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The detection of lubricating oil viscosity changes in gearbox transmission systems driven by sensorless variable speed drives using electrical supply parameters

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Abstract. Lubrication oil plays a decisive role to maintain a reliable and efficient operation of gear transmissions. Many offline methods have been developed to monitor the quality of lubricating oils. This work focus on developing a novel online method to diagnose oil degradation based on the measurements from power supply system to the gearbox. Experimental studies based on an 10kW industrial gearbox fed by a sensorless variable speed drive (VSD) shows that measurable changes in both static power and dynamic behaviour are different with lube oils tested. Therefore, it is feasible to use the static power feature to indicate viscosity changes at low and moderate operating speeds. In the meantime, the dynamic feature can separate viscosity changes for all different tested cases.

1. Introduction

Gearbox lubricants are critical in maintaining efficient and effective operations [1]. Lubricating oils must reduce wear and friction at the contact surfaces and separate them to ensure appropriate operation and avoid failures. Lube oil properties also effects gear dynamics, such as vibration, power characteristics and heating [2]. Therefore, continuously monitoring changes in lubricant properties is crucial for avoiding defects within machines [3] and prevent unexpected breakdowns. Lubricants in gearboxes are degraded mainly due to oxidation, particle and water contaminations [1]. Both oxidation [4] and water [5, 6] generally increase the lube viscosity.

Studies show that oil properties considerably affect gearbox behaviors and performance due to churning and splashing [7]. Oil churning causes significant power losses in the gearbox. churning losses increase with increasing viscosity at low speeds, yet these losses decrease at high speeds [8, 9]. Likewise , as found in [10] viscosity increases temperature due to internal lube friction. However, high temperature motivates chemical activities and good tribological layer formation. Conversely this will decrease the viscosity and hence thinner oil film is formed.

Different offline techniques have been developed for monitoring oil degradation [11-16]. However these techniques are not always applicable, require addition measuring equipment and expensive to implement. The need for an easy to apply, reliable and cost effective condition monitoring technique is becoming more imperative important in order to provide timely assessment of oil quality.

Vibration and current signature analysis are the most widely used schemes for condition monitoring and diagnosis of different equipment and faults detection. Though, the research on developing lubricating degradation detection based on these schemes is very little. Rui and Linilson [17] studied the relationship between the viscosity and vibration signature. They found that vibration features in high frequency ranges can be correlated with the oil viscosity. Nevertheless, the potential of using signatures from electrical measurements for lube oil degradation detection based on viscosity is not yet well discovered [3].

Therefore, this study investigates the effect of varying oil viscosity in a gearbox transmission system on power supply parameters from a variable speed drive (VSD). After an examination of the effect on gear transmission process, an experimental study was performed based on a 10 kW gearbox transmission system with four different oils in turn. The diagnostic capability of both a static feature and dynamic feature which are developed based on the current and voltage measurements are then examined for different operating conditions.

2. Oil Viscosity Related Power Losses in Gearboxes

Power loss sources in a gear transmission relate to various gear parameters [4, 15] such as teeth geometry, specific sliding, and lube properties. Yet the viscosity is a key element in improving the gearbox efficiency and performance. Research in [4, 15] show that the use of a lubricant with a suitable viscosity could save up to 20% of power losses. Power losses P_T in gears can be approximated as follows [15]:

$$P_T = P_{fr} + P_{spl} + P_{M1} + P_{M0} + P_{sl} \tag{1}$$

where P_{fr} denotes gear friction power loss and P_{spl} is gear churning power loss, which are more significant compared with other three losses: P_{M1} denoting load dependent power loss in rolling bearings, P_{M0} denoting power loss in rolling bearings, and P_{sl} denoting seal power loss. The gear frictional power losses are load dependent and also related to gears geometry, number of teeth of both gear and pinion (z_1, $z_2$respectively), and friction coefficient(μ_m), and can be estimated based on [18-20]:

$$P_{fr} = \pi\left(\frac{1}{z_1}+\frac{1}{z_2}\right)\left(1-\left(\frac{g_f+g_a}{p_b}\right)+(\frac{g_f}{p_b})^2+(\frac{g_a}{p_b})^2\right)P_{in}\mu_m \tag{2}$$

It shows that the average friction coefficient has a significant impact on P_{fr}. According to studies in [18, 19, 21], the friction coefficient can be calculated from the following equation:

$$\mu_m = 0.048\left(\frac{F_{bt}/b}{v\,.\,\rho_c}\right)^{0.2}\eta_{oil}^{-0.05}{R_a}^{-0.25}X_L \tag{3}$$

Equation (3) shows that μ_m is inversely proportional to the lube viscosity η_{oil} and velocity v. On the other hand, the churning loss P_{spl} in a gear are load independent losses; and mainly depend on the velocity, geometry of the moving parts immersed in the oil and oil density ρ and viscosity, which can be estimated from [18, 19, 22]:

$$P_{spl} = \frac{\pi}{30}.n.\left[\frac{1}{2}.\rho\left(\frac{\pi.n}{30}\right)^2 A_i\left(\frac{d}{2}\right)^3\right]\left[\left(\frac{2.h}{d}\right)^{0.45}\left(\frac{V_{oil}}{d}\right)^{0.1}F_R^{-0.6}Re^{-0.21}\right] \tag{4}$$

Equation (4) shows the complex influence of gear geometry and velocity on the power losses due to oil churning and splashing. The Reynolds number R_e depends on the oil density and viscosity and given as:

$$R_e = \frac{\rho UD}{\eta_{oil}} \tag{5}$$

While losses from churning in bearings depend on bearing type and size, bearing arrangement, and lubricant viscosity supply [8], and can be calculated from [21]:

$$P_{M0} = \frac{\pi}{30}.n.G_{Br}.{\eta_{oil}}^{2/3}.10^{-3} \tag{6}$$

where: P_{in} donates input power, g_f is the length of approach, g_a represents the length of recess, F_R Froude number, R_a mean roughness, p_b base pitch, F_{bt} tooth normal force in the transverse section, X_L an adjustable parameter relating to each lubricant, b face width, $v_{\Sigma c}$ sum velocity at pitch point, ρ_c

equivalent curvature radius at pitch point, ρ specific weight, V_{oil} is oil volume, G_{Br} a parameter depends on the bearings geometry , n input speed (rpm), D a characteristic linear dimension, U the mean velocity of the flow and η_{oil} is the dynamic viscosity.

Equations (2) to (6) show that oil viscosity has a significant effect on gearbox power losses. The frictional power loss is inversely proportional to viscosity values and operating speeds, as shown by Equations (2) and (3). Conversely, the power losses from churning increase as the speed and viscosity increase, by Equations (4) to (6). However, the churning induced loss may be more dominant as its fractional power value is higher. Nevertheless, both of these two types of losses will also alter the dynamics of gear transmission. Especially, the churning effect can reduce the effect of damping and increase the moment of inertia of the rotational system. Consequently, it leads to more oscillatory motion of the system.

In theory, these power losses can be reflected by the VSD behavior. Particularly, when the mechanical system has any disturbances such as those caused by viscosity changes, the VSD adjusts the electrical supply parameters in order to maintain the operation at the desired speed. Previous studies [23, 24] show that both dynamic and static effects occurring on downstream machines can be observed in the electrical signals. Specifically, the dynamic effect can be represented by the sideband components at frequencies related to supply and shaft frequencies. The amplitude changes at the supply frequency can be based to examine the static effects. While in systems driven by sensorless VSDs the supply parameters are adjusted by the control system. This may give more chances to observe such effects, rather than just using the feature frequency components based on the high slippage changes under direct voltage/Hz control methods.

3. Test facility and Procedures

The test facility employed for this study consists of a mechanical system and an electrical control system as shown in the schematic of Figure 1. The mechanical system includes a 15kW AC induction motor as the prime driver, two back-to-back two stage helical gearboxes for coupling the AC motor with a load generator using flexible spider rubber couplings. The first gearbox operates as a speed reducer while the other is a speed increaser so that the system maintains sufficient speed for the load generator to produce sufficient load to the AC motor through the two gearboxes. The control system consists of a programmable logic controller (PLC) for setting up different speed-load profiles specified by operator, an AC VSD, Parker 650V, that can be set either to a sensorless flux vector control mode or V/Hz mode for adjusting the speed of the system, a DC VSD, Parker 550c, ensuring a controlled load to the AC motor by regulating the torque of the load generator.

A high speed data acquisition system collects the data from sensors measuring vibration, three phase currents and voltages, gearbox temperatures sends it into a PC for post processing and analysis in the Matlab environment. The dynamic data is used for both evaluating the performance of the conventional analysis methods for detecting and diagnose different oils viscosities, and also for benchmarking the developed scheme from the static data.

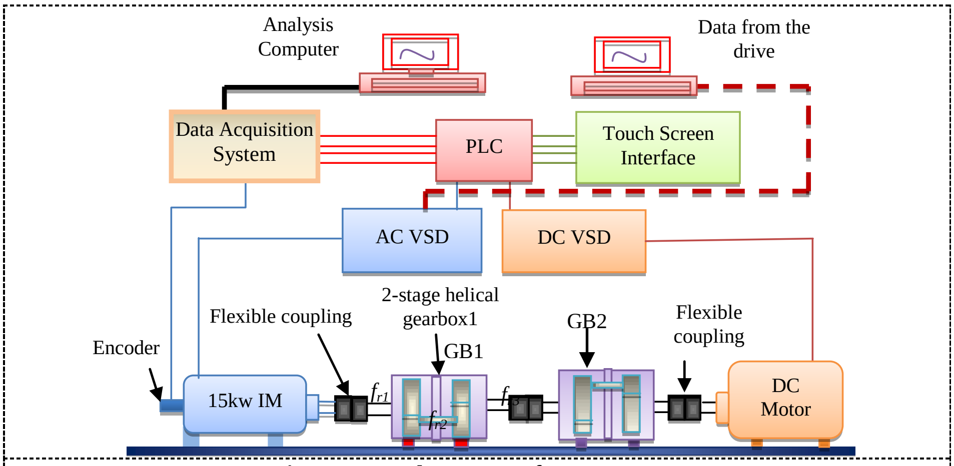

Figure 1. Schematic of test system.

Tests were carried out on the gearbox 1, denoted as GB1, which is a common industrial gearbox with a transmission ratio of 3.6 and a power rate of 10kW at 1460rpm. Four different oils having different viscosities, EP 100, EP 320, EP650 and EP 1000 respectively, have been tested. The gearbox manufacturer recommends the EP 320. The EP 650 have been made in the laboratory by mixing 61% of EP 1000 with 39% of EP 100, while other types have been provided from a supplier that recommended by the gearbox manufacturer, with specifications listed in table 1.

Table 1. Specifications of the oils used for tests.

	Specific Gravity (at 15°C)	Kinematic Viscosity (at 100°C, c.St)	Kinematic Viscosity (at 40°C, c.St)	Viscosity Index	Pour Point (°C)	Flash Point (°C)
EP 100	0.885	10.95	100	93	-9	200
EP 320	0.901	23.5	320	92	-9	200
EP 1000	0.927	71.0	1000	140	-6	200

This allows the variation of different measurements underlying to examine wide range of viscosities for defining the corresponding detection methods. The alignment of the test rig was firstly minimized by tuning installation base carefully for the lowest vibration. Oil was added and removed from GB1 without affecting the alignment condition using the drainage holes on the GB1. The rig is operated under three speed settings: 50%, 75% and 100% of the full motor speed, under four incremental load settings: 0%, 30%, 70%, and 100% of the gearbox rated load for each speed cycle, attempting for examining the detection performance under variable speed and load operations, which are common scenarios in real applications. Each load setting was for a period of two minutes and changed to the next step automatically by the PLC controller incorporated in the rig control system. In total, each load cycle lasts 8 minutes. In addition, the VSD was set under sensorless control mode for evaluating the detection capability under this particular mode.

To ensure the data quality for reliable comparison each speed/load cycles ran consecutively five times for each of oil type. During these repeating operations, the lube temperature in GB1 was observed on-line and reached to around 46°C-47°C from the room temperature when the system operating parameters also became stabilized. By using an automated acquisition procedure based on time advancement, 40 seconds of dynamic data were collected at every load setting. In the meantime, the static data from the VSD were also logged for the entire speed/load cycle. Moreover, oil samples were also taken for measuring their viscosity values under different temperatures.

4. Results and Discussion

Previous work [3] shows that the average spectral amplitudes at the supply frequency and motor speed associated sidebands can represent the influence of viscosity changes on the features of static and dynamic electrical power respectively. Yet, it was difficult to extract consistent changes based on these characteristic frequencies from voltage and current spectra separately. This is due to the fact that the VSD acts on both current and voltage simultaneously to maintain the system speed, and also because of the high noise associated with the drive actions. Therefore, the power signal from the combination of both the current and voltage was based to extract the spectral amplitudes at these characteristic frequencies.

4.1. Viscosity measurements results

The viscosity of each type of oils was measured before test. The measurement was done based on rotary viscometer test method. The results are given as an absolute dynamic viscosity in centipoise (cP), equivalent to Pa•s in SI units. As shown in figure 2 (a), differences in viscosity values are clear between tested oils and become smaller as temperature increases.

4.2. Influence of temperature

To examine the influence of temperature on the system, signals from the lubricant temperature sensors in GB1 and GB2, and speed are processed to obtain their static feature values. Figure 2 (b-d) shows these key measurements against testing run numbers under different loads. It can be seen in figure 2 (b and (c) that temperature in GB1 and GB2 increases gradually and reaches stable status by the 3rd test when the system stabilized. Noticeably, differences in temperature values between different lubricants in GB1 represent viscosity values of lubricants. In addition, the similarity of temperature trends in GB2 shows that tests were conducted with good consistency between different tests, which shows critically that the churning loss is much more significant than the frictional loss.

The temperature stabilization affects not only the losses inside the gearbox but also the circuitry performance of the electric and electronic components in the VSD based system. When it is under the lower temperature during the transient operation, the effect is stronger as the load and speed exhibit wider variation. As shown in figure 2 (d) during the low temperature operation for the 1st test run the VSD has poorer performance in maintaining the speed of the system at the set-point, which leads to higher speed under high load. On the other hand, when the system reaches its stable conditions the VSD is then able to control the speed with higher accuracy under different load settings, as shown by the speed results for the testing runs 3 to 5. However, the test 5 shows a temperature drop for the EP 1000 oil, indicating the instability either due to lubricant or ambient temperature. Based on these observations, it can be concluded that measurements from the 3rd and 4th test runs have less transient effects and more stable for examining the effect of lube viscosity more accurately.

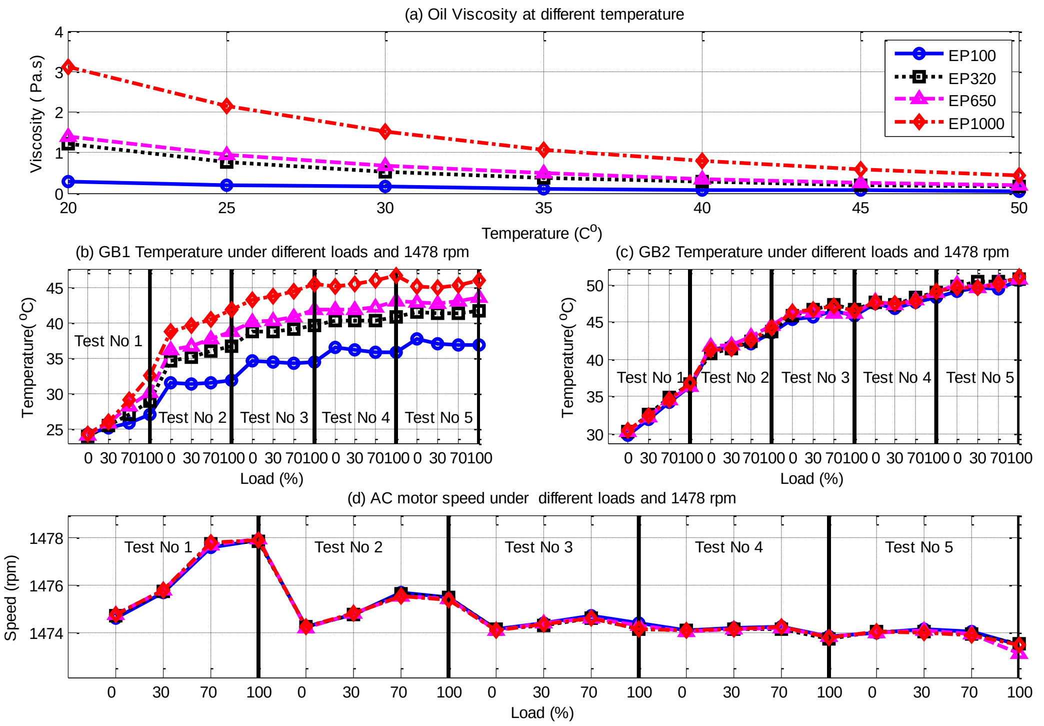

Figure 2. System behaviour under different operating conditions

4.3. Effect of oil viscosity on the power spectra

In addition to the power loss oil churning also affects the dynamics of the rotational system. When gear pairs rotate, a large quantity of oil circulates with the gear motion. The amount of oil formed increases with the speed. It means that this effect will decrease the oil level in the gearbox reservoir. Consequently, it lowers the damping effect of the rotating motion. In addition, the effective moment of inertia can also vary as the shape of the rotating oil is not perfectly uniform due to the inherent eccentricity and unbalanced mass. This generates more torsional oscillations at the shaft frequency which then modulate the supply component of power system. The power spectra have been investigated in order to investigate the effect of this phenomenon. Figure 3 displays the power spectra for the EP 100 and EP 1000 representing the highest and the lowest viscosities under different operational conditions. It shows the feature frequencies related to the tested gearbox. Particularly, the sidebands at the shaft frequency exhibit noticeable changes with viscosity, indicating the potential of using them for diagnosis. It also shows that the speed has a significant effect, where the higher speed the more mass circulates with gears and hence the more oscillations.

4.4. Viscosity change detection

To analyze the performance of power signals, both static and dynamic parameters from the power supply data have been investigated. The analysis is performed by averaging the results from the 3rd and 4th testing runs and then differences to values of the EP100 test data are made in percentages to obtain more reliable analysis. Figure 4 (a - c), depicts the changes in the static data of power in (%). It shows that at low and moderate speeds i.e. at 50 and 75% shown in figure 4(a) and (b) respectively, changes in the static power represent the differences in viscosity, displaying good performance for oil viscosity changes detection and diagnosis.

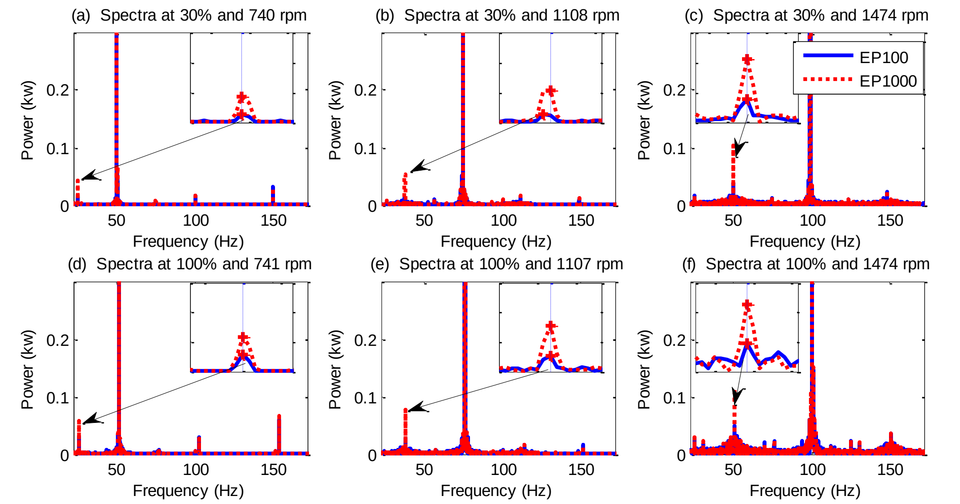

Figure 3. Power spectra under different operating conditions.

However, when the speed is high, i.e. at 100% in figure 4 (c), it shows poor performance in make difference between EP650 and EP1000 oils. This can be explained due to higher disturbances from oil churning and splashing. The drive adjusts the electrical supply parameters to maintain the system stability, and hence more noise generated preventing from separating signals at high speed. On the other hand, the dynamic feature of the sideband amplitudes in figure 4 (d-f) shows more correct performance in indicating different oils under different operating conditions, making it more suitable for monitoring the change of oil quality.

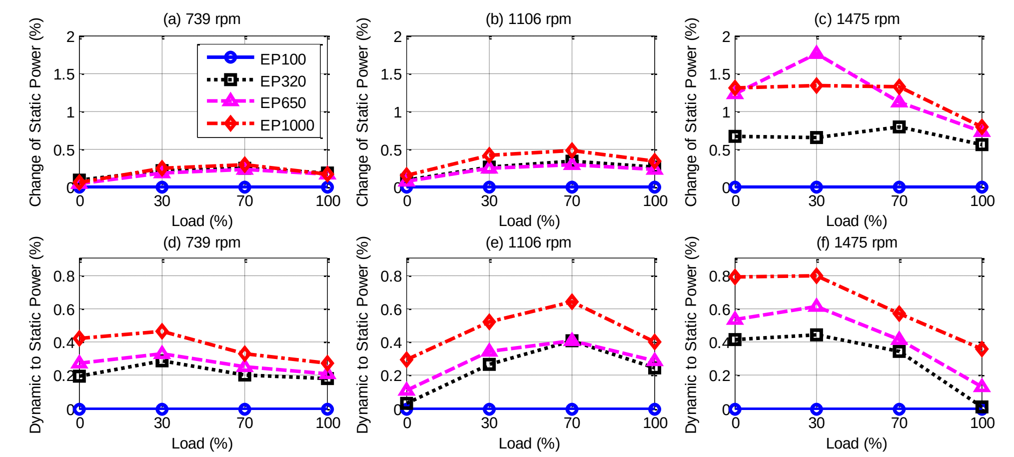

Figure 4. Changes in power signals under different operating conditions.

5. Conclusion

In this work, a new online and cost effective method is developed to diagnose lube oil degradation based on measurements of electrical parameters. The change of oil viscosity due to oil degradation will cause corresponding changes in both static power consumption and dynamic behavior of a gearbox transmission system. These changes have been verified experimentally with a 10 kW gearbox fed by a sensorless VSD. Specifically, it has found that the increase in oil viscosity lead to a measurable increase of power consumption due to the effect of viscous friction and churning.

Simultaneously, the effect also changes the dynamics of the gear transmission system as it reduces damping effect and increases the unbalance of inertia moments. Therefore, it leads to higher oscillation of rotation system, which eventually reflected by increasing the sidebands around supply frequency. Based on these two changes a static power feature and a dynamic power feature can be developed to make differences between different oils under different operating conditions. Results show that the static power feature can show viscosity changes correctly at low and moderate speeds. However the dynamic feature gives the expected diagnostic performance as it can separate viscosity changes for all different cases.

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