VIBRATION ANALYSIS OF A PERMANENT MAGNET SYNCHRONOUS MOTOR WITH A GEARBOX

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Abstract: Presented paper describes experiment carried out on a permanent magnet synchronous motor with a gearbox. Such experiment was conducted to diagnose the motor condition through acceleration measurement. In the beginning, there are described order analysis and Vold-Kalman filter method used to analyze vibration signal during constant but also variable rotational speed. Paper contains also information about the measurement extended with instrumentation based on CompactDAQ platform. Multiple test scenarios were put forward including constant motor rotational speed and torque as well as speed or torque transitions. The results showed benefits of proposed methods and also leaded to a few recommendations for following, more targeted, measurement.

Keywords: Order analysis, Vold-Kalman filter, electric motor, accelerometer

1 INTRODUCTION

The aim of this paper is to analyze vibration signal from the motor measured during the experiment and pick possible sources of vibration to help with reducing vibration level and enable higher lifespan without maintenance. The experiment will be conducted with multiple scenarios including constant and variable rotational speed and load moment.

2 THEORETICAL DESCRIPTION OF USED METHODS

2.1 ORDER ANALYSIS

Time signals are not suitable for detailed analysis therefore frequency analysis is kind of standard in this field. In case of rotating machines, measured signals are excited mainly by the motor cyclic motion, that can be usually time-varying. It is beneficial to recalculate measured signal according to the machine rotational speed. An even-time signal becomes an even-angle signal. We call such analysis as order analysis because instead of frequency, term *order* (abbrev. ord) is used.

For instance, ord 1 represents a signal with the frequency of rotational speed, ord 2 means doubled rotational speed. Signals analyzed using conventional frequency analysis would be smeared but order signals will not suffer from this phenomena [1].

2.2 VOLD-KALMAN FILTER

Vold-Kalman filter (VKF) is adaptive filter with tunable center frequency and filter bandwidth. It is used to extract sinusoidal signal of time-varying amplitude and frequency from vibration or other signals. To adjust actual center frequency, instantaneous rotational speed is needed. The second generation of the filter (VKF2) described here outputs only a signal envelope. This is usually more convenient for diagnosis purposes.

There are two equations – data and structural – regarding the VKF. Data equation sums all orders p and a noise η together to the measured signal $\mathbf{y}$ according to the equation

$$\mathbf{y} = \sum_{p=1}^{P} \mathbf{x}_p e^{j\Theta_p} + \eta \,, \tag{1}$$

where every order is modulated using cumulative phase Θ_p calculated from order frequency $\mathbf{f}_p$ and sampling period T_s

$$\Theta_p = 2\pi T_\mathrm{s} \cdot \mathrm{cumsum}(\mathbf{f}_p) \,. \tag{2}$$

Structural equation describes how the rotational motion modulates the sinusoidal signal – the order. It is difference equation of K-th order (for purposes of this article $K = 1$ is used)

$$\nabla x_n = x_n - x_{n-1} = \varepsilon_n \,, \tag{3}$$

that fits the order envelope. Term n represents index of every signal sample and ε enables that the envelope can vary slightly.

Both equations are combined together in criterion function

$$J = \varepsilon^T \varepsilon + \eta^T \eta \,, \tag{4}$$

that minimizes error terms from Eqs. (1) and (3) and leads to final matrix form of VKF2

$$\left(\mathbf{A}^T \mathbf{R}^T \mathbf{R} \mathbf{A} + \mathbf{E}\right) \mathbf{x} = \mathbf{y} \,, \tag{5}$$

where band matrix $\mathbf{A}$ contains elements from Eq. (3) at main diagonal and above, square matrix $\mathbf{R}$ contains weighting factors r at main diagonal that can adjust filter bandwidth (higher r means narrower bandwidth). Matrix $\mathbf{E}$ stands for identity matrix and powered T is conjugate transpose.

Sparse system from Eq. (5) is solved in domain of complex numbers and the envelope is a modulus of the solution. An effective tool for solving such system is Cholesky decomposition [2].

3 EXPERIMENT

The experiment is focused on a permanent magnet synchronous motor with 9 phases and 18 winding slots. Every phase uses two slots and total power rating is 55 kW. Since the motor power density is higher at higher speed, the unit contains also a gearbox (Fig. 1) consisting of input (motor) shaft, countershaft and output shaft. These two stages decrease output rotational speed by the total ratio of 9.337 by the gears 19/58 (stage 1) and 17/52 (stage 2). The motor is powered using inverter working at 10 kHz and the motor output is loaded with a dynamometer.

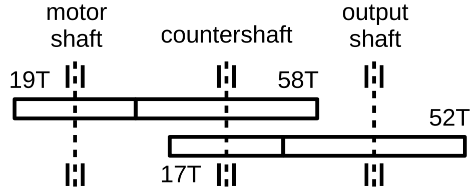

Figure 1: Kinematic scheme of the gearbox inside the motor.

3.1 Sensors Locations and Measurement System

The measurement used 5 accelerometers PCB type 352C02, 3 were mounted radially and 2 axially related to the motor shafts. Additionally, 2 shaft rotational speeds were measured, output speed with B&K 2981 tacho probe and motor speed with built-in magnetic sensor. Also, the dynamometer torque was measured through its direct output. The accelerometers were mounted to tapped holes present on the motor housing.

Measurement system was created using NI CompactDAQ chassis with set of different modules. Two NI 9234 modules were used to measure all 5 PCB accelerometers and B&K 2981 tacho probe and enabled also easier cabling since feature the current excitation for all sensors compatible with IEPE standard. Also, module NI 9215 to measure motor speed with built-in magnetic sensor was utilized. The last quantity – the dynamometer torque – was measured through its direct output using NI 9219. Sampling frequency of both NI 9234 and NI 9215 was 51.2 kHz and NI 9219 used 100 Hz. The timing of all modules was tightly synchronized.

3.2 Run Scenario

There were conducted multiple scenarios to measure enough data and have more complex point of view on the motor behavior. Measurement during steady conditions as well as during rotational speed or torque transitions was made.

1. As much as 12 combinations of constant speeds 50, 100, 150 and 200 rpm and torques 0, 100 and 250 Nm were selected, every combination was recorded for 30 seconds.
2. Number of torque changes from 50 to 250 Nm and from 250 to 50 Nm were measured during constant rotational speed 200 rpm. Torque change was about 30 Nm per second.
3. Rotational speed was changed from 10 to 200 rpm and from 200 to 10 rpm during multiple torques 0, 100 and 250 Nm. Rotational speed change was driven by the controller, which made the speed change nonlinear.

4 VIBRATION SIGNALS ANALYSIS

Standard spectrum does not provide convenient results, therefore some method of order analysis should be used. For this purposes, there must be known instantaneous rotational speed. Two rotor

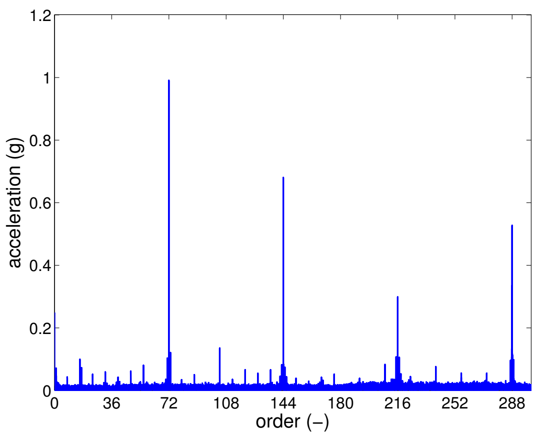

Figure 2: Order spectrum calculated from run-up with 0 Nm torque.

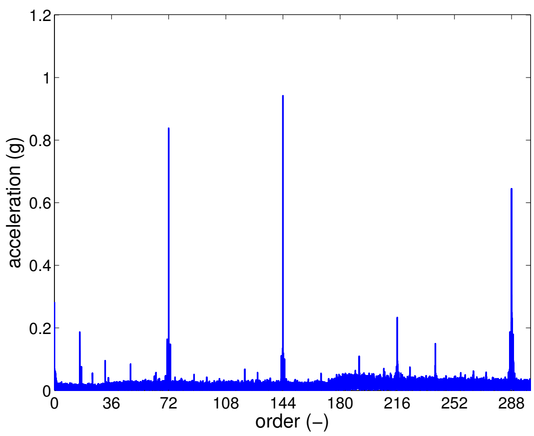

Figure 3: Order spectrum calculated from run-up with 100 Nm torque.

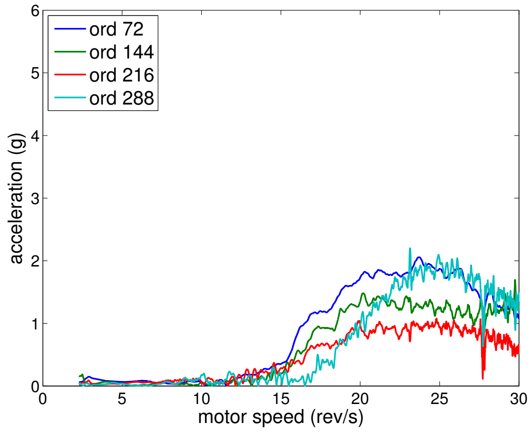

Figure 4: Signal filtered using the Vold-Kalman filter during run-up with 0 Nm torque.

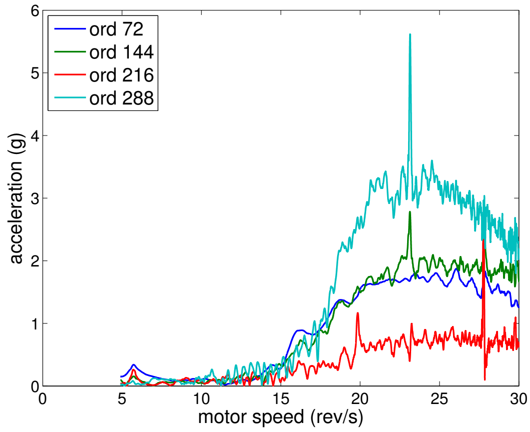

Figure 5: Signal filtered using the Vold-Kalman filter during run-up with 100 Nm torque.

speeds were available – at input (motor) and output shafts. The first one is more important, however the signal to be processed was strongly affected by disturbances mainly of impulsive origin from the inverter. Fortunately, the signal was sinusoidal with variable frequency, thus passband filtering was used with acceptable results.

Now, order analysis can be utilized. Machine condition is easier to determine during rotational speed variances since it is much easier to determine what is fixed frequency (resonance) and what is directly connected with revolution. This is reason why such signals will be used in the following analysis. Since all radially mounted accelerometers brought nearly the same signals because the motor chassis is very stiff, only a signal from one accelerometer nearby the motor shaft was selected.

Next step was to inspect an amplitude of the first or second orders related to shaft speed that could mean its unbalance. Such effect was not found. Neither orders of other shafts indicated such effect, amplitudes were negligible. Characteristic frequencies of bearings inside the motor are unknown, thus not inspected. Possible damage of gears is also disproved since none order connected with gears orders showed high amplitude. On the other hand, order 72 and its multiples show excessively high amplitudes without a load as shown in Fig. 2 as well as with a load 100 Nm at Fig. 3, respectively. Such orders are multiples of 9 (number of phases) and multiples of 18 (winding slots) and might imply excitation issues, especially, when such orders are present regardless of a load.

Another view at the signals is provided by the Vold-Kalman filter of the second generation. Totally 4 orders revealed previously were examined – 72, 144, 216 and 288. Bandwidth was selected to 0.1 % of current order frequency. Resulting envelopes are depicted in Fig. 4 (without a load) and in Fig. 5 (with a load 100 Nm). Graphs are displayed with dependency at motor rotational speed, not a time. It is clearly visible at Fig. 5 that at the rotational speed about 23 rev/s, there is a considerable peak at order 288 and slightly smaller peak at order 144. Without a load, there is no such peak. This may show the dynamometer issue.

5 CONCLUSION

The experiment conducted on the motor showed that the order analysis is efficient tool for determining machine condition during its normal working conditions, especially during a run-up that was mostly used. Order spectra depicted the main possible sources of vibration that must be additionally evaluated through motor construction and way how the motor is controlled. Especially orders that are integer multiples of motor phases and motor pole pairs showed excessively high amplitude compared to the other ones. Vold-Kalman filter enabled to show also an envelope that signalized a peak during a run-up at constant rotational speed when the motor was loaded with the dynamometer. Thus, further analysis will be focused on winding currents that will be additionally measured and on relation between the motor and the dynamometer that can induce some unwanted signals to the motor through the shaft. Achieved results from this analysis will be used to modify control algorithm such that the motor will exhibit lower vibrations.

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REFERENCES

[1] GADE, Svend, Henrik HERLUFSEN, Hans KONSTANTIN-HENSEN a Niels Johan WISMER. BRUEL & KJAER. Order tracking analysis. *Technical review* [online]. Nærum, Dánsko, 1995, **1995**(2) [cit. 2015-10-26]. ISSN 0007-2621.

[2] TŮMA, Jiří. *Vehicle gearbox noise and vibration: measurement, signal analysis, signal processing and noise reduction measures*. Chichester, England: Wiley, 2014, 261 p. Automotive series (Wiley). ISBN 978-1-118-79761-7.