End-quality assessment of electrical motors based on the concept of virtual sensors

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Abstract: The virtual sensor is a concept that refers to "measuring" physical quantities that cannot be directly accessed by physical sensors. This is done in an indirect way by making use of other sensory outputs and signal processing. In this paper we adopt this concept for the problem of finding flaws in electrical motors in a non-invasive manner. A prototype aimed at quality assessment is presented and is shown to be able to measure the overall motor quality, as well as details about the quality of each assembly part. This is done solely based on information drawn from vibration and electrical signals.

Keywords: virtual sensor, signal processing, fault diagnosis, quality assessment, electrical motors

1 Introduction

Reliable end–quality assessment is (almost) the last step in the manufacturing process, which has to ensure that the end–products conform to the required quality standards. In this paper we focus on the problem of end–quality assessment of electronically commutated (EC) motors. The main goal is the development of a fast and accurate fault detection system, which is capable of assessing the overall quality grade of the product.

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In our approach we implement the proposed fault detection system using the concept of virtual sensor. Virtual sensor usually stands for a piece of application software that performs processing of data sets collected from available physical sensors[1]. The underlying software is based on prior knowledge about the observed system.

2 The concept of virtual sensors for condition assessment

In the context of quality control of industrial products, we need a system composed of HW and SW modules that are able to produce reliable estimates of the system condition from readings collected from physical sensors. In the application shown below, only vibrational, current and voltage sensors are applied. Prior to digital signal processing the physical sensor output should pass through the signal conditioning stage. The key modules of the virtual sensor for assessing system condition are depicted in *Figure 2*.

The first module refers to as *feature extraction*, which essentially transforms the set of n measured signals $X \in R^n$ into a new set of m signals called *features* $\varphi \in R^m$. Ideally, features should depend exclusively on system condition and should be independent of the system operating

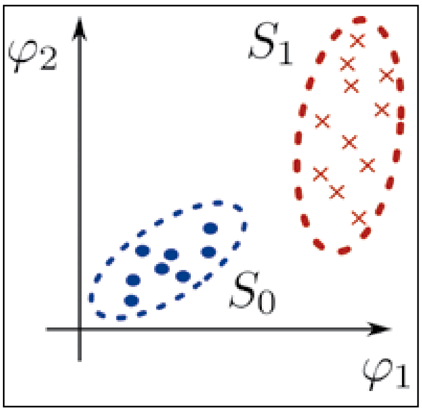


Figure 1. *Hypothetical feature distribution*

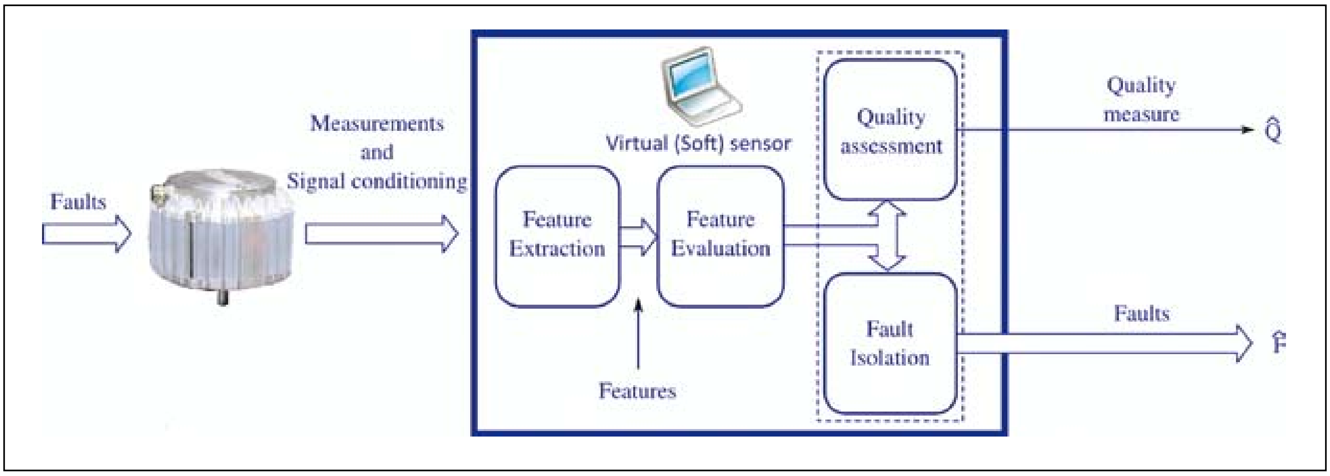


Figure 2. *The concept of virtual sensor for condition assessment of EC motors*

conditions [6]. Typically, in the case of no fault, features take values from a restricted set of values $S_o \in R^m$ which are often close to zero. In the presence of a fault, values of the feature depart away from the set S_o. This effect is shown in *Figure 1*.

The role of feature evaluation stage is to decide whether all the components of φ are within S_o. If not, the presence of fault is detected. All we know at that stage is that there is a fault somewhere in the system, but yet not exactly where.

The role of fault isolation is to reveal possible fault origin on the basis of information drawn from the feature values. More precisely, the final output is a ranked list of tentative faults origins with associated probabilities.

In this paper we expand the classical concept of virtual sensors for condition monitoring – by adding an additional module that performs overall quality assessment *(Figure 2)*. This quality assessment is also based directly on the evaluated feature values.

3 Practical problem

The described concept was employed to an end-quality assessment system in Domel dd. Domel is world recognized manufacturer of electrical motors. Part of their production is devoted to electronically commutated motors for HVAC applications. One of the main concerns in the production process is assessment of the motor condition as soon as the assembly process is over in a timely and reliable manner.

Figure 3 shows the test rig composed of a fixed pedestal on top of which a metal disk is positioned. The metal disk holds three rubber dampers that suspend the tested EC motor. The assessment session starts by positioning the EC motor vertically on the rubber dampers in such a way that the drive-end bearing is on the bottom. Afterwards, two accelerometers are positioned on the motor housing nearest to the both bearings.

Besides vibrations, the motor current and supply voltage are measured throughout the assessment session. The test bed is constructed in a way, which minimises the environmental disturbance, hence guaranteeing repetitive experimental conditions.

4 Feature extraction

The effectiveness of the complete process of end-quality assessment relies on proper selection of the extracted features. Therefore, the feature extraction process was specifically tailored for a set of likely faults in an EC motor.

The structure of the feature extraction module for the EC motors is shown in *Figure 4*. Features are determined as values of specifically selected spectral components. The calculation of

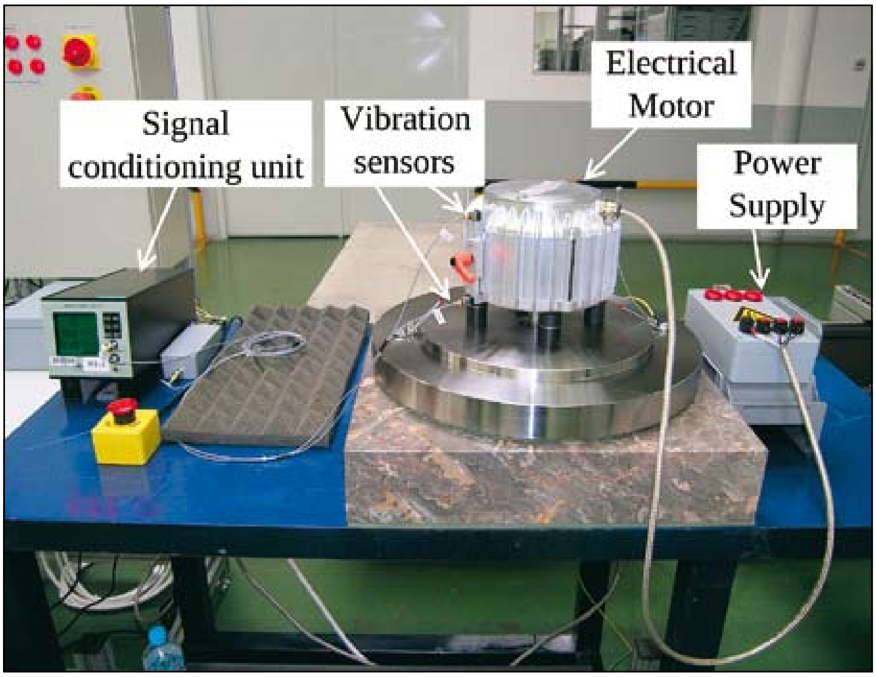


Figure 3. *The quality assessment test bed*

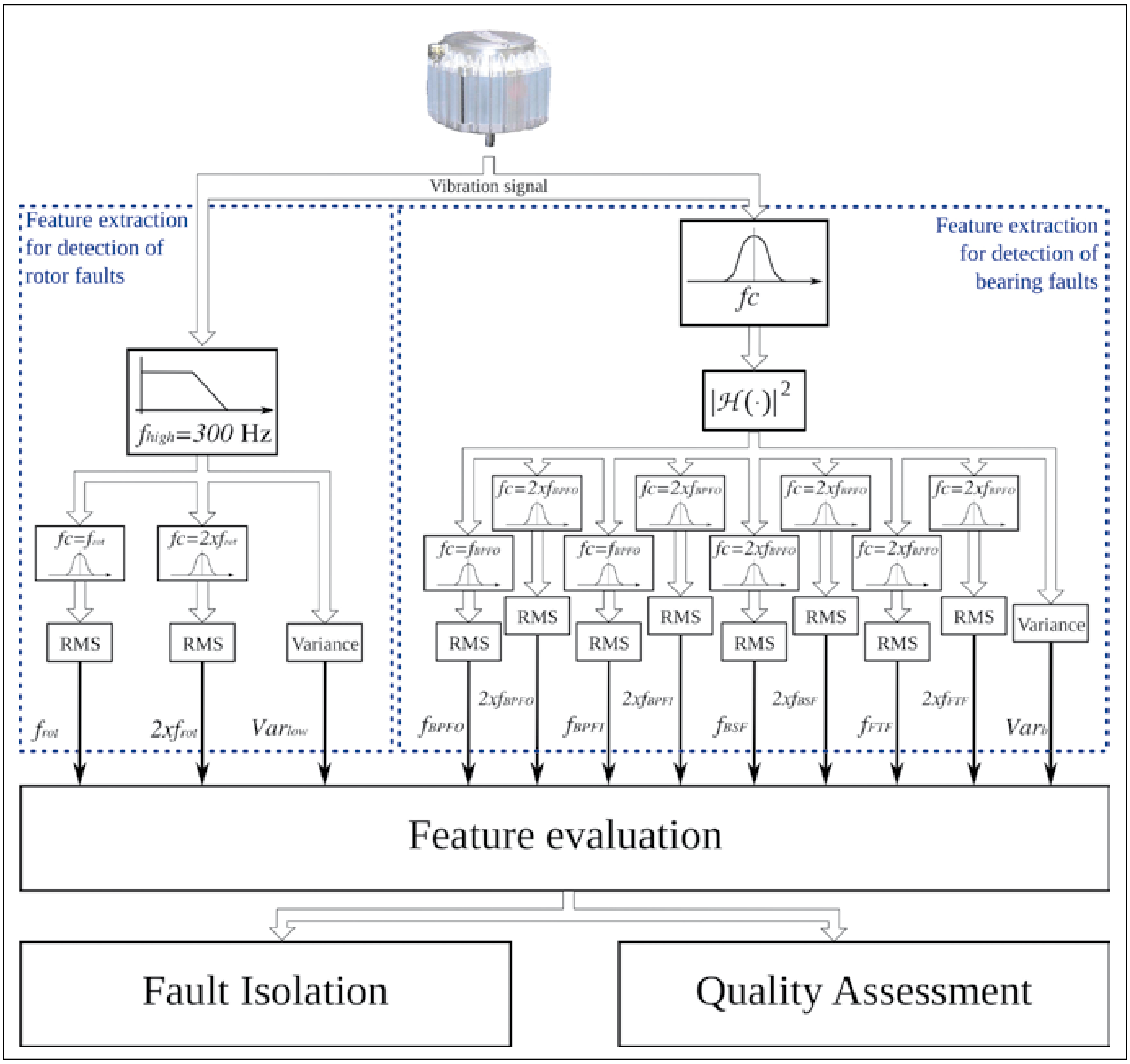


Figure 3. *The quality assessment test bed*

these feature values follows specific signal processing procedures capable of analysing the particular vibrational patterns produced by the most frequent mechanical faults.

4.1 Rotor faults

The rotor faults studied in this work include:

- mass unbalance, and
- misalignment faults caused by improper assembly.

The presence of either of the faults influences the moments of inertia on the rotor. Under constant rotational speed, such a change reflects into increased amplitudes of the spectral components at the rotational frequency f_{rot} and its higher harmonics $n \times f_{rot}, n \in \{2,3,\ldots\}$. Therefore, the original vibration signals are first low-pass filtered and afterwards the amplitudes of the specific spectral components are extracted as feature values.

4.2 Bearing faults

Bearings in EC motors are the most susceptible to mechanical faults. Mainly, these mechanical faults are caused by inevitable material fatigue, which leads to surface damages and ultimately to bearing failure. Also other factors like improper bearing lubrication, improper mounting and alignment, as well as improper handling during the assembly process can cause damages which significantly shorten the expected bearing life. Therefore, it is of great importance that the entire EC motor is fault free.

The detection of bearing faults is a bit more difficult than the detection of rotor faults. Bearing faults are characterized by specific amplitude modulations that typically occur in a higher frequency range. The frequency of these modulations can be estimated using the rotational speed f_{rot} of the inner ring and the bearing's physical characteristics, i.e. the pitch diameter D, the rolling element diameter d, the number of rolling elements Z,

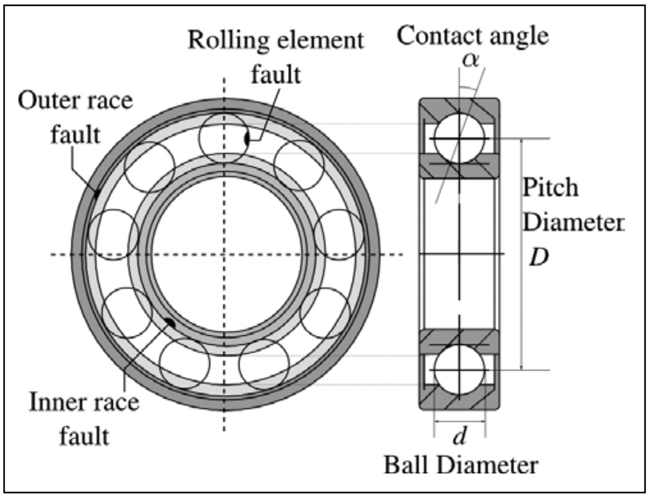


Figure 5. *Bearing dimensions used for the calculation of the bearing's characteristic frequencies*

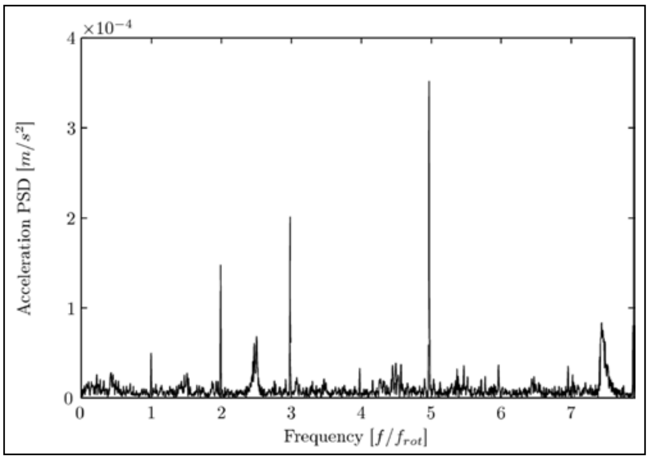
Table 1. *Frequencies characterizing bearing faults [7]*

Bearing pass frequency inner race (BPFI)	$f_{BPFI} = \frac{Zf_{rot}}{2}\left(1+\frac{d}{D}\cos\alpha\right)$
Bearing pass frequency outer race (BPFO)	$f_{BPFO} = \frac{Zf_{rot}}{2}\left(1-\frac{d}{D}\cos\alpha\right)$
Fundamental train frequency (FTF)	$f_{FTF} = \frac{f_{rot}}{2}\left(1-\frac{d}{D}\cos\alpha\right)$
Ball spin frequency (BSF)	$f_{BSF} = \frac{Df_{rot}}{2d}\left(1-\left(\frac{d}{D}\cos\alpha\right)^2\right)$

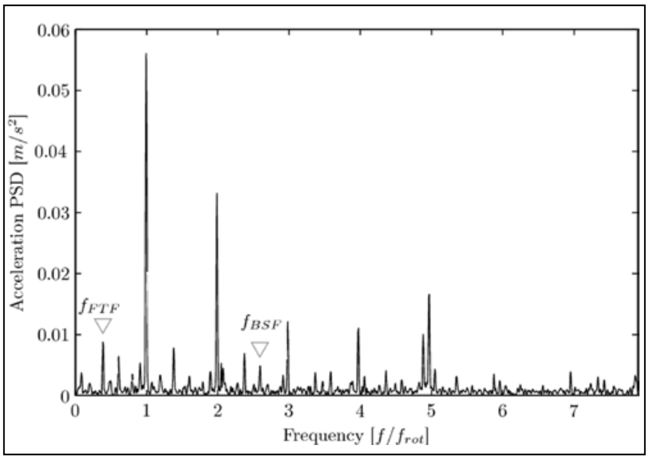
and the contact angle α (cf. Figure 4). Using these parameters the bearing fault frequencies can be calculated according to the relations shown in *Table 1* [7].

Feature extraction part is realized by calculating the envelope spectrum of vibrational signals by means of Hilbert transform. Prior to that, the vibrational signal is band-pass filtered [8]. The final feature set (extracted from the envelope) consists of the amplitudes of the spectral components located at the bearing fault frequencies (cf. Figure 4). Envelope spectra from several characteristic bearing faults are shown in *Figure 6*.

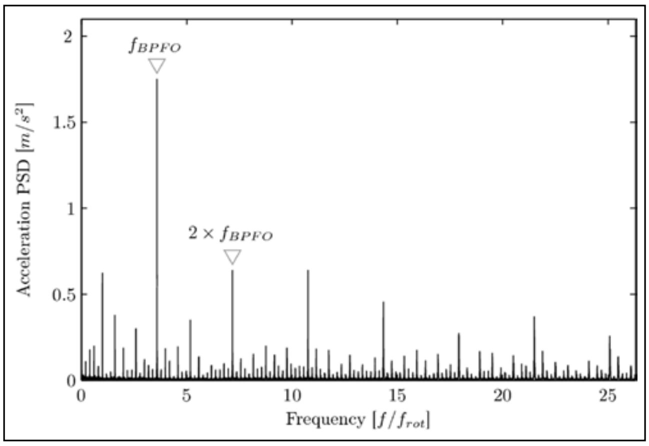
Fault-free case is shown in the Figure 6a. It should be noted that the amplitudes of the spectral components in this case are significantly lower than in all other cases (scale is multiplied by 10^{-4}). In the other three figures, spectra from different faults are shown. The spectrum of each of these cases is dominated by spectral components located at frequencies that represent characteristic frequencies associated to the bearing faults



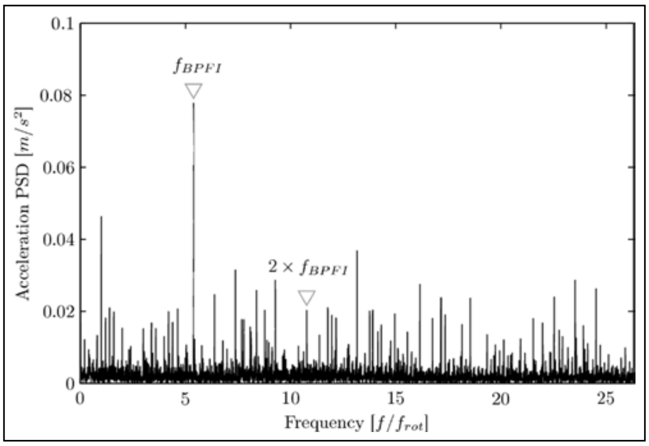
a) Fault-free motor



b) Improper lubrication



c) Outer race fault



d) Inner race fault

Figure 6. *Envelope Spectra*

(listed in Table 1). These frequencies are marked with inverted triangles.

5 Fault isolation and quality assessment module

The fault isolation and quality assessment of the examined EC motors is based on the selected values of the features and the pre-selected thresholds that mark the distinction between good and bad products. Consequently, the motor quality was assessed by analyzing how close are the extracted feature values to these thresholds. The quality assessment process gives information about the quality of each motor element, thus implicitly performing the fault isolation task too.

The problems of fault isolation and overall motor quality assessment are split into two sub-problems, i.e. assessment of the quality of the electrical part and mechanical part separately. Assessment of the mechanical components can be done by aggregating the estimates of the quality of the rotor shaft and the motor bearings. Finally, the quality of these two components can be directly inferred from information contained in the measured feature set. Such a decomposition process leads to the hierarchical structure shown in *Figure 7*.

Such a hierarchical approach introduces two improvements:

1. the results of the fault isolation task is a list of most probable faults accompanied with the estimated degree of belief and
2. for each examined motor the system provides an abstract measure in a form of *utility function*, which represents the overall quality of each examined EC motor.

The aggregation of the information drawn from the feature set was performed by evidential reasoning approach (ER) [9].

6 Experimental results

The experimental results show the effectiveness of the proposed virtual sensor when applied to fault diagnosis and quality assessment of mechanical parts of the EC motor. The aggregation process, described in the previous section, is a key process in calculating the value of the utility function for each examined EC motor. As a first step we have to define the evaluation grades associated to the products. In the case of EC motors' mechanical part was evaluated using 5 distinct evaluation grades:

NS = "NotSatisfactory"
G = "Good"
VG = "VeryGood"
E = "Excellent" and
T = "Top"

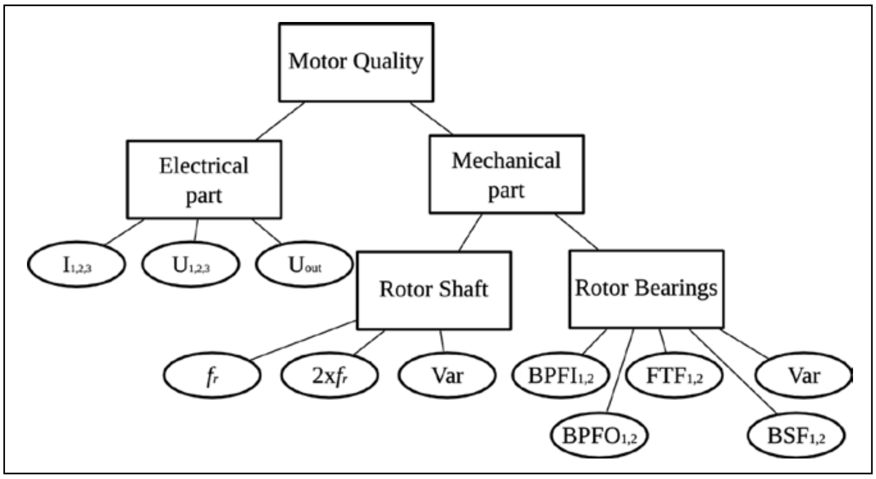


Figure 7. *Structure of the module reffered to as Quality assessment (see Figure 2)*

Estimation of the value of the utility function begins by specifying the utility value *u* for each evaluation grade. The particular values were determined by setting $u(T)=1$ and $u(NS)=0$ and the utilities of all other grades were set as equidistant points in the interval $[u(NS),u(T)]$. Afterwards, the extracted feature values are aggregated following the ER approach [9]. The aggregation process results in a set of membership degrees, which show to what extent the observed motor belongs to a specified evaluation grade. Finally, the overall utility value is a weighted sum of the utility value of each grade multiplied by the calculated membership degree.

6.1 Results

The proposed approach is applied to a batch of 130 EC motors. Motors with different quality as well as motors with mechanical damage were included. The decision whether the motor was acceptable or not was done by examining the two criteria:

1. the value of the utility function, and
2. the membership degree assigned to the *"NotSatisfactory"* evaluation grades.

The overall expected utility values for the tested motors are shown in *Figure 8*. There are three distinctive groups marked with different shades of grey:

1. the first group contains motors with acceptable quality;
2. the second group contains motors that some belief assigned to the evaluation grade *"NotSatisfactory"*; and
3. the third group consists of only two motors that represent special cases for which the efficiency of the algorithm is the most expressed.

The motors belonging to the group with the highest utility values are the ones that have belief assigned to the top evaluation grades *H*. Consequently, these motors can be regarded as units with acceptable quality.

The second group of motors include units that have some of the belief assigned to the *"NotSatisfactory"* evaluation grade. Since utility for this evaluation grade is zero $U(H_{NS})=0$, these motors have lower utility value. Despite the fact, that some of the motors have utility value above the threshold, some of their components exhibit unsatisfactory quality. Thus, the assessment process simultaneously performs the fault isolation task too.

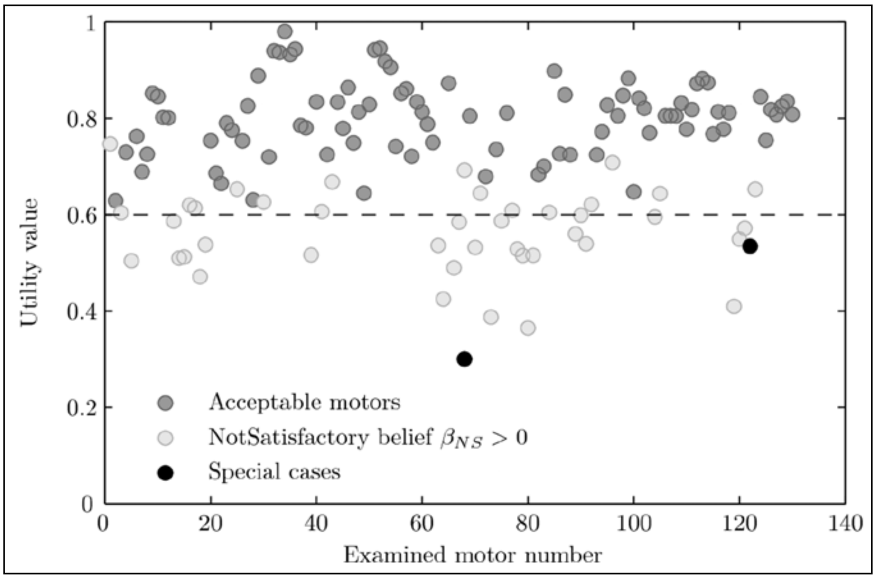


Figure 8. *Overall utility value for the test batch of motors*

By using the presented results, we can conclude that the decision whether the quality of mechanical part should be accepted or not, can be based on the information obtained from the state of the general aggregated attribute as well as the calculated expected utility value. The results prove the capability of the method to detect motors with both severe damages as well as motors whose mechanical quality is unacceptable in spite of the desirable low attribute values.

7 Conclusion

The paper presents the realisation of a virtual sensor for end-quality assessment of EC motors. The complexity of the virtual sensor may vary with respect to the sensitivity requirements, complexity of the observed system reliability and fast response time. We have shown that by performing a proper signal processing and data analysis step, one can significantly improve the accuracy of the virtual sensor.

Furthermore, the effectiveness of the data processing step considerably simplified the step of incorporating background process knowledge into the development of the virtual sensor. In our case, this knowledge was represented by a simple hierarchical structure.

Finally, by having properly selected features, the final output of the virtual sensor was obtained by so-called evidential reasoning aggregation approach. This approach has two major benefits with respect to the so-called data-driven black-box approaches:

- allows simple incorporation of prior experts knowledge, and
- the complete aggregation process as well as the generated output are intuitively understandable.

Therefore, by selecting the best possible methods for each step in the development of a virtual sensor we were capable to produce fast, reliable and accurate end-quality assessment system.

References

[1] Raja B., Abdelsalam H., Vishak S., and Shinyoung L.. 2007. Virtual sensors for service oriented intelligent environments. In Proceedings of the third conference on IASTED International Conference: Advances in Computer Science and Technology (ACST'07). ACTA Press, Anaheim, CA, USA, 165-170.

[2] Didier, G., Ternisien, E., Caspary, O., Razik, H., 2007. A new approach to detect broken rotor bars in induction machines by current spectrum analysis. Mechanical Systems and Signal Processing 21, 1127–1142.

[3] Juričić, D., Moseler, O., Rakar, A., 2001. Model-based condition monitoring of an actuator system driven by a brushless dc motor. Control Engineering Practice 9, 545–554.

[4] Röpke, K., Filbert, D., 1994. Unsupervised classification of universal motors using modern clustering algorithms. In Proc. SAFEPROCESS'94, IFAC Symp. on Fault Detection, Supervision and Technical Processes II, 720–725.

[5] Sasi, B., Payne, A., York, B., Gu, A., Ball, F., 2001. Condition monitoring of electric motors using instantaneous angular speed. In: paper presented at the Maintenance and Reliability Conference (MARCON), Gatlinburg, TN.

[6] Vachtsevanos, G., Lewis, F. L., Roemer, M., Hess, A., Wu, B., 2006. Intelligent Fault Diagnosis and Prognosis for Engineering Systems. Wiley.

[7] Tandon, N., Choudhury, A., 1999. A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings. Tribology International 32, 469–480.

[8] Boashash, B., Apr 1992. Estimating and interpreting the instantaneous frequency of a signal part i: Fundamentals. Proceedings of the IEEE 80 (4), 540 –568.

[9] Yang, J.-B., Xu, D. L., 2002. On the evidential reasoning algorithm for multiple attribute decision analysis under uncertainty. IEEE Transactions on Systems, Man, and Cybernetics 32, 289–304.

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Končna kontrola kakovosti električnih motorjev na podlagi koncepta virtualnih senzorjev

Razširjeni povzetek

Virtualni senzor je koncept, ki omogoča »merjenje« fizikalnih pojavov, ki jih običajno ni mogoče neposredno meriti s fizičnimi senzorji. Razlog je lahko, da je to preveč zahtevno ali celo neizvedljivo. Namesto da tovrstne pojave neposredno merimo, poskusimo njihovo vrednost oceniti na podlagi dostopnih meritev iz drugih fizičnih senzorjev, in sicer s postopki za obdelavo signalov.

V prispevku je koncept virtualnega senzorja prirejen za potrebe nadzora kakovosti elektromotorjev z elektronsko komutacijo. Namen je zanesljivo ugotavljanje kakovosti izdelka na podlagi »merjenja« velikosti morebitnih napak, ki se lahko pripetijo med proizvodnim procesom.

Izvedba »virtualnega« senzorja temelji na platformi materialne opreme, ki služi za pripravo razpoložljivih signalov iz vibracijskih senzorjev ter senzorjev električnih veličin. Spremljevalna programska oprema vsebuje module za generiranje značilk, vrednotenje značilk ter modul za lokalizacijo napak. Izvirni doprinos predstavlja modul za oceno kakovosti celotnega izdelka. Končna rezultata »virtualnega« senzorja sta ocena kakovosti elektromotorja in lokacija morebitnih poškodb in njihovih verjetnosti. Modul za generiranje značilk je sestavljen iz nabora pasovno prepustnih filtrov, ki priskrbijo informacijo o gostoti moči signala vibracij pri frekvencah, ki so značilne za mehanske napake, kot so masna neuravnovešenost, nesoosnost ter interne napake na ležajih. Dimenzija nabora značilk je dovolj visoka, tako da omogoča enolično lokalizacijo napak in s tem maksimalno diagnostično ločljivost.
Novost, ki loči sistem od doslej znanih, je modul, ki temelji na hierarhičnem računanju kakovosti celotnega elektromotorja na podlagi ocenjenih kakovosti posameznih sestavnih komponent. Slednje se določajo iz izračunanih značilk.

V članku je podrobneje predstavljena izvedba laboratorijskega prototipa »virtualnega« senzorja za merjenje kakovosti elektromotorjev vključno z eksperimentalnimi rezultati, dobljenimi na naboru 130 motorjev. Na podlagi prototipa se planira izvedba linije za končno kontrolo kakovosti elektromotorjev z elektronsko komutacijo neposredno na proizvodni liniji.

Ključne besede: virtualni senzor, obdelava signalov, diagnostika napak, kontrola kakovosti, elektromotorji