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## RECOGNITION OF ARMATURE CURRENT OF DC GENERATOR DEPENDING ON ROTOR SPEED USING FFT, MSAF-1 AND LDA

### ROZPOZNAWANIE SYGNAŁÓW PRĄDU TWORNIKA GENERATORA PRĄDU STAŁEGO W ZALEŻNOŚCI OD PRĘDKOŚCI OBROTOWEJ WIRNIKA Z ZASTOSOWANIEM FFT, MSAF-1 I LDA\*

*Recognition of states of electrical systems is very important in industrial plants. Article describes a recognition method of early fault detection of DC generator. The proposed approach is based on an analysis of the patterns. These patterns are the armature currents of selected electrical machine. Information contained in signals of armature current is depending on generator state. Researches were carried out for four states of generator with the use of Fast Fourier Transform (FFT), method of selection of amplitudes of frequencies (MSAF-1) and Linear Discriminant Analysis (LDA). The results of analysis show that the method is efficient and can be used to protect DC generators. This method was verified with the aid of acoustic signals recognition method.*

**Keywords:** fault detection, pattern recognition, armature current, DC generator.

*Rozpoznawanie stanów układów elektrycznych jest bardzo ważne w zakładach przemysłowych. W artykule opisano metodę rozpoznawania stanów przedawaryjnych generatora prądu stałego. Proponowane podejście jest oparte na badaniu wzorców. Wzorce te są prądami twornika wybranej maszyny elektrycznej. Informacja zawarta w sygnałach prądu twornika jest zależna od stanu generatora. Przeprowadzono badania dla czterech stanów generatora z zastosowaniem FFT, metody wyboru amplitud częstotliwości (MSAF-1) i liniowej analizy dyskryminacyjnej (LDA). Wyniki analizy pokazują, że metoda jest skuteczna i metoda może być stosowana do ochrony generatorów prądu stałego. Metoda została zweryfikowana za pomocą metody rozpoznawania sygnałów akustycznych.*

**Słowa kluczowe:** detekcja uszkodzenia, rozpoznawanie wzorców, prąd twornika, generator prądu stałego.

#### 1. Introduction

Nowadays rotating machines are more complex than 20 years ago. Electrical generators deteriorate over time gradually. Condition of machines can be recovered through appropriate maintenance activities. In recent years, many signal processing methods were applied for diagnostics of electrical devices and machines [6, 7, 10, 11, 41]. Most of them were based on patterns recognition. Development of diagnostic systems is important to guarantee quality of machines and materials [2, 8, 11-14, 27, 29, 30, 33, 35, 36, 40, 44]. Diagnostic of electric machines can be based on various signals such as: electric, acoustic, thermal, magnetic or vibroacoustic [6, 8-11, 15, 16, 42, 43]. An armature current is a diagnostic signal. It can be measured by measuring card and LEM current sensor. Armature current can be used to diagnose type of fault. The analysis of armature current of Direct Current generator can decrease the costs of maintenance of these types of generators in the industrial plant and wind plants. It can also lead to the more modern diagnostic systems.

In this paper authors propose early fault detection technique. This technique uses method of selection of amplitudes of frequencies (MSAF-1) and Linear Discriminant Analysis to classify feature vector.

#### 2. Recognition of armature current of Direct Current generator

Recognition of armature current is not an easy problem. The database of patterns is needed to solve this problem. This database is used in a pattern creation process. Second database of test samples is needed in an identification process. These databases should be prepared properly.

The process of recognition of armature current can be defined as two processes: pattern creation process and identification process. First of them starts with registering of armature current. Signal of armature current is converted to the TXT file with data. After that TXT file is split into small samples of current. The next step is selection of amplitudes of frequencies. In this purpose authors propose new method described in chapter 2.2. The method gives us 1 feature vector from 1 sample. At the end of the pattern creation process Linear Discriminant Analysis is used to create patterns (Fig. 1).

The identification process is based on the same methods as previous process. Feature vectors are calculated by the same processing methods. After that feature vectors are compared by Linear Discriminant Analysis.

(\*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie [www.ein.org.pl](http://www.ein.org.pl)

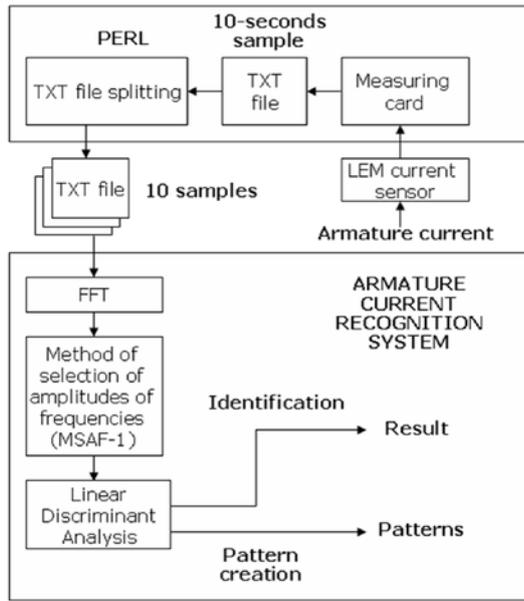


Fig. 1. Process of recognition of armature current of DC generator with the use of method of selection of amplitudes of frequencies and Linear Discriminant Analysis

2.1. Measurement of armature current

Direct current generator has been loaded by an external resistance. This armature current was measured by LEM current sensor and measuring card. Then signal of armature current was converted to the text file. After that TXT file was split into small samples of current. Each sample had duration time of 1 second. Sampling frequency of measuring card was 20000 Hz, so sample contained 20000 values. Spectrum of frequency of armature current was presented in Figure 2.

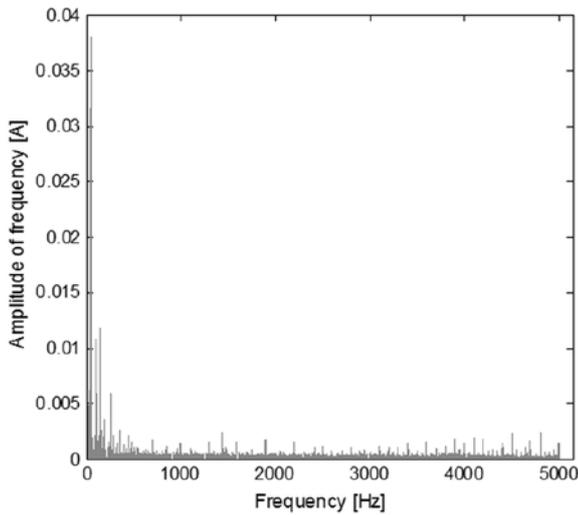


Fig. 2. Amplitudes of frequencies of armature current depending on frequency for faultless DC generator with rotor speed 600 rpm

2.2. Method of selection of amplitudes of frequencies

Proposed method of selection of amplitudes of frequencies (MSAF-1) was based on differences between amplitudes of various states of DC generator. The armature current was dependent on the state, rotor speed and construction of generator. Steps of MSAF-1 are following:

- 1) Calculate spectrum of frequency for each state of DC generator.
- 2) Calculate differences between states of DC generator: **a-b**, **a-c**, **a-d**, **b-c**, **b-d**, **c-d**, where **a** denoted the spectrum of armature current of faultless DC generator, **b** denoted the spectrum of armature current of DC generator with 3 shorted rotor coils, **c** denoted the spectrum of armature current of DC generator with 6 shorted rotor coils, **d** denoted the spectrum of armature current of DC generator with broken rotor coil.
- 3) Calculate absolute values of differences between states of DC generator:  $|a-b|$ ,  $|a-c|$ ,  $|a-d|$ ,  $|b-c|$ ,  $|b-d|$ ,  $|c-d|$ .
- 4) Select 8 maximal amplitudes of the frequencies for each difference between states of DC generator:  $\max_1|a-b|$ , ...,  $\max_8|a-b|$ , ...,  $\max_1|c-d|$ , ...,  $\max_8|c-d|$  and determine corresponding frequencies.
- 5) Find common frequencies (1-8) and then determine for these frequencies the amplitudes of spectrum for each state of DC generator.

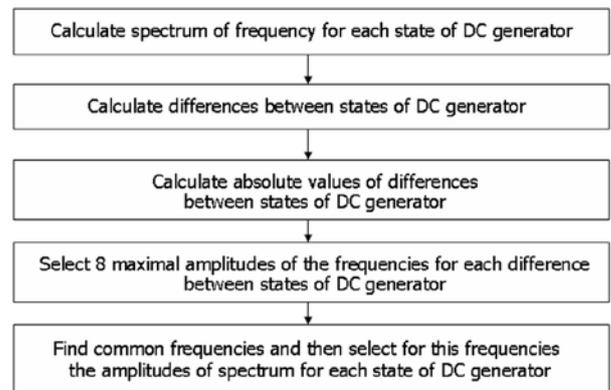


Fig. 3. Block scheme of MSAF-1

The method of selection of amplitudes of frequencies of DC generator in form of block scheme has been presented in Fig. 3.

Differences between spectra for 4 states of DC generator with rotor speed 600 rpm were presented in Figures 4–6. Selection of common amplitudes of frequencies for 4 states of DC generator with rotor speed 600 rpm was presented in Figure 7.

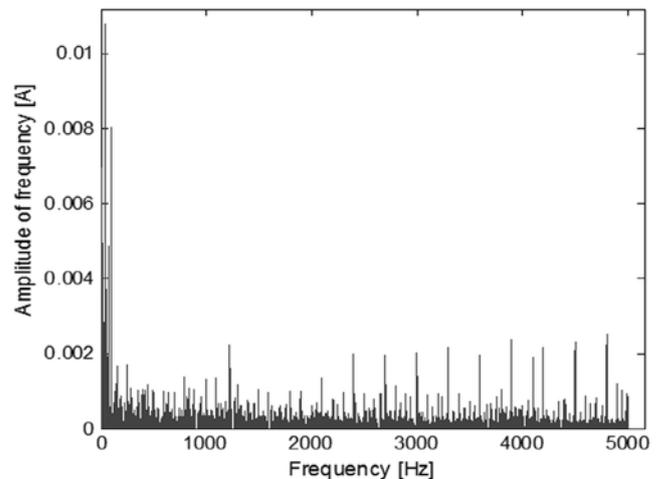


Fig. 4. Difference between frequency spectrum of armature current of faultless DC generator and DC generator with 3 shorted rotor coils (a-b) with rotor speed 600 rpm

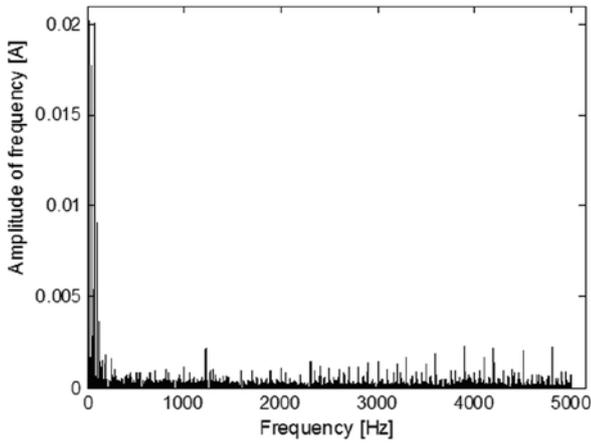


Fig. 5. Difference between frequency spectrum of armature current of faultless DC generator and DC generator with 6 shorted rotor coils (a-c) with rotor speed 600 rpm

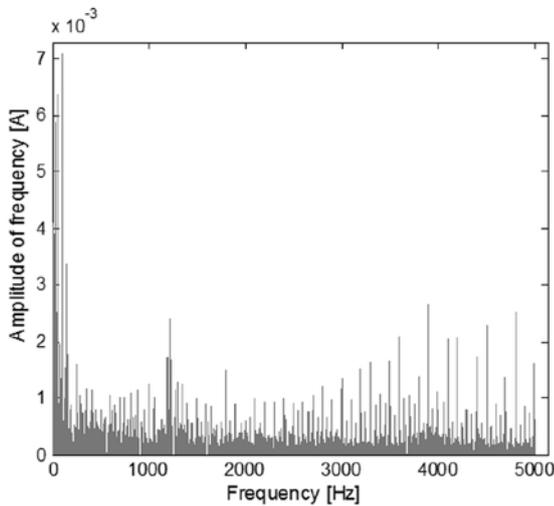


Fig. 6. Difference between frequency spectrum of armature current of faultless DC generator and DC generator with broken coil (a-d) with rotor speed 600 rpm

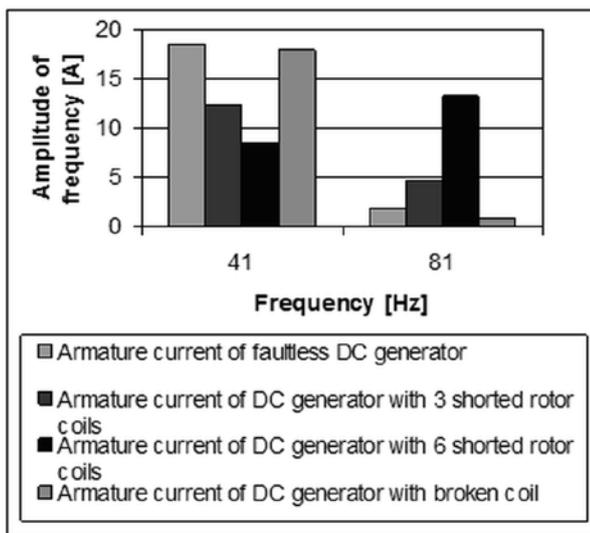


Fig. 7. Selection of common amplitudes of frequencies for 4 states of DC generator with rotor speed 600 rpm (41 and 81 Hz)

Selected amplitudes of frequencies formed the feature vector used by Linear Discriminant Analysis.

### 2.3. Linear Discriminant Analysis

There are many methods for data processing and feature vectors classification [3–5, 17–26, 28, 31, 32, 34, 37–39, 41, 45–48]. The feature vectors are processed by Linear Discriminant Analysis (LDA). LDA maximizes the ratio (quotient) of between-class variance to the within-class variance. Maximal ratio guarantees separability between the classes. Data sets and the test sets should be formulated appropriately at the beginning of classification. Training sets are defined as  $set_1, \dots, set_k$ . Next the mean for each training set and mean of all training sets are computed.

The means of sets  $set_1, \dots, set_k$  are defined as  $\mu_1, \dots, \mu_k$ . Whereas the mean of all training sets is called  $\mu$ . This mean is given by equation 1:

$$\mu = p_1 \times \mu_1 + \dots + p_k \times \mu_k \quad (1)$$

where  $p_1, \dots, p_k$  are the a priori probabilities of the classes.

Next a linear combination of features is created by Linear Discriminant Analysis. This method uses within-class scatter matrix and between-class scatter matrix [1, 32]. Both matrices are used to formulate criteria for separability of the classes. Within-class scatter matrix is defined as follows:

$$W = \sum_{k=1}^c \sum_{i=1}^{N_k} (x_i^k - \mu_k)(x_i^k - \mu_k)^T \quad (2)$$

where  $\mu_k$  denotes the mean of class  $k$ ,  $x_i^k$  is the sample with the index  $i$  of class  $k$ ,  $c$  denotes the number of classes of training sets, and  $N_k$  is the number of samples of class  $k$  [1, 31].

Between-class scatter matrix is expressed by formula:

$$B = \sum_{k=1}^c (\mu_k - \mu)(\mu_k - \mu)^T \quad (3)$$

where  $\mu$  denotes the mean of all training sets,  $x, \mu$  vectors of dimensions equal to the selected number of common frequencies.

The ratio of between-class scatter matrix determinant to the within-class scatter matrix determinant is the criterion of Linear Discriminant Analysis. In this method it is essential to maximize the ratio  $(Det|B| / Det|W|)$  [31]. The axes of the transformed space are defined by the solution obtained by maximizing the ratio  $(Det|B| / Det|W|)$ .

### 3. The results of recognition of armature current

Measuring card and LEM current sensor were used to record armature current signals. Parameters of current signal were: sampling frequency - 20000 Hz, format - TXT. Operation parameters of DC generator with rotor speed 600 rpm were following:

- faultless DC generator:  $U_a = 51$  V,  $I_a = 70$  A,  $U_e = 159.1$  V,  $I_e = 2.5$  A,
- DC generator with 3 shorted rotor coils:  $U_a = 50.5$  V,  $I_a = 71.5$  A,  $U_e = 160.8$  V,  $I_e = 2.5$  A,  $I_{sc} = 58$  A,
- DC generator with 6 shorted rotor coils:  $U_a = 50$  V,  $I_a = 70.5$  A,  $U_e = 161.2$  V,  $I_e = 2.5$  A,  $I_{sc} = 138$  A,

– DC generator with broken coil:  $U_a = 50.5$  V,  $I_a = 70$  A,  $U_e = 163.3$  V,  $I_e = 2.5$  A,

where  $U_a$  - armature voltage of DC generator,  $I_a$  - armature current of DC generator,  $U_e$  - excitation voltage of DC generator,  $I_e$  - excitation current of DC generator,  $I_{sc}$  - current of the short-circuit.

Groups of three and six loops rotor coils were shorted with the use of resistance  $R_{sc} = 0.085$  mΩ. This resistance was connected with DC generator to protect the rotor windings. Investigations were carried out for four current signals: armature current of faultless DC generator, armature current of generator with 3 shorted rotor coils, armature current of generator with 6 shorted rotor coils (Fig. 8), armature current of generator with broken coil. 32 training samples with a duration of one second were used in the pattern creation process. 128 test samples with a duration of one second were used in the identification process.

SHORT CIRCUIT

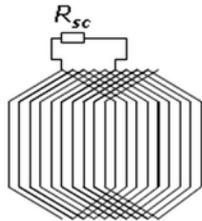


Fig. 8. Scheme of rotor windings of DC generator with 6 shorted coils

Armature current recognition efficiency determines the relationship:

$$ACRE = \frac{NoWRTS}{NoATS} 100\% \quad (4)$$

where:  $ACRE$  – armature current recognition efficiency,  $NoWRTS$  – number of well recognized test samples,  $NoATS$  – number of all test samples.

Researches were carried out for DC generator with rotor speed 700 rpm, 600 rpm, 500 rpm, 400 rpm. Armature current recognition efficiency depending on the rotations of rotor is presented in Figures 9 and 10.

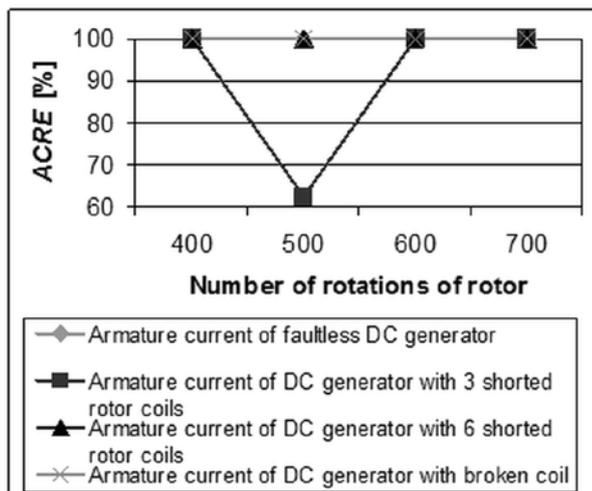


Fig. 9. Armature current recognition efficiency depending on the rotor speed of DC generator

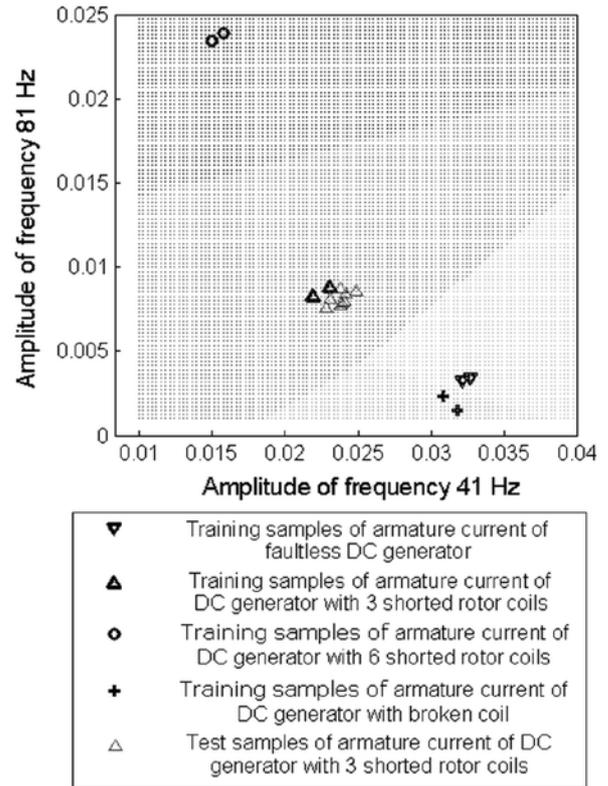


Fig. 10. Recognition of test samples of armature current of DC generator with 3 shorted rotor coils with rotor speed 600 rpm

Armature current recognition efficiency of faultless generator was 100%. 8 of 8 test samples were classified as faultless generator. The samples were prepared on the basis of measurements and authors knew that these 8 test samples were generated by faultless generator. Armature current recognition efficiency of generator with 3 shorted rotor coils was 62.5-100%. Armature current recognition efficiency of generator with 6 shorted rotor coils was 100%. Armature current recognition efficiency of generator with broken coil was 100%. Results for the two-element vectors were good. If the system selects the number of common amplitudes of frequency equal 1-8, then LDA will process 1-8 element vectors.

#### 4. Conclusion

In this paper authors proposed technique and a system of recognition of armature current of DC generator. Researches involving the application of signal processing methods to armature current recognition has been carried out for faultless DC generator and faulty DC generator.

The experiments proved that the methods such as MSAF-1, FFT, and LDA were sufficient enough for diagnostics of DC generator. Armature current recognition efficiency of DC generator was 100% for rotor speed 400 rpm, 600 rpm, 700 rpm. When the rotor speed was equal 500, then armature current recognition efficiency of DC generator was 62.5-100%.

Advantage of this method over acoustic signal recognition is that the armature current is easier to process. Further researches will focus on implementations of new processing methods and cooperation of various diagnostic signals.

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