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HIGH-FREQUENCY METHODS FOR DETECTING INSULATION DEFECTS IN MESH WINDING GENERATORS OF POWER PLANTS BASED ON RENEWABLE ENERGY SOURCES

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In this article, the main parameters for monitoring the insulation state of the windings of electrical machines are analyzed, the input resistances of the windings are studied as generalized parameters, and the calculation of high-frequency processes in the winding using circuit substitution schemes is carried out. A method for detecting defects in housing insulation is proposed, as well as a method for detecting short-circuited turns in multi-turn general-purpose asynchronous generator. It is shown that resonance phenomena in the absence and presence of a defect in the form of a short-circuited turn of one of the three phases of the winding of an electric machine are of a different nature when artificial resonances are created in the winding at lower or higher frequencies compared to common resonance.

Keywords: *frequency characteristics, inter-turn insulation, multi-turn coils, eddy currents.*

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ВИСОКОЧАСТОТНІ МЕТОДИ ВИЯВЛЕННЯ ДЕФЕКТІВ ІЗОЛЯЦІЇ ВСИПНИХ ОБМОТОК ГЕНЕРАТОРІВ ЕНЕРГОУСТАНОВОК НА ОСНОВІ ВІДНОВЛЮВАЛЬНИХ ДЖЕРЕЛ ЕНЕРГІЇ

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У цій статті проаналізовано основні параметри для контролю стану ізоляції обмоток електричних машин, досліджено вхідні опори обмоток як узагальнені параметри, проведено розрахунок високочастотних процесів в обмотці за допомогою ланцюгових схем заміщення. Запропоновано спосіб виявлення дефектів корпусної ізоляції, а також метод виявлення короткозамкнених витків в багатовиткових асинхронних двигунах

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загального призначення. Показано, що резонансні явища при відсутності та наявності дефекту у вигляді короткозамкненого витка однієї з трьох фаз обмотки електричної машини мають різний характер при створенні в обмотці штучних резонансів на нижчих або вищих частотах порівняно з природним резонансом.

Ключові слова: *частотні характеристики, міжвиткова ізоляція, багатовиткові котушки, вихрові струми.*

Introduction. Pulse width modulated electric drives, static power converters and asynchronous generators are widely used in various industries due to their suitable characteristics and application flexibility [1, 2]. The effects of high-frequency voltage components introduced by the pulse-width modulation method are usually not taken into account when analyzing the electromechanical characteristics of a generator. On the contrary, a high *dV/dt* applied to the generator introduces a small amount of high-frequency leakage currents through the dissipated distributed capacitance between the stator winding and the generator housing. Since the generator housing is usually connected to earth using a grounding circuit, high frequency leakage currents present in the electrical network can cause electromagnetic interference [3].

The high-frequency model proposed in this paper is based on lumped parameters and is related to the classical model of quantitative generator data; it is accurate in the frequency range from several hertz to several megahertz. This type of model avoids the use of distributed parameters and is therefore suitable for circuit simulation. High-frequency phenomena include two main capacitive effects associated with: capacitance between the winding and ground; inter-turn capacitance of the winding. In this work, by means of circuit simulation in specialized software [4], acceptable results were obtained.

Object of research

The object of the study is an autonomous gasoline generator with a capacity of 3.8 kV·A. Structurally, the power electrical installation is a synchronous clear-pole generator with electromagnetic excitation. The parameters of the studied generator and its winding data are given in the Table. 1.

Table 1. Parameters of studied synchronous generator

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№	Parameter	Value
1	Full rated power, kV·A	3.8
2	Nominal line voltage, V	380.0
3	Nominal phase current, A	5.75
4	Number of phases, connection diagram	3/Y
5	The number of turns in the coil	17
6	Diameter of the winding wire, mm	1.0·3
7	Number of parallel branches	1
8	Step of winding along the grooves	17; 15; 13
9	Outer diameter of stator boring, mm	225.0
10	The inner diameter of the stator bore, mm	145.0
11	Active length of the stator magnetic core, mm	80.0
12	The number of stator slots	36
13	Stator winding insulation class	F
14	The size of the air gap, mm	0.5
15	Stator winding weight, kg	4.1

Methods of research

It is obvious that both of the above capacitances are in fact distributed, but as mentioned earlier, the proposed approach is based on lumped parameters [5]. Fig. 1 shows a phase high frequency substitution scheme.

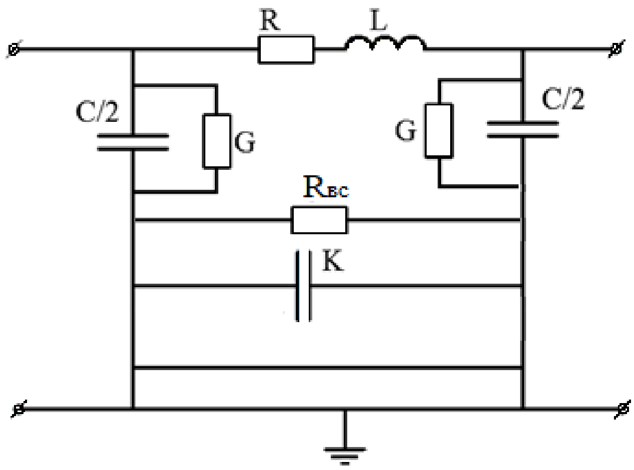

Fig. 1. – Equivalent circuit with lumped parameters

On Fig. 1: R_{ec} – resistance of eddy currents; R – phase resistance of the stator and rotor; L – inductance; K is the longitudinal capacitance representing the inter-turn distributed capacitance; C is the transverse capacitance, which represents the distributed capacitive pairs between the winding and the ground; G is the conductivity, which represents the eddy currents inside the magnetic circuit and the housing.

The parallel connection of the equivalent circuit elements *L* and *K*, as well as *C* and *G*, are generally accepted and do not need additional explanations. Parallel rather than series connection of elements *L* i *r* follows from simple physical considerations. The eddy currents induced in the steel sheets of the stator and rotor are, as it were, the secondary currents of the transformer. As is known, it is convenient to represent the equivalent circuit of a transformer as a parallel connection of the reactance corresponding to the primary winding and the loading resistance representing the secondary winding [6].

It is important to emphasize that the quantities must be considered as values relating to the star connected phase. The winding up to the distributed capacitance was represented by two combined capacitances of the same value, the first of which was connected between the phase terminal and ground, and the second between the generator neutral and ground. A star connection of the generator is envisaged, but the delta connection of the generator does not invalidate the model justification.

Phase resistance *R* and phase inductance *L* at 50/60 Hz obtained from closed-loop tests. As the results of the experiment showed, the generator response quickly fades over time. The typical resistance values *R* are too low to explain the observed damping [7].

An analysis of the physical phenomenon leads to the assumption that the damping factor is associated with the fact of energy dissipation at high-frequency eddy currents. As a consequence, the resistance *R*, which represents eddy currents, must be connected in parallel with the leakage inductance. To characterize the generator in the high frequency range, it is possible to assess the frequency response of the two impedances given in Fig. 2, a and Fig. 2, b.

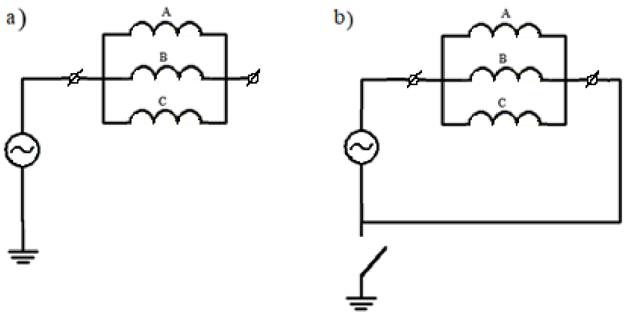

Fig. 2 – Connections for measuring impedance: a) Z_{wg}; b) Z_{wn}

The impedance Z_{wn} is the result of a measurement between three phases connected together with the generator neutral, with a floating earth (Fig. 2, a). The impedance Z_{wg} is the result of the measurement between the generator three phases connected together and the earth terminal, with the generator floating neutral (Fig. 2, b).

In the considered frequency range, the phase resistance *R* is much less than the inductance L [8]. In the following reasoning, the stator resistance can be neglected. Circuit impedances in Fig. 2, a and Fig. 2, b can be easily evaluated by simulation in various circuit simulation applications [4]. Below are the simulation diagrams (refer to Fig. 3).

The evaluation of the parameters used in the substitution scheme was calculated from the frequency characteristics taken on the generator.

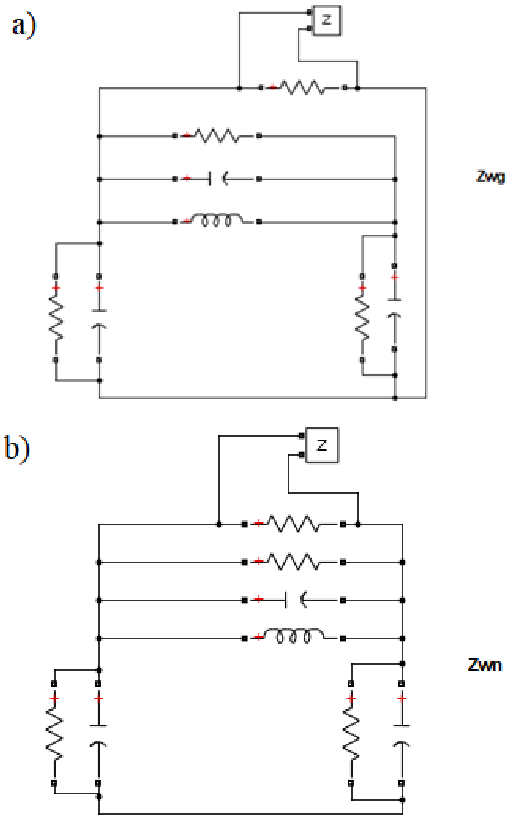

Fig. 3 – Electrical circuits for simulation: a) impedance Z_{wg}; b) impedance Z_{wn}

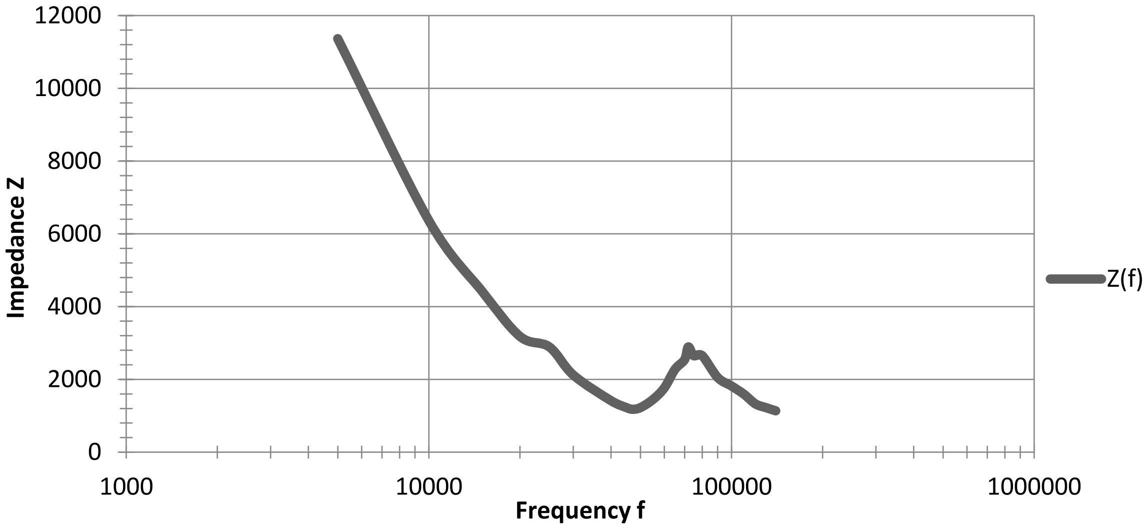

Fig. 4 – Experimental results for the frequency response of the impedance Z_{wg}.

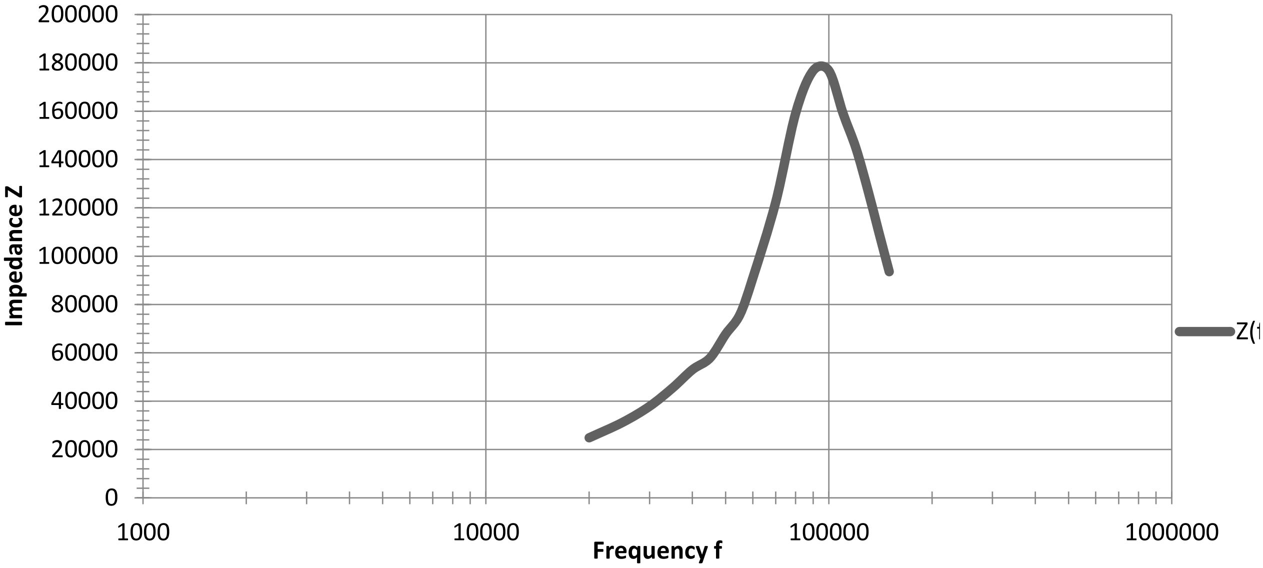

Fig. 5 – Experimental results for the frequency response of the impedance Z_{wn}.

A comparison between experimental and simulation results is shown below. Fig. 4 and Fig. 5 show the experimentally measured frequency responses. Fig. 6 and Fig. 7 show the frequency response simulation results.

Defect detection

The reliability problem of inter-turn insulation of electrical machine windings is relevant and demands the creation of effective methods and devices which are based on the comparison of the input active-inductive parameters of the windings. The most sensitive to inter-turn short circuits are bridge circuits for connecting windings to a test voltage source with subsequent processing of the received diagnostic signal.

Based on the analysis of the effect of a short-circuited turn

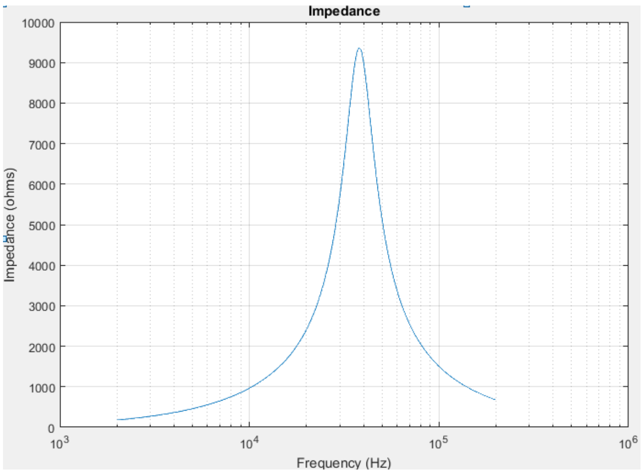

Fig. 6 – Simulation results for frequency response of the impedance Z_{wg}.

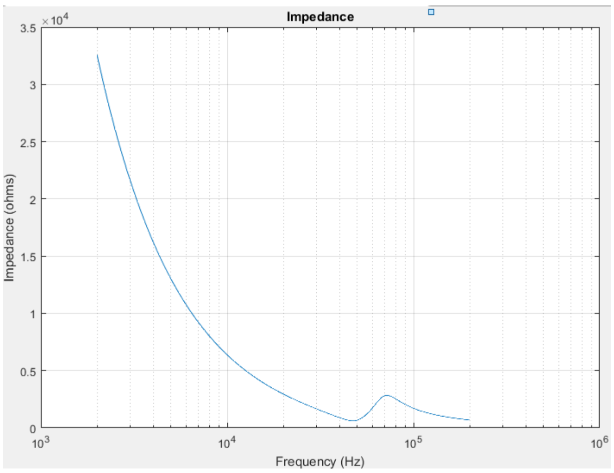

Fig. 7 – Simulation results for frequency response of the impedance Z_{wn}.

tools and equipment for diagnosing windings, in particular, this applies to windings of electrical machines with a large number of turns, in which the detection of one or more short-circuited turns is a difficult task and requires the creation and use of sensitive equipment [2].

An analysis of the sensitivity to turn-to-turn short circuits and the reliability of the control of inter-turn insulation of various connection schemes for the asynchronous generator windings and known from the literature and developed devices for monitoring the inter-turn insulation of the windings of electrical machines shows that the most

on the active-inductive parameters of the phases of the asynchronous generator windings, it was proposed that short-circuited turns should be detected by changing the quality factors of the phases

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{1}{R}\sqrt{\frac{L}{1/L\omega^2}} = \omega\frac{R}{L},$$

since $\omega = 1/\sqrt{LC}$ due to a short-circuited coil at the optimal frequency f_{opt}, corresponding to the greatest impact of a short-circuited turn on the active resistance of this phase. At this frequency, the quality factor of the winding has a maximum value, and the active losses in the winding copper are equal to the active losses in steel [9].

In order to obtain maximum sensitivity to inter-turn short circuits, two or three phases of the winding are connected according to the bridge scheme to the circle of the self-oscillator (Fig. 8) and in series with the inductance *L* of each of the phases, an additional capacitance *C* is connected such that a resonant mode is created at the frequency f_{opt}:

$$f_0 = f_{opt} = 1/2\pi\sqrt{LC}\ .$$

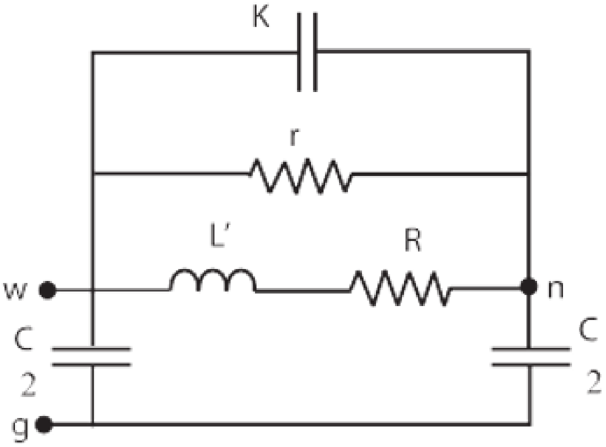

Fig. 8 – Proposed circuit diagram of the high frequency phase

When connecting the windings of asynchronous generators according to the bridge scheme in Fig. 9, the unbalance voltage of the bridge U_{12} is affected by the technological asymmetry of the phase parameters, and the main reason for the asymmetry is the capacitive asymmetry, which is expressed in the difference between the interphase capacitances between nodes 1-3 and 2-3. Capacitive asymmetry in the windings of generators reaches up to 20% and is systematic [10]. Then, if the phase-to-phase capacitances between the above nodes in Fig. 9, a differ by Δ*C* (parameters R_f and L_f are determined considering phase-to-phase capacitances in the absence of asymmetry) by equivalent transformations at a frequency f_0, it is possible to go from the scheme in Fig. 10, a, to the scheme in Fig. 10, b, where equivalent values for *R* and *C*:

$$\frac{\Delta R}{R} = 6\frac{\Delta C}{C}\left(1 - \frac{\Delta C}{C}\left(\frac{1}{Q} + \frac{1}{Q^2}\right)\right).$$

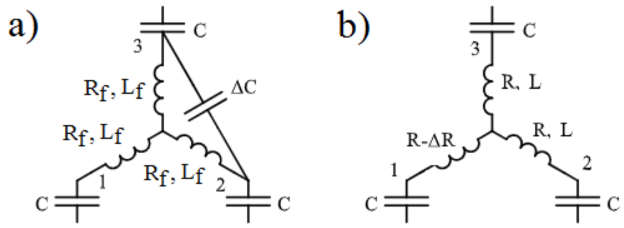

Fig. 10 – Substitution schemes for electrical machine winding: a) scheme with capacitive asymmetry; b) circuit equivalent

Fig. 11 and Fig. 12 show graphs of impedance versus frequency of the input voltage. Fig. 12 shows a graph of impedance versus frequency when the generator is turned on in an idle circuit, resonance is observed at a frequency of 72 kHz. In Fig. 12 the experiment was carried out with a defect, one short-circuited turn, respectively, the resonance is observed at a frequency of 78 kHz. The frequency difference between a winding without a defect and a winding with a short-circuited turn is 6 kHz, which is a significant value that is easy enough to fix using conventional equipment. The input impedance at the resonant frequency in the first case is 2892.71 Ohms, and in the second case 2447.67 Ohms, the relative difference between the values is 18.2%, which is also quite easy to determine using conventional devices.

The graphs depicted in Fig. 11, c and in Fig. 11, d also show the dependence of the impedance on the frequency when turned on at idle, but with a capacitance of 4700 μF connected to the housing in order to shift the resonant frequency to lower frequency domain. In this case, the resonant frequencies are 38 kHz for an experiment without a defect (Fig. 11, c) and 40 kHz for an experiment with a defect (Fig. 11, d) with one short-circuited turn. The frequency difference between the winding without a defect and the winding with a short-circuited turn is 2 kHz, which is not as noticeable as in the above experiments. The input resistance at the resonant frequency in the first case is 9358.766 Ohms, and in the second case 8838.835 Ohms

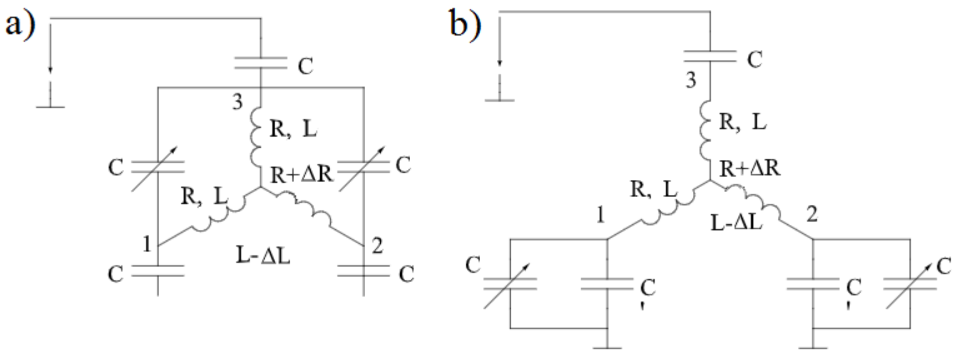

Fig. 9 – Compensation schemes for technological phase asymmetry

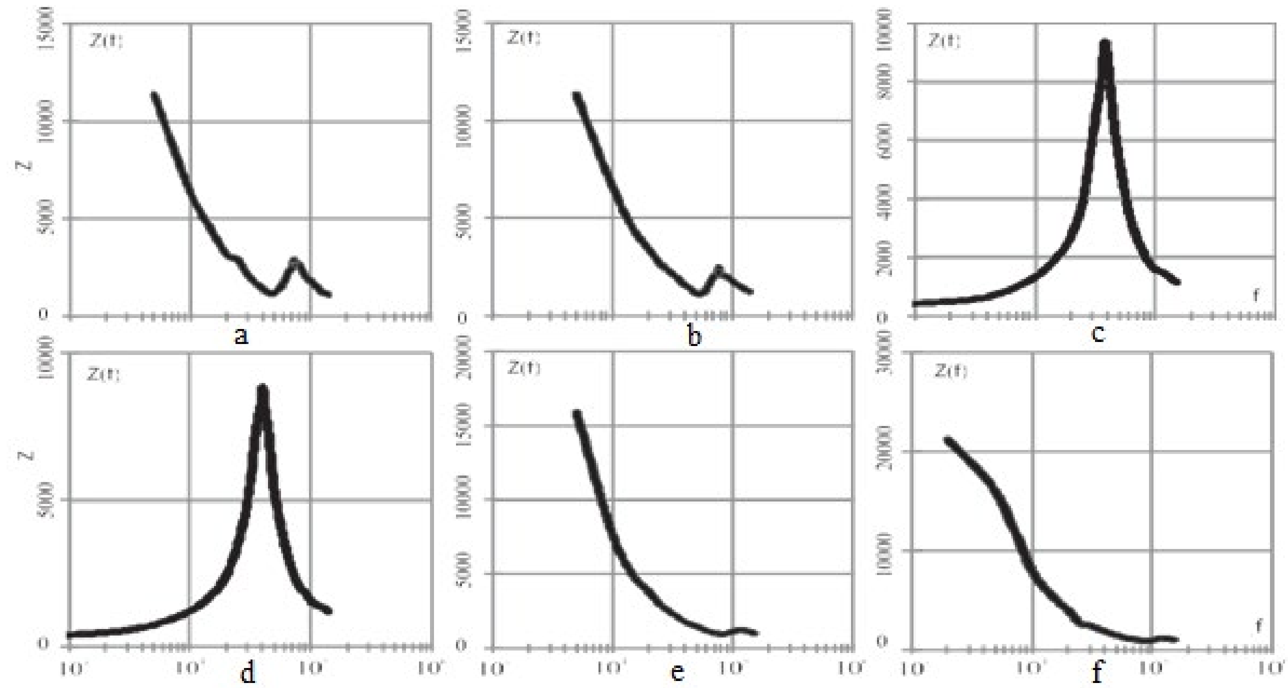

Fig. 11 – Dependence plot Z(f) for the connection scheme at idle:
a) resonance at a 72,000 Hz frequency; b) with a defect (one turn is short-circuited), resonance at a 78,000 Hz frequency; c) with an additional connection of a 4700 μF capacitance to the housing, resonance at a 38,000 Hz frequency; d) with an additional connection of a 4700 μF capacitance to the housing and a defect (one turn is short-circuited), resonance at a 40,000 Hz frequency; e) with an additional connection of a 4700 μF capacitance in parallel to the phase, resonance at a 117,000 Hz frequency; e) with an additional connection of a 4700 μF capacitance in parallel with the phase and a defect (one turn is short-circuited), resonance at a 120,000 Hz frequency

and the relative difference between the values is 5.9%. Therefore, connecting a capacitance to the housing is not useful for detecting defects in the winding.

Subsequent experiments were carried out to connect an additional capacitance of 4700 μF in parallel with the generator phase, which made it possible to shift the resonant frequency to higher frequency domain. For this case, the resonant frequency is 117 kHz for an experiment without a defect and 120 kHz for an experiment with a short-circuited turn, the frequency difference is also small, as in the previous experiment, only 3 kHz. The input impedance at the resonant frequency for an experiment without a defect is 1223.839 Ohm, and for an experiment with a short-circuited turn is 1178.511 Ohm, the relative difference between the values reaches 3.8%. According to literature sources, it was established that at the frequency corresponding to the maximum quality factor, the active resistance of the winding is mainly determined by active losses in copper, and at higher frequencies – by active losses in the steel of the magnetic circuit. Further, it was found that during inter-turn short circuit due to the current in the short-circuited turn, the active losses in the copper coils sharply increase, which leads to an increase in the total losses in the copper winding.

At the same time, due to the demagnetizing effect of the current in the short-circuited turn, the flux of mutual induction between the turn and the coil decreases, leading to a decrease in inductance and active losses in the steel of the magnetic core. The conducted studies on the change in the high-frequency parameters of the winding in the presence of a short-circuited turn in the coil of the asynchronous generator showed that a decrease in inductance by 5% and an increase in active losses in steel by 5% correspond to the calculation of the high-frequency process shown in Fig. 12, b, d, e.

The use of frequency characteristics to control the insulation of multi-turn coils of electrical machines is possible in the following ways:

1) Setting the resonant frequency for the three phases of the windings and comparing them with each other.

2) Setting the value of the input resistance of each phase and also in comparing them with each other.

Technological asymmetry caused by underwinding or phase overwinding leads to approximately the same change in $\Delta R/R$ and $\Delta L/L$. Therefore, by connecting additional capacitances C_1 and C_2 and adjusting them according to the scheme in Fig. 9, a it is possible to fully compensate the capacitive asymmetry of the winding and only partially compensate active-inductive asymmetry. Also, when connecting capacitances according to the scheme in Fig. 9, b, the active-inductive asymmetry can be compensated completely, the capacitive asymmetry can be partially compensated.

Based on the analysis of sensitivity to inter-turn short circuits and the reliability of control, it was found that devices of the EL-I type are based on a comparison of two voltage curves on the phases of the generator winding when it is

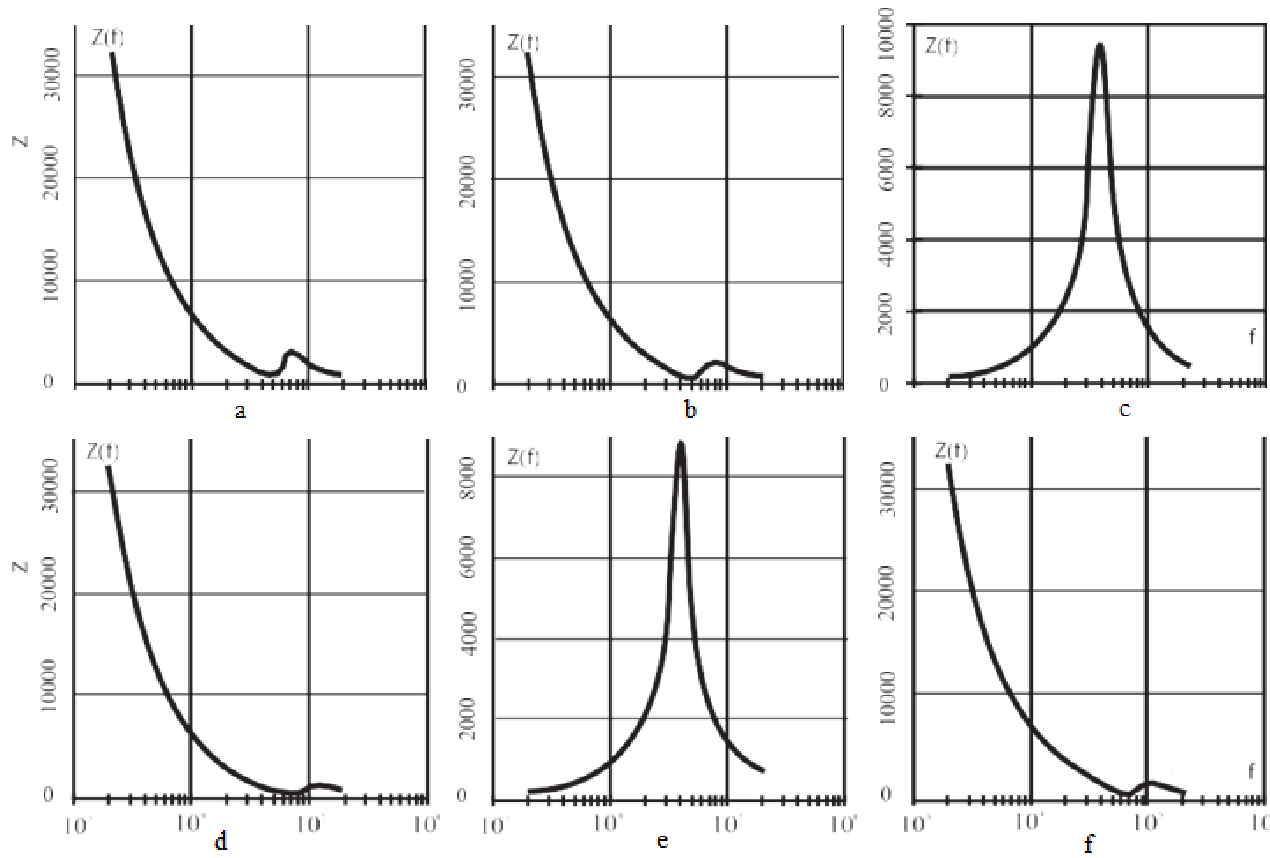

Fig. 12 – Dependence plot Z(f) simulation results for the connection scheme at idle: a) simulation results of the resonance at a 72,000 Hz frequency; b) with a defect (one turn is short-circuited), resonance at a 78,000 Hz frequency; c) with an additional connection of a 4700 μF capacitance to the housing, resonance at a 38,000 Hz frequency; d) with an additional connection of a 4700 μF capacitance in parallel to the phase, resonance at a 117,000 Hz frequency; e) with an additional connection of a 4700 μF capacitance to the housing and a defect (one turn is short-circuited), resonance at a 40,000 Hz frequency; e) with an additional connection of a 4700 μF capacitance in parallel with the phase and a defect (one turn is short-circuited), resonance at a 120,000 Hz frequency.

switched according to the scheme in Fig. 13, a, are little sensitive both to inter-turn short circuits and to the technological asymmetry of the winding phases.

In devices known from literature sources and based on the bridge method for monitoring turn insulation of windings by connecting resistors *R* in the bridge branch according to Fig. 13, b and applying a pulsed voltage source, the mode

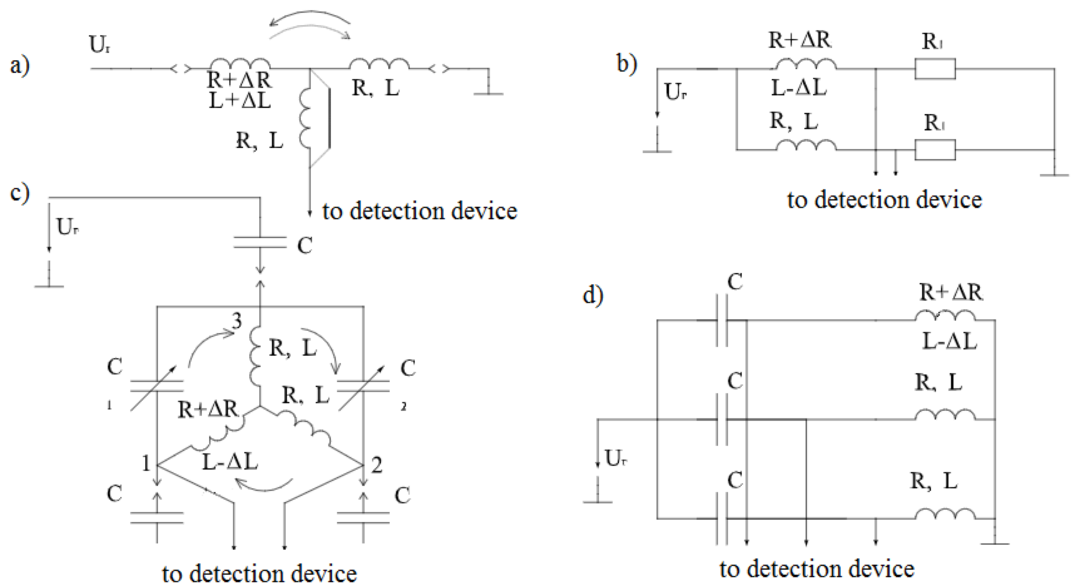

Fig. 13 – Schemes for detecting a short-circuited turn

for detecting inter-turn short circuits at the optimal frequency is not provided. Therefore, the sensitivity of these devices to inter-turn short circuits is also low.

High sensitivity and reliability of turn insulation control to the absence of metal turn-to-turn short circuits in almost all windings of asynchronous generators are achieved in the presented register of turn-to-turn faults RVZ-2 and in automatic turn fault detection devices USKZV-5A, operating according to the scheme in Fig. 13, c. In these installations, operating in the self-oscillator mode, with the help of inductance *L* and capacitance *C*, a resonant mode is created at the optimal frequency f_{opt}.

Conclusions

The article proposes a high-frequency model for an induction generator based on lumped parameters. The results of experimental and software simulations of different type generators are in good agreement both in frequency and in time parameters. The proposed high frequency model can be added to the known dynamic model. It is possible to obtain a complex model that allows the analysis of high-frequency and low-frequency phenomena using standard software.

Experiments have shown that resonant phenomena in the absence and presence of a defect in the form of a short-circuited turn in one of the three phases of the generator winding affect differently when the resonant frequency is shifted to the low-frequency domain from the common resonant frequency and when shifted to the high-frequency domain, respectively. The input impedances of the phases in the domain of frequencies below the common resonance are greater in the absence of defects, and at frequencies above the common resonance, it is less in the absence of defects.

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