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Three-phase current sensor for motor protection against turn-to-turn and phase-to-phase short circuits

Three-phase current sensor for motor protection against turn-to-turn and phase-to-phase short circuits

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Abstract. The main causes of electric motor failures are transients at power supply interruption and short circuit in stator windings. Most of the failures are due to short circuits. Phase-to-phase short circuits refer to the most severe damage of electrical installations, which are also dangerous for other intact electric consumers. Therefore, electrical plants require a high-speed protection against phase-to-phase short circuits in the stator windings and connections with the commutator. The most difficult to detect are turn-to-turn (or inter-turn) faults in stator windings, especially when a small number of winding turns is shorted. Currently, there is no standard way to detect turn-to-turn short circuits in stator windings. It is difficult to detect turn-to-turn fault in magnitude of phase currents, so it is complicated to provide sufficient protection sensitivity. Thus, the development of new protection devices for detect turn-to-turn short circuit is considered relevant. The article presents a three-phase current sensor based on measuring the magnetic field from the three phases simultaneously. This method will identify turn-to-turn and phase-to-phase short circuits by magnetic-field pattern. The presented method increases the protection sensitivity and speed of protection response. The effectiveness of the proposed method is demonstrated by mathematical modeling.

Keywords: electric motor, turn‑to‑turn short circuit, phase-to-phase short circuit, short-circuit protection, three-phase current sensor, magnetic field, magnetosensitive element, magnetic-field pattern, finite element method, simulation.

1. Introduction
Electric motors are the main consumers of electrical energy in industrial enterprises. Therefore, failure of the electric motor can cause heavy damage. Early detection of abnormalities during motor operation would eliminate subsequent damage and reduce repair cost and motor outage time [1].

Stator faults are about 30-40% of failures of motors [2]. It is necessary to highlight turn-to-turn and phase-to-phase short circuits among other failure causes.

A turn-to-turn fault is a short circuit between two turns of same phase [3]. Turn-to-turn faults are usually the result of the development of a frame fault, local insulation overheating and defects of the active stator steel or the result of the breakdown of the stator phase in the case. They are a dangerous type of damage and are characterized by the flow of high currents in shorted turns with a slight change of the current in the undamaged part of the winding.

In contrast to phase-to-phase short circuits, turn-to-turn short circuits occur only in the motor frame. A phase-to-phase fault is a short circuit between any two phases [4]. They are accompanied by

high currents, several times higher than the rated stator current, and voltage reduction in the supply main. In order to prevent failures, it is necessary to use motor protection.

Differential protection is used to protect a motor against phase-to-phase short circuits [5]. Differential protection provides high sensitivity to short circuits on the terminals and in the windings of an electrical installation, but cannot detect turn-to-turn short circuits [6].

Standard motor protection is generally not designed to detect a turn-to-turn short-circuit. The operating values of such devices are usually limited by necessity of offset from the phase current unbalance, caused by other factors of line voltage unbalance, stator winding asymmetry, etc.

Many different methods have been developed for detecting turn-to-turn short-circuits. Motor Current Signature Analysis (MCSA) is the most preferred method [7] for diagnosing failures in both induction [8] and synchronous motors [9].

In [10], described the use of the extended Park's vector approach (EPVA) for diagnosing the occurrence of stator winding faults in operating three-phase motors. A comparative study a new method, called Park–Hilbert (P–H), with the MCSA and EPVA method is performed in [11].

In [12], a method is described, based vibration signature analysis.

Modeling, study and determining the parameters of motors with turn-to-turn insulation fault is first step in the development of fault diagnosis and fault tolerant machine design [13].

Finite element method (FEM) is used for parameter identification of the motor under fault condition in [14-16].

However, there is still no single method for detection of turn-to-turn short circuits.

Accordingly, the development of new principles and protection devices that detect turn-to-turn faults is considered relevant.

The key problem in the development of turn-to-turn fault protection is the difficulty to detect these short circuits in magnitude of phase currents in the traditional phase-by-phase measurement.

As a result of the research, the three-phase current sensor was developed for control and protection system of an electric motor, based not on phase-by-phase current measurement, but on measuring the magnetic field from three phases simultaneously.

The purpose of this article is to present the developed three-phase current sensor for motor protection against turn-to-turn and phase-to-phase short circuits and its effectiveness. This is achieved by modeling of the magnetic field in ELCUT software using calculation of phase currents in MATLAB/Simulink software.

2. Materials and Methods

The patent has been obtained for the developed three-phase current sensor [17]. The description of this device is given below.

The sensor case is made of ferromagnetic material to reduce the influence of external magnetic fields on the sensor readings. In the center of the case at the same distance from the grooves for the power cables of the phases there is a sensor device for measuring the magnetic induction vector. Magnetoresistors KMZ 10A and KMZ 10C are used as a sensor device.

According to electromagnetic field theory, a rotating magnetic field with a rotation frequency equal to a frequency of the supply voltage will be created in the center of the device, where the magnetoresistors are located orthogonal.

Magnetoresistors of the current sensor perceive the magnetic component of the three-phase system that rotates in space. The "rotating in space" vector of the generalized current from three phases is proportional to the magnetic component.

The microprocessor presents output in the form of a fixed vector in the coordinate system that rotates with the frequency of three-phase currents [18]. The generalized current will be equal to the value of the phase current increased by one and a half times for a symmetric system of three-phase currents [19].

The change of magnetic-field pattern, which the current sensor registers during one complete period, is a consequence of the emergency mode of the monitored electric network.

Figure 1 shows the three-phase current sensor for motor protection against turn-to-turn and phase-to-phase short circuits.
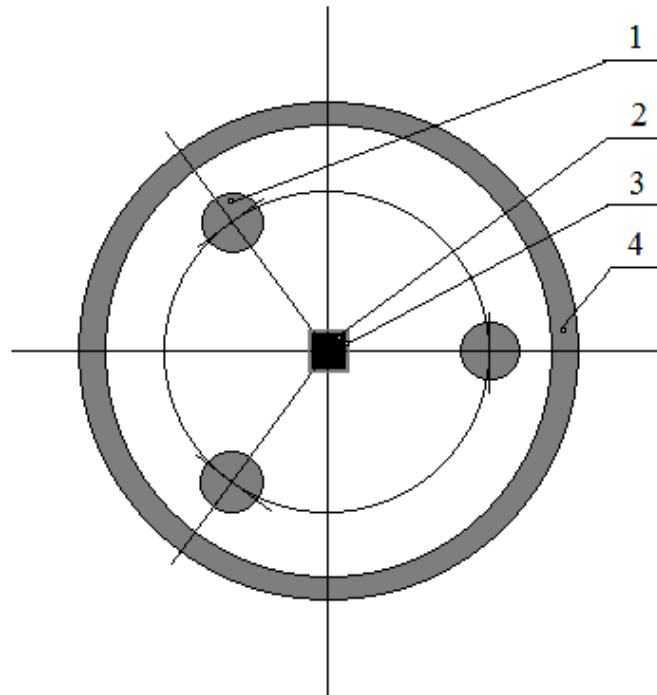

Figure 1. Three-phase current sensor for motor protection against turn-to-turn and phase-to-phase short circuits: 1 – power cable of the phase; 2 – sensor device; 3 – microprocessor; 4 – ferromagnetic case.

Due to the use of this device, there is no need to install a current transformer for each phase, but only one as a magnetic field sensor, which measures the total magnetic field of the three phases.

The speed of protection response will be provided by reducing current unbalance that usually caused by non-identical characteristics of current transformers.

The device operation principle is described below.

The sensor device measures the magnetic field that produced by conductors. The magnetic-field pattern will identify the type of emergency. The magnetic field at the center of the device will be rotating field in balanced conditions, unlike emergency conditions.

3. Results

The mathematical model of calculation of phase currents for a three-phase device (an induction motor) in MATLAB/Simulink software, taking into account the presence of turn-to-turn short circuits in phase A (figure 2) is developed. The basis is the method of determining the parameters of the motor and phase currents described in [20-21].

Due to turn-to-turn short circuits, an unbalance of the phase resistances and stator current unbalance occur. In shorted turns, a high current appears. In this, the main magnetic field in the motor remains close to circular.

The analysis of currents for phase-to-phase short circuit is performed for a solid short circuit. The currents of faulty phases will be equal, increased in amplitude and opposite in phase in a two-phase circuit, and the current of fault-free phase will be zero. Phase currents will be equal and increased in amplitude in a three-phase circuit [22].
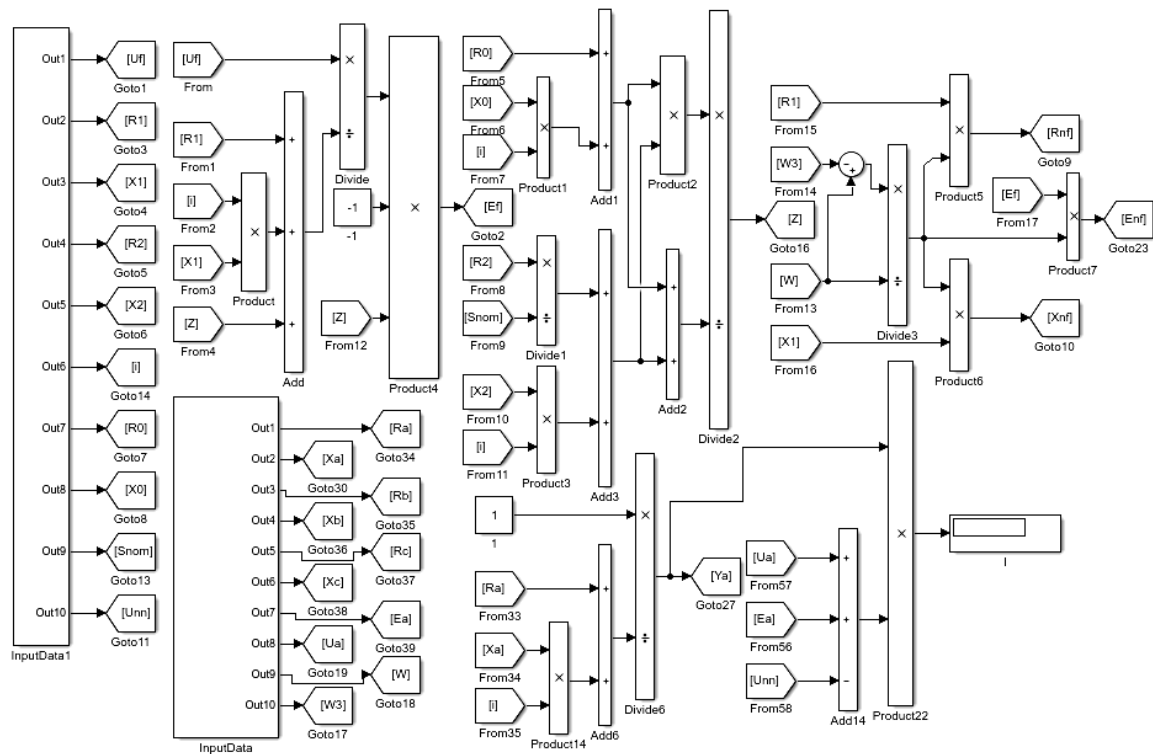
Figure 2. Mathematical model for calculating phase currents in MATLAB/Simulink software.

The model of the magnetic field in the center of the current sensor in ELCUT software in balanced conditions and in emergency conditions using the results of the model in MATLAB/Simulink software and vector diagrams [23] is developed. At low frequencies, the magnetic field in a first approximation can be considered quasi-stationary. Therefore, the vector magnetostatic model can be used.

Figure 3 shows the finite element model of the proposed device. Figure 4 shows the pattern of magnetic-field vectors (*H*) in balanced conditions for one complete period of system simulation.
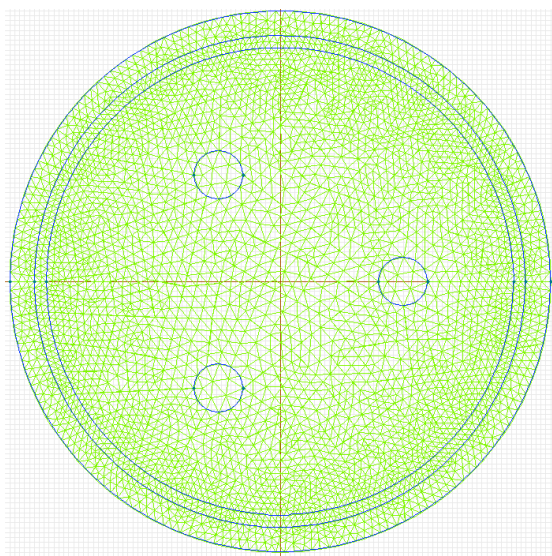

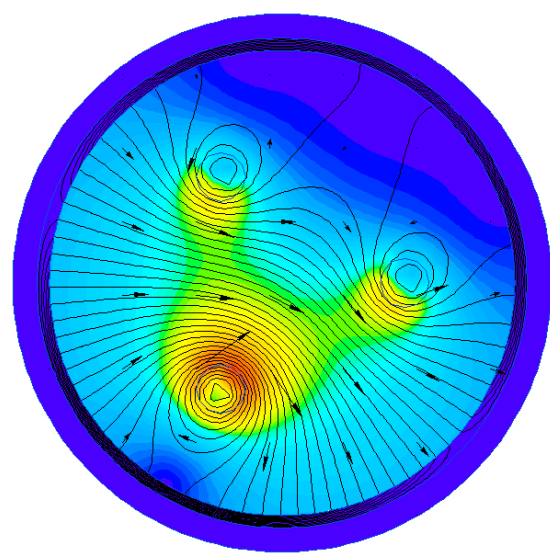**Figure 3.** Finite element model.

Figure 4. Magnetic-field pattern.

Table 1 shows the results of measuring the local values of the module of the magnetic field strength (H) and its projections (H_X and H_Y) for balanced conditions. Input data is current densities in phases (δ_A, δ_B and δ_C). The phases of the magnetic-field vector (Ψ_H) were calculated. The measurements were conducted at 13 stages to obtain the hodograph of the magnetic-field vector [24] for one complete period in all the studied modes.

Table 1. Measurement results of local values (balanced conditions).

Stage	Phase ($^\circ$)	δ_A (A/m^2)	δ_B (A/m^2)	δ_C (A/m^2)	H (A/m)	H_x (A/m)	H_y (A/m)	ψ_H ($^\circ$)	B (mT)
1	0	0	-2206542	2206542	4620,9	4620,9	-17,1	359,79	5,81
2	30	1273948	-2547895	1273948	4626,1	4002,0	-2320,6	329,89	5,81
3	60	2206542	-2206542	0	4621,4	2310,7	-4002,2	300,00	5,81
4	90	2547895	-1273948	-1273948	4611,5	0,4	-4611,5	270,00	5,80
5	120	2206542	0	-2206542	4606,0	-2310,1	-3985,2	239,90	5,79
6	150	1273948	1273948	-2547895	4611,0	-4001,6	-2291,0	209,79	5,79
7	180	0	2206542	-2206542	4620,9	-4620,9	17,1	179,79	5,81
8	210	-1273948	2547895	-1273948	4626,1	-4002,0	2320,6	149,89	5,81
9	240	-2206542	2206542	0	4621,4	-2310,7	4002,2	120,00	5,81
10	270	-2547895	1273948	1273948	4611,5	-0,4	4611,5	90,00	5,80
11	300	-2206542	0	2206542	4606,3	2310,1	3985,2	59,90	5,79
12	330	-1273948	-1273948	2547895	4611,0	4001,6	2291,0	29,79	5,79
13	360	0	-2206542	2206542	4620,9	4620,9	-17,1	-0,21	5,81

Simulation results for turn-to-turn short circuit (10% shorted turns in phase A) are presented in Table 2. The current density is calculated using the currents of mathematical modeling in MATLAB/Simulink software.

Table 2. Measurement results of local values (turn-to-turn short circuit).

Stage	Phase ($^\circ$)	δ_A (A/m^2)	δ_B (A/m^2)	δ_C (A/m^2)	H (A/m)	H_x (A/m)	H_y (A/m)	ψ_H ($^\circ$)	B (mT)
1	0	833114	-2626609	2179253	5195,9	5032,4	-1293,1	345,59	6,529
2	30	2083993	-2651294	1258192	5302,2	4094,1	-3369,1	320,55	6,663
3	60	2776469	-1965567	0	4987,1	2059,9	-4542,3	294,39	6,267
4	90	2724991	-753168	-1258192	4529,3	-528,1	-4498,4	263,30	5,692
5	120	1943355	661042	-2179253	4404,5	-2973,6	-3249,2	227,54	5,535
6	150	640998	1898126	-2516384	4758,2	-4622,3	-1129,3	193,73	5,979
7	180	-833114	2626609	-2179253	5195,9	-5032,4	1293,1	165,59	6,529
8	210	-2083993	2651294	-1258192	5302,2	-4094,1	3369,1	140,55	6,663
9	240	-2776469	1965567	0	4987,1	-2058,9	4542,3	114,38	6,267
10	270	-2724991	753168	1258192	4529,3	529,1	4498,4	83,29	5,692
11	300	-1943355	-661042	2179253	4404,5	2973,6	3249,2	47,54	5,535
12	330	-640998	-1898126	2516384	4758,2	4622,3	1129,3	13,73	5,979
13	360	833114	-2626609	2179253	5195,9	5032,4	-1293,1	-14,41	6,529

Similarly, the modeling was performed in other modes. The results are presented in the form of hodographs of the magnetic-field vector in figure 5.
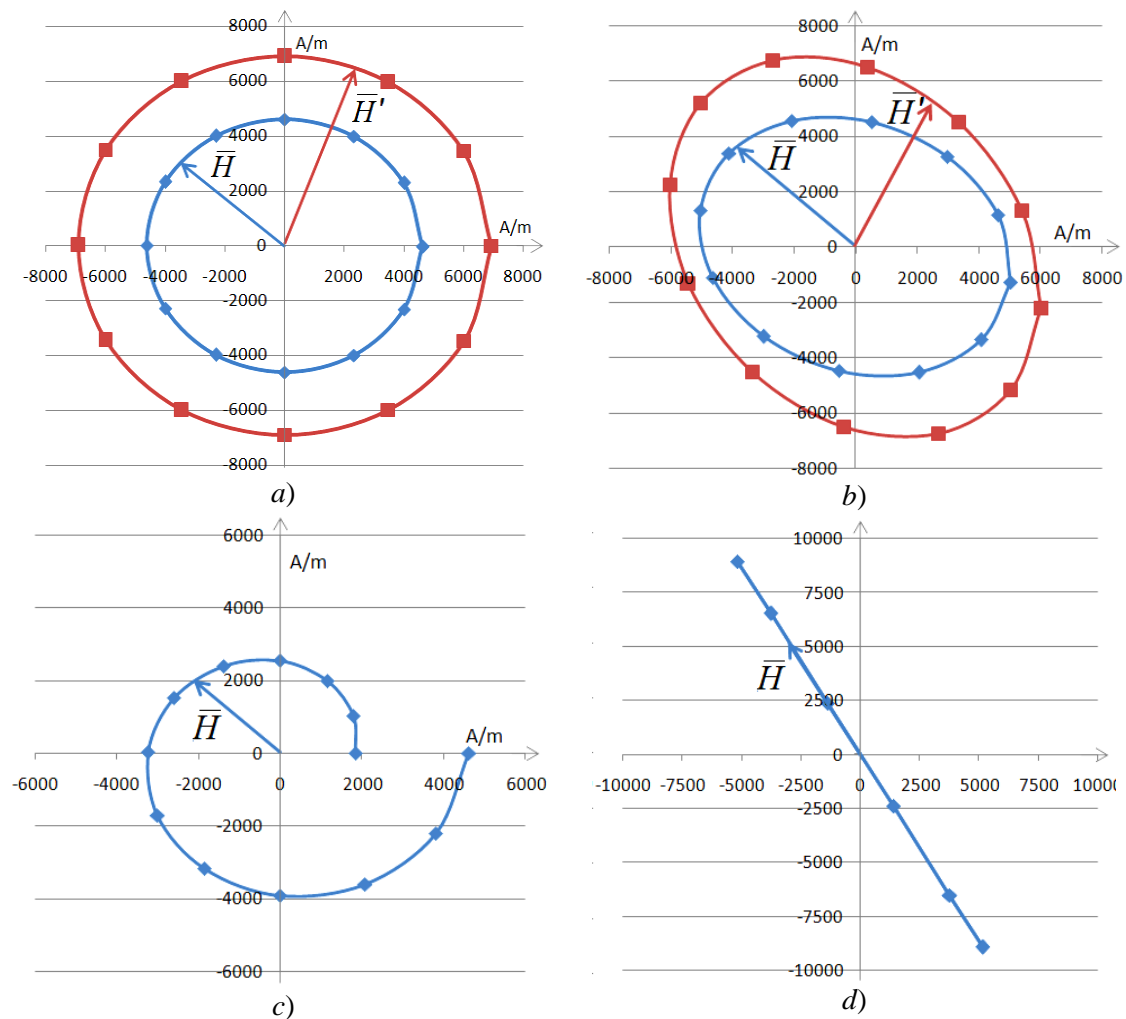
Figure 5. Hodographs of the magnetic-field vector in balanced conditions (*a*), turn-to-turn short circuit (*b*), supply fail (*c*) and external two-phase short circuit (*d*).

4. Discussion

The simulation results show that the three-phase current sensor able to detect turn-to-turn and phase-to-phase short circuits.

Changing magnetic-field pattern to elliptical, spiral or linear means that there is an accident in the measured three-phase system.

The hodograph of the magnetic-field vector will be circular with an amplitude |H| in balanced conditions, and in a three-phase short circuit - with an increased amplitude |H'| (figure 5 (a)).

The hodograph of the magnetic-field vector will be elliptic with an amplitude |H| for 10% shorted turns, and for 30% shorted turns - with an increased amplitude |H'| (figure 5 (b)).

The hodograph of the magnetic-field vector will be spiral with an amplitude |H| for supply fail or overload (figure 5 (c)).

The hodograph of the magnetic-field vector will be linear with variable amplitude |H| for two-phase short circuit (figure 5 (d)).

In the mathematical model, the phase currents were determined without taking into account influence of current unbalance on the main flux of the motor.

This assumption, firstly, allows studying the effect of reducing the number of turns in faulty phase on unbalance of the phase currents without taking into account the influence of other factors. Second-

ly, it simplifies the determination of phase currents without using method of symmetrical components. Thirdly, it introduces a reliability coefficient into the developed relay protection when calculating currents.

The proposed three-phase current sensor can be used in the construction of relay protection and automation devices.

A balanced protection device based on the three-phase current sensor has been developed. But instead of the power cables of the phases, coaxial conductors are used. The input cables of the electrical installation are connected to the current carrying wire, and the return cables of the electrical installation are connected to the outer conductor [25].

Currently, the experimental setup is under development to confirm theoretical conclusions and simulation results.

5. Conclusion

It is necessary to protect a motor against phase-to-phase and turn-to-turn short circuits. Differential protection detects phase-to-phase faults, but does not detect turn-to-turn short circuits. Currently, there is no single method for detecting turn-to-turn faults.

This article presents the three-phase current sensor, using which it is possible to detect turn-to-turn and phase-to-phase short circuits. The proposed device consists of a ferromagnetic case, a microprocessor, power cables of phases and magnetoresistors in the center of the sensor.

The three-phase current sensor measures the total magnetic field from three phases simultaneously. Speed of protection response will increase due to the design of the sensor. The operating principle of the device is to determine the conditions (balanced or emergency) by a magnetic-field pattern.

The model of the magnetic field for balanced conditions and the models of the magnetic field for emergency conditions were developed in ELCUT software. The elliptical, spiral or linear magnetic-field pattern means a violation of the balanced conditions.

The three-phase current sensor can also be used in the construction of relay protection and control system devices of electric motors.

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