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October 19, 2021

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Abstract

This article presents a new method of identification of inter-turn shorting for a model of induction motor. Analysis of the tested signals executed by means of discrete wavelet transformation was used in the diagnostics procedure using the algorithm of the decision tree. The obtained results of test simulations for five important state variables describing physical quantities show the effectivity and sensitivity of the proposed approach during changes of load current in the tested model of induction motor.

1 Introduction

Diagnostics of electromechanical processes concerns the recognition of undesirable changes of states, which presents in form of sequence set actions executed in a limited time by means of machines and devices working with determined resources.

The time-frequency analysis using wavelet transformation is one of the most popular and increasingly used methods in diagnostics of changes for physical quantities in electromechanical processes. This method enables multi-stage decomposition of signal with variable resolution (Zając, 2009).

In the last few years, a number of papers have been published presenting new techniques for fault detection in dynamic systems using time-frequency methods. Some of them can be mentioned:

- detection of methods of rotor bars cracked in the squirrel-cage induction motor on the basis of analysis of stator's current by means of using Fourier's transformation as well as discrete wavelet transformation (Da Costa & Kashiwagi & Mathias, 2015),
- using of discrete packet wavelet analysis of signal stator's current in detection faults of stator winding of the induction motor (Mathew, 2017),

- analysis of possibilities of using of wavelet discrete transformation of envelope stator's current to detection of inter-turn shorting in induction motor, at the earliest possible moments of fault creation (Wolkiewicz & Kowalski, 2015),

- presentation of the discrete wavelet transform (DWT) on the Park's vector modulus of current signals (Sonje & Kundu & Chowdhury, 2019),

- performing a time–frequency method for inter-turn fault detection in the stator winding of PMSM using improved wavelet packet transform (Liang & Chen & Liang & Wang, 2018).

2 Description of the execution of identification tests of the inter-turn shortings in induction motor

Inter-turn shorting faults are the main causes of the stator winding insulation failure. In the proposed work, a new algorithm is suggested to detect these faults in the induction motor.

The diagram of one coil of stator windings with the routed-out turns has been shown in Figure 1. The number of the winding, which the turn was routed out from to the terminal box on the machine casing was indicated by the number at each turn. As a result of connecting the appropriate numbers of routed-out turns with resistance and ammeter selected windings were short-circuited. For the purpose of reduction of current and protection of the motor from overheating in the next measurements, an additional resistance was used. The value of the additional resistance was used between 5 and 6 Ω and had no effect on different details of the analyzed signals. Stator windings of the tested motor were powered from a low-voltage three-phase network and were joined in a star connection (Zając & Sułowicz, 2016).

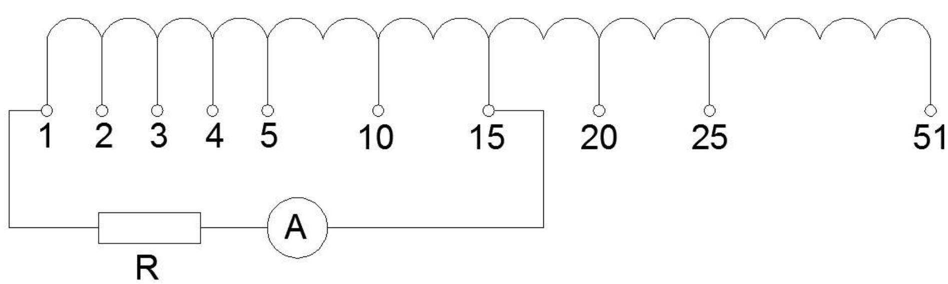

Figure 1: Presentation of diagram of routed-out turns from one of the modified coils of stator windings (Zając & Sułowicz, 2016).

The accuracy of discrete wavelet transformation (DWT) can be obtained by selecting the proper wavelet type and its order along with suitable number levels of decomposition. For this purpose, the best-suited mother wavelet was investigated by testing various orthogonal wavelet functions on simulated signals. It was noticed that the accepted wavelets are to be the best choice for the detection of an inter-turn fault in the induction motor.

Wavelet transformation for discrete signals is made according to the following decomposition:

$$S = A_1 + D_1 = A_2 + D_2 + D_1 = A_3 + D_3 + D_2 + D_1 \qquad (1)$$

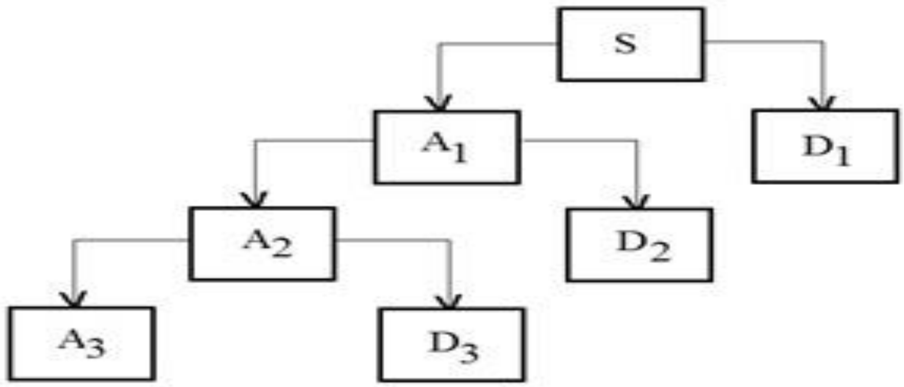

Figure 2: Presentation of operation diagram for discrete wavelet transformation.

The tests have been carried out in five test groups, with the following five values of load current: 1 A, 2 A, 3 A, 4 A, and 5 A. Each test group contained seven cases with different cases of inter-turn shorting. Results of simulations for all physical quantities have been written in matrix X_1. Elements of matrix X_1 have been written for each set load current. Cases of inter-turn shorting A have been determined between the first coil and next coils in the following order: A=1(case of inter-turn shorting between coil 1 and coil 2), A=2(case of inter-turn shorting between coil 1 and coil 3), A=3 (case of inter-turn shorting between coil 1 and coil 5), A=4 (case of inter-turn shorting between coil 1 and coil 10), A=5 (case of inter-turn shorting between coil 1 and coil 15), A=6 (case of inter-turn shorting between coil 1 and coil 20), and A=7 (case of inter-turn shorting between coil 1 and coil 25).

In the proposed identification method simulation tests have been executed for the following physical quantities:

a) current in the short-circuited winding,
b) electromagnetic moment of the induction motor,
c) rotational speed of the induction motor's rotor,
d) vibration acceleration for axis *x*,
e) vibration acceleration for axis *y*,
f) three phase currents,
g) three phase voltages,
h) signal proportional to magnetic axial flux,
i) sound pressure,
j) zero voltage.

The wavelet type and its order have been selected in such a way that the shape of the basic wavelet approximately would be adequate to the character of the transient course of the tested physical quantity, obtained as a result of a simulation for the case of the inter-turn shorting between coil 1 and coil 2.

As a result of the executed tests for current in the short-circuited winding wavelet, *sym5* has been made for all tested individual physical variables. In simulation tests, it was accepted normalization of values for tested physical quantities to the range fixed by means of determining parameters calculated for current in the short-circuited winding. It was caused that choice only the one wavelet type and its order in simulation tests has been used in simulation tests.

Simulation tests have been executed with a sampling frequency equal to 50 kHz. The time duration of every simulation test was equal to 10 s.

The level of wavelet decomposition fixed for the analysis depends both on the frequency associated with the component of the signal carrying information about the fault, and on the center frequency of the basic wavelet. The central frequency is the center of the spectrum where the basic wavelet concentrates most of its energy.

For the purpose of determining of level wavelet decomposition for the tested physical quantity, it is necessary to calculate the length of the wavelet's carrier. This level corresponds to the scale *s* which has been determined by means of the following formula:

$$d_1 = 2^{(s)}; \quad s = 1,2,3...12 \tag{2}$$

where:

d_1 – parameter determining the length of wavelet's carrier on the level decomposition corresponding to the scale *s*.

In executed simulation tests the sampling time d_2 was equal $2 \cdot 10^{-s}$ s. The length of wavelet's carrier d_1 for tested physical quantity has been calculated according to the formula:

$$d_1 = \frac{f_c}{f_a \cdot d_2} \tag{3}$$

where:

f_a – the frequency of analyzed diagnostic signal determined on the basis of transient course of a tested physical quantity,

f_c – the central frequency of basic wavelet used to the execution of analyses,

d_2 – the sampling time for executed simulation test.

Frequency f_a has been determined on the basis of the character of transient course for tested physical quantity.

The sampling time concerns sampling frequency by means of the formula:

$$d_2 = \frac{1}{f_p} \tag{4}$$

where:

f_p – the sampling frequency determined for every simulation test.

In every group of tests values of matrix's elements X_1 have been normalized to the range [a_3, a_4] for all tested physical quantities except current in the short-circuited winding according to the formula:

$$X_{2((i)j)} = \begin{cases} \left(\dfrac{(X_{1(i)(j)} - a_{1(i)})}{(a_{2(i)} - a_{1(i)})} \right) * (a_{4(i)} - a_{3(i)}) + a_{3(i)}; \\ i \in \langle 1,7 \rangle; \; j = 1,2 \ldots 500000 \end{cases} \tag{5}$$

where:

a_1 – the minimal value of matrix's elements X_1 determined in the test,

a_2 – the maximal value of matrix's elements X_1 determined in the test,

a_3 – the initial value of the range containing normalized values X_2 determined in the test for current in the short-circuited winding,

a_4 – the final value of the range containing normalized values X_2 determined in the test for current in the short-circuited winding,

i – a number of tested case of inter-turn shorting.

Therefore, values of variables a_1 and a_2 have been calculated in the following way:

$$a_{1(i)} = \min\left(X_{1(i)(j)}\right); \quad i \in \langle 1,7 \rangle \tag{6}$$

$$a_{2(i)} = \max\left(X_{1(i)(j)}\right); \quad i \in \langle 1,7 \rangle \tag{7}$$

Calculations for values of variables a_3 and a_4 have been realized by means of using formulas:

$$a_{3(i)} = \frac{\sum_{j=1}^{500000} X_{1(i)(j)}}{500000}; \quad i \in \langle 1,7 \rangle \tag{8}$$

$$a_{4(i)} = \max\left(X_{1(i)(j)}\right); \quad i \in \langle 1,7 \rangle \tag{9}$$

On the basis of results obtained in the series of tests, it was decided to use for the proposed identification algorithm 4096 samples choosing in the descending order from matrix X_1 for current in the short-circuited winding and also from matrix X_2 for other tested physical quantities.

Therefore, in executed simulation tests values of matrix's elements X_1 and also matrix X_2 have been written to matrix X_3 in the following way:

$$X_{3(i)(j)} = \begin{cases} \left[X_{1(i)(1)} \geq X_{1(i)(2)} \ldots \geq X_{1(i)(4096)}\right]; \\ \left[X_{2(i)(1)} \geq X_{2(i)(2)} \ldots \geq X_{2(i)(4096)}\right]; \\ i \in \langle 1,7 \rangle;\ j = 1,2 \ldots 4096 \end{cases} \tag{10}$$

For this purpose of enabling of identification's process for the used decision tree, it was necessary determining sum s_1 as a result of set calculations executed for coefficients of discrete wavelet transformation X_6.

Calculations for coefficients of discrete wavelet transformation have been executed for all set changes of inter-turn shorting and have been obtained by means values of matrix's elements X_5.

Values of matrix's elements X_5 represent five values in Fibonacci sequence and have been calculated according to the formula:

$$X_{5(i)(j)} = \begin{cases} X_{4(i)(j)}; & \text{for } j \leq 2 \\ X_{5(i)(j-1)} + X_{5(i)(j-2)}; & \text{for } j > 2 \\ i \in \langle 1,7 \rangle;\ j = 1,2 \ldots 5 \end{cases} \tag{11}$$

where:

X_4 – values of matrix's elements X_4 determined in the test.

The Fibonacci sequence sets the appropriate values in ascending order. It causes increasing the differences between its values for different cases of inter-turn shortenings. Thus, the Fibonacci sequence can be effectively used for the identification process.

Values of matrix's elements X_4 have been determined by means of appropriate arithmetic means for matrix's elements X_3 by means of the formula:

$$X_{4(i)} = \lfloor m_{1(i)}, m_{2(1)} \rfloor; \quad i \in \langle 1,7 \rangle \tag{12}$$

However, values of arithmetic mean m_1 and m_2 have been calculated in the following way:

$$m_1 = \frac{\sum_{j=1}^{1000} X_{3(i)}}{1000}; \quad i \in \langle 1,7 \rangle \tag{13}$$

$$m_2 = \frac{\sum_{j=1001}^{2000} X_{3(i)}}{1000}; \quad i \in \langle 1,7 \rangle \tag{14}$$

Value of sum s_1 for every physical quantity has been determined by means of the formula:

$$s_{1(i)} = \sum_{j=1}^{12} X_{8(i)(j)}; \quad i \in \langle 1,7 \rangle \tag{15}$$

where:
X_8 – values of matrix's elements X_8 determined in the test.

For the purpose of determining of matrix's elements X_8 it is necessary using of the formula:

$$X_{8(i)(j)} = \begin{cases} \left(\frac{(X_{7(i)(j)} - a_{5(i)})}{(a_{6(i)} - a_{5(i)})} \right) * (a_{8(i)} - a_{7(i)}) + a_{7(i)}; \\ i \in \langle 1,7 \rangle; \; j = 1,2 \ldots 12 \end{cases} \tag{16}$$

where:
a_5 – the minimal value of matrix's elements X_7 determined in the test,
a_6 – the maximal value of matrix's elements X_7 determined in the test,
a_7 – the initial value of the range containing normalized values X_8 determined in the test,
a_8 – the final value of the range containing normalized values X_8 determined in the test,
i – a number of tested case of inter-turn shorting.

Therefore, values of variables a_5 and a_6 have been calculated in the following way:

$$a_{5(i)} = \min\left(X_{7(i)(j)}\right); \quad i \in \langle 1,7 \rangle; \; j = 1,2 \ldots 12 \tag{17}$$

$$a_{6(i)} = \max\left(X_{7(i)(j)}\right); \quad i \in \langle 1,7 \rangle; \; j = 1,2 \ldots 12 \tag{18}$$

Determining of values of variables a_7 and a_8 have been realized by means of using formulas:

$$a_{7(i)} = X_{5(i)(4)}; \quad i \in \langle 1,7 \rangle \tag{19}$$

$$a_{8(i)} = X_{5(i)(5)}; \quad i \in \langle 1,7 \rangle \tag{20}$$

Values of matrix's elements X_7 represent calculated sums of coefficients obtained as a result of a discrete wavelet transformation for every tested physical quantity calculated on every level decomposition according to the formula:

$$X_{7(a)(i)} = \sum_{j=1}^{4096} X_{6(a)(i,j)}; \quad a \in \langle 1,7 \rangle; i = 1,2 \ldots 12 \qquad (21)$$

where:

X_6 – values of the matrix's elements X_6 containing calculated coefficients of discrete wavelet transformation determined in the test,

a – a number of tested case of inter-turn shorting,

i – an index number within the X_6 matrix.

The decision tree applied in the proposed algorithm enables correct inter-turn shorting's identification by means of calculated values s_1.

The correct identification of the number for inter-turn shorting follows as a result of obtaining the value of sum s_1 located in the range determined for tested inter-turn shorting.

The range for every number of inter-turn shorting has been determined by means of calculation s_1 for simulation test executed in the test group with the load current equal to 1 A and also for simulation test executed in the test group with the load current equal to 5 A.

Therefore, the calculated value of s_1 for the purpose obtaining of the correct identification of number for inter-turn shorting must fulfill the following condition according to the formula:

$$s_{1(i)} \in \left\langle a_{9(i)(c)}, a_{10(i)(d)} \right\rangle; \quad i \in \langle 1,7 \rangle \qquad (22)$$

where:

a_9 – the minimal value determined in the test for calculated values s_1,

a_{10} – the maximal value determined in the test for calculated values s_1,

c – test executed for load current equal 1 A,

d – test executed for load current equal 5 A.

Values of variables a_9 i a_{10} have been by means of the formulas:

$$a_{9(i)} = \min\left(s_{1(i)(c)}, s_{1(i)(d)}\right); \quad i \in \langle 1,7 \rangle \qquad (23)$$

$$a_{10(i)} = \max\left(s_{1(i)(c)}, s_{1(i)(d)}\right); \quad i \in \langle 1,7 \rangle \qquad (24)$$

For all tested physical quantities have been calculated three ranges with using of the following formulas:

$$s_2 = \left\langle a_{9(2)(a)}, a_{10(2)(b)} \right\rangle; \quad i \in \langle 1,7 \rangle \qquad (25)$$

$$s_3 = \left\langle a_{9(4)(a)}, a_{10(4)(b)} \right\rangle; \quad i \in \langle 1,7 \rangle \qquad (26)$$

$$s_4 = \left\langle a_{9(6)(a)}, a_{10(6)(b)} \right\rangle; \quad i \in \langle 1,7 \rangle \qquad (27)$$

where:

c – tests executed for load current equal 1 A,

d – tests executed for load current equal 5 A.

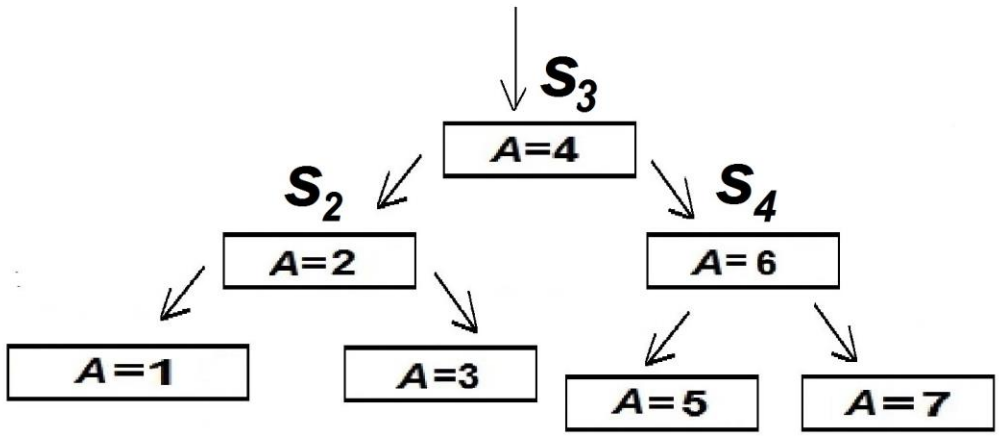

Figure 3: Presentation of operation diagram for used decision tree. On figure symbols described by means of letter *A* concern tested cases of inter-turn shorting.

Calculated three ranges s_2, s_3 and s_4 have been used in the decision tree for identification inter-turn shorting. In this way, it is possible to fast and effective identification process.

In case if calculated value s_1 is not located in one with determining ranges and is less than lower boundary of the tested range it this value is tested with the next determined range and located after the left side of the decision tree. Otherwise, value s_1 is tested with the next determined range and located after the right side of the decision tree.

Tested inter-turn shortings	***Results of calculations for s_1***	***Results of calculations for s_2, s_3 and s_4***
between coil 1 and coil 5, load current 1 A	**2.721**	<1.355, 1.764 > <5.395,5.694> <10.047, 10.143>
between coil 1 and coil 3, load current 2 A	**1.557**	
between coil 1 and coil 25, load current 3 A	**11.717**	
between coil 1 and coil 2, load current 4 A	**1.001**	
between coil 1 and coil 15, load current 5A	**7.870**	

Table 1: Selected calculated values for phase voltage u_1 in tested induction motor

Tested inter-turn shortings	***Results of calculations for s_1***	***Results of calculations for s_2, s_3 and s_4***
between coil 1 and coil 2, load current 1 A	**1.919**	
between coil 1 and coil 5, load current 2 A	**5.246**	<2.773, 3.458>
between coil 1 and coil 10, load current 3 A	**10.666**	<10.290, 10.705>
between coil 1 and coil 20, load current 4 A	**19.211**	<19.039, 19.541 >
between coil 1 and coil 25, load current 5 A	**22.532**	

Table 2: Selected calculated values for signal proportional to magnetic axial flux ϕ in tested induction motor

Tested inter-turn shortings	***Results of calculations for s_1***	***Results of calculations for s_2, s_3 and s_4***
between coil 1 and coil 15, load current 1 A	**11.472**	
between coil 1 and coil 10, load current 2 A	**8.856**	<2.026, 2.854 >
between coil 1 and coil 3, load current 3 A	**2.527**	<7.976, 9.179 >
between coil 1 and coil 25, load current 4 A	**19.625**	<16.074, 16.561 >
between coil 1 and coil 2, load current 5 A	**1.963**	

Table 3: Selected calculated values for vibration acceleration a_x for axis x in tested induction motor

In Table I to Table V, the column labeled *Tested inter-turn shortings* contains shortings identified in the tests for exemplary physical quantities. However, the column *Results of calculations for* s_2, s_3 *and* s_4 comprises the bolded final results of calculations of sum's value s_1.

Bolded values of sum s_1 in Table I to Table V are correct results obtained finally in the process of identification of the inter-turn shortenings.

Tested inter-turn shortings	***Results of calculations for*** s_1	***Results of calculations for*** s_2***,*** s_3 ***and*** s_4
between coil 1 and coil 25, load current 1 A	**24.282**	<2.991, 3.789> <11.058, 11.700 > <20.708, 20.945 >
between coil 1 and coil 20, load current 2 A	**20.751**	
between coil 1 and coil 2, load current 3 A	**1.733**	
between coil 1 and coil 3, load current 4 A	**2.988**	
between coil 1 and coil 5, load current 4 A	**4.855**	

Table 4: Selected calculated values for rotational speed n in tested induction motor

Tested inter-turn shortings	***Results of calculations for*** s_1	***Results of calculations for*** s_2***,*** s_3 ***and*** s_4
between coil 1 and coil 2, load current 2 A	**1.508**	<1.866, 2.764> <9.761 , 10.356 > <19.734, 19.951 >
between coil 1 and coil 25, load current 2 A	**23.117**	
between coil 1 and coil 15, load current 3 A	**14.952**	
between coil 1 and coil 10, load current 4 A	**9.997**	
between coil 1 and coil 5, load current 5 A	**3.595**	

Table 5: Selected calculated values for current in the short-circuited winding i_z in tested induction motor

3 Conclusions

Presented system of inter-turn shorting's detection contained algorithm decision tree enabling correct fault identification as a result of changes of values coefficients for wavelet decomposition and concerning of tested physical quantities. The identification process has been executed by means determined by the Fibonacci sequence.

Applied discrete wavelet transformation in a noticeable way increases the efficiency of analysis of non-stationary signals. This method, used in the diagnostic system, can identify in a good way of appearing of inter-turn shorting because effects of her use can be used on the calculated sums as a result of normalization executed for coefficients of the discrete wavelet decomposition. Executing of simulation tests confirmed functioning of proposed methodology of inter-turn shorting detection.

On the basis of executed simulation tests, it can notice, that ensuring appropriate ranges of changes of parameters for the Fibonacci sequence as well as coefficients of discrete wavelet decomposition enables obtaining of big efficiency of detection's process and inter-turn shorting identification.

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