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Method of Shorted Turn Monitoring in the Turbogenerator Rotor Winding

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Abstract: - The represented method of monitoring the shorted turn in the winding of the turbogenerator rotor is based on the analysis of spectral structure of electromotive force induced by a magnetic field of the rotor in the induction sensor. Results of analytical and numerical calculations of magnetomotive force and magnetic field of the rotor with shorted turns in the winding are given. The damaged coil is determined by comparison of calculations and experimental data. Research results of the turbogenerator at the power station are shown. It is shown also that shorted turns and air gap eccentricity influence similarly on the magnetic field and magnetic forces.

Key-Words: - **T**urbogenerator, rotor winding, shorted turn, magnetic field, spectral analysis.

1 Introduction

According to the inspection executed by the company Generatortech, Inc. [1], more than 50 % of turbogenerators at power stations are operated with shorted turns in the rotor winding and have no problems with it. However generators with more than 5 % shorted turns show increased vibrations, restriction of capacity, sudden switching-off, damages of retaining rings. There is a tendency of annual increase of the number of shorted turns in the investigated machines. Thus, it is necessary to detect duly the shorted turns in the rotor winding and perform continuous monitoring of the process development at operation of the turbogenerators.

Now there are two basic methods for the continuous monitoring of short circuits of rotor windings at power stations: the monitoring of the form of the electromotive force (EMF), induced in the induction sensor, placed in air-gap [2,3,4], or the analysis of current structure in a stator winding used as measuring winding [3,5].

The monitoring with the help of induction sensors, offered by Albright D.R. [1,2], has received wide recognition. Induction sensors for measurement of radial and tangential field components are placed at a distance of 40%-60 % of air-gap height from the surface of the rotor. The form of output voltage or electromotive force, induced by the rotating magnetic field in the sensor, repeats tooth kink of the rotor. In case of shorted turns in the rotor winding the height of corresponding peaks and dips varies, the form of induced EMF is not so symmetric relative to zero. Using these changes one can determine coils with shorted turns. The special time-delay lines allow to compare wave forms of two poles at an oscillograph. Advantage of the method is relative simplicity and clarity of the monitoring, but the method is effective for turbogenerators with rather small number of turns in the rotor coils.

2 The Spectrum Monitiring

With increase in the number of turns in rotor coils, the shorted turn of a coil becomes less noticeable in EMF curve of the sensor. For example, if the rotor coil has 20 turns, then at short circuit of one turn the change of the curve of the EMF sensor as compared with the defective coil will make up no more than 5% and can be attributed to the inaccuracy of measurements. Even if at present there are no problems with operation of the turbogenerator, short circuit not revealed duly can be the beginning of the failure process. Subjectivity of the qualitative conclusion according to rather small change of the EMF curve form complicates the analysis; there may be the ambiguous conclusions about presence of shorted turns.

In this connection we have offered additional features of the shorted turns monitoring in the rotor winding at operation of the turbogenerator, based on the spectral analysis of EMF induced in the sensor

[6,7]. Based on the frequency structure and relative size of separate spectrum components in frequency area we have arrived at conclusion of presence of shorted turns. Criterion of serviceability of the rotor is practical absence of even harmonic components in the EMF spectrum of the sensor. At presence of even harmonic components, the coil with shorted turns is determined by their comparison with spectrum structure of EMF of a faultless turbogenerator and with results of numerical modeling of possible short circuits. The offered method does not require additional equipment for the turbogenerator, it is convenient for algorithmization and is a development of the traditional induction monitoring. The measuring device is the narrow-band spectrum analyzer or electronic digital oscillograph with a computer. Also two opposite connected induction sensors with the identical frequency characteristics can be used, installed at identical distance from the surface of the rotor and shifted for pole division over the circle of the stator. As the spectral analysis in frequency area supplements the analysis of the measured signal form of the sensor in time, the accuracy of the monitoring increases. By way of explanation we shall consider the basic electromagnetic ratios.

3 Magnetomotive Force

In no-load condition the turbogenerator magnetic field is created by a current in the rotor winding representing concentric coils, placed in radial slots of the rotor. Magnetomotive force (MMF) of the rotor winding is distributed symmetrically among poles, it has two axes of symmetry for the period of expansion and consequently can be submitted as Fourier series containing odd harmonic components, multiple to the number of pole pairs

$$f(\varphi)=\frac{4Fq}{\pi}\sum_{n=1,3,5,...}\tfrac{1}{n}k_{wn}k_{bn}\sin(np\varphi) \qquad (1)$$

where the distribution factor for coils with identical number of turns and identical slots pitch

$$k_{wn}=\frac{2p}{z_2}\sin\frac{\pi n}{2}\gamma\Big/\sin\frac{\pi np}{z_2'} \qquad (2)$$

Factor of disclosing the slot

$$k_{bn}=\sin\frac{\pi nb}{2\tau}\Big/\frac{\pi nb}{2\tau}\,. \qquad (3)$$

Here $F=IW/(2a_2)$ is the MMF, necessary for transferring of a magnetic flux through one air-gap, I - rotor current, W - the number of turns in the coil, a_2- the number of parallel branches of the rotor winding, $q=z_2/4p$ - the number of coils per pole, τ- polar division of the rotor, z_2- the number of slots with winding, z'_2 - the number of slot points of the rotor, b - width of the groove of the rotor, p - the number of pole pairs, $\gamma=z_2/z_2'$ - share of wound part of the rotor. The first coil has the greatest pitch, last q - accordingly the least pitch.

The shorted turn accompanying partial or full switching-off of the turn can be presented by superposition of symmetric distributed MMF of the winding and opposite MMF of the shorted turn. Thus, spectrum MMF will contain generally odd and even harmonics, both the greater and the smaller order (for multipolar machines) concerning the number of pole pairs. Factors of expansion will depend on the arrangement of the coil on a pole and on the arrangement of the pole itself. Let, for example, short circuit has taken place in any k coil of l-st pole. The total magnetic flux in two-dimensional magnetic field at the period of expansion is equal to zero. That is there is no constant component of the field. Then MMF expansion of the shorted turns of this coil in a harmonic series will be

$$f_{kl}(\varphi)=\frac{4F_{kl}}{\pi}\sum_{n=1,2,3,...}\frac{1}{n}\left[a_{nkl}\cos(n\varphi)+b_{nkl}\sin(n\varphi)\right] \quad (4)$$

where the factors of expansion are

$$a_{nkl}=\cos\frac{\pi n(2l-1)}{2p}\sin\frac{\pi n[\tau-(2k-1)t]}{2p\tau},\ n=1,2,3,...$$

$$b_{nkl}=\sin\frac{\pi n(2l-1)}{2p}\sin\frac{\pi n[\tau-(2k-1)t]}{2p\tau},\ n=1,2,3,.... \qquad (5)$$

Here F_{kl} is MMF, corresponding to the turn-to-turn short circuit, t - tooth division of the rotor.

For the bipolar machine the expression of the expansion factors becomes simpler, even and odd harmonics are separated.

Fig 1a, 2a shows the spectra of even harmonics of MMF caused by short circuit in 1-st and 9-th coils of the bipolar machine. Occurrence of the even harmonics of MMF, which has not been connected to the number of the machine poles pairs, testifies the infringement of electric symmetry in the rotor and is an attribute of shorted turns in the rotor.

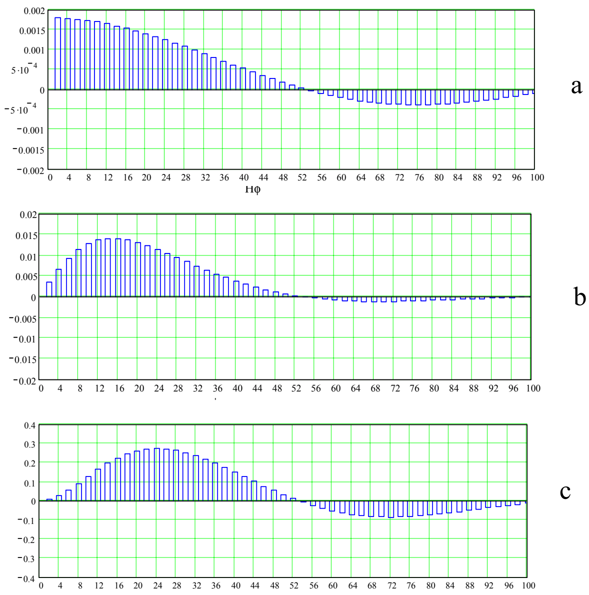

Figure 1. Even harmonics of MMF(a), Hφ(b), EMF(c) in the sensor at a fault in the first coil.

More sophisticated analysis of electric asymmetry of the rotor can be made according to linear current load, that is according to derivation of changing MMF along a circle of the rotor.

Linear current load of the rotor MMF is received by differentiating (1) at angular coordinate

$$J(\varphi) = \frac{4Fq}{\tau} \sum_{n=1,3,5,7,...} k_{wn} k_{bn} \cos(np\varphi). \qquad (6)$$

Accordingly from expression (4) the linear current load of the shorted turn of k coil and l pole is the following.

$$J_{kl}(\varphi) = \frac{4F_{kl}}{p\tau} \sum_{n=1,2,3,...} - a_{nkl} \sin(n\varphi) + b_{nkl} \cos(n\varphi) \qquad (7)$$

Formulas (6), (7) are received for the stationary rotor. At rotation of the rotor, MMF and linear current load waves of the rotor winding rotate together with the rotor at the same angular speed $\omega' = \omega / p$, where ω - circular frequency. For linear current load of a symmetric winding it is received:

$$J(\varphi, t) = \frac{4Fq}{\tau} \sum_{n=1,3,5,7,...} k_{wn} k_{bn} \cos n\,(\omega t - p\varphi) \qquad (8)$$

Corresponding expression for rotating waves of linear current load of the shorted turn is:

$$J_{kl}(\varphi, t) = \frac{4F_{kl}}{p\tau} \sum_{n=1,2,3,4,...} c_{nkl} \cos[n(\omega' t - \varphi) - \psi_{nkl}] \qquad (9)$$

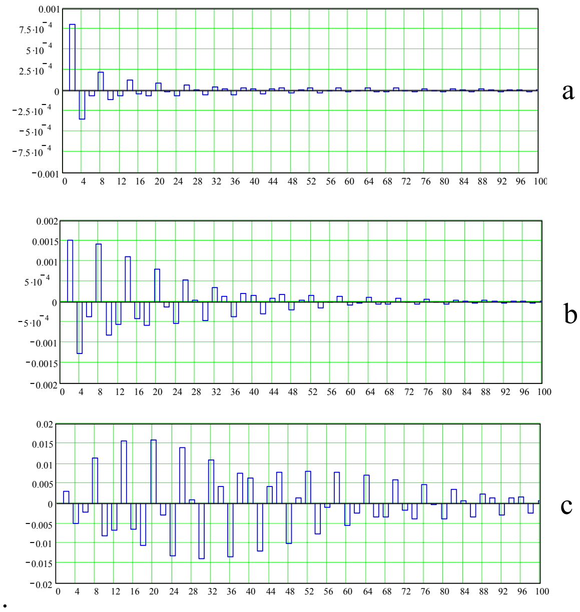

Figure 2. Even harmonics of MMF(a), Hφ(b), EMF(c) in the sensor at a fault in the ninth coil.

where c_{nkl}, y_{nkl} are determined by factors a_{nkt}, b_{nkt}.

4 Magnetic Field and EMF in the Sensor

Linear current load of the rotor as a boundary condition unequivocally determines a magnetic field at no load condition of the turbogenerator. At indefinitely high magnetic permeability of steel the tangential component of magnetic field density is equal to current load on the rotor surface and aspires to zero on the surface of the stator. These boundary conditions correspond to the solution of Laplace's equation for tangential component of magnetic field intensity in air-gap. In view of possible shorted turns in the rotor winding the solution looks like:

$$H_\varphi(r,\varphi,t) = \frac{4F_{kl}}{p\tau} \sum_{n=1,2,3,...} \frac{c_{nkl}\left(\frac{r_0}{r_1}\right)^n \left[\left(\frac{r_1}{r}\right)^n - \left(\frac{r}{r_1}\right)^n\right]}{1 - \left(\frac{r_0}{r_1}\right)^{2n}} \cos[n(\omega' t - \varphi) - \psi_{nkl}], \qquad (10)$$

where r_0, r_1, r - respectively, bore radii of the rotor, stator and radial coordinate of the sensor installation.

Expression (10) is approximate and can be used for the qualitative analysis of the magnetic field. From the comparison (10) and (9), according to properties of potential functions, it is seen, that at no load condition the tangential constituent of the magnetic field density near to the rotor surface is convenient to analyze the distribution of linear current load (fig.1b, 2b) with the purpose of determination of shorted turns. Expression (10) can be specified by the serration of cores and saturation, however for reception of quantitative results it is expedient to use numerical methods. It is necessary to note also, that at saturation for determination of the field it is necessary to set resulting linear current load.

Analysis of MMF by using radial component of the magnetic field intensity in the steady-state short circuit condition is possible also. The radial component of the field is weakened at height of the gap much less, than tangential one, therefore the sensor focused on radial component of the field, can be placed at the greater distance from the rotor surface.

In the load conditions the analysis becomes complicated, as additional fields of the high current harmonics, for example, from nonlinear rectifier load of the generator are imposed on fields of electric and magnetic asymmetry of the rotor.

Complex amplitude of EMF E, induced in the stationary sensor by variable magnetic field, is determined from (10) according to Maxwell law

$$E = -w_p\, d\Phi/dt = -jw_p\omega'\,\mu_0\, S_p \sum_{n=1,2,3,...} nH_n \qquad (11)$$

where w_p and S_p are the number of turns and section of the measuring sensor, H_n and Φ are harmonics of the field intensity and the magnetic flux which is taking place through the sensor.

From (11) it is seen, that the amplitude of harmonic EMF in the sensor is proportional to the time order of the field harmonics, coinciding with spatial order of MMF and the rotor current load harmonics. In this connection the weakened high harmonics amplified in EMF of the sensor in comparison with harmonics of low orders and they are expedient for using in the diagnostic purposes. It is shown on fig. 1c, 2c.

Practically offered monitoring at power stations means periodic determination of the form and spectrum of the sensor signal and comparison with the reference data received at bench tests of the given machine. At occurrence of even harmonics for definition of the coil with shorted turns numerical calculation should be made in view of real distribution of currents in turns of coils, as well as taking into account the properties of constructive materials, serration of cores, geometrical sizes of turbogenerators with the postprocessor harmonic analysis of calculation results of the field in the location of the sensor. Fig. 3a,b,c represents distribution of the magnetic flux density along the section of the rotor at no load condition at nominal excitation both at absence of short circuits, and at shorted turns in various coils. Fig. 4a,b shows comparison of results of numerical modeling of tangential component of the magnetic field in the air-gap at absence of short circuits and at short circuit of one of 18 turns in the coil. It is practically impossible to determine shorted turn according to the form of curves in this case. At the same time at frequency spectra of EMF, made at Fig. 4c,d for the same cases the occurrence of even harmonics is visible at shorted turn. The spectrum of even harmonics has changes depending on coil, which has shorted turn. But according to the results of numerical experiments, position of the shorted turn at height of the coil changes spectral structure of the field and EMF in the sensor a little. At use of the spectral monitoring of shorted turns with the help of the induction sensor it is necessary to exclude the inaccuracies connected to influence of possible magnetic asymmetry of the rotor, the inaccuracy of measuring devices and numerical modeling, especially at the analysis of the high harmonic of the spectrum. At shorted turns in a slot part of coils there is an additional axial component of the field that demands numerical calculation of the three-dimensional magnetic field. The task becomes complicated also at simultaneous shorted turns in different coils.

5 Influence of Air Gap Eccentricity

As an example of occurring in practice deviations from idealized design module let us examine the eccentric rotor position relative to the stator bore (static eccentricity) and relative to axis of rotation (dynamic eccentricity). The value of the eccentric air gap between the rotor and the stator being restricted with the first term of small parameter expansion may be presented by the formula:

$$\delta = \delta_0\left[1 - \varepsilon\, cos(\omega_\varepsilon t - \varphi)\right], \qquad (12)$$

where: δ_0 – uniform air gap, ε - relative eccentricity, ω_ε - angular speed equal to zero at static eccentricity and angular speed of the rotor rotation ω' at dynamic eccentricity.

The second term of formula (12) defines additional rotating harmonic components of the symmetric rotor winding magnetic field H_ε that spatial orders differ from MMF harmonics orders by 1 and frequencies coincide with MMF frequency by ω' at dynamic eccentricity.

$$H_\varepsilon = \sum_{n=1,3,5,...} H_{\varepsilon mn}\, cos\left[(n\omega \pm \omega_\varepsilon)t - (np \pm 1)\varphi\right] \qquad (13)$$

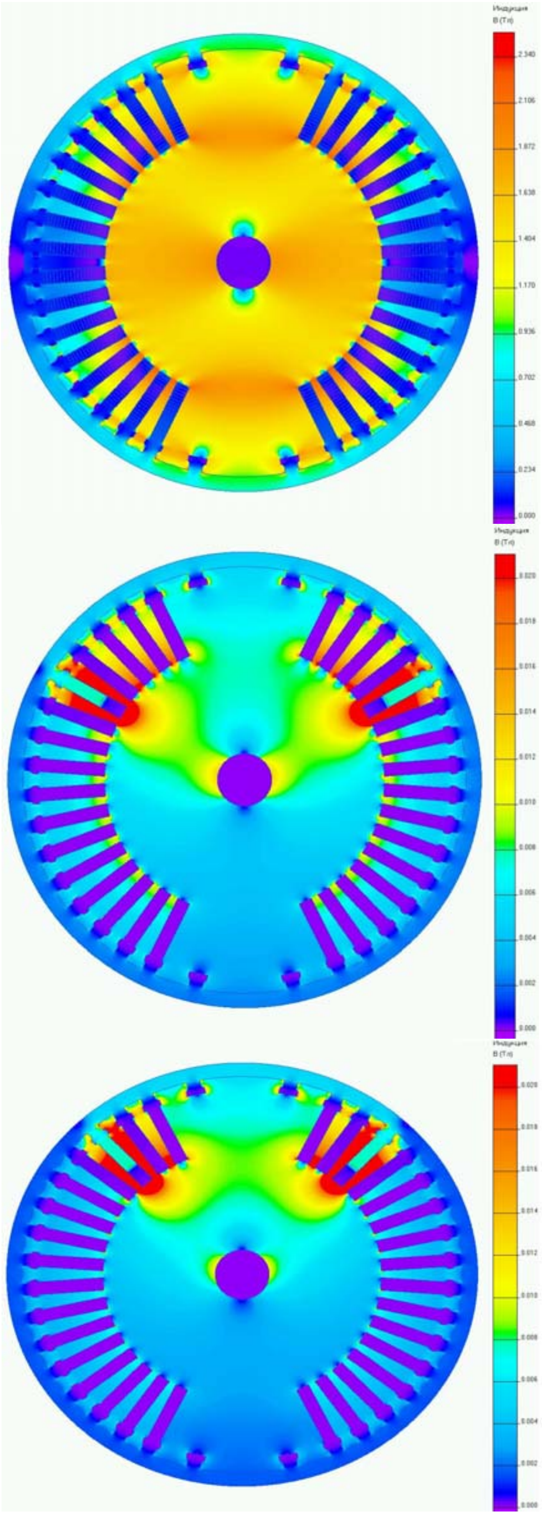

Figure 3. Magnetic flux density along the section of the rotor

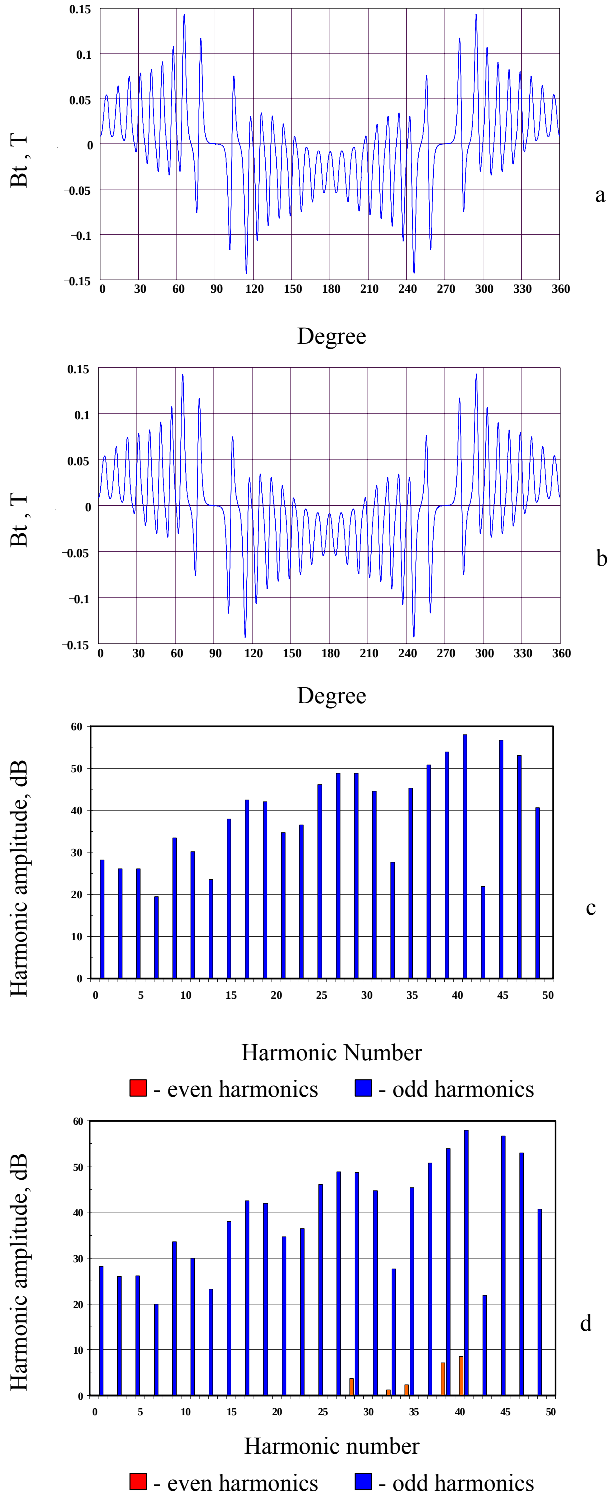

Figure 4. Magnetic field and EMF spectra at absence and at one of 18 shorted turn

In accordance with the formulas (12), (13) it follows, that at dynamic eccentricity the EMF even harmonics similar to EMF harmonics from turn-to-turn short circuits in the rotor winding are induced in the measuring sensor.

Thus, the action of the rotor body dynamic magnetic eccentricity on the sensor is similar to the action of the rotor winding electrical asymmetry. As a result of similarity, the magnetic forces at turn-to-turn short circuits in the rotor winding are appeared.

In unsaturated machines the amplitudes of additional field harmonics from the air gap dynamic eccentricity are proportional to the half of the eccentricity relative value [8]. Due to high accuracy of the high-speed turbogenerator rotors balancing, the error added by the air gap eccentricity to the shorted turn diagnostics is insignificant.

6 Results of Tests

With the help of the given method in conditions of the power station the monitoring of winding short circuits in the rotor of the turbogenerator with hydrogen cooling on which there was an assumption of presence of shorted turns is carried out. The turbogenerator is maintained more than 40 years without any problems connected with shorted turns. Each coil of multiple-turn rotor winding has 18 turns. It is difficult to draw a conclusion on presence of shorted turns in the rotor winding using the form of EMF curve in the induction sensor of the given turbogenerator (fig. 5a). At the same time the analysis of spectral structure of EMF in frequency area specifies unequivocally the presence of shorted turns (Fig. 5b). Now the further monitoring of the given turbogenerator is made to trace the evolution of process and to exclude serious failure.

7 Conclusion

It is shown, that in turbogenerators with multiple-turns coils of the rotor winding the traditional monitoring of shorted turns according to the shape of EMF curves in the induction sensor is complicated.

The offered additional monitoring includes the spectral analysis of structure of induced EMF in the sensor and comparison of spectra and curves of EMF, taken at the factory-manufacturer, with the results, received during operation. According to the presence of even harmonics in a spectrum it is concluded about shorted turns in the winding of the rotor. For determination of the coil with short circuit the test data are compared with results of numerical modeling.

It is shown that rotor winding shorted turns like as air gap eccentricity excite unidirectional magnetic forces.

At absence of thermal imbalance, appreciable increase of current, losses and heating in the field winding, the operation of turbogenerators with the shorted turn can be allowed at the continuous monitoring of the winding condition.

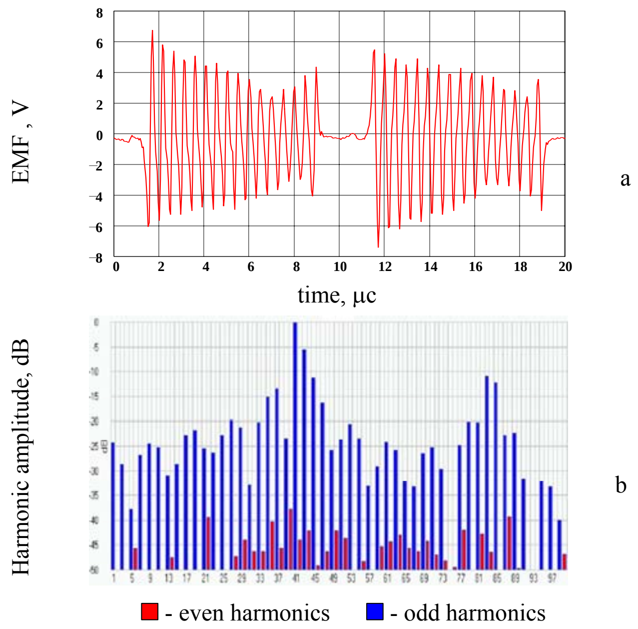

Figure 5. Form of EMF curve (a) and spectral structure of EMF (b) in the induction sensor.

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