, apparent viscosity, as well as mechanical stability, water resistance, among others, depend largely on the types of thickeners added to the base oil. Thickeners used in greases can be soap-free (inorganic, such as silica gel or bentonite, and organic, such as polyurea, urea or fluorocarbon), simple or complex metal soaps composed, as follows:

• Barium is a simple metal soap and has a drop point value higher than 176ºC, however it is not recommended for continuous operations at high temperature due to its degradation, therefore, it can operate in conditions of greater temperature variation. Used on the most diverse occasions, however, it is not recommended for applications at low temperatures and high speeds. Barium complex soap can be used for high speed greases. Compatible with most thickeners, however, as it is a heavy metal, it presents toxicity issues related to health, safety and environmental problems, thus it is banned in several countries.

• Lithium is one of the most used compound, and this thickener withstands extreme temperatures, acceptable at high and low temperatures according to the formulation. One of the reasons for its good performance at low temperatures is the low pour point, making it acceptable under low temperature. The use of this thickener for high temperatures requires a modification in its formula, therefore, the application of the same grease for wide range operational conditions requires a carefully evaluation. In general, the lithium thickener has good stability, water resistance and pumpability. Lithium greases are negligibly soluble in water and the ability to adhere to metal surfaces is good. Grease formulation with lithium complex soap in general ensure good properties from simple lithium and improve specific characteristics. The lithium grease in general have some limit for a wide range of applications but it is an economical choice.

• Polyurea: this thickener is a product of the reaction between isocyanates and amines. Polyurea greases have antioxidant properties, very good water resistance, good mechanical stability and excellent performance under medium and high temperatures. However, its lubrication properties in extremely low ambient temperature operation is poorer than that of other thickeners, and the toxic nature of the raw material still limits the production of greases with this thickener. Polyurea thickener is largely used in rotating electric machines due to excellent performance under medium and high operation temperature providing a long-life lubrication.

• PTFE: perfluoropolyethers are used as lubricants in aggressive environments and generally require an equally inert polytetrafluoroethylene thickener. Applications for this type of grease include contact with aggressive solvents or high temperature applications. Inert greases of this type are also used to lubricate pumps for oxygen and nitrous oxide in hospitals, where contact with other greases can create a risk of fire or explosion. Components containing sensitive or reactive plastics, rubbers or ceramics can also be lubricated with this type of grease.

This summary present a general overview about thickeners overall performance, but it is important consider that most grease manufacturers uses complex soap, for example, barium complex or lithium complex, and the grease properties can be changed significantly when compared with the simple compound.

3.8 GREASE MISCIBILITY

In general, the bearing and lubricant suppliers do not recommend the mixture of greases with different base oil formulation or different thickeners. The incompatibility can reduce the grease lubrication performance due to oil bleed characteristics changing. In addition, the drop point and consistency of the mixture can considerably change, indicating chemical incompatibility.
In special cases where it is extremely difficulty to remove the original grease, some analysis can be carried out in order to mitigate the lube failure risk caused by the mixture.
The miscibility analysis should consider that the mixture grease results variation before and after mixed must be smaller than the difference of each grease individually. In general, it is recommended at least two tests before and after the Roll Stability Test according ASTM D1831 [16]:

- Cone penetration according ASTM D217 [17];
- Dropping point according ASTM D2265 [18]

Obviously, for proper performance assurance, recommends to develop a transition plan for most critical applications. Carefully inspection of temperature and vibration after mixed lubricant, and if possible, others tests about miscibility must be conducted to avoid any lubrication failure, as example the four ball test according DIN 51350 [19] with many mixture proportions in percentage such as 100/0, 75/25, 50/50, 25/75 and 0/100.

3.9 LUBRICATION INTERVAL

WEG uses its own method for lubrication interval calculation and three factor needs to be considered in equal importance levels for proper lubrication: bearing design, service condition and maintenance. In more details, some relevant data to consider during design are operating temperature, speed rotation, bearing types and sizes, bearing loads, shaft position, grease selection and lubricant performance parameters. The operation will affect according to different service regime, including start/stop cycles, long rest or out-of-service period, active environment and storage time and condition. The lubrication interval is frequently root cause of failures due incorrect or severe applications without correct adjustment in the interval. Motors with variable frequency driver (VFD), operating with excessive ambient temperature (>50°C), or vibration levels typically high, excessive moisture or dusty contamination requires special attention. Motors in storage for long time or operation condition different from continuous, the lubrication interval should be defined by the grease lifetime, which can change according to storage or installation condition. In addition, a common mistake is bearing over-lubrication causing overheating and excessive power loss. The performance of each grease recommended by WEG is determined through many bearing tests at laboratory and extensive validation in prototypes. The lubrication interval with different grease from main nameplate or manuals cannot define accurately and the bearing reliability can reduce significantly. Finally, lubrication procedure with proper materials complete the requirements for ensure safety and reliability.

3.10 ROLLING BEARINGS OIL LUBRICATED

All the rolling-element bearings described at item 3 can be oil lubricated, which has the purpose to give a fluid film and remove heat from the bearing load zone. Some bearing types under specific conditions are favorable to have oil lubrication, such as the spherical roller thrust bearing at vertical motors with driven axial thrust load (vertical pumps and hydro turbine application). This bearing type has an internal design that creates a pumping action, which produces an oil flow from small to the large roller face. Its pumpability contributes to increase the oil convection property and consequently, increases the heat exchange.
In addition, oil lubrication is indicated for rolling-element bearings applied in high-speed condition, and as well as in hydrodynamic bearings, there are multiple lubrication types, such as oil bath and external oil circulation. The advantage and disadvantages are presented at item 3.2.
The oil specification should be the same of hydrodynamic bearings indicated at item 2.1, except the information about EP additives, which can be used in rolling bearings when applied in low speed with high loads condition. Generally, the EP additive application relates to the viscosity ratio (k) < 1, where high temperature and local rough contact activates the extreme pressure additive, increasing bearing life in very tough lubrication conditions.

4 CONCLUSION

The bearing lubrication condition contributes directly in the bearing performance in most relevant aspects, for instance, bearing lifetime, operation temperature, vibrations, and wear. A proper bearing lubrication is responsible for the reliability of a rotating electrical machine. Through this paper, it is possible to understand about bearing lubrication principles and good practices to evaluate the lubricant type in pursuit of best lubrication condition for each application, even when submitted to special conditions, such as ambient temperature, speed, loads, moisture, vibration, and contaminations.

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