Rotor Fault Detection in Induction Machine Based on the TSA Method Applied to Stator Current

N. NGOTE, S. GUEDIRA, and M. CHERKAOUI

Abstract— **The purpose of this paper is to present a method to detect an induction motor rotor fault, by exploiting the cyclostationary characteristics of electrical signals. In fact, the induction motor defects are the most complex in terms of detection since they interact with the 50 Hz carrier frequency within a restricted band around 50 Hz. The first part of this study is devoted to the implementation of an induction motor model on MATLAB. The rotor fault is simulated by adding 10% to the rotor resistance value on one of the rotor phases. The Time Synchronous Averaging (TSA) method applied to the stator current will allow conditioning the electrical signal in order to detect the motor defects. The second part of this study is dedicated to confirm the simulation results with an experiment. For this purpose, various tests are performed on a test bench, including an industrial three-phase wound rotor asynchronous motor of 400V, 6.2A, 50Hz, 3kW, 1385rpm. The rotor fault is carried out by adding an extra 40mΩ resistance on one of the rotor phases (i.e. 10% of the rotor resistance value per phase, R_r=0.4Ω). From the stator voltage and current acquisition, and by application of the TSA method to the stator current, the electrical signal is conditioned in order to obtain a sensitive indicator allowing to detect the motor defects and hence, the simulation results are confirmed.**

I. Introduction

The electrical drives using induction motors are very common within industrial applications due to their low costs, high performance and robustness. However, there are various reasons, related to the stator or rotor, which can sometimes affect the well-functioning of these machines [1,2]. The appearance of a fault in the drive modifies its operation, which affects its performance. There are mainly two approaches for the monitoring of the electrical-drive system: the mechanic's, based on the vibration, speed and torque measures, and the electro-technician's, based on the current and voltage measures [3-9]. Within a predictive maintenance framework, the proposed method is dedicated to the monitoring of asynchronous machines based on a statistical approach by development of an indicator resulting from the electrical signals of the machine (current and voltage). Indeed, the current signal presents a non-stationary behavior related to the machine operating process and the electrical phase fluctuations [10-12]. Very little work has been done to exploit the electrical-signal cyclostationary characteristics [12-15], and it seems interesting to adapt these signal treatment tools to the electrical signal case.

In this paper, the particular case of rotor failures is treated. Those generally lead to an increase of a one-phase rotor resistance value [16]. As a first step, the induction motor dynamic model is performed and the simulation of healthy and defective motor operation is made. In a second step, an industrial three-phase wound rotor asynchronous motor is used to perform these two tests (healthy and defective cases). The rotor defect has been created by adding a 10% value extra resistance on one phase of the rotor, for both the simulation and experimental-test cases.

A simple comparison between the stator current RMS in the healthy and defective modes of the no-load machine does not allow detecting the failure (the variation is about 0.03% in the simulation and 1% in the experimental test). The stator current RMS cannot thus be used as a sensitive rotor defect indicator. A preliminary conditioning of this indicator will precisely make it possible to exploit the stator current cyclostationarity. By application of the TSA method [17], the residue related to the machine mechanics is obtained by subtraction. After conditioning, the new energy indicator will allow the easy distinction of the healthy and defective cases (the variation of the indicator value being clearly higher).

The rest of this paper is organized as follows. In Section II, the induction motor dynamic model is presented. The TSA method principle is developed in Section III. Then, in Section IV, the proposed model is used for studying the machine behavior under healthy and faulty conditions, using MATLAB software. Section V is devoted to the presentation of experimental results performed on the test bench. Finally, conclusions are mentioned in Section VI.

II. Dynamic Model of Induction Machine

To develop the dynamic model of the induction motor, the following assumptions are made:

- The induction machine is considered as symmetrical, three phase windings
- The winding is symmetrically distributed, such that the spatial magnetomotive force (mmf) is sinusoidal
- The surface windings have negligible depth
- The core is assumed to have infinite permeability
- Hysteresis, eddy current and slotting effects can be neglected
- The air gap is assumed to be uniform

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With these assumptions, the stator & rotor electric equations can be written as follows [18]:

$$[V_s]=[R_s]\cdot[I_s]+\frac{d[\Phi_s]}{dt} \quad ; \quad [V_r]=[R_r]\cdot[I_r]+\frac{d[\Phi_r]}{dt} \quad (1)$$

Where:

$$[V_s]=\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad ; \quad [I_s]=\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad ; \quad [\Phi_s]=\begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix}$$

$$[V_r]=\begin{bmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{bmatrix} \quad ; \quad [I_r]=\begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} \quad ; \quad [\Phi_r]=\begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix}$$

$$[R_s]=\begin{bmatrix} R_{sa} & 0 & 0 \\ 0 & R_{sb} & 0 \\ 0 & 0 & R_{sc} \end{bmatrix} \quad ; \quad [R_r]=\begin{bmatrix} R_{ra} & 0 & 0 \\ 0 & R_{rb} & 0 \\ 0 & 0 & R_{rc} \end{bmatrix}$$

- v_{sa}, v_{sb}, v_{sc}, v_{ra}, v_{rb} and v_{rc} are respectively the abc stator and rotor voltages;
- i_{sa}, i_{sb}, i_{sc}, i_{ra}, i_{rb} and i_{rc} are respectively the abc stator and rotor currents;
- φ_{sa}, φ_{sb}, φ_{sc}, φ_{ra}, φ_{rb} and φ_{rc} are respectively the abc stator and rotor flux linkages;
- R_{sa}, R_{sb}, R_{sc}, R_{ra}, R_{rb} and R_{rc} are respectively the abc stator and rotor resistances.

Note that in the case of a healthy induction motor, $R_{sa}=R_{sb}=R_{sc}$ and $R_{ra}=R_{rb}=R_{rc}$; but, if a rotor failure occurs, it will cause an electrical imbalance and will induce a change in resistance values that are no longer equal to each other [16].

Considering the inductances matrix [L] given by:

$$[L]=\begin{bmatrix} [L_s] & [M_{sr}] \\ [M_{rs}] & [L_r] \end{bmatrix} \quad (2)$$

Where:

$$[L_s]=\begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix} \quad ; \quad [L_r]=\begin{bmatrix} L_r & M_r & M_r \\ M_r & L_r & M_r \\ M_r & M_r & L_r \end{bmatrix}$$

$$[M_{sr}]=[M_{rs}]^t=$$

$$\begin{bmatrix} M_{sr}\cos\theta & M_{sr}\cos\left(\theta+\frac{2\pi}{3}\right) & M_{sr}\cos\left(\theta-\frac{2\pi}{3}\right) \\ M_{sr}\cos\left(\theta-\frac{2\pi}{3}\right) & M_{sr}\cos\theta & M_{sr}\cos\left(\theta+\frac{2\pi}{3}\right) \\ M_{sr}\cos\left(\theta+\frac{2\pi}{3}\right) & M_{sr}\cos\left(\theta-\frac{2\pi}{3}\right) & M_{sr}\cos\theta \end{bmatrix}$$

L_s and L_r are respectively the stator and rotor self inductances, M_s and M_r are respectively the mutual inductance between two stator and two rotor coils, M_{sr} is the maximal mutual between stator and rotor windings and θ is the rotor angular position. The mutual inductances between the stator and rotor windings are assumed to be sinusoidal functions of θ.

Hence, the electrical equations can be written as follows:

$$[V]=[R]\cdot[I]+\frac{d[\Phi]}{dt} \quad ; \quad [\Phi]=[L]\cdot[I] \quad (3)$$

Where:

$$[V]=\begin{bmatrix} [V_s] \\ [V_r] \end{bmatrix} \quad ; \quad [I]=\begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} \quad ; \quad [\Phi]=\begin{bmatrix} [\Phi_s] \\ [\Phi_r] \end{bmatrix}$$

$$[R]=\begin{bmatrix} [R_s] & [0] \\ [0] & [R_r] \end{bmatrix}$$

Equation (3) can also be written as follows:

$$[V]=[R]\cdot[I]+\Omega_r\frac{d[L]}{d\theta}[I]+[L]\frac{d[I]}{dt} \quad (4)$$

Where $\Omega_r = d\theta/dt$ is the rotor angular velocity.

The induction-motor equation of motion can be written as follows:

$$J\frac{d\Omega_r}{dt}+f\cdot\Omega_r=T_{em}-T_L \quad (5)$$

Where J is the moment of inertia, f is the friction, T_L is the load torque and T_{em} is the electromagnetic load torque, given by:

$$T_{em}=\frac{1}{2}[I]^t\frac{d[L]}{d\theta}[I] \quad (6)$$

Hence, the motion equation becomes:

$$-T_L=\frac{1}{2}[I]^t\frac{d[L]}{d\theta}[I]+f\cdot\Omega_r+J\frac{d\Omega_r}{dt} \quad (7)$$

Finally, the induction motor equations can be written in state representation form as follows:

$$[U]=[B]\cdot[X]+[A]\frac{d[X]}{dt} \quad (8)$$

Where [X] and [U] are respectively is the state vector and command vector, defined as:

$$[X]=\begin{bmatrix} [I] \\ \Omega_r \\ \theta \end{bmatrix} \quad ; \quad [U]=\begin{bmatrix} [V] \\ -T_L \\ 0 \end{bmatrix}$$

[B] and [A] are two 8x8 matrices defined as follows:

$$[B]=\begin{bmatrix} [R]+\Omega_r \frac{d[L]}{d\theta} & 0 & 0 \\ \frac{1}{2}[I]^t \frac{d[L]}{d\theta} & f & 0 \\ 0 & -1 & 0 \end{bmatrix} \quad ; \quad [A]=\begin{bmatrix} [L] & 0 & 0 \\ 0 & J & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The model presented in Equation (8) will be implemented on MATLAB in order to simulate the three-phase induction machine operation. The 4th order Runge Kutta method will be used to resolve this equation.

III. TIME SYNCHRONOUS AVERAGING (TSA)

The asynchronous motor operating process and the electric supply fluctuations cause the non-stationary behavior of the stator current signal. Previous research [9,10] has applied time/frequency representation techniques with an aim of identifying the signatures of the faults not in the frequential field, but in the time/frequency plan.

However, there has been very little work [12-15] exploiting the electrical-signal cyclostationary characteristics to identify the faults which occur in an asynchronous-motor drive. The idea is to extend the application of these signal-processing tools to the case of electrical signals. In this work, the first-order cyclostationarity of stator current and voltage will be largely exploited.

Furthermore, a rotor fault can be detected by highlighting a stator-current amplitude or phase modulation. However, the modulated-signal weak frequency band makes it too difficult to detect modulation. An alternative to overcome this difficulty is proposed by [17]: the Time Synchronous Averaging (TSA) method. It's a way to reshape the signal before its processing. The TSA method allows the separation between the excitation sources and, consequently, fault identification.

The stator current $I_s(t)$ can be decomposed as follows:

$$I_s(t)=I_{s_h}(t)+I_{s_{mec}}(t)+n(t) \tag{9}$$

Where $I_{sh}(t)$, $I_{smec}(t)$ and n(t) and are respectively the stator-current harmonic component, the mechanical-structure-related stator current and the noise.

In fact, the asynchronous motor monitoring consists of supervising the signal harmonic part. So, harmonic frequency (50Hz) which is related to electrical phenomena and mechanical-structure-related frequency must be separated.

For this purpose, the TSA method will be applied to the stator current. In fact, the stator current is the sum of a determinist signal $I_{sh}(t)$ and a random signal $I_{srand}(t)$ (sum of I_{smec} and n); whose average value is zero. The synchronous averaging of N stator-current samples is done by:

$$I_{s_{avg}}^{N}(n \cdot T_{samp})=\frac{1}{N}\sum_{k=1}^{k=N} I_s^k(n \cdot T_{samp}) \tag{10}$$

Where:

- $T_{samp}=1/f_{samp}$; f_{samp} is the sampling rate;
- I_s^k is the k^{th} stator current cycle;
- n is the sample row (n=1 to N_{samp}; N_{samp} is the number of samples per 50Hz cycle)

For the large value of N:

$$\lim_{N\to\infty} I_{s_{avg}}^{N}(t)=I_{s_h}(t) \tag{11}$$

Note that only the harmonic part $I_{sh}(t)$ corresponding to 50Hz frequency remains in the averaged signal; since the random-component average value is zero.

Thus, the synchronous averaging allows an effective separation between electrical-related and mechanical-related components.

The subtraction between the stator current $I_s(t)$ and the synchronous averaged current $I_{savg}^{N}(t)$ (equal to $I_{sh}(t)$ for the large value of N) gives the residual current $I_{sres}(t)=I_{srand}(t)$ where only mechanical-related frequencies remain.

It's a very interesting property that will allow conditioning a mechanical-structure-related indicator monitoring eventual faults (such as rotor defects.)

IV. SIMULATION RESULTS

The asynchronous motor operation will first be simulated in the healthy case.

The defective case will be simulated by adding an extra resistance on one of the rotor phases (i.e. 10% of the rotor resistance value per phase).

The simulation is performed for the two following cases:

- no-loaded motor;
- motor with a 65% nominal load.

This simulation will be made for a 20 seconds period (The number of current cycles N = 20s x 50Hz = 1000).

Table 1 below summarizes the induction motor parameters used for simulation:

TABLE I. INDUCTION MOTOR PARAMETERS

Motor parameters	**Values**
Nominal voltage RMS value	400 V
Nominal stator frequency	50 Hz
Stator resistance	1.9 Ω
Stator leakage inductance	11.5 mH
Rotor resistance	4.0 Ω
Rotor leakage inductance	11.5 mH
Mutual inductance	239.7 mH
Moment of inertia	0.1282 kg.m2
Friction factor	0 N.m.s
Number of pole pairs	2

Fig.1 below shows the stator current in the healthy and faulty cases for the no-loaded motor.

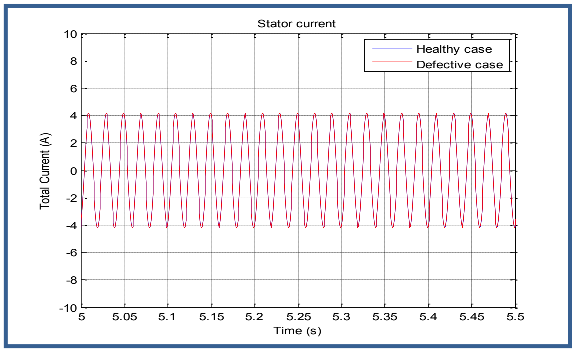

Figure 1. No-loaded-motor stator current

The healthy and defective stator current curves are indistinguishable. So the stator current shape in the healthy and defective modes does not allow detecting the failure. Moreover, even the comparison between the stator current RMS values in the healthy and defective cases does not allow us to detect the fault, as shown in Table II. Therefore, a first indicator K1 is defined according to the relation:

$$K1 = \frac{I_{S_{RMS}}(\text{defective}) - I_{S_{RMS}}(\text{healthy})}{I_{S_{RMS}}(\text{healthy})} \quad (12)$$

TABLE II. STATOR CURRENT RMS VALUES

	Stator Current RMS		K1
	Healthy case	***Faulty case***	
No-loaded motor	2.9769 A	2.9770 A	0.003%
Loaded motor	4.2804 A	4.2817 A	0.030%

There is almost no variation of the K1 indicator between the healthy and defective cases. It cannot be used like a sensitive indicator of rotor defect. The idea now is to compare the residual current obtained after the subtraction between the stator current and TSA stator current. Fig.2 and Fig.3 below show the residual current in the healthy and faulty cases respectively for the no-loaded and loaded motor.

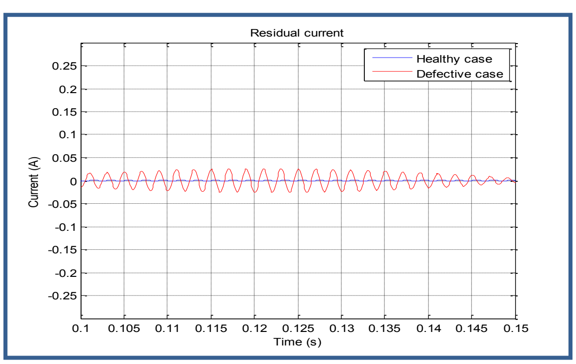

Figure 2. Residual current in no-loded case

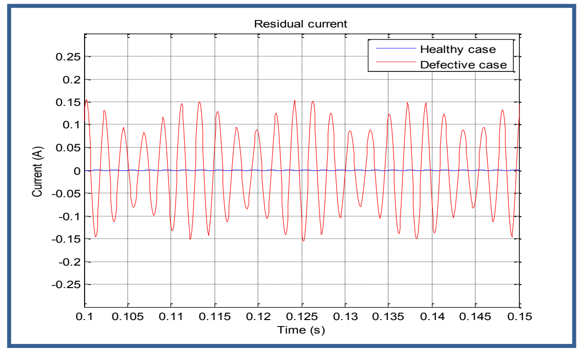

Figure 3. Residual current in loaded case

The monitoring of the residual current shape makes it possible to clearly detect the defective case. In fact, with a no-load engine, where the fault is hardest to detect, the two shapes show already the difference between healthy and faulty cases.

V. EXPERIMENTAL RESULTS

The testing ground used includes an industrial three-phase wound rotor asynchronous motor of 400V, 6.2A, 50Hz, 3kW, 1385rpm. The rotor fault has been carried out by adding an extra 40mΩ resistance on one of the rotor phases (i.e. 10% of the rotor resistance value per phase, Rr=0,4Ω).

Fig.4 below shows the Test Bench photos.

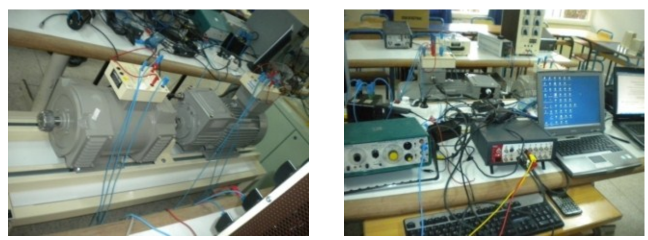

Figure 4. Wound rotor asynchronous motor & Data Acquisition System

The sampling rate taken is 25.6 kHz, so the number of samples per average cycle of 50 Hz is 512 (25600/50 = 512).

However, a problem of cycle drift from one electric cycle to another appears; it's due to the electrical supply fluctuations.

The cyclic statistic rules cannot be directly applied to these signals to extract desired information, except if a way to compensate these fluctuations is proposed.

A. Signal synchronization

A preliminary stage is needed: the current and voltage signals must be re-sampled according to a reference which "follows" these fluctuations: it's "the synchronization of the current and voltage signal". Therefore, a re-sampling algorithm which allows synchronizing the acquired signals (stator current and voltage) is developed. Synchronization is operated by compensation of the delay between the various electric cycles. The purpose is to synchronize all electric cycles according to the same reference, so all cycles must be superimposed after the synchronization process. To do this, voltage signal is first cut out in slices, each one corresponding to one period (20 ms), and each period containing an integer number of samples N. Then, the shift between the first period, taken as a reference, and the others is estimated and, each period is shifted to make it coincide with the first one (reference). If the two periods are already synchronous, the shift is then null. The stator current shape before and after synchronization are represented in Fig.5.

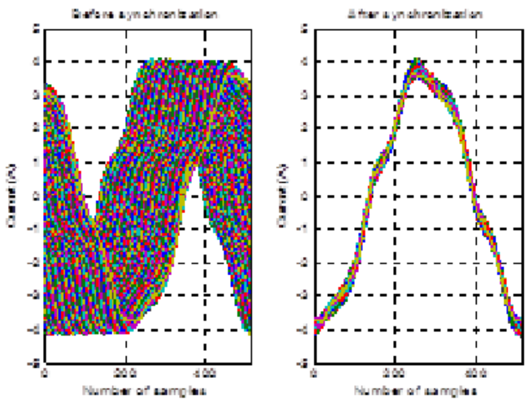

Figure 5. Superposition of 1000 current cycles before and after synchronization

Once all cycles are synchronized, the signal is rebuilt by setting these cycles end to end.

All cycles are now synchronous and the "synchronous averaging" can be carried out.

A. *Results*

Fig.6 below shows the experimental stator current in the healthy and faulty cases for the no-loaded motor.

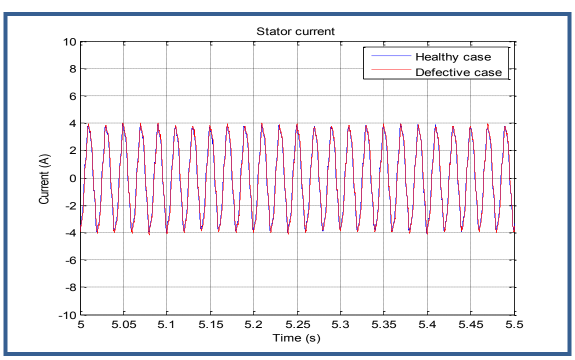

Figure 6. Experimental stator current (no-loaded motor)

As in simulation, the distinction between healthy and defective cases is quasi impossible.

Table III below gives the experimental stator current RMS and K1 indicator values for no-loaded and loaded motor cases.

As in simulation, there is too little variation of the K1 indicator. So it cannot be used like a sensitive indicator of rotor defect.

TABLE III. EXPERIMENTAL STATOR CURRENT RMS VALUES

	Experimental Stator Current RMS		**K1**
	Healthy case	***Faulty case***	
No-loaded motor	2.61 A	2.63 A	1.05%
Loaded motor	3.72 A	3.76 A	1.25%

The idea now is to use residual signal, obtained by subtraction of the TSA signal from the synchronized signal. This action reduces the electrical contribution, and, consequently, makes the extraction of mechanical-related information easier.

Fig.7 and Fig.8 show the healthy and defective residual stator currents respectively for the no-loaded and loaded motor.

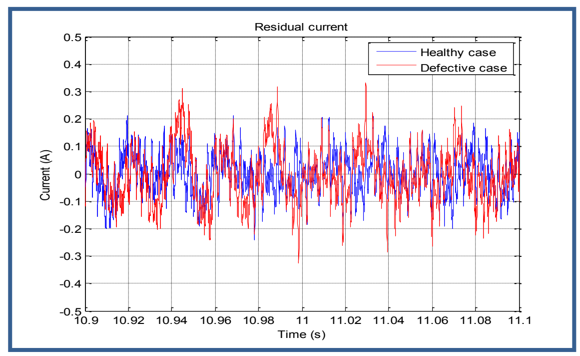

Figure 7. Experimental residual current (no-loaded motor)

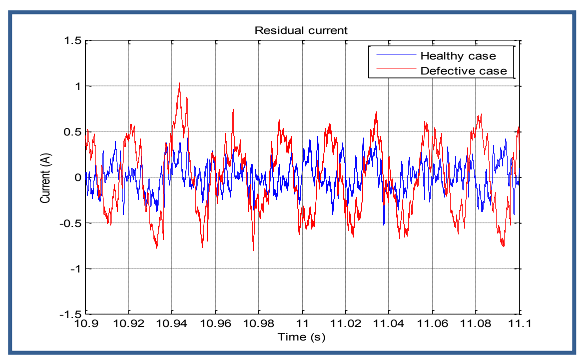

Figure 8. Experimental residual current (loaded motor)

The experimental residual current RMS, obtained after the subtraction between the experimental stator current and TSA stator current, is calculated according to the relation:

$$I_{sres_{RMS}} = \sqrt{\frac{1}{N_{samp}} \sum_{n=1}^{n=N_{samp}} I_{sres}^2 \left(n \cdot T_{samp}\right)} \qquad (13)$$

Where N_{samp} corresponds to the number of current samples and $T_{samp}=1/f_{samp}$; f_{samp} is the sampling rate.

Therefore, electrical signal is conditioned in order to obtain a second indicator K2 defined according to the relation:

$$K2 = \frac{I_{sres_{RMS}}(\text{defective}) - I_{sres_{RMS}}(\text{healthy})}{I_{sres_{RMS}}(\text{healthy})} \qquad (14)$$

TABLE IV. EXPERIMENTAL RESIDUAL CURRENT RMS VALUES

	Experimental Residual Stator Current RMS		**K2**
	Healthy case	***Faulty case***	
No-loaded motor	0.0748 A	0.0914 A	22.07 %
Loaded motor	0.1584 A	0.3858 A	143.6 %

The conditioned indicator K2, on the other hand, allows an easy distinction of the healthy and defective cases (the variation is from 22% for the no-loaded motor to nearly 145% in the case of loaded motor).

VI. CONCLUSION

In this article, the proposed method of asynchronous-motor-failure monitoring has two major advantages:

- First, it is a method which is based on the analysis of the "current" signal. It can therefore be applied even to the inaccessible engines (such as the engines immersed in the motor-driven pump groups), unlike the methods based on the analysis of the accelerometer signal, where a direct access to the engine is necessary to be able to place the sensors there.
- Besides, the approach is relatively simple: the monitoring of the residual current RMS makes it possible to clearly detect the defective case. In fact, with a no-load engine, where the fault is hardest to detect, the K2 indicator already shows a difference between healthy and faulty cases that exceeds 20%.

Finally, the MATLAB-simulation results have been widely validated by the experiment.

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