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RECOGNITION OF MONOCHROME THERMAL IMAGES OF SYNCHRONOUS MOTOR WITH THE APPLICATION OF QUADTREE DECOMPOSITION AND BACKPROPAGATION NEURAL NETWORK

ROZPOZNAWANIE MONOCHROMATYCZNYCH OBRAZÓW CIEPLNYCH SILNIKA SYNCHRONICZNEGO Z ZASTOSOWANIEM KWADRATOWO-DRZEWOWEJ DEKOMPOZYCJI I SIECI NEURONOWEJ*

Technological progress and decreasing prices of thermographic cameras make their application to monitoring and assessing a technical state of machines is profitable. In article is described the recognition method of imminent failure conditions of synchronous motor. The proposed approach is based on a study of thermal images of the rotor. Extraction of relevant diagnostic information coded in thermal images is important for diagnosing of machine. It can be performed with the use of selected methods of analysis and recognition of images. Studies were carried out for two conditions of motor with the application of quadtree decomposition and backpropagation neural network. The experiments show that the method can be useful for protection of synchronous motor. Moreover, this method can be used to diagnose equipments in steelworks and other industrial plants.

Keywords: *Maintenance, recognition, thermal images, synchronous motor, neural network.*

Postęp techniczny i malejące ceny kamer termowizyjnych sprawiają, że ich zastosowanie do monitorowania i oceny stanu technicznego maszyn jest opłacalne. W artykule opisano metodę rozpoznawania stanów przedawaryjnych silnika synchronicznego. Proponowane podejście jest oparte na badaniu obrazów cieplnych wirnika. Ekstrakcja istotnej informacji diagnostycznej zakodowanej w obrazach cieplnych jest ważna dla diagnozowania maszyny. Zabieg taki może być wykonany z użyciem wybranych metod analizy i rozpoznawania obrazów. Przeprowadzono badania dla dwóch stanów silnika z zastosowaniem kwadratowo-drzewowej dekompozycji i sieci neuronowej z algorytmem wstecznej propagacji błędów. Eksperymenty pokazują, że metoda może być przydatna do zabezpieczania silników synchronicznych. Ponadto metoda może być stosowana do diagnozowania urządzeń w hutach i innych zakładach przemysłowych.

Słowa kluczowe: *Eksploatacja, rozpoznawanie, obrazy cieplne, silnik synchroniczny, sieć neuronowa.*

1. Introduction

Thermography is a non-invasive, safe and modern technique of thermal visualisation. Every object on the earth generates infrared radiation. The intensity and spectrum distribution of this radiation depends on the temperature of the mass and the radiation properties of its surface layer. Thermographic camera is able to detect this type of radiation, even small changes in temperature can be accurately monitored. Afterwards recorded data are computer-processed and shown in the form of temperature maps that provide for a detailed analysis of the temperature field. Thermographic camera measures the infrared radiation emitted from an object. This camera shows an image of these temperature differences. The darker areas are those that radiate less thermal radiation. Radiation is emitted from the surroundings and is reflected by the object. To measure temperature accurately, it is necessary to compensate for the effects of a number of the different radiation sources. This is done automatically by the thermographic camera. The thermographic techniques have found many applications, for example in industry, building, energetics, veterinary medicine.

In animals or humans, changes in vascular circulation result in an increase or decrease in their tissue temperature. Thermographic process can be used to evaluate the situation in that area of the body. For example, heat generated by inflammation is transmitted to the overlying skin. After that this energy is dissipated as internal energy. Next thermographic camera and special software can measure thermal radiation.

Advantage of this technique is that it does not require physical contact with the object. It enables measuring temperature distribution of surface. There are also some limitations for thermography. Thermal images should be taken for the clear object (free of dirt and moisture). The investigated object should be out of direct sunlight and wind currents [16].

Studies of infrared thermography have been conducted for numerous applications [16]. Infrared thermography is also used in diagnostics of electrical machines. These machines are constructed of steel elements. Thermal and mechanical properties of steel elements were investigated in the literature [12-15, 17, 21, 23, 24, 27, 28, 30-33, 36, 37]. The article describes the method of diagnosis of a synchronous motor. This technique is based on recognition of thermal

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** images of the rotor with the application of quadtree decomposition and backpropagation neural network.

2. Process of recognition of thermal images of synchronous motor

The process of recognition of thermal images contains two phases. First of them is patterns creation process (fig. 1).

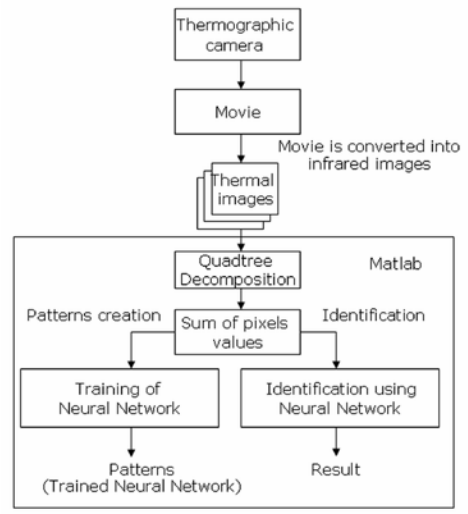

Fig. 1. Process of recognition of thermal image of synchronous motor with the use of quadtree decomposition and neural network

Second phase is identification process. These phases include methods used in image processing. At the beginning of patterns creation process movie is recorded in the computer memory. After that movie is converted into thermal images. These images create training set. Next quadtree decomposition of the image is used. In next step sum of pixels values is calculated. Each sample which is used in patterns creation process gives us one sum of pixels values. This sum of pixels creates feature vector. Next all vectors are used to training of neural network. Steps of identification process are the same as for pattern creation process. Significant change occurs in the classification. In this step neural network is used to identify sample from test set.

2.1. Video recording

All objects emit a certain amount of infrared radiation as a function of their temperatures. Generally the higher an object's temperature is, the more thermal energy this object emits. Thermographic camera can detect this radiation in a way similar to a video camera recording visible light. Thermographic camera can work in darkness because it does not need an external light. Thermographic camera used in experiments was installed 0.25m above rotor of synchronous motor. It recorded images at a resolution of PAL D-1 (640 × 460 pixels) in grayscale with a resolution of 8 bits (values 0–255). Next recorded movie is transferred to a PC. It is stored in permanent memory in AVI format (Audio Video Interleave).

2.2. Acquisition of thermal images

Film with a duration of 1 second has 25 monochrome thermal images. To extract a single thermal image from the movie, a program in a Perl scripting language was implemented. This program uses *mplayer* library. As a result, monochrome thermal images are obtained. Each monochrome image has resolution 256 × 256 pixels.

2.3. Quadtree decomposition of monochrome image

Quadtree decomposition divides a square image into four equal-sized square blocks. Next it analyzes each block to see if it meets criterion of homogeneity [19]. In the event that a square block meets the criterion, it is not divided any further. If it does not meet the criterion, it is subdivided again into four blocks and the criterion is used to those blocks. This process is repeated iteratively until each block meets the criterion. The result can have blocks of several different sizes.

Moreover quadtree decomposition is appropriate primarily for square images whose dimensions are a power of 2, such as 128 × 128, 256 × 256 or 512 × 512. These images can be divided until the blocks are 1 × 1 [19].

Monochrome thermal images of rotor of synchronous motor were presented in figures 2–3.

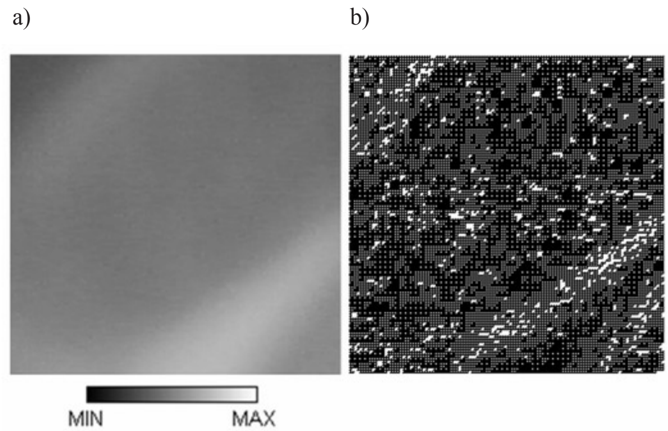

Fig. 2. a) Monochrome thermal image of rotor of faultless synchronous motor, b) Thermal image of rotor of faultless synchronous motor after quadtree decomposition

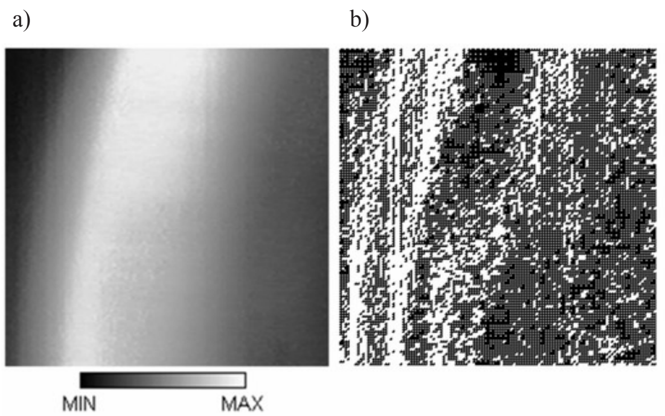

Fig. 3. a) Monochrome thermal image of rotor of synchronous motor with faulty ring of squirrel-cage, b) Thermal image of rotor of synchronous motor with faulty ring of squirrel-cage after quadtree decomposition

2.4. Selection of features

Thermal image contains 256 × 256 pixels. Each pixel has a value from range 1–16 (1 – black pixel, 16 – white pixel). The sum of all pixels values of the image is a feature. This feature creates a feature vector (fig. 4).
Feature vector will be used in classification step.

2.5. Backpropagation neural network

In the literature there are many methods of analysis and recognition [1–11, 18, 20, 22, 25, 26, 29, 35, 38]. The patterns creation process uses feature vectors and backpropagation neural network. Neural

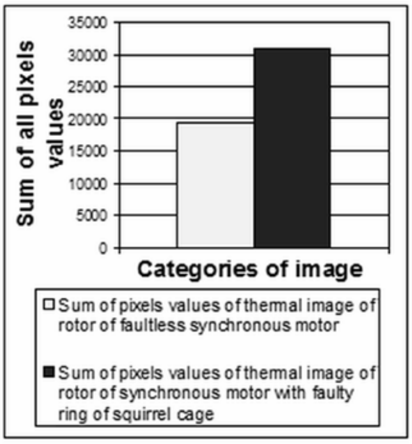

Fig. 4. Sums of pixels values for two categories of thermal images

network consists of many neurons connected by synapses. The learning process of a back-propagation neural network takes place in two phases. In the forward phase, the output of each neuron in each layer and the errors between the actual outputs from the output layer and the target outputs are computed, in the backward phase, weights are modified by the back-propagation errors that occurred in each layer of the network [34]. Structure of backpropagation neural network is shown in figure 5.

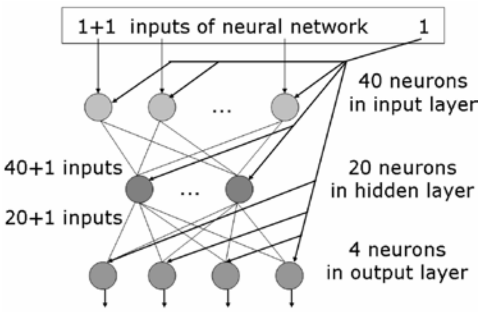

Fig. 5. Structure of backpropagation neural network used in proposed method

During the training of neural network patterns are stored in the form of floating point numbers. System uses character encoding. It converts name of category into the floating-point numbers (ASCII code divided by 128 – vector **a**). Neural network collects the values from all of its input connections (1 feature). After the training of neural network it is necessary to perform the identification process. During identification process floating point values are obtained on the output of neural network (vector **c**).

These four values are converted to ASCII characters. In the identification process the value of the output neuron in the output layer is not equal to the exact value of the character in ASCII code divided by 128. One of the two characters is selected with the help of Manhattan metric (1). This metric calculates the distance defined as:

$$d(\mathbf{c},\mathbf{a}) = \sum_{i=1}^{n} (|c_i - a_i|) \tag{1}$$

where **c** and **a** are vectors with the same lengths, $\mathbf{c} = [c_1, c_2, \ldots, c_n]$, $\mathbf{a} = [a_1, a_2, \ldots, a_n]$.

For example, for the category of recognition “ring” (image of rotor of synchronous motor with faulty ring of squirrel-cage) the following values should be obtained:

ASCII_CODE (r) / 128 = 114 / 128 = 0.890625,
ASCII_CODE (i) / 128 = 105 / 128 = 0.8203125,
ASCII_CODE (n) / 128 = 110 / 128 = 0.859375,
ASCII_CODE (g) / 128 = 103 / 128 = 0.8046875.

New feature vector **y** is assigned to the class w_j when:

$$d(\mathbf{c},\mathbf{a_j}) = \min_i (d(\mathbf{c},\mathbf{a_i}) \Rightarrow \mathbf{y} \to w_j \tag{2}$$

where i=1, 2,…, M, j=1, 2,…, M,
$\mathbf{a_i}$, $\mathbf{a_j}$ are vectors containing floating point numbers, **y** is a new feature vector, **c** is a new vector, obtained in the identification process (in output layer), M is the number of classes.

3. Results of thermal image recognition of synchronous motor

Investigations were carried out for two different categories of thermal image of synchronous motor. They are defined as follows: faultless synchronous motor, synchronous motor with faulty ring of squirrel-cage (fig. 6).

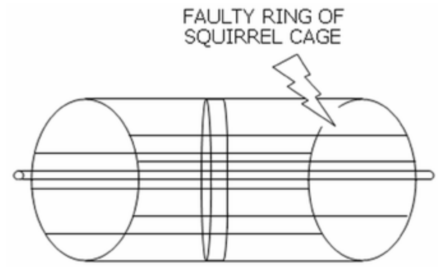

Fig. 6. Faulty ring of squirrel-cage of synchronous motor

Synchronous motor had following operational parameters: faultless synchronous motor, U = 300 V, I = 21.5 A, synchronous motor with faulty ring of squirrel-cage, U = 300 V, I = 77 A,
where: U – supply voltage, I – current of one motor phase.

Thermographic camera recorded two movies. These movies contained thermal images of faultless synchronous motor and synchronous motor with failure.

The process of patterns creation was carried out for 20 monochrome thermal images. Identification process was carried out for 80 monochrome thermal images. Efficiency of recognition of thermal image is defined as:

$$T = \frac{K_1}{K} \tag{3}$$

where: T – efficiency of recognition of thermal image, K_1 – number of correctly identified samples, K – number of all samples.

Efficiency of recognition of thermal image of synchronous motor was presented (tab. 1).

Table 1. Results of recognition of thermal images

Kind of thermal image	Efficiency of recognition of thermal image
Faultless synchronous motor	100%
Synchronous motor with faulty ring of squirrel-cage	100%

4. Conclusion

Thermography can generate important information when the possibilities of conventional diagnostic techniques have been exhausted. In this paper authors proposed a method and a system of recognition of thermal images of synchronous motor. Researches involving the use of image processing methods to thermal diagnostics has been carried out for synchronous motor without faults and motor with faulty ring. Results of recognition of thermal images were good for quadtree decomposition and backpropagation neural network. Efficiency of recognition of thermal images of synchronous motor was 100%. The experiments show that the method can be useful for protection of synchronous motor in steelworks and other industrial plants. A limitation of the method was that the thermographic camera recorded the image of temperature of the surface of the rotor. Further researches should be continued to examine other failures of electrical machines.

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