1. Introduction

Due to the global warming effects, depletion of fossil fuels and other ecological and financial reasons various car manufacturers returned to produce cars with hybrid and hybrid electric power trains\cite{1,2,11}.

Certainly reliable electric drive for vehicles requires reliable electric motors. There are various motor types applied here, in this study however, switched reluctance motor (SRM) is analysed. One of its strongest advantages is resistance to damages and independence to rare earth magnets that can be expensive or its availability might be in danger\cite{3,4}.

Although the motor is somewhat resistant to damages, still, as another types of electric machinery, it can undergo various types of electrical and mechanical faults. The crux of this research is to determine the characteristic signals of SRM mechanical faults that are most typical in its lifetime.

1.1. Purpose of the study

The mechanical faults that can occur in SRM most commonly can be divided as following: misalignment, imbalance, looseness, bent shaft, cocked bearing on a shaft and bearing defects\cite{7,8}.

Each of the machine fault has different characteristic in the signal, thus the aim of the research is to determine the specific fault. Having this knowledge can be crucial for anticipating the damage and subsequently reducing its potential in the downtime of the machinery\cite{8}.

There are numerous solutions for motor diagnostics. In this study the current signal will be observed with comparison of the vibration signal from accelerometer. The other existing possibilities for the scrutiny as the voltage or heating application will be omitted in this study.

The similar experiments were performed on the BLDC motor by P. Szulim et al.\cite{12}\cite{13}. The motor underwent mechanical faults (eccentricity, imbalance) and the authors described their conclusion. The measurement method was similar to the one described in this study, by means of the current and acceleration sensors.

2. SRM mechanical faults

As it was mentioned before the faults that can exist in electric motor generally can be divided into mechanical and electrical ones. The scope of the work are mechanical faults in switched reluctance motor which are: eccentricity/misalignment (dynamic) of the air gap and rotor (or load) imbalance. These are the damages that occur in any type of electric motor and can be found commonly in everyday life of the machines. Each type of electric motor fault cause detrimental symptoms that can be observed as higher...
vibration and thus noise, stronger torque pulsations, higher losses, unbalanced currents and voltages within the machine circuit [9, 10].

2.1. Eccentricity (misalignment)

Eccentricity is a very common mechanical fault that occurs often in all of the types of electrical machines. Basically it causes the non-uniform air-gap between rotor and stator. This phenomenon can be identified in the current spectrum as fault harmonics caused by varying inductances making unbalanced magnetic flux in the air-gap. Should this problem be severe the stator can touch the rotor causing the damage of both of them. There are two types of eccentricity: the static and dynamic (Fig. 1 and 2)

![Fig. 1. Static eccentricity](image1.png)

![Fig. 2. Dynamic eccentricity](image2.png)

In the static eccentricity the centerline of the shaft is at constant offset from the center of the stator, thus non-uniform air-gap is also constant. In the dynamic eccentricity the offset between the shaft’s centerline and stator varies in time changing the air-gap length in time. Because of irregularity of the air-gap, magnetic flux changes values there and it results in the unbalanced currents which can be found in the current spectrum. In reality, both static and dynamic eccentricity occur simultaneously. The causes of eccentricity can be numerous as the faults of rotor construction (noncircularity, imbalance), missing or damaged elements in its construction (e.g. bolts), bad mounting or bearing damage.

The eccentricity can be easily detected in the line current spectrum because of its much higher amplitudes in comparison to the signal noise.

2.2. Imbalance

Imbalance is a very common fault. It causes almost half of the machine problems directly or indirectly. When the mass centerline and geometric centerline do not coincide then imbalance takes place. The static, dynamic and coupled imbalance can be distinguished but in real life only coupled imbalance exists with the majority of either static or dynamic imbalance.
The reason of the formation of this kind of failure is similar to the other types of faults, mostly by manufacture defects, debris on the parts of machinery or additional unbalanced shaft fittings.

Because the imbalance produces dynamic loads, the bearing experiences fatigue from excessive stresses.

3. Test bench

The test bench consists of special elements that can cause mechanical faults: the misalignment, imbalance. It should enable researcher to examine the motor in its full range of operation, so it is important to have the load for the motor with freely regulated load torque. The load should have as low torque fluctuation without producing undesirable noises during measurements. With this motor it is possible to have specific motoring torque and to test the examined motor in generating mode. The tested motor is the switched reluctance motor manufactured by Huayang Electric especially for the purpose of this research. It has low nominal power (550W) and small size, thus it can be used as a drive in minor electric vehicles. Between the load motor and the tested SRM (the tested motor can be interchangeable) there is torque meter inserted between two clutches. Electronic systems were also designed for the manual control to operate these 2 motors (Fig. 3).

Proper systems also enable the conditioning of measurement signals and adjusting them to acceptable levels for measuring hardware. The control system for DC motor was designed as a current source with regulated efficiency. Both systems allow either the manual control of test bench or automatic by means of proper analogue signals what makes measurement automation possible. For the purpose of acquisition and data analysis a dedicated software in LabVIEW environment was written.

4. Results

The mechanical faults performed on the test bench were dynamic eccentricity and rotor imbalance. The first phenomenon delivered more complex results thus it is described more thoroughly.

4.1. Eccentricity

It was possible to test 0.25 mm of misalignment with different loads and speeds.
Fig. 4. Comparison between the current frequency from healthy motor and with misalignment (with 1 Nm load and 1000 rpm).

In Fig. 4 the results from the experiment with 1 Nm load and 1000 rpm are shown. It is clear that the highest frequency peak is at 100 Hz. The rotational frequency was 400 rpm, thus 16.67 Hz and rotor has six salient poles. Therefore, $16.67 \times 6 = 100$ Hz. Apart from this the 3th (300Hz) and 5th (500Hz) harmonics are also noticeable.

The exact experiment is shown in Fig. 5 as vibration in X-axis. Certainly the vibration detector attracts incomparably much more noise. Clearly it is little difference between two measurements, therefore the majority of the noise is produced on the test bench per se.

4.2. Rotor imbalance

The second and ultimate mechanical fault was rotor imbalance.
Fig. 5. Comparison between the vibration frequency from healthy motor and with misalignment (with 1 Nm load and 1000 rpm).

Fig. 6. Comparison between the current frequency from healthy motor and with rotor imbalance (with 2 Nm load and 2000 rpm).
The experiments of imbalance did not signal any differences whatsoever. Due to the phenomenon itself and properties of the test bench the imbalance could not manifest itself (Fig. 6).

![Graph showing vibration frequency comparison](image)

**Fig. 7.** Comparison between the vibration frequency from healthy motor and with rotor imbalance (with 2 Nm load and 2000 rpm).

In Fig. 7 we can observe the same experiment as above but as vibration. This shows much more additional frequency in the signal due to test bench imperfections. The signals with and without faults are almost identical.

5. **Summary**

Switched Reluctance Motor is the electric motor with numerous advantages. Although it is resistant to damages still it can be prone to typical mechanical faults as another types of motors. The crucial point is to determine how the motor behaves during different types of faults. Having that information one can detect and anticipate possible mechanical damage and high costs of motor replacement.

The experiments on the test bench of 2 motor faults presented clear effects of two different mechanical faults, even having in consideration the drawbacks of test bench. Dynamic eccentricity manifests itself in numerous harmonics in lower frequency, the imbalance, however, is almost imperceptible.

This research can be expanded to a multitude of options. One can add another mechanical faults as static eccentricity, bearing damage and others. It is advisable to compare the results from SRM with another electric motors. Should the SRM be applied in electric vehicles more commonly, e.g. when electric vehicles will be more popular, it
would be easier to determine what are the advantages and drawbacks of the durability of this motor as a drive from the higher number of test pieces.

References:

Abstract
In this paper author describes mechanical faults in SRM (eccentricity and rotor imbalance) that were performed on the test bench as experiments. SRM is a brushless motor with electronic commutation made from iron. This motor possess some qualities by which can be applied at location where the reliability is highly important. Signals described in this study are measured from accelerometers (from three different axes) and from the current clamp. The results are shown as spectra. The aim of this research is to register the damage, its identification in the spectrum and finding characteristic
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Streszczenie
W tej pracy autor opisuje mechaniczne uszkodzenia w SRMie (ekscentryczność i niewyważenie wirnika), które zostały wykonane na stanowisku pomiarowym jako eksperymenty. SRM to silnik bezszczotkowy z elektroniczną komutacją, wykonany z żelaza. Silnik ten posiada właściwości dzięki którym może być stosowany w miejscach, gdzie niezawodność jest niezmiernie ważna. Sygnały opisywane w pracy pobrane są z acelerometrów (z trzech różnych osi) i czujnika prądowego. Wyniki tych badań pokazane są w formie widm. Celem badań jest zarejestrowanie uszkodzenia, jego identyfikacja na wykresie widma i znalezienie charakterystycznych różnic pomiędzy przebiegiem z uszkodzeniem (niewyważenie i ekscentryczność) i bez niego. Porównane są wyniki poszczególnych badań jako drgania oraz przebieg prądu.

Słowa kluczowe: SRM, silnik reluktancyjny, diagnostyka

differences between graph with fault (imbalance and eccentricity) and without it. The results are compared as vibrations and current.

Keywords: SRM, switched reluctance motor, diagnostics