

Detecting cracks on graphite commutators using estimated amplitude of resistance

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Abstract – In this paper, the method for detecting cracks on graphite commutator with resistance measurement is described. Resistance is measured with four-point resistance measurement method when commutator is rotated. Result of measurement is surface resistance profile of graphite from which a cracks can be recognized. Information of the crack on the commutator graphite surface is hidden in the amplitude behaviour of a strongly distorted signal. Since the period of the amplitude changing is not constant the interpolation DFT algorithm is used first to estimate the current period along the turn of the rotated commutator around its axis and upon this the amplitude of the fundamental component. The amplitude estimation is achieved with only one DFT coefficient at $i=1$ for an almost coherent measurement interval of one period. Behaviour of the amplitude changing shows that the commutator with crack has specific increase of the amplitude around peak value and frequencies of the amplitude distribution can be used for the reliably checking of the crack presence.

Keywords – Commutator, resistance, DFT, frequency, amplitude estimation

I. INTRODUCTION

The problem of estimation of the basic three periodic signal parameters (frequency, amplitude, and phase, respectively) arises in many fields like the identification of dynamic systems, the analysis of harmonic distortion in power measurements and in impedance measurement, etc. In many applications it is a challenge to estimate signal parameters in the shortened measurement time spreaded over one signal period [1] or even shorter. After estimation of the signal period the behaviour of amplitude is typically of interest [2] as in the case of detecting of cracks on the graphite plate of commutator.

The commutator is the integral part of an electric motor, it is mounted on the rotor and rotates with it. Through the brushes that glide over the surface of the commutator, an electric circuit is formed, which drives the axis of the motor. It consists of individual copper lamellas, which are

isolated from each other, and each pair of lamellas are connected by conductors that form a winding on the rotor as shown in Fig.1.



Fig. 1. The position of the commutator on the rotor

A graphite commutator is a special type of commutator where the copper lamellas are replaced by the graphite ones. The copper base is soldered with a graphite plate, which is later filled with phenolic mass and sawn on the individual lamellas. Thus, the new sliding surface of brushes is graphite. The advantage of the graphite commutators is in the longer life cycle, better efficiency, lower spark, and consequently minor disturbances [3]. During the process of sputtering the commutator, changes in the structure of the material may occur (Fig. 2: cracks on the graphite plate), which can affect the operation of the commutator, therefore it is necessary to be reliably checked.

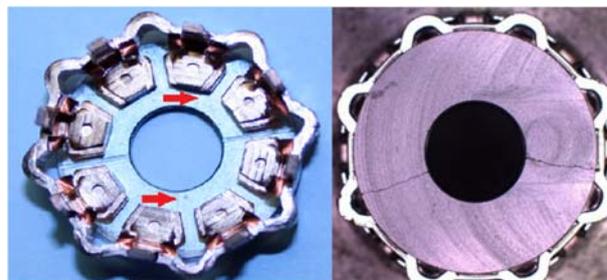


Fig. 2. Cracks on the commutator surface

The cracks in the material also mean a change in the local electrical resistance (the resistance of the material increases), so cracks can be detected by measurement of

the electrical resistance. The thin cracks on the graphite plate always appear radially across the entire graphite plate (Fig. 2, right figure), what greatly simplifies the measurement method and detection of cracks (Fig. 3).

For cracks detection, a relative change in resistance is important. Since the measured resistances are relatively low, we use the four-point measurement method. This method uses four measuring contacts, two for current, with which we force a known current (about 500mA), and two for voltage, to measure the voltage drop caused by the forced current. By using this method, the resistance of the measuring cables of current circuit is cancelled, and only the voltage drop is measured between the voltage contact points (Fig. 3). The used voltage measuring system had a range of $\pm 200\text{mV}$ with 16-bit resolution, which allows the measurement of the low voltage levels and this corresponds to resolution of a few $\mu\Omega$.

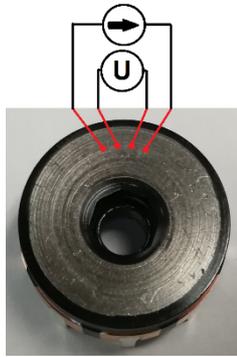


Fig. 3. Measuring scheme and arrangement of measuring contacts

The commutator is rotated around its axis and the measuring contacts slide along the graphite surface. If a crack occurs between the voltage contacts it reflects as an increased change in the measured voltage. The stepping motor rotates the commutator at a rate of two turns per second and with sampling frequency $f_s = 1\text{kHz}$ we detect voltage drops for the full commutator turn on $N = 500$ points in 0.5 seconds. The result of the measurement is therefore a graph showing the change of voltage in time dependence (Fig. 4: curve a).

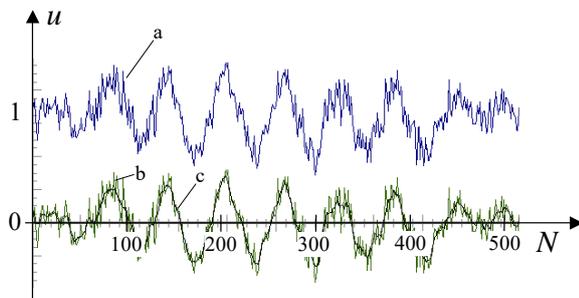


Fig. 4. Raw captured voltage signal on commutator without crack; a – original signal, b – signal with subtracted mean value, c – smoothed signal

The measurement problem is to find the rapid change of the amplitude (Fig. 5) since on the good commutator graphite surface (Fig. 4) the voltage signal varies due to contacts of copper hooks with the graphite plate (Fig. 2: eight copper hooks in one turn).

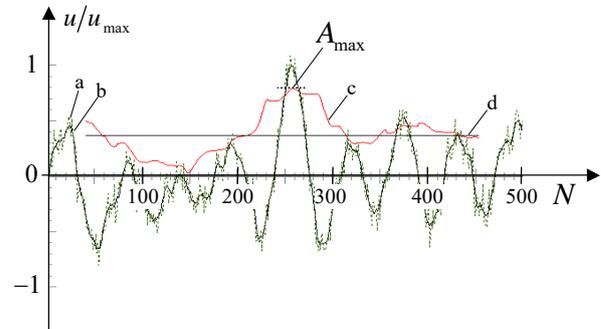


Fig. 5. Captured voltage signal on commutator with crack. Values of the signals are normalized to the peak value of the filtered input signal. a – original signal subtracted by mean value, b – smoothed signal, c – estimated amplitude, d – median value of the amplitude values

II. AMPLITUDE ESTIMATION BELOW ONE PERIOD TIME

The information of presence of the crack is hidden in the amplitude behaviour of a distorted signal. All parameters are changing: period of the fundamental component, amplitude, phase, and signal is distorted by large noise (Fig. 4). Several solutions have been suggested in the literature to estimate signal component parameters. Some methods are based on the least squares (LS) methods, Kalman filters, recursive estimators, as well as discrete Fourier transform (DFT)-based approaches [4],[5]. The last approach is the non-parametric approach with the high accuracy and low computational burden but has restrictions and disadvantages, such as leakage effect and picket fence effect.

These methods usually estimate the frequency by searching for the maximum in the spectrum and upon this two or three local DFT coefficients are used to improve suitable parameter estimation by interpolation, with which the effects of leakage caused by incoherent sampling are compensated and finite frequency resolution could be improved adopted suitable windowed function [6]. However, such methods involve a compromise between the accuracy of the signal parameters measurement and the length of the observation interval; accuracy decreases, as the interval becomes smaller and especially below one period. Recently, some proposals have been published [7],[8], in which authors move investigation of the measurement time for the parameters estimation also around and below one sine signal period. In [8], only the DC DFT coefficient is used in the estimations employing two different windows for frequency estimation and moving window to estimate other two parameters. In this

approach, improved estimation of the amplitude is used with the changing window length.

The periodic band limited analogue signal composed of M components and sampled by $f_s = 1/\Delta t$ can be expressed $g(n\Delta t) = w(n\Delta t) \cdot \sum_{m=0}^{M-1} A_m \sin(2\pi f_m n\Delta t + \varphi_m)$ with f_m , A_m , and φ_m as frequency, amplitude, and phase of the particular component, respectively. Parametric estimation methods use this expression as a model while the non-parametric methods find information about components using DFT. The DF transformation of the windowed signal $w(n) \cdot g(n)$ on N sampled points at the spectral line i is given by:

$$G(i) = \frac{1}{2j} \sum_{m=0}^M A_m (W(i - \theta_m) e^{j\varphi_m} - W(i + \theta_m) e^{-j\varphi_m}) \quad (1)$$

The component relative frequency $\theta_m = f_m/\Delta f$ is the component frequency related to the base frequency resolution $\Delta f = 1/N\Delta t = 1/T_M$ or multiplied by the measurement time $\theta_m = f_m \cdot T_M$. It consists of an integer part and the non-coherent sampling displacement term $-0.5 \leq \delta_m < 0.5$ ($\theta_m = i_m + \delta_m$).

Shortening of the observation time T_M below the fundamental period $\theta_1 = T_M/T_1 = f_1/\Delta f \leq 1$, where the relative position of the fundamental frequency component is between $i=0$ (DC coefficient) and $i=1$, causes the leakage disturbances of the DFT coefficients. One possibility to deduce the frequency as the first component parameter from the average signal value or the DC coefficient (2) is to use two different windows in estimation if windows have the symmetric amplitude spectra $|W(\theta)| = |W(-\theta)|$ [4].

$$G(0) = \frac{A_1}{2j} |W(\theta_1)| (e^{j(\varphi_w + \varphi_1)} - e^{-j(\varphi_w + \varphi_1)}) \quad (2)$$

If the function $W(\theta)$ of window used is analytically known, the DC DFT coefficients can be expressed. For estimations, the well-known Rife-Vincent windows class I (RV1) or cosine windows [4] are used where the phase part $\varphi_w = \pi(N-1)/N \cdot \theta = a \cdot \theta$ is not dependent on the window order and one can use this property to estimate the relative frequency from the DC DFT coefficient. Using Euler formula, expression (2) can be rearranged in a simple sinusoidal function:

$$G(0) = |G(0)| = A_1 |W(\theta_1)| \cdot |\sin(a\theta_1 + \varphi_1)| \quad (3)$$

From here the relative frequency can be deduced using two RV1 windows on the same data set and putting the two

DC coefficients in the quotient where the component amplitude A_1 and phase contribution due to the same argument $a\theta_1 + \varphi_1$ are subtracted [8].

$$r_{1,0} = \frac{|G_{\text{Hann.w.}}(0)|}{|G_{\text{Rect.w.}}(0)|} = \frac{1}{2(1-\theta_1^2)} \Rightarrow \theta_1 = \sqrt{1 - \frac{1}{2r_{1,0}}} \quad (4)$$

To get an image of the frequency estimation error behaviour a double scan was made changing phase between $-\pi/2 < \varphi < \pi/2$ at every value of the changing frequency. Fig. 6 shows maximal values of errors $E_{\max}(\theta)$ using DC coefficients and (4) in comparison to the classical 2-point interpolation with the Hann window (5).

$$\theta_1 \doteq 1 + \frac{2 \cdot |G(2)| - |G(1)|}{|G(1)| + |G(2)|} \quad (5)$$

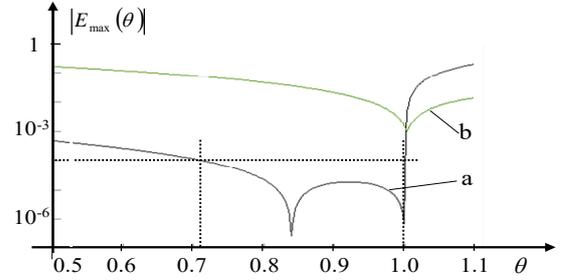


Fig. 6. Absolute maximal values of errors of the frequency estimation in relation to the relative frequency; a – using DC coefficients and (4), b – using 2-point interpolation with Hann window and (5); $A_1 = 1$, $N = 1024$

Very good estimation of frequency (4) on the actual points N_0 in the measurement window can be used to accurately estimate the number of sampling points in one period N_1 and belonging relative frequency with displacement δ_1 :

$$N_1 = \text{floor} \left(\frac{N_0}{\theta_{1,m}(N_0)} \right) \quad (6)$$

$$\theta_1(N_1) = \theta_{1,m}(N_0) \cdot \frac{N_1}{N_0} \rightarrow \delta_1(N_1) = \theta_1(N_1) - 1 \quad (7)$$

After signal period (frequency) estimation, the amplitude of the fundamental component can be estimated by the one-point estimation using the largest local DFT coefficient at $i=1$ and the one-point estimation neglecting the long-range leakages in (1) due to very small displacement values ($|\delta_1| < 0.01$) [7].

$$A_1 \doteq 2 \frac{|G(1)|}{|W_{\text{Rect.w.}}(\delta_1)|} \quad (8)$$

III. CRACK DETECTION

Demonstration of the amplitude estimation using above equations can be seen in Fig. 7 with voltage signal acquired on commutator without crack and in Fig. 5 with voltage signal acquired on commutator with crack. Due to the presence of noise, the signals were previously smoothed by moving average of 6 points, what means approximately one tenth of the nominal signal period $N_{\text{period}} = 500/8 \doteq 62$ (Figs. 5 and 7: curves b).

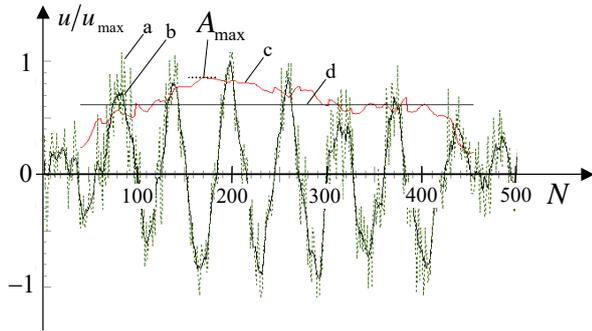


Fig. 7. Captured voltage signal on commutator without crack. Values of the signals are normalized to the peak value of the filtered input signal. a – original signal subtracted by mean value, b – smoothed signal, c – estimated amplitude, d – median value of the amplitude values

Comparing Figs. 5 and 7 one can conclude that the radial crack on the graphite surface causes significant increasing of the voltage amplitude symmetrical around amplitude peak A_{max} in interval for about one nominal signal period $N_{\text{period}} \doteq 62$ (Fig. 5). The distribution of amplitudes between values of the amplitude median (Figs. 5 and 7: curves d) and the amplitude peak can be used for the decision about good and bad commutator (Figs. 8 and 9).

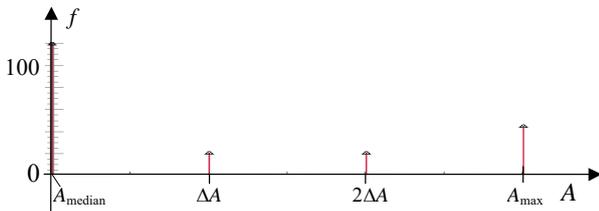


Fig. 8. Frequency f of the amplitude distribution of signal form Fig. 5 with crack

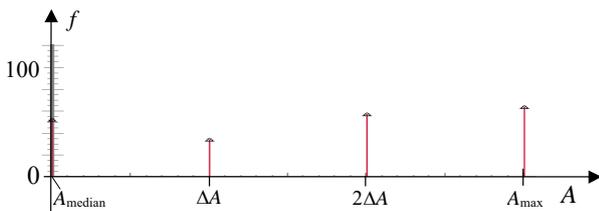


Fig. 9. Frequency f of the amplitude distribution of signal form Fig. 7 without crack

The commutator with crack has narrower distribution of amplitudes around peak value and sum of the two most right frequencies gives value of 66 (Fig. 8) what is in the border of 10% of the nominal points of the period $N_{\text{period}} \doteq 62$ and this condition is used for the estimation of crack. Success of decision about goodness of commutator was more than 94% on 1000 trials.

IV. CONCLUSIONS

The paper presents the problem of detection the crack on the commutator graphite surface where information is hidden in the amplitude behaviour of very distorted signal. Since the period of the amplitude changing is not constant the interpolation DFT algorithm is used first to estimate the current period along the turn of rotated commutator around its axis and upon this the amplitude of the fundamental component is estimated with only one DFT coefficient at $i=1$ in almost coherent measurement interval of one signal period.

Behaviour of the amplitude changing shows that the commutator with crack has specific increase of the amplitude around peak value and frequencies of the amplitude distribution can be used for the reliably checking of the crack presence.

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