




Investigation of Various Condition Monitoring Techniques Based on a Damaged Wind Turbine Gearbox

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INVESTIGATION OF VARIOUS CONDITION MONITORING TECHNIQUES BASED ON A DAMAGED WIND TURBINE GEARBOX

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ABSTRACT

The National Renewable Energy Laboratory presented an investigation of various wind turbine drivetrain condition monitoring (CM) techniques at the 7th International Workshop on Structural Health Monitoring held in 2009. The study contained in this report is a continuation of the 2009 paper and focuses on results obtained by various CM techniques from a damaged Gearbox Reliability Collaborative test gearbox. The purpose of the study is to demonstrate the capabilities and limitations of each technique. In order to provide the audience a relatively complete picture, a brief discussion of CM system implementation is provided first. The dynamometer test setup, along with some failure information on the damaged gearbox obtained during its disassembly, is presented next, followed by the CM results obtained during the retest of the damaged gearbox. For comparison and discussion purposes, earlier results obtained from a test gearbox under healthy condition will also be included. Finally, the paper will conclude with some observations obtained during the tests.

BACKGROUND

Wind energy is presently the fastest growing renewable energy source in the world. However, the industry still experiences premature turbine component failures, which lead to increases in the cost of energy. With the installation of offshore turbines and the increase in turbine size, these failures become extremely costly. As a result, there is a need for the industry to increase turbine reliability and reduce downtime. Among the various subsystems comprising a utility-scale wind turbine, the gearbox has been shown to cause the longest downtime and is the most costly to maintain throughout a turbine's 20-year design life [1].

To understand the causes of premature failures in wind turbine gearboxes and propose possible improvements to the wind industry, the National Renewable Energy Laboratory (NREL) has initiated a consortium called the Gearbox Reliability Collaborative (GRC). The GRC brings together different parties involved in the gearbox design, manufacture, and maintenance with the common goal of improving the reliability and extending the lifetime of wind turbine gearboxes.

Condition Monitoring (CM) is one research area under the GRC. It can help the industry achieve the goal of improved turbine uptime by enabling better operation and maintenance practices. In a broad sense, CM of a utility-scale wind turbine can target almost all of its major subsystems, including blades, nacelle, drivetrain, tower, and foundation. The CM discussed in this paper is narrower, however, and focuses on the monitoring of the wind turbine drivetrain, i.e. the main bearing, gearbox, and generator for a geared turbine.

Various tests have been conducted under the GRC. During the field test of one GRC gearbox, it experienced two unexpected oil losses that led to damage to its internal components. The damaged gearbox provided a unique opportunity to evaluate different CM technologies by retesting of this gearbox in the NREL 2.5 MW dynamometer. Various CM techniques were applied during the retest; their results are the focus of this paper.

This study is a continuation of the paper, "Investigation of Various Wind Turbine Drivetrain Condition Monitoring Techniques" [2], presented at the 7th International Workshop on Structural Health Monitoring (IWSHM) held in 2009. The main objective of the study discussed in this paper is to demonstrate the capabilities and limitations of each CM technique. First, a brief discussion of CM system implementation is provided. Then the dynamometer test setup and some failure information on the damaged gearbox obtained during its disassembly is presented. Next, the CM results obtained during the retest of the damaged gearbox are described. For comparison and discussion purposes, earlier results obtained from a test gearbox under healthy conditions are included. The paper concludes with observations obtained during the GRC tests.

CONDITION MONITORING SYSTEM IMPLEMENTATION

The CM system was mainly implemented using an integrated approach by working with several commercial equipment suppliers. It took an integrated approach because no single technique can provide the comprehensive and reliable solutions needed by the industry. Four CM techniques were initially applied: Acoustic Emission (AE) (specifically, stress wave); vibration; offline (or kidney loop) real-time lubricant CM; and offline oil sample analysis. As the GRC tests progressed, inline (or main loop) real-time lubricant CM and electric signature-based techniques were added.

Figure 1 illustrates the CM system setup, excluding the offline oil sample analysis, for the retest of the damaged gearbox in the NREL 2.5-MW dynamometer test facility. This setup is designed so that whenever a wind turbine drivetrain component starts to fail, one or several of these monitoring technologies will detect the change and provide reliable diagnostics. The stress wave represents the AE-based technique, which covers the frequency range above 20 kilohertz (kHz). Inline particle counts are the number of ferrous particles seen in the main lubrication loop with a size greater than 350 micrometers (μm). The offline oil condition sensor measures total ferrous debris in parts per million (ppm); relative humidity as a percentage; and oil quality (changing with the level of such contaminants such as soot, oxidation products, glycol, water, etc.) in customized scale [2]. The offline International Organization for Standardization (ISO) cleanliness level indicates the amount of particles seen in 1 milliliter (mL) of monitored lubricant that can be classified into three size bins: ≥4 µm, ≥6 µm, and ≥14 µm [3]. Offline particle counts reflect the amount of particles detected in the kidney loop, and the total counts can be divided into five size bins for both ferrous and non-ferrous particles. Vibration uses accelerometers that target frequency ranges from close to direct current (DC) up to 10 kHz. Electric signature measures three-phase electric currents and voltages fed by the test turbine generator to the grid.

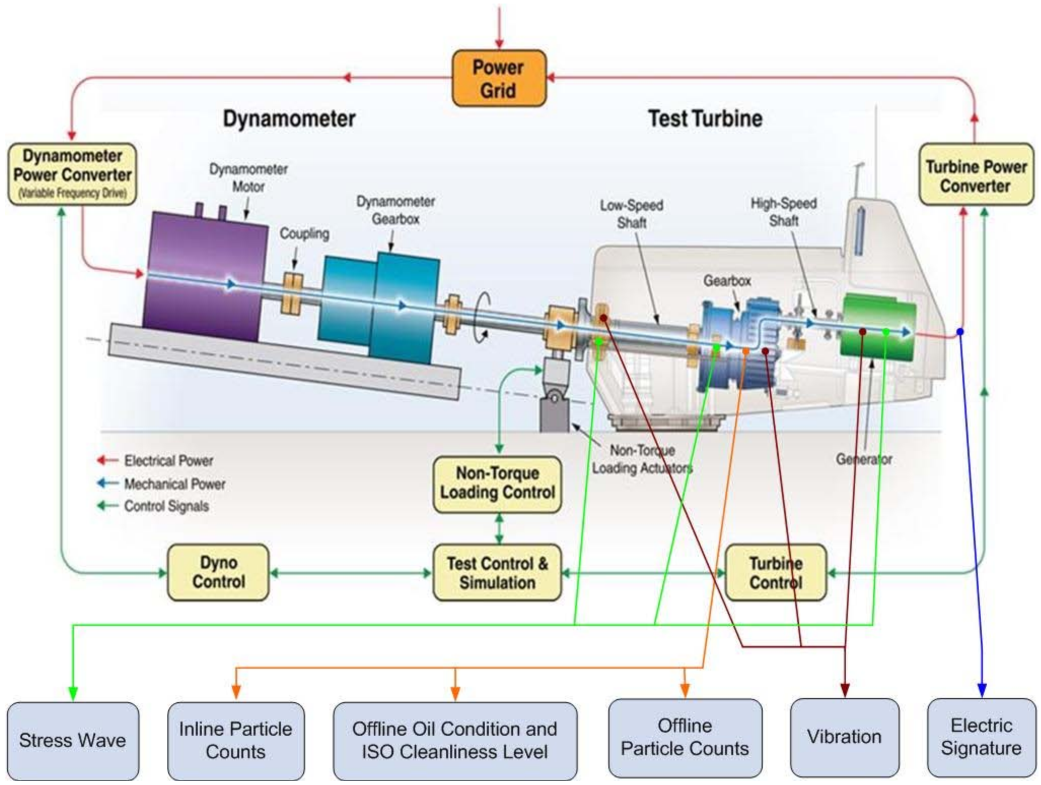


Figure 1. The GRC CM system implementation.

TEST SETUP

Different GRC dynamometer tests have a similar setup with only minor variations. Figure 2 shows one dynamometer test configuration with the test turbine installed. Figure 3 illustrates the test gearbox internal configuration.

Figure 4 shows one type of damage that occurred to the test gearbox. The damaged component is the high-speed stage gear located on the Intermediate-Speed Shaft (ISS). The gear suffered from severe scuffing. The main root cause of this damage is lubricant starvation and overheating contacting gear teeth surfaces. The high-speed stage pinion has 22 teeth, and the gear has 88 teeth. At 1800 revolutions per minute (rpm), this gear set has a meshing frequency of 660 Hz. The detection of this damage will be used in the following section to illustrate the results obtained by various CM techniques.

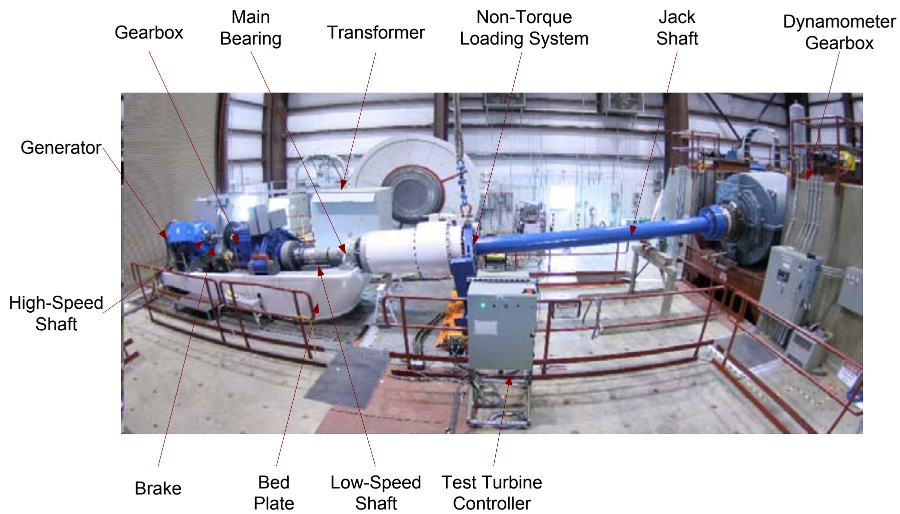


Figure 2. Dynamometer setup with a test turbine installed. (NREL/PIX16913)

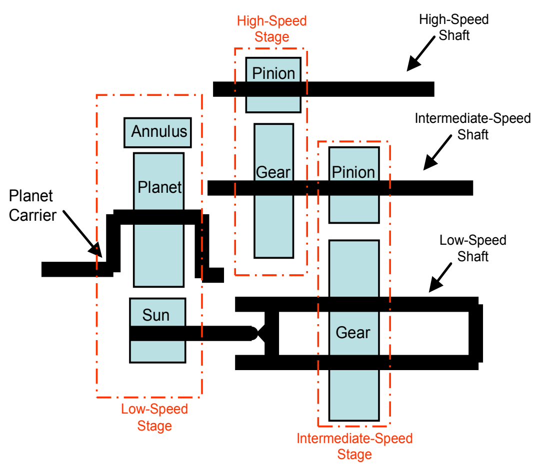


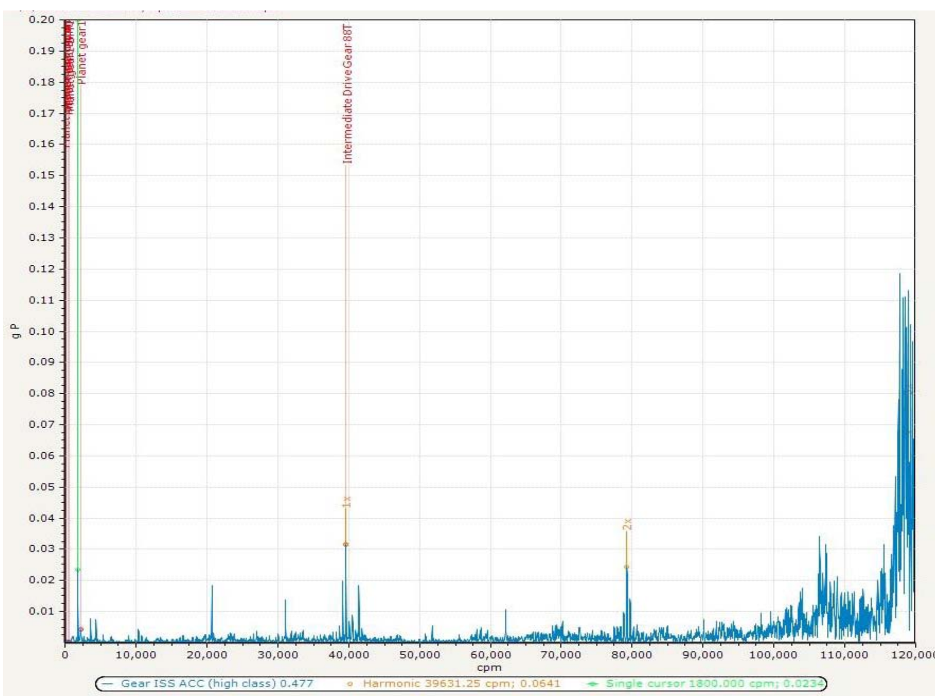
Figure 3. Internal configuration of the test gearbox. Figure 4. Damage to high-speed stage gear.

RESULTS FROM VARIOUS CM TECHNIQUES

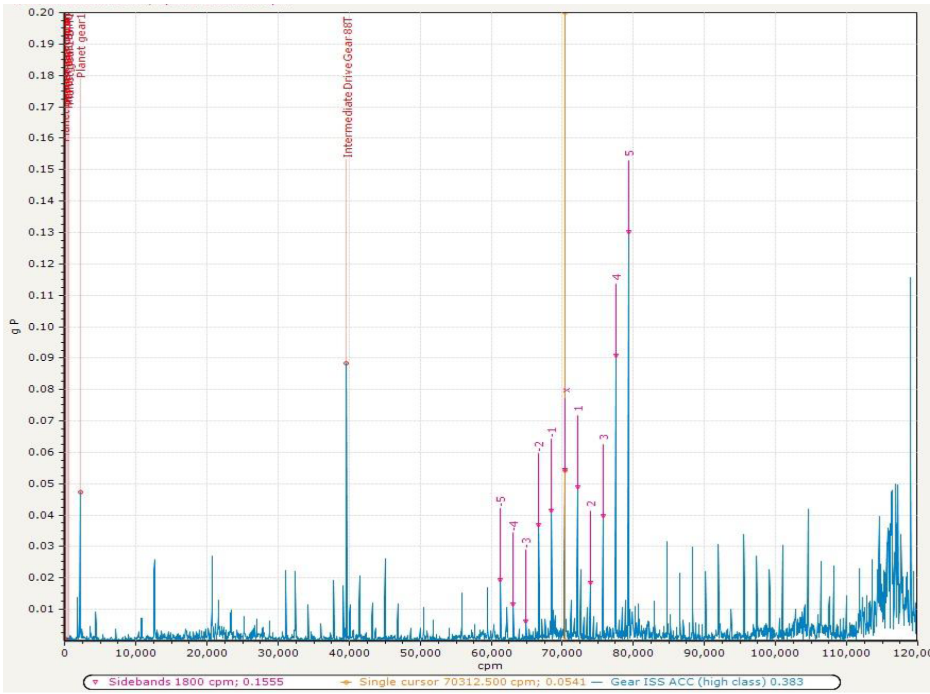
The GRC project is a work in progress. Various tests have been conducted over several years. This section of the paper presents some results obtained during the retest of the damaged gearbox in the NREL dynamometer. Selected earlier results obtained from a healthy gearbox are also presented for comparison and discussion.

The first set of results (Figure 5 [4]) was obtained by the vibration-based CM technique. They are spectra of vibration data collected by one accelerometer mounted to the ISS on the back cover of the test gearbox. Figure 5 (a) shows measurements from the healthy gearbox, and Figure 5 (b) shows data collected from the damaged gearbox. For both figures, the horizontal axis shows frequency in counts per minute (60 cpm = 1 Hz) and the vertical axis shows acceleration with a *g* (1 *g*=9.8 *m/s^2*). The fundamental high-speed stage gear meshing frequency (GMF) of 39,600 cpm or 660 Hz, and its 2nd harmonic are labeled in the figures. By comparing Figure 5 (b) to 5 (a), it is clear that the damaged gearbox has more frequency components and an elevated amplitude for GMF sidebands. For illustration purpose, the ten sideband frequencies (five below and five above) the 2nd harmonic of the high-speed stage GMF are labeled in Figure 5 (b). Such a spectrum pattern as illustrated in Figure 5 (b) typically represents abnormal gear set behaviors. Since the sideband frequencies are clearly around 39,600 cpm, it is easy to tell that the problematic gear set is on the high-speed stage. In addition, the amplitude of the fundamental high-speed stage GMF has increased from 0.0325 g for the healthy gearbox to 0.0875 g for the damaged gearbox. Such an increase in GMF amplitude is another indication of abnormal gear set behavior. Even without a detailed calculation, it is obvious that the energy contained in the frequency spikes from the damaged gearbox is much higher than that from the healthy gearbox. This is a result of both increased amplitude of those frequencies already contained by the healthy gearbox and the addition of energy caused by new frequency components in the damaged gearbox. Based on these findings, it is reasonable to conclude that the vibration-based monitoring technique can successfully diagnose such gear set damage.

The second set of results (Figure 6) was obtained by the AE (specifically, stress wave)-based CM technique. The stress wave sensor was mounted axially in the middle of all three shaft ends on the back of the test gearbox. The sensor output is conditioned to generate a stress wave pulse train, which represents a time history of individual shock and friction events that have occurred in the monitored machine [5]. By first finding the peak amplitude of each of the pulses in the stress wave pulse train, and then distributing these peaks into voltage bins that correspond to the value of each reading, the resultant diagram—called a Stress Wave Amplitude Histogram [5]—as shown in Figure 6, is generated. In healthy machines, the distribution should be a narrow bell shape and located at the lower end of the voltage scale, as illustrated by Figure 6 (a). In abnormal machines, the distribution



(a) Healthy gearbox

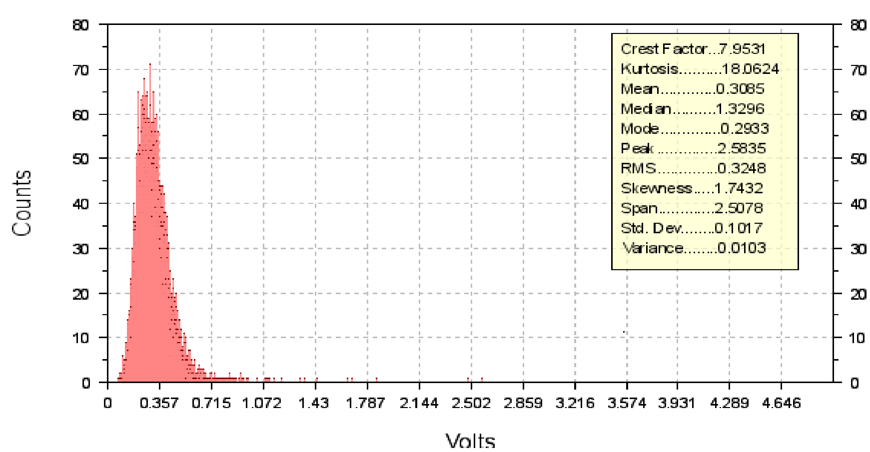


(b) Damaged gearbox

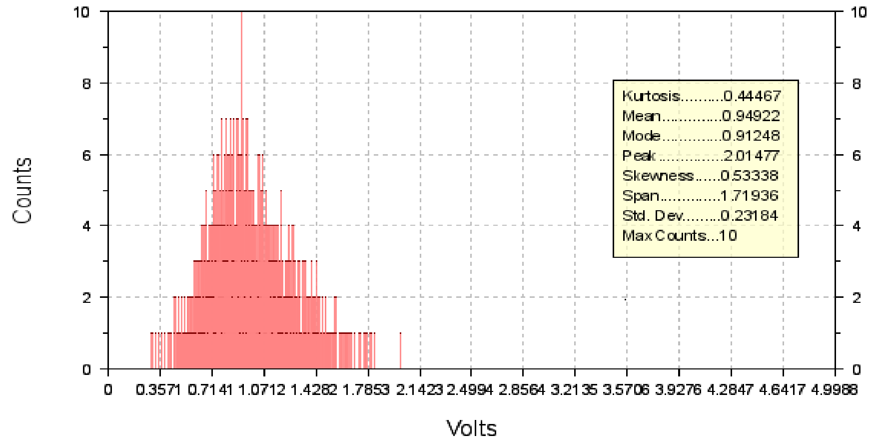
Figure 5. Readings from vibration-based CM technique.

should be much broader and shifted to the right on the amplitude scale, as illustrated by Figure 6 (b). Figure 6 (a) implies that the monitored gear sets were healthy and Figure 6 (b) implies that the monitored gear sets were problematic. In order to identify whether the damaged gear set is on the high-speed or the intermediate-speed stage, it is necessary to get some frequency domain information. Because such results are expected to be similar to those obtained from the vibration-based technique, they are not presented.

The third set of results (Figure 7) was obtained from the oil-based CM technique; specifically, these results were obtained from the inline oil particle counting sensor. The counts represent the number of ferrous particles with a size greater than 350 μm and detected by the sensor over a certain period of time. As shown in Figure 7, the particle generation rate reached about 70 particles per hour



(a) Healthy gearbox



(b) Damaged gearbox

Figure 6. Readings from AE-based CM technique.

on 9/16, when the damaged gearbox was tested. Comparatively, about 11 particles were generated over a period of 4 hours from a healthy gearbox [6]. It is therefore reasonable to conclude based on the oil particle counting results that the retested gearbox has high particle-generation rates. Some damage has occurred to its internal components, and further investigation is recommended. However, due to the lack of frequency information provided by either the vibration or AE-based technique, it is difficult for real-time oil CM to determine where the wear was generated.

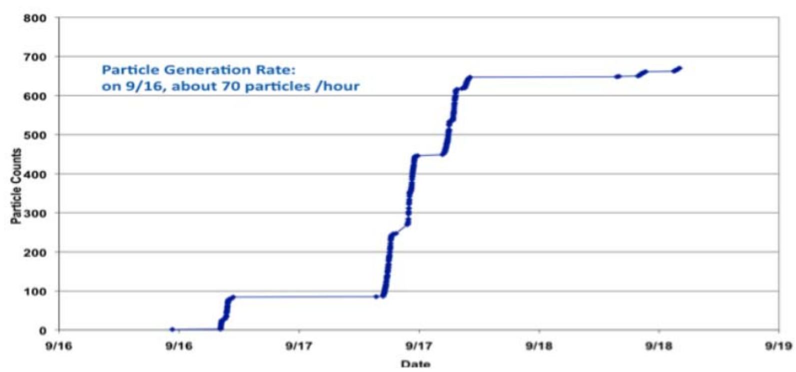


Figure 7. Readings from oil-based CM technique.

Additional investigation within the realm of oil CM tecniques was conducted by sending both oil samples taken during the disassembly of the damaged test gearbox and filter cloth used to drain its oil to a dedicated oil analysis laboratory. One test of the filter cloth conducted using a scanning electron microscope (SEM) analysis indicated that the major particulate constituents were steel, iron oxide, brass, and zinc. These elements most likely came from gears or bearings [7].

If the oil analysis results are considered as the fourth set of reported results, the fifth set of results should be from the electric signature-based technique. However, preliminary analysis of the electric currents and voltages collected during the retest of the damaged gearbox did not show any indication of gearbox damage. One possible reason is that the damage on the test gearbox is not severe enough for the electric signature-based technique to detect. Therefore, no detailed results are reported here.

CONCLUSIONS AND FUTURE WORK

This paper reports results obtained using various CM techniques based on the test of a damaged wind turbine gearbox. It is clear that each technique has its strengths and limitations. The results presented here demonstrate that vibration and AE-based techniques can diagnose the test gearbox to have abnormal behavior and pinpoint the damage location using some analysis in the frequency domain. However, they cannot provide information on lubricant condition and identify possible root causes for such damage. The real-time oil CM technique, on the other hand, showed increased particle generation rates when the gearbox with damaged components was tested. Therefore, it can be used to identify possible damage to gearbox components. The offline oil sample analysis could be used to identify possible sources of wear particles and support root causes analysis. However, the oil-based CM technique cannot tell the stage of the test gearbox at which the damage occurred. Based on the damage level experienced by the test gearbox, the electric signature-based technique appeared less effective than the vibration, AE, or oil-based monitoring techniques for gearbox damage diagnostics. These results demonstrate the necessity to integrate various techniques when conducting wind turbine drivetrain CM. Further research will be conducted on data fusion trying to increase CM diagnostics reliability and its cost effectiveness.

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