ANNOTATION

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UPDATE OF ROTOR ECCENTRICITY DIAGNOSTIC SYSTEM ON ELECTRIC MACHINES USING CAPACITIVE SENSORS

This thesis work offered is dedicated to update of rotor eccentricity diagnostic system on electric machines using capacitive sensors.

Actuality of the work. Rotating electric machines (EM) in electric power industry and industrial production are used for production of electric power and as electric drives. At the moment, CIS countries use about 20 million EMs. And EM practical use demonstrates that substantial part of them for a long time operates with static rotor eccentricity that exceeds the technological eccentricity.

As it is known, rotor eccentricity in EM results in air-gap irregularity, induction of additional magnetic fields in air gap and as a result it leads to deterioration of electromagnetic characteristics and growing loss of electric energy. Considerable rotor core displacement interferes with the stator core which results in its heating. Intensive stator core heating leads to intensive breakage of stator winding insulation and causes short circuit in it. In its turn, rotor core heating can lead to breakage or burn-out of rotor winding.

In such cases, stator winding of the machine needs a time-taking and expensive repair and when rotor cast winding burns out it will totally comes out of action. Besides, during repair of winding it is necessary to get rid of «rubbing» of stator core from air gap side. Otherwise, the further operation of electric machines will lead to «fire in steel» because of short-circuit in core laminated sheets. This process requires long-time and hard manual work.

Timely detection of rotor eccentricity and its value can help both to reduce electric power consumption and prevent damage of electric machine. The following scientists made a great contribution to development and update of EM rotor eccentricity diagnostic system: Geller B., Gamata V., Voldek A.I., Novozhilov A.N., Kletsel M.Ya., Manukovskiy A.V., Kryukova Ye.V., Mirzoyeva S.M., Nikiyan N.G., Veinreb K.B., Gashimov M.A., Rogachyov V.A., Surkov D.B., Tonkikh V.G., Petukhov V.N., Potapenko A.O. and many others.

However, despite of evident achievements in this field, so far devices for detection of rotor eccentricity and its value are still less popular in industry. One of the reasons is that EM winding current or winding stray magnetic field were usually used as data source. However, data parameters offered by that data sources varied because of rotor eccentricity and fluctuation of electric mains parameters during operation modes and shut-down time in rundown mode. Need in reset of it would sharply reduce diagnostic system's sensitivity to eccentricity.

On the contrary, diagnostic systems that obtain data on rotor displacement from capacitive measuring sensors (MSs) have no such disadvantages. However,

all that is known about such diagnostic systems is drawn from few sources published describing several capacitive MSs construction diagrams. So, in this context update of EM rotor eccentricity diagnostic system using capacitive MSs is an acute question.

The goal of this study is update of EM rotor eccentricity diagnostic system using capacitive MSs.

In order to achieve this goal the following tasks shall be set and fulfilled:

- to develop capacitive MSs capable of being installed on all types of AC machines;
- to develop boundary conditions and software for modelling capacitive MSs parameters based on the net method by means of which a «zonal» method for capacitive MSs modelling shall be developed depending on rotor core teeth position during rotation;
- to select a reference damage criterion for EM rotor eccentricity diagnostic system;
- to investigate all factors capable to affect the sensitivity of diagnostic system with capacitive MSs and to develop a measuring chain capable to reduce the influence of the factors mentioned;
- to develop diagrams and justify parameters of measuring chain elements as high-frequency generator, measurement bridge and bandpass filter as well as an independent source to provide these elements with power supply with stabilized direct-current voltage;
- to develop a method to diagnose rotor eccentricity and a device to complete this task where one of the electrodes of capacitive sensors is EM shaft;
- to develop a method to diagnose rotor eccentricity and a device to complete this task where one of the electrodes of capacitive sensors is metallic foil on stator core coil brace and the other one is rotor core surface.

The object of the study is EM rotor eccentricity diagnostics with the view of updating EM rotor eccentricity diagnostic system using capacitive sensors.

The subject of the study is update of EM rotor eccentricity diagnostic system by means of using capacitive sensors.

The main tools to obtain study materials are:

- fundamentals of EM design theory;
- fundamentals of EM status diagnostics theory;
- theoretical basics of electric engineering;
- programming, physical modelling and full-scale experiment.

The scientific novelty is defined by:

1. By comparison of advantages and disadvantages of the already known technical solutions that allow determination of rotor eccentricity the reasons that reduce its sensitivity were studied.

2. Based on the net method a new capacitive MSs modelling method was proposed with arbitrary shape of electrodes as well as a software to complete this task.

3. A «zonal» method was developed for modelling capacitive MSs as a function of both rotor eccentricity value and its teeth position as well as poles with the reference to MSs during rotation.

4. It is proposed to use capacitive MSs components as the reference criterion of rotor eccentricity. The component values for analysis as a function of rotor eccentricity and its teeth and poles positions with the reference to MSs are determined by expansion of the capacitance into Fourier series.

5. A new diagnostic system measuring chain was developed which consists of measurement bridge and two-stage bandpass filter with passing frequency equal to vibration frequency of the power source in form of high-frequency generator.

6. Based on the microprocessor quartz generator a high-frequency vibration source was developed with frequency rate of 100-120 kHz. It has fixed frequency $f_г$ and output voltage amplitude $U_г$ and two-stage bandpass filter on gyrators capable to provide output voltage stability within working temperature range of the machine.

7. An independent source with stabilized direct-current voltage was developed to provide the diagnostic system elements with power supply, as well as methods for calculation of current and voltage transformer parameters providing this source with power supply from electric mains.

8. A new rotor eccentricity diagnostic method was developed as well as the method for determination of tripping tresholds of the rotor eccentricity detection device. Here, one of the MSs electrodes is rotor shaft and passing frequency f_0 of the measuring chain bandpass filter is equal to high-frequency generator rate $f_г$.

9. Capacitive MSs on stator coil brace were studied with the reference to rotor eccentricity value and it was found out that in asynchronous and synchronous machines with nonsalient pole rotor the capacitive MSs constant component shall be used as the reference damage criterion. At the same time, in salient pole rotor synchronous machine for this purpose both the capacitive MSs constant component and the first harmonic component can be used; in this respect the use of the second one is more preferable.

10. A new method for diagnosing rotor eccentricity of electric machines was developed as well as method for determination of tripping thresholds where one of MSs electrodes is the surface of rotor core or its poles. Herewith, pass frequency f_0 of measuring chain bandpass filter can be equal to carrier frequency $f_г$ or side frequencies $f_г \pm f_c$, in this respect, use of the last one to diagnose machines with salient pole rotor is more preferable.

The practical effect of the work consists of the following:

1. It was proved that the most perspective technical solutions for detection of EM rotor eccentricity are the ones that use capacitive MSs as MSs. It means that diagnostics results do not depend on fluctuation of electrical mains parameters and load as well as on EM shut-down time when diagnosing the machine in run down mode.

2. The method developed based on the net method and software for modelling capacitive MSs with arbitrary electrode shapes gives the opportunity to calculate it with the accuracy of 4.5%. This can allow its use for controlling the accuracy of «zonal» method developed for modelling capacitive MSs parameters.

3. The «zonal» method developed with calculation accuracy of 13% allows modelling capacitive MSs as a function of rotor eccentricity value and rotor core teeth and poles positions with the reference to MSs during rotation.

4. Use of Fourier method for determination of capacitive MSs components can help to find out ones with maximum values and the components that heavily depend on rotor eccentricity and when used as the reference damage criterion.

5. A measuring chain developed based on measurement bridge and two-stage bandpass filter is capable to provide a reliable protection for diagnostic system against external electric and magnetic fields when these elements are located inside the EM.

6. High-frequency vibration source developed based on the microprocessor quartz generator and its software can help to provide frequency instability $f_Г$ within $\pm(0{,}1-0{,}5)\cdot10^{-6}$ Hz and output voltage amplitude $U_Г$ within ±2-5% when ambient air temperature changes from –30 to +80 degrees.

7. Two-stage bandpass filter developed on gyrators can provide amplitude variation of output voltage equal to 2-2.5% within the frequency range of 114-127 kHz and when ambient air temperature varies from –30 to +80 degrees.

8. The independent power source developed can help to provide all diagnostic system elements with stabilized voltage of 12V with current consumption of up to 0.2A.

9. The methods developed for calculation of current and voltage transformer parameters providing it with electric power from EM electric mains gives the opportunity to calculate them for a wide range of output voltage and current parameters.

10. In the rotor diagnostic system developed where one of the electrodes is rotor shaft the capacitive MSs are located inside the EM and other elements of the diagnostic system in a single block are located on its external surface. Such construction can help to avoid long connector wires and easily provide a reliable protection for the system elements against electric and magnetic fields, as well as more «light» temperature mode during operation, easy control of correct operation of the device and its adjustment without machine disassembling.

11. In rotor eccentricity diagnostic system developed the capacitive MSs (where one of electrodes is a metallic foil on stator coil brace and the other is rotor core surface or pole surface) and measuring chain are located on MSs coil brace, and other elements of the diagnostic system in a single block are located on EM external surface. This makes MSs construction and installation more easy.

Approbation of the study results. Main statements of the thesis were reported and discussed at the 17-th International conference entitled " Satpayev readings " (Pavlodar) in April, 2017, at the 9-th International conference entitled " Toraigyrov readings " (Pavlodar) in November, 2017; at the VIII-th International

scientific and technical conference entitled "Technical sciences: problems and solutions" (Moscow) in February, 2018.

Publications. Regarding to this document 11 works were published including 3 works in the magazines recommended by VAK RK, two articles in «Vestnik OmGTU» (Russia) magazine and 3 patents of invention were submitted: 2 of them in RoK, 1 in Russian Federation. Also, two articles were accepted for publication: «Elektrotekhnika» (Moscow, Russia) magazine, 2019 and «Przeglad Elektrotechniczny» (Poland) magazine, 2018 entering the Scopus citation base.

Structure and volume of the thesis. The thesis consists of introduction, 3 chapters, conclusion and 2 attachments. It comprises 101 pages, has 61 figures and 4 tables. The reference list used includes 80 names.

The first chapter describes EM constructional features and types of eccentricity. Analysis of the constructional features of rotating EMs demonstrated that the main cause of rotor eccentricity laid in constructional elements securing rotor position with the reference to stator where the main reason of rotor eccentricity was shaft displacement. Process equipment used nowadays and human factor lead to the fact that EM production plants produce items with the eccentricity of up to 0.1-0.12. Moreover, rotor eccentricity features were described with air-gap irregularity, induction of additional magnetic fields in it, deterioration of EM electromagnetic characteristics and rise of electric energy loss for about 0.45-3.95%. The analysis of the already known methods for detection of rotor eccentricity on EMs that come out of action or EMs that are still in operation demonstrated that the most perspective way is application of a method where capacitive MSs is used to obtain the damage criterion. In this respect, EM diagnostics results do not depend on variation of electric mains parameters, load jumps and EM parameters changes as well as its operation mode. MSs capacitance used in EM rotor eccentricity diagnostic system depends both on rotor eccentricity and rotor core surface shape. Therefore, the already known capacitance modelling methods do not allow modelling parameters of such MSs during rotor rotation.

In the second chapter a capacitive MSs modelling method was developed for rotor eccentricity diagnostic system which is based on the net method. This method with the accuracy of up to 4.5% can help to perform modelling with arbitrary electrode shape. The «zonal» method offered for modelling capacitive MSs for rotor eccentricity diagnostic system allows its easy modelling as a function of rotor teeth positions during its rotation with calculation accuracy of up to 13%. The reference criterion of rotor eccentricity was found out which can be determined through analysis of MSs harmonic capacitance range depending on rotor eccentricity value. In asynchronous machines where one of the electrodes of capacitive MSs of the diagnostic system is rotor shaft surface or rotor surface with closed or open slots; the constant component shall be used as the reference damage criterion in the diagnostic system. In synchronous machines where one of the electrodes of capacitive MSs of the diagnostic system is salient pole rotor surface its constant component or the first harmonic components of its capacitance shall be used as the reference damage criterion. In synchronous machines where one of the electrodes of capacitive MSs of the diagnostic system is nonsalient pole rotor

surface its constant component shall be used as the reference damage criterion since the first harmonic component value is much more less.

It was found out that the measuring chain in form of a measuring bridge with band-pass filter where the bridge is powered by the high-frbreakage47generator satisfies in the best way possible the requirements of the EM rotor eccentricity diagnostic system with MSs where one of the electrodes is grounded.

In the third chapter at Pavlodar state university named after Toraigyrov («Electric power» department) jointly with Manukovskiy A.V. (PhD in Technical Sciences) the design of the quartz generator and its software was finished off for the measuring chain of the diagnostic system updated; this can provide sufficient stability for frequency and amplitude as well as permissible level of harmonics of the signal generated within the required temperature range. It was found out that the two-stage filter on gyrators is capable to provide a pass band of 5 kHz with gain bandwidth of Q= 60 dB within working temperatures ranging from –30 to +80 degrees which is quite sufficient for diagnostic system. An analysis is made based on which an independent source with stabilized direct current was selected capable to provide power supply for the high-frequency generator and the two-stage filter of the system diagnosing the low-voltage and high-voltage electric machines with the help of small size and cheap voltage transformers as well as standard ТЗРЛ split-type and through-type current transformers.

The rotor eccentricity diagnostic system with MSs was updated where one of electrodes is EM shaft. This system can control both the shaft displacement and direction of the displacement. In addition, all elements are located on EM external surface that enables to create a shielding to protect from external electric and electromagnetic fields and provide an access to control the functionability of the device and set up tripping limits.

The rotor eccentricity diagnostic system was updated where one of MSs foil-type electrodes is located in coil braces. This can help to control both the shaft displacement and direction of displacement. In addition, measurement bridge and bandpass filter are located on protruding part of the coil brace and other elements are located on EM external surface. Thus, it makes MSs manufacture and installation more easy.