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AN EVALUATION OF THE TECHNICAL STATE OF A STARTER USING THE HALL EFFECT- PART I

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Summary. The article presents the results of diagnostic laboratory investigations into electric starters with an application of spectrum analysis of magnetic induction. Premises for the choice of investigative methodology have also been discussed.

Key words: diagnostics, damage, electric starter, Hall sensor.

INTRODUCTION

The required modern car standards are constantly growing. There is demand for highly effective, reliable cars, which would be cheaper in exploitation, fault-tolerant, more durable etc. And the reliability of cars is the basic factor of exploitation safety as well as their production quality.

Both agricultural tractors and car vehicles involve serial reliability structure. In this case a vehicle's reliability depends on a good quality of all its systems, also the ones which start up a combustion engine.

The leading function during a start-up of a combustion engine belongs to an electric starter. Its condition decides on the work readiness of a combustion engine and, consequently, of a vehicle or a machine aggregate. A continuous diagnostics of a starter promotes its optimal use as well as an unfailing engine's start-up. It also prevents premature damage.

The basic principle of start-up circuit diagnosis in a vehicle is control of its completeness and continuity. During this process one must check the controlled circuit from its feeding source (battery) to the receiver (starter) including the steering circuit; control the correctness of electric connections (if they are made using junctions and nuts) and if they are continuous. The connections may be affected by vibrations in the car or during repair of another car element. The quality of these connections is very important, that is the purity of the surfaces through which the current flows. However, as to the starter, its faults are difficult to detect and the diagnosis is carried out after its removal from the vehicle. It is a labour-consuming phase, eliminating the vehicle from exploitation.

To reach the basic aims of functional diagnostics, one should select such starter's parameters which can optimally enable or facilitate making proper decisions concerning its technical state and which allow well in advance to predict an approach of its elements to a border or critical state.

In view of the growing number of tractors and self-propelled machines as well as an increase of their exploitation for work, a new diagnostic method has been worked out and presented for a combustion engine's electric starter.

THE AIM OF THE PAPER

One of the ways to prolong the period of a starter system's reliable work is taking care of its good technical condition and efficiency by its diagnostics and replacement of the damaged elements.

The so far used practical diagnostic methods of electric starters of combustion engines have not allowed for an execution of full diagnostics of these devices directly in a vehicle. A precise examination of starters applying the so far used methods requires their removal from a vehicle, disassembly of aggregates and components and their detailed verification. Only following the realization of the mentioned actions, is it possible to start tests in idle gear and under load, carried out on testing stands.

The aim of the present paper is to work out a new method of an assessment of the technical condition of electric starters applied to starting up combustion engines in agricultural vehicles, using the Hall effect.

THEORETICAL BASIS OF THE DIAGNOSTIC METHOD

In order to begin the running of a starter, magnetic fields must be initiated inside the device, coming from a stator with its excitation winding as well as from the rotor winding. The current, feeding the electric motor of a starter, initiating the electromagnetic field, causes the turn of the rotor. In the winding of the revolving motor, as a result of an existence of magnetic field of excitation as well as shifting in this field of the conductors of rotor, the electromotive force E is induced.

Since the return of this strength is opposite to transfluent current and the voltage feeding the starter, it is often defined as counterelectromotive force. Its power is lower than the power of the voltage feeding the starter by the drops of voltage on windings inside the starter and on brushes, which can be expressed by the following equation:

$$E = U_a - U_r - U_s, \tag{1}$$

where:
U_a – battery voltage,
U_r – drops of voltage on motor windings and conductors,
U_s – drops of voltage on a starter's brushes.

The value of counterelectromotive force decides on a starter's electromagnetic values. The value of this force depends on the starter's constant constructional c_m, the magnetic flux Φ_{wz}, which is produced by excitation winding, as well as on the rotor's rotational speed n, which can be presented by the following equation:

$$E = c_m \, \Phi_{wz} \, n. \tag{2}$$

Internal electromagnetic power P_{em} of the starter is characterized by the following dependence:

$$P_{em} = E \cdot I, \tag{3}$$

where:
E – counterelectromotive force,
I – intensity of the current flowing through the starter.

If value E is expressed as product of resistance R and current's intensity I, then the general dependence of electromagnetic power of direct current electric machines can be described by the equation:

$$P_{em} = R \cdot I^2. \tag{4}$$

The starter's electromagnetic moment M_{em} (result of magnetic field's effect on a conductor with current), without accounting for losses, can be determined by the dependance:

$$M_{em} = c_1 \, \Phi_{wz} I. \tag{5}$$

Because $\Phi_{wz} = c_2 \cdot I$, whereas $c = c_1 \cdot c_2$, therefore , where c_1, c_2, c – constants constructional of a starter.

The basis for a formulation of a set of a mathemathical model's equations within the approach of theory of circuits is the ideological diagram of a serial starter presented in Fig. 1.

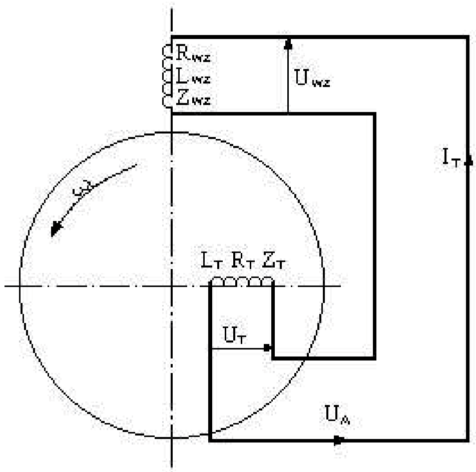

Fig. 1. Ideological diagram of a direct current serial starter [Borsuk W. 1984]

The above-presented figure points at the following general voltage equation:

$$U_A = (R_T - R_{wz}) \cdot I_T(t) + \frac{d\psi_T}{dt} + \frac{d\psi_{wz}}{dt}, \tag{6}$$

where:
U_A – feeding voltage (on connectors of battery),
R_T – resistance of armature winding,

R_{wz} – resistance of excitation winding,
ψ_T – stream associated with armature winding,
ψ_{wz} – stream associated with excitation winding,
$\frac{d\psi_T}{dt}$ – voltage induced in armature windings,
$\frac{d\psi_{wz}}{dt}$ – voltage induced in excitation windings,
I_T – current of armature.

Car starters are electromagnetically strenuous electric machines, which means that their magnetic circuits are saturated. Thus, in equation of voltages it is not possible to assume constant inductance values, that is why one should operate with associated streams.

Magnetic flux, generally, can undergo changes in time *t*. Besides, relative movement can ocurr of an electric circuit in relation to a bundle of magnetic flux, and therefore the associated stream can be generally expressed as [Borsuk W. 1984]:

$$\psi = f(t, x). \tag{7}$$

In the case, when transitory states are considered in a series machine of direct current, the expression for associated armature stream looks as follows:

$$\psi_T = z_T \cdot \Phi_T(I_T, x). \tag{8}$$

As results from the above:

$$\frac{d\psi_T}{dt} = z_T \cdot \frac{d\Phi_T}{dt} = z_T \cdot \left(\frac{\delta\Phi_T}{\delta I_T} \cdot \frac{dI_T}{dt} + \frac{\delta\Phi_T}{\delta x} \cdot \frac{dx}{dt} \right). \tag{9}$$

where:

$x = \varphi(t)$ – relative dislocation of armature circuit in relation to the bundle of associated stream,
z_T – number of laps of armature winding,
Φ_T – the main magnetic flux of armature circuit.

The first link of equation (9) $\left(z_T \cdot \frac{\delta\Phi_T}{\delta I_T} \cdot \frac{dI_T}{dt} \right)$ describes drop of armature circuit inductance voltage. The inductance $\left(z_T \cdot \frac{\delta\Phi_T}{\delta I_T} \right)$ is dependent on magnetic flux excited by the current flowing through armature winding, whereas the second link $\left(z_T \cdot \frac{\delta\Phi_T}{\delta x} \cdot \frac{dx}{dt} \right)$ results from the fact that the armature electric circuit moves relatively to the bundle of magnetic flux, and at the same time $\frac{dx}{dt} = V$ denotes the velocity of the armature electric circuit's motion.

Simultaneously, link $\left(z_T \cdot \frac{\delta\Phi_T}{\delta x} \cdot \frac{dx}{dt} \right)$ describes the electromotive force of rotation SEM excited in armature, and after some simple transformations it can be expressed as follows:

$$z_T \cdot \frac{\delta\Phi_T}{\delta x} \cdot \frac{dx}{dt} = e = \frac{N \cdot p}{a} \cdot \Phi_T \cdot n, \tag{10}$$

where:
$c_N = \frac{N \cdot p}{a}$ – constant constructional of a starter,
N – number of armature's active rods,
p – number of pole pairs,

a – number of branch pairs parallel to armature winding,
$n = \frac{\omega}{2\pi}$ – rotational speed of rotor,
ω – angular speed of armature,
and therefore:

$$z_T \cdot \frac{\delta \Phi_T}{\delta x} \cdot \frac{dx}{dt} = c_N \cdot \Phi_T \cdot n = \frac{c_N}{2\pi} \cdot \Phi_T \cdot \omega = \frac{N \cdot p}{2 \cdot \pi \cdot a} \cdot \Phi_T \cdot \omega = c_E \cdot \Phi_T \cdot \omega . \tag{11}$$

Dependence (11) referred to equation (9) provides a general expression of induced voltage in armature winding:

$$\frac{d\psi_T}{dt} = z_T \cdot \frac{\delta \Phi_T}{\delta I_T} \cdot \frac{dI_T}{dt} + c_E \cdot \Phi_T \cdot \omega(t). \tag{12}$$

The expression of stream associated with exciting circuit of a starter looks as follows:

$$\psi_{wz} = z_{wz} \cdot \Phi_{wz}(I_T), \tag{13}$$

and therefore:

$$\frac{d\psi_T}{dt} = z_{wz} \cdot \frac{d\Phi_{wz}}{dt} = z_{wz} \cdot \frac{\delta \Phi_{wz}}{\delta I_T} \cdot \frac{dI_T}{dt}, \tag{14}$$

where:
$I_T = f(t)$ – current flowing through exciting circuit (for series machine of direct current it is the current of armature),
z_{wz} – number of laps of excitation winding,
Φ_{wz} – magnetic flux of excitation winding.
The magnetic flux of excitation winding Φ_{wz} is enlarged in relation to the
main magnetic flux by the leakage flux $_s$, i.e.:

$$\Phi_{wz} = \Phi_T + \Phi_s. \tag{15}$$

With regard to saturation of magnetic circuit, inductance of excitation winding is a variable value, dependent on changes of excitation stream values. All inductive parameters of car starter are non-linear functions of load current. Taking into account the dependence:

$$U_A = E_A - R_A \cdot I_T, \tag{16}$$

where:
E_A – electromotive force of uncharged battery,
R_A – internal resistance of battery,
as well as dependence (12) and (14) in equation (6), the following expression was received:

$$E_A = \left(R_T + R_{wz} + R_A\right) \cdot I_T(t) + \left(z_T \frac{\delta \Phi_T}{\delta I_T} + z_T \frac{\delta \Phi_{wz}}{\delta I_T} \right) \cdot \frac{dI_T}{dt} + c_E \cdot \Phi_T \cdot \omega(t). \tag{17}$$

From the above-mentioned dependences it results that the system's electric factors have the greatest effect on working parameters of a combustion engine's starter. Due to natural or accelerated wear the co-operation of feeding elements (e.g. brush-commutator pair) deteriorates. Hence, the starter's power and moment drop, due to a weaker influence of magnetic fields of the stator's and armature's excitations. Taking opportunity of this fact, it is possible to assess the wear level of a starter‘s elements by taking measurements of its magnetic flux. In other words, the magnetic flux of a starter can be used as its diagnostic parameter.

TESTING STAND

Taking measurements of a starter working extravehicular is possible during the course of action of test stand diagnostics. For investigations of an influence of exploitation damages on exit profiles of combustion engines’ electric starters in laboratory conditions the Bosch testing stands were used, which were afterwards adapted to investigations on the Hall phenomenon’s application to the new diagnostic method. This had in view preliminary investigations on the usefulness of this method to functional diagnostics of starters. If these devices were used for diagnostics inside a vehicle, it would be difficult to eliminate the overlapping faults of a combustion engine.

The measuring apparatus applied in the testing stand includes:

- a voltmeter for measurement of direct current voltage in the range from 0 to 40 V,
- an amperometer for measurement of current in the range from 0 to 1200 A,
- revolution counter in the measuring range from 0 to 40 000 rpm^{-1},
- mobile computer of PC class with an installed measuring card,
- a sensor of magnetic field in the measuring range to 0,25 T,
- a feeder of the Hall sensor.

During investigations into an influence of starters’ damages on their output profiles on a testing stand there were used a voltmeter, amperometer and revolution counter. The variable load was obtained by loading the brake of the gear-wheel co-operating with the starter’s gear. Excitation current consumed by the device during its running was the measure of the starter’s load. Gradation of load was executed for every 100 A.

For the measurement of magnetic induction intensity a sensor was used (Fig. 2), whose functioning is based on the Hall phenomenon. This phenomenon results from the magnetic field’s influence on the current in a semi-conductor.

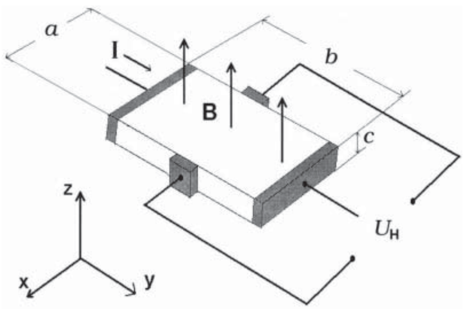

Fig. 2. The diagram of Hall sensor’s use for investigations into magnetic induction in a starter: I – hallotron current, B – magnetic induction, U_H – Hall voltage *a,b,c* – respectively, the length, width and thickness of semi-conductor

The running of this sensor depends, among other things, on the stability of feeding voltage, therefore an individual feeder was applied. The measuring track consisted of the AC converter adapted for the direct measurement of voltage variables in the values range ±10V. The other measured values have to be processed to the value proportional to their voltage.

A block diagram of the testing stang for investigations into diagnostic signals coming from the magnetic field in the starter's converter is presented in Fig. 3

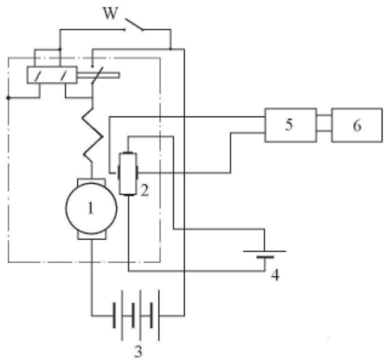

Fig. 3. Block diagram of the testing stand: 1 – starter, 2 – Hall sensor, 3 – battery, 4 – feeding of Hall sensor, 5 – converter of signal, 6 – computer

An evaluation and verification of the electric starter's technical state were conducted after a comparison of Hall voltage courses for an efficient starter, treated then as the model ones, and for a faulty one. In order to exclude any possible unserviceability of a selected starter, its diagnostic evaluation by the Bosch method was conducted. For a simulation of typical mechanical or electric damages, some elements were disassembled (for example the brushes) and purposefully damaged (e.g. muffs of bearings were drilled to enlarge the clearance between the co-operating pair of shaft's pivot and bearing end).

Considering the character of running of starters as well as conditions of their work, the method of damage simulation was applied for the investigations and the following kinds of damages were selected:

- friction between pole shoes and rotor (damaged slide bearing),
- drossy or arid commutator,
- worn-out brushes,
- simultaneous occurrence of all the mentioned damages.

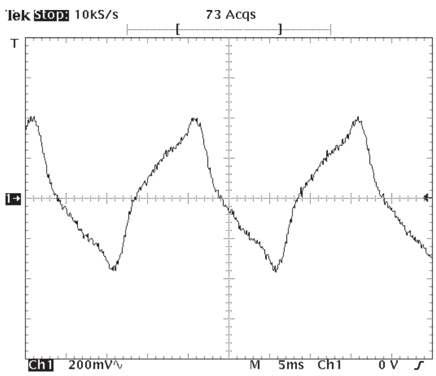

Fig. 4. Oscillogram of magnetic flux around a pole shoe

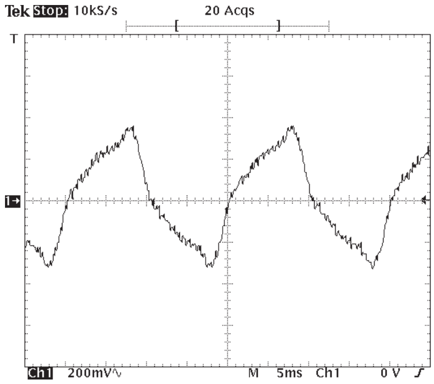

Fig. 5. Oscillogram of magnetic flux on the screw of a pole shoe

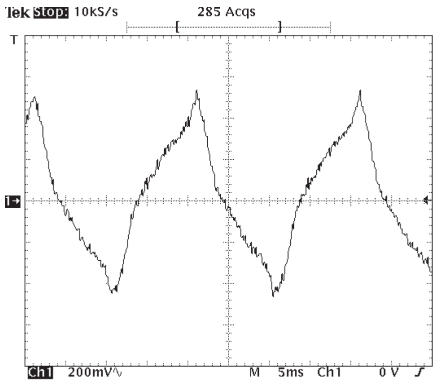

Fig. 6. Oscillogram of magnetic flux on the border between the screw and yoke

Aiming at investigations into the usefulness of a diagnostic method to an assessment of starters installed in a car, a Hall sensor was fixed in the armature zone of a starter and during the starting of the combustion engine the courses of Hall voltage U_H were recorded on the output from the semi-conductor's connectors.

The site of Hall sensor's fixing was experimentally determined. The size of amplitude found out with the digital oscillograph Tektronix TDS 380 was studied at the sites of the fixing of the starter's pole shoe on the stator's external side in three places: around the pole shoe, directly on the screw fixing the starter's pole shoe to its yoke as well as on the border of bolt head and yoke's hole. The oscillograms are presented in Figs. 4, 5 and 6.

As it results from the presented oscillograms, the largest intensity of the starter's magnetic field's stream was observed on the border of bolt head fixing the pole shoe to the yoke's casing. This site is the determinant of fixing the Hall sensor on the starter because of the strongest field's signal here.

The starter selected for laboratory investigations was 0 001 369 014 produced by Bosch, Germany, applied in the starting circuits of the Lamborghini Formula, Racing and Champion tractors.

The popularity of usage in the Polish agriculture of the mentioned tractors and machine engines was considered during the choice of a starter for investigations into the new diagnostic method.

RESULTS OF LABORATORY INVESTIGATIONS AND THEIR ANALYSIS

The results of testing stand investigations into the studied starter using the Hall phenomenon for both an efficient starter and one with simulated damages are presented in Figs. 7-11.

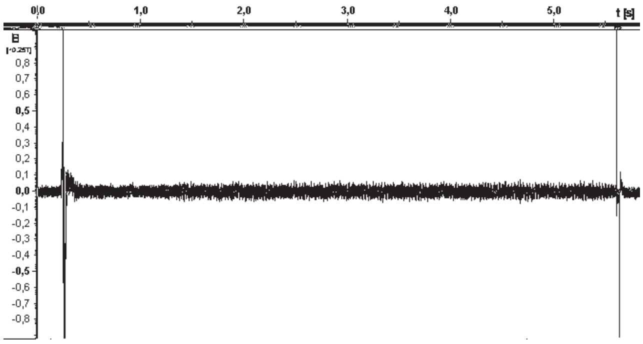

Fig. 7. The course of changes of magnetic induction recorded for an efficient starter

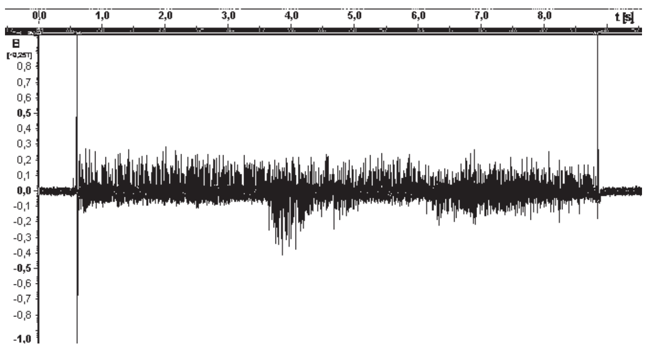

Fig. 8. The course of changes of magnetic induction recorded for a starter with simulated damage of sliding muffs

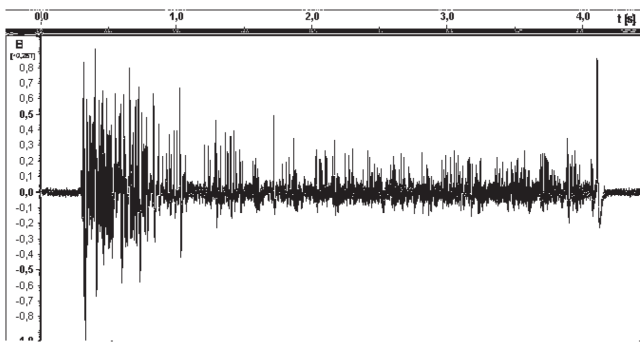

Fig. 9. The course of changes of magnetic induction recorded for a starter with simulated damage of commutator

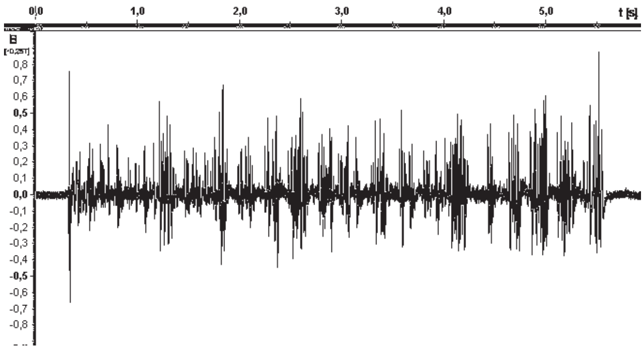

Fig. 10. The course of changes of magnetic induction recorded for a starter with simulated damage of brushes

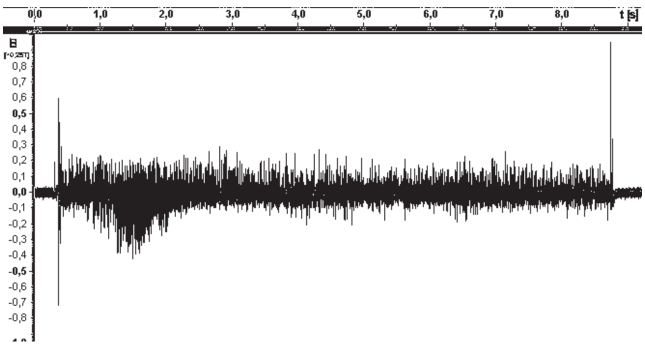

Fig. 11. The course of changes of magnetic induction recorded for a starter with simulated simultaneous occurence of all the mentioned damages

CONCLUSION

During the carried-out laboratory tests using the Hall phenomenon, dependences were observed among all the simulated damages of starters and magnetic induction's intensity. These measurements illustrate the magnetic processes occuring in the starter, considering significant differences in the consumption of the provided current and the accompanying change of the device's technical state.

The mechanical processes in the starter cause an occurence of electric phenomena around its poles. Due to the recording of magnetic induction in an efficient starter (Fig. 7) it is possible to observe a small alteration of this value. During the simulation of damage of sliding muffs and the friction between pole shoes and rotor (Fig. 8), alternating magnetic field's values are observed accompanied by an alternating consumption of current from battery.

They also change the interaction between the magnetic fields of stator and rotor which results in an increase of current's consumption from battery. As a result, an alternating magnetic induction occurs. Similar magnetic induction parameters can be observed during the simulation of damage of brushes and commutator's starter (Fig. 9-10). They are caused by disturbances of rotor's feeding due to commutator's roughness and inappropriate adhesion of brushes (when commutator is damaged) as well as a periodical lack of contact of brushes with commutator.

It can also be observed, that a periodical lack of contact of brushes with the starter's commutator causes an occurence of considerable changes in magnetic induction, which is shown in Fig. 10.

Fig. 11 presents the course of changes of magnetic induction recorded for a starter with simulated simultaneous occurence of all the mentioned electromechanical damages. The course of magnetic induction is similar to the one recorded for an efficient starter, however the difference is, that the intensity of this induction is considerably higher with all the damages occuring simultaneously than with an efficient electromechanical system of a starter.

The conducted simulation investigations into an influence of electromechanical damages on courses of magnetic induction showed essential dependences among the simulated damages and intensity of magnetic induction.

Summing up, an application of the Hall sensor to measurement of changes of magnetic induction depending on the state of an electric machine allows for a diagnosis of both the damages of an electric system, for example the brush-commutator, and the mechanical damages, for example the damages of sliding muffs. It is connected with the growth of a rotor's tractive resistances, and the involved higher consumption of current from a source of energy. Due to damages of this type, a growth of magnetic induction's intensity in a machine also occurs, which provides us with an image of an occurring damage through its recording.

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