Simulation of Processes in Traction Electric Actuators of Autonomous Vehicles

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Contribution to the state of the art

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Abstract: At the stage of construction of traction electric drives of electric power systems (EPS) the analysis of electromagnetic and energy processes in various operational and emergency modes is needed. The calculation of complex multi-electromechanical systems of modern vehicles is only possible by computer simulation. The programming of such complex systems by traditional methods is practically impossible, or is a time-consuming process. The use of universal modeling systems is the only possible way of modeling of multi-component systems. In this article we deal with the mathematical model of the synchronous generator of autonomous vehicle in computer-aided design (CAD) OrCAD 10.0 (Pspice). The software package OrCAD 10.0 (Pspice) is one of the most versatile in the field of simulation of electrical circuits with a large number of components. OrCAD libraries contain proven by the time mathematical models of practical application of electric power components and it is continuously ever-growing. At the end of the article the characteristics for different modes of operation of a synchronous generator are summarized.

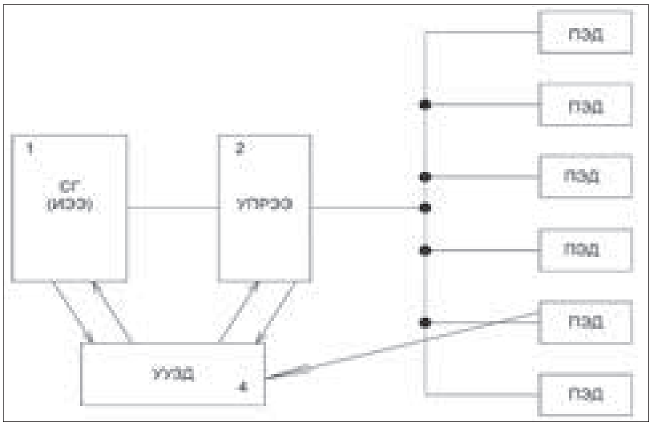
Keywords: traction electric drive, autonomous locomotive, marine engine, mathematical model, energy processes, electromechanical system, synchronous generator, the hysteresis loop.

In traction electric drives of modern vehicles, including autonomous locomotives of railways, ships and vessels regardless of the type of driving (traction) engine as a primary power source the synchronous generators are applied, which are geared by diesel engines or turbines.

The analysis of electromagnetic and energy processes in electric drives of such vehicles, including comparative analysis, is worth while carrying out on mathematical models of traction electric drives, which allows to enter in the analyzed system the parameters of its components with any required accuracy. These system parameters are: the source of power, converters and regulators of parameters of energy transmitted from the source to electric engines and the engine themselves.

The most suitable for the simulation of electromagnetic and energy processes in complex multi-electromechanical systems, which also include traction electric drives, is a software package OrCAD 10.0. This is allows to perform multivariate calculations of electromagnetic and energy processes in such systems during reasonable time.

Using the specified software package the system under analysis is divided into interconnected individual modules that are managed by a specific algorithm.



СГ – synchronous generator (power source)
ИЭЭ – power source
УПРЭЭ – converting and electric energy regulating device
ПЭД – drive motors
УУЗД – control, protection, and diagnostics device

Figure 1. The power circuit structure of the of electric equipment of traction electric drive of autonomous vehicle: 1 – synchronous generator (power source); 2 - converting and electric energy regulating device; 3 - drive motors; 4 - control, protection, and diagnostics device.

In particular, the traction electric drive of the autonomous vehicle, as electromechanical system, can be represented by the structure, shown in Figure 1 and including four modules 1-4.

Mathematical models should be drawn up for each of the modules of the analyzed system, depending on the purpose of the analysis. The given algorithm defines the interaction of the mentioned models and allows obtaining of the required solution of the problem.

In this paper the mathematical model of the input module of the analyzed system - synchronous generator type SGDM - 5000 - 8 - OM4, used in traction motor drives of ship vehicles is regarded.

The building of the model of a synchronous generator is started with the creation of the model of the magnetic core.

The model of the magnetic core is based on the template created on the basis of the model Giles-Atherton [6, 7]. The initial data for the model are:

1. The size of the gap, Gap [centimeters];
2. the cross-section area of the core, Area [square centimeters];
3. the length of the median line of the core, Path [centimeters];
4. the duty factor of the core, Pack (dimensionless).

In addition, to construct a model of the core it is necessary to set the hysteresis loop for the core material (Figure 2).

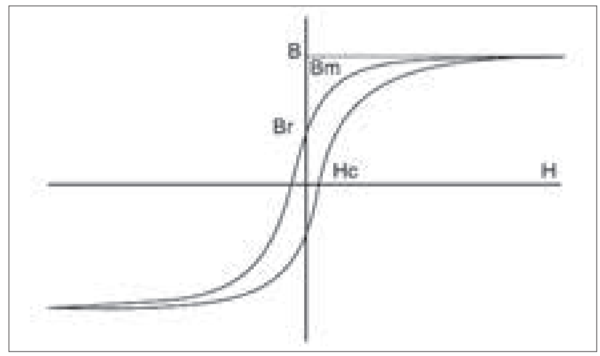


Figure 2. The hysteresis loop for the core material

For Figure 2 the following symbols are accepted:

Hc [Oersted] - the electromagnetic field strength of the core when induction equals to zero;

- Br [Gauss] - induction in the core when the electromagnetic field strength equals to zero;
- Hm [Oersted] - the electromagnetic field strength of the core when induction equals to the saturation induction;
- Bm [Gauss] – the saturation induction.

In addition to that, the value of initial magnetization (Initial Perm) is set.

The initial information is entered in the Model Editor in table of Hysteresis Curve and Parameters. The information in the table of Hysteresis Curve is entered in the form of:

- (0, Br);
- (Hc, 0);
- (Hm, Bm).

The attempt to construct a more accurate hysteresis loop for more points does not give positive results, because only the first three pairs of numbers listed in the table are consider in the Model Editor.

In the version OrCAD 9.2 is used the 2nd level (LEVEL = 2) of core model, and in version OrCAD 10.0 - the 2nd (LEVEL = 2) or the 3rd (LEVEL = 3).

For the third level we introduce the following assumptions [7]:

1. the loop is static, its shape does not depend on the frequency variation of the electromagnetic field strength H;

2. the saturation induction B_m for the model of the magnetic core is defined as the asymptote of the hysteresis loop. The manufacturers of the magnetic core typically define saturation as point on the hysteresis loop, above which a decrease of penetrability in the core begins to limit its application. If the values B_m are taken directly from the reference tables of manufacturers cores, the core model will work with a low value of the value B_m. Taking into account the different definitions of the saturation induction, it is not recommended to use values of B_m from the reference data; instead of it, it is used the values B_m, which was defined directly on the hysteresis loop;

3. The model of the air gap may be incorrect at low operating frequencies (typically <100 Hz). Obtained in this case error is caused by the 0,001Ω resistor introduced in series with the inductor of core. To improve the accuracy of the modelling of air gap one of the following conditions should be met: winding resistance is greater than or equals to 0.1Ω; the inductive component of the impedance (ZL) is greater or equals to 0.1 Ω. The verification showed, that in this case these conditions are hold true.

The value of inductive impedance component is calculated by the formula as $|Z_L| = \omega L_{eq}$,

where $\omega = 2\pi f$ - angular frequency; L_{eq} - equivalent inductance.

When replacing the L_{eq} on an equivalent expression, we obtain:

$$|Z_L| = \frac{2\omega\mu A n}{L},$$

where μ - magnetic permeability; A - area; n - number of windings; L - length;

The results of the calculation circuit, comprising a core, in which saturation induction B_m is greater than 10^6 G, may differ from the results of simulation of real cores [7].

In case of convergence problems appearing while modelling of core with very high saturation induction and very low coercive force the core should be replaced by the ideal core, which model provides the calculation of the saturation induction at infinite and zero coercive force.

In [5] we analyzed the problems of modification PSpice-model of the magnetic core for defining its parameters by reference characteristics; also we proposed modification PSpice-model to account the magnetic properties of materials.

MS - saturation magnetization (magnetization saturation) [ampere / meter] = 4,903,089.039498;

A - shape parameter of no hysteresis magnetization curve (thermal energy parameter) [ampere/meter] = 48.64212819596;

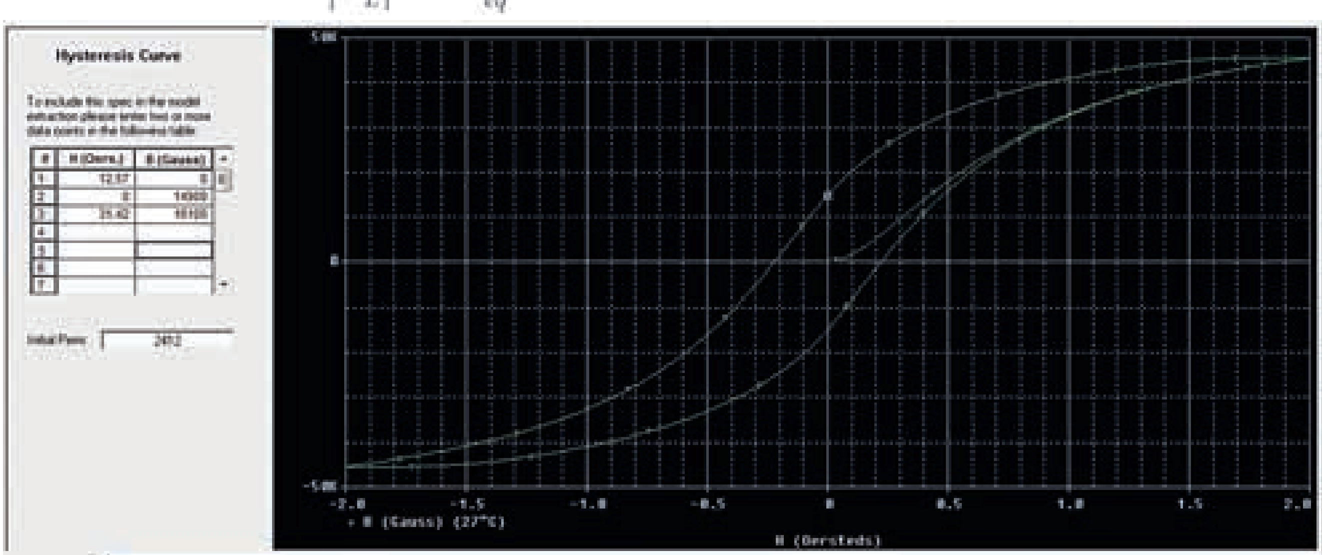


Figure 3. The hysteresis loop for the core model of the electrical plate steel of steel quality 2412.

C – the constant value of elastic displacement of domain edges (domain flexing parameter) = 0,01001;

K - the constant value of mobility of domain (domain anisotropy parameter) [amperes / meter] = 19.8446694766.

Hysteresis loop for the constructed model of the core is shown in Figure 3.

Now we develop a model of the specific magnetic core. Its parameters, according to the task: GAP = 0,968 cm, AREA = 143,184 cm^2, PATH = 101,9 cm, PACK = 1. As the core material the electrical plate steel of quality 2412 was used. The values of B_r, H_c, H_m and B_m are taken from the passport. So, H_c = 12,57 Oe, B_r = 1,49 * 104 G, H_m = 31,42 Oe, B_m = 1,6 * 104 G. According to these data we calculated the required characteristics of the model.

The next step will be the modelling of a synchronous generator operating in short circuit and idling modes. The electric diagram of such generator is shown in Figure 4.

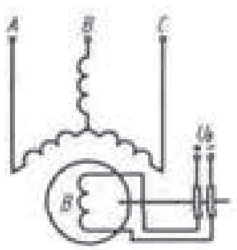


Figure 4. The electric diagram of a synchronous generator

The scheme of the developed model is shown in Figure 5.

The vehicles EPS are complex systems consisting of several diesel or turbo-generators and dozens or even hundreds of asynchronous motors, dozens of static loads. The most advisable way to carry out the study of such systems is by using models of synchronous generators in the phase coordinates. However, the presence of variable coefficients in the equations of these elements causes considerable computational difficulties which at solving of the given tasks by the traditional research methods are non-defined. Currently the objectives of the study of transients in EPS are solved by using the models of synchronous generators written in the axes *d*, *q*. The presentation of synchronous generators mathematical models in this form in case of applying the program PSpice a/d is decisive. The program PSpice a/d generates the communication equations between the electric machines models recorded in this way, and they are compiled automatically, without the researcher intervention. Moreover, generated in this way models easily integrate into the available in libraries DesignLab components.

The type of the differential equations of AC electrical machines is different depending on the choice of the voltage vector direction, the flux linkages, the initial mode (generator or motor). The transients study method by using the PSpice program is suitable for any form of differential equations.

The three-phase synchronous generator with salient-pole rotor is analysed. The generator has a symmetrical three-phase winding on the stator. The field coil and the damper winding are located on the rotor. The damper winding is intended primarily for damping of the rotor fluctuations, the improvement of the conditions of pulling into synchronism and prevention from overvoltage in the stator windings under unbalanced load conditions. The system of differential equations describing electromagnetic and electromechanical transient processes in a synchronous generator includes the equation of the equilibrium voltage of all electrical circuits in the stator and rotor and the equation of rotor operation.

$$\begin{cases} \psi_d = x_s i_d - E_{\delta q}; \\ \psi_q = x_s i_q + E_{\delta d}; \\ \psi_r = \frac{x_{ad}}{x_r} E_{\delta q} + \frac{x_{sr}}{x_r} E_q; \\ \psi_{rdi} = \frac{x_{ad}}{x_{rdi}} E_{\delta q} + \frac{x_{srdi}}{x_{rdi}} E_{rqi}; \\ \psi_{rqk} = -\frac{x_{aq}}{x_{rqk}} E_{\delta d} - \frac{x_{srqk}}{x_{rdi}} E_{rdk}; \\ \frac{d\psi_r}{dt} = \frac{1}{T_r}\left(E_r - E_q\right); \\ \frac{d\psi_{rdi}}{dt} = -\frac{1}{T_{rdi}} E_{rqi}; \\ \frac{d\psi_{rqk}}{dt} = -\frac{1}{T_{rqk}} E_{rdk}; \\ \frac{ds}{dt} = \frac{1}{T_j}(M_T - M_E); \\ \frac{d\delta}{dt} = \omega_s(s - s_v); \\ E_{\delta q} = \vartheta_d \left(x_{ad}\, i_d + E_q + \sum_{i=1}^{n_d} E_{rqi} \right); \\ \frac{1}{\omega_s}\frac{d\psi_d}{dt} + (1+s)\psi_q + r i_d = -u_d; \\ (1+s)\psi_d + \frac{1}{\omega_s}\frac{d\psi_q}{dt} - r i_q = u_q. \end{cases}$$

- where ψ_d, ψ_q, i_q, i_d are the flux linkage and current of the equivalent damping windings under longitudinal and transverse axes, respectively;
- x_s- reactive impedance of the stator leakage;
- $E_{\delta d}$, $E_{\delta q}$- longitudinal and transverse component of the EMF; x_{ad}, x_{aq}- reactive impedance of the stator (armature) reaction in the longitudinal and transverse axes;
- r - reactive impedance of the stator winding;
- $x_r = x_{ad} + x_{sr}$, $x_{rdi} = x_{ad} + x_{srdi}$, $x_{rqk} = x_{aq} + x_{srqk}$- reactive impedance of the excitation winding, longitudinal and transverse damping circuits;
- $E_q = \frac{\omega_s M_{ad} i_r}{\omega_s M_{ad}\, i_{6r}}$, $E_{rdk} = \frac{\omega_s M_{ad} i_{rdi}}{\omega_s M_{ad}\, i_{6rd}}$, $E_{rqi} = -\frac{\omega_s M_{aq} i_{rqk}}{\omega_s M_{aq}\, i_{6rq}}$ Is the EMF induced in the stator by the magnetic field of the currents of the rotor contours during the synchronous rotor speed;
- x_{sr}, x_{srdi}, x_{srqk}- reactive impedance of the leakage of the excitation winding, longitudinal and transverse damping circuits;
- ψ_r, ψ_{rdi} , ψ_{rqk}- - flux linkage of excitation winding of i- longitudinal and k – transverse equivalent damping circuits;
- $T_r = \frac{x_r}{\omega_s r_r}$- the time constant of the excitation winding when other circuits are open, with;
- E_r - excitation voltage;
- s - slide;
- M_T - torque of the generator drive motor;
- M_E- generator electromagnetic torque;
- ω_s- synchronous angular velocity;
- ϑ_d- the saturation parameter along the longitudinal axis;
- $T_j = J\frac{\omega_S^2}{S_6 p^2}$ - inertial constant of the generating unit.

Using the above system of the synchronous generator differential equations with variable coefficients all the main processes of the synchronous generator can be modelled.

In this diagram a three-phase network is modelled by the sinusoidal voltage sources U1, U2, U3. The voltage amplitude is 3642 V, the magnitude of the DC component equals to 0, and the frequency is 50 Hz. The shift between the phases is by 120 electrical degrees. The inductors L1, L2, L3 simulate the filters protecting against the interference in the network. The wire resistance is modelled by using resistors r1, r2, r3, r4, r5. The resistor r6 simulates the idle mode, and the resistor r7 simulates the short circuit mode. The inductors L4, L5, L6, L7, L8 simulate the actual generator operation. The number of windings is taken from the passport data of the synchronous generator SGDM - 5000 - 8 - OM4 type. Element K2 simulates the core operation which model is described above.

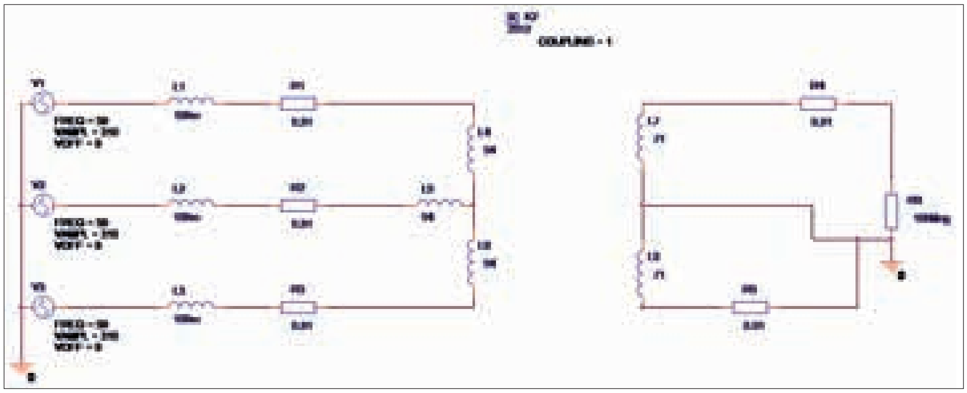


Figure 5. The diagram of model a synchronous generator

Figure 6 shows the power in the idle mode, and Figure 7 shows the power in the short circuit mode.

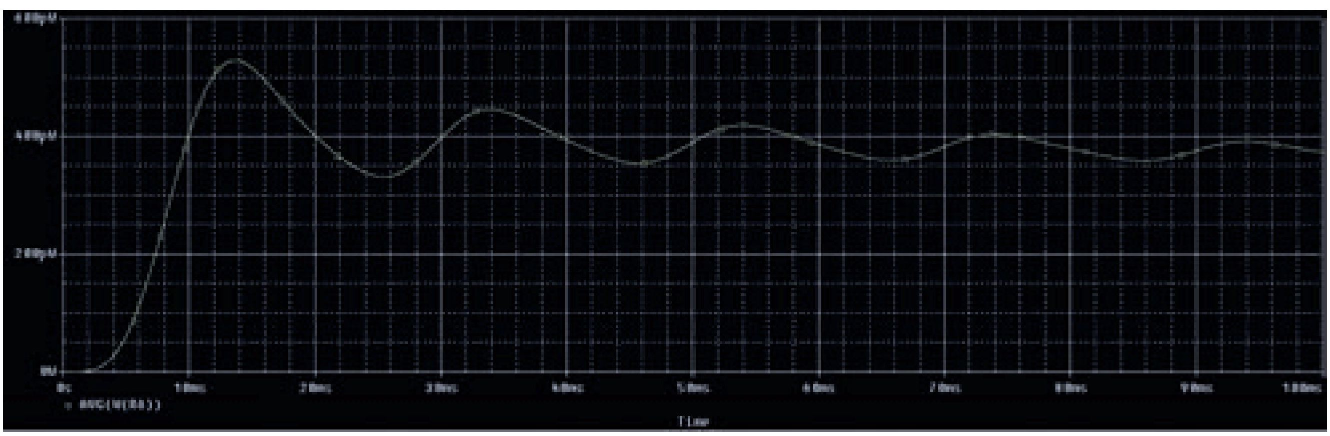


Figure 6. Power in the idle mode

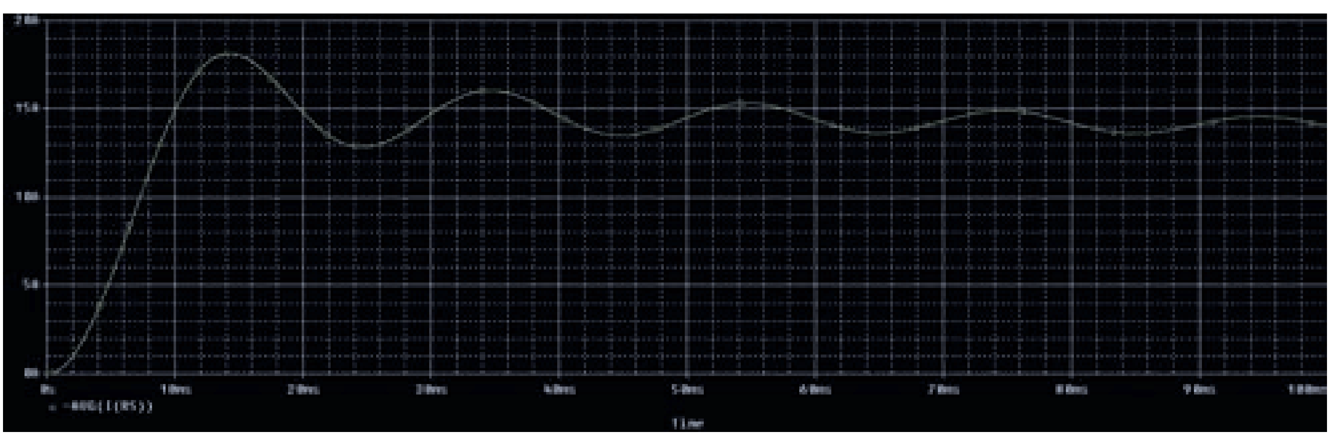


Figure 7. Power in the short circuit mode

The oscillograph records demonstrate clearly that in the idle mode the energy is not released. This fact confirms the adequacy of the model. It also proves that the regulation quality is at a high level.

Finally, the last stage of the simulation is the analysis the synchronous generator processes in the real load mode. According to the calculations, the load is simulated by the current source I1. The complete diagram of a synchronous generator model is shown in Figure 8.

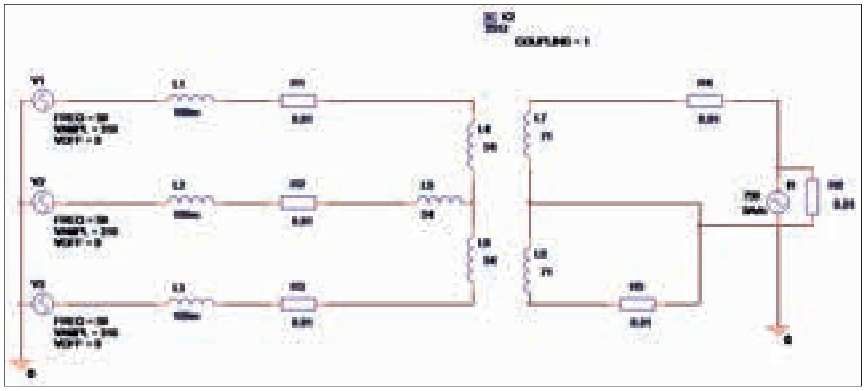


Figure 8. The diagram of a synchronous generator model operating in load mode

Figure 9 shows the load current oscillograph record, and Figure 10 shows the load voltage.

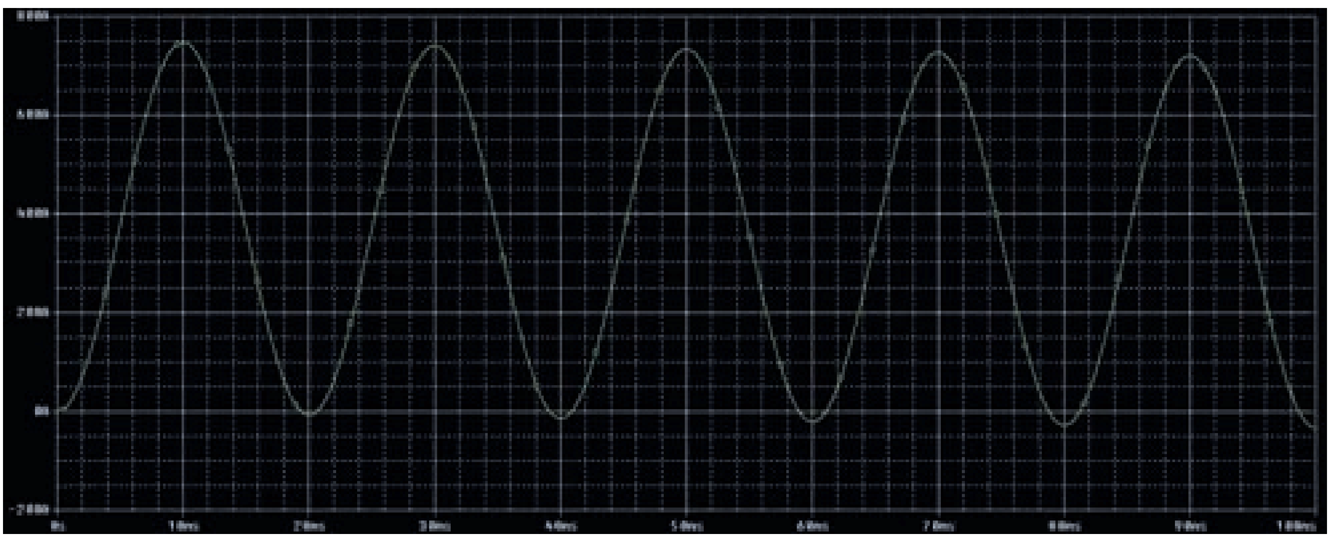


Figure 9. The load current oscillograph record

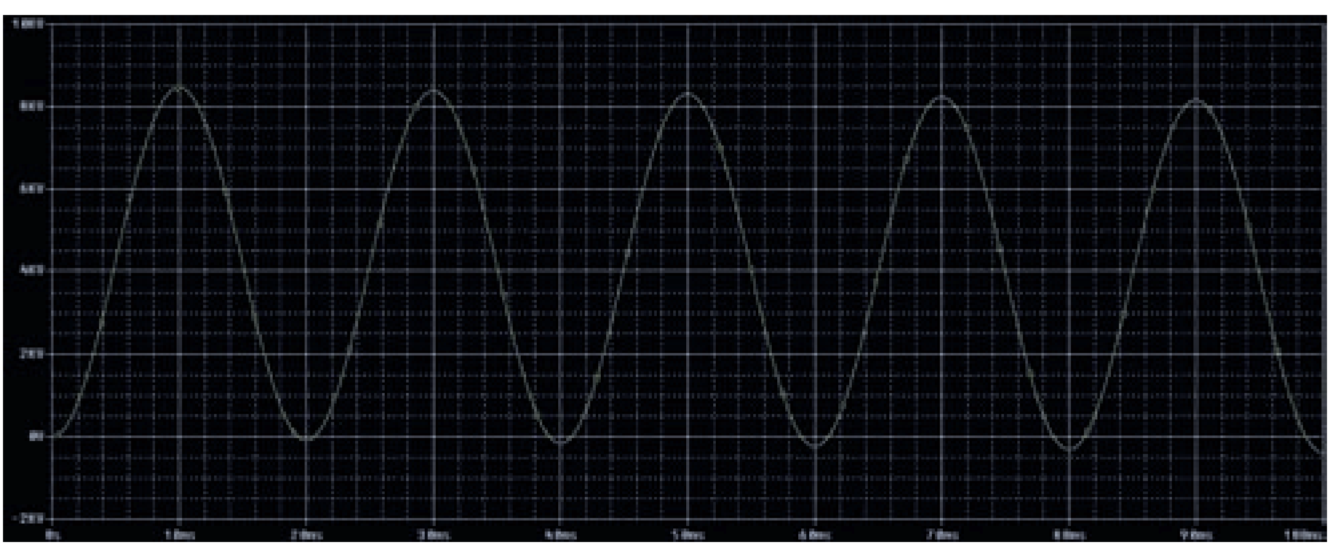


Figure 10. The load voltage oscillograph record.

The proposed model of a synchronous generator for autonomous locomotive takes into account the actual characteristics of electrical steel of core and allows to obtain the necessary characteristics of the generator in a wide range of loads. The model can be used for analyze of electromechanical processes in autonomous traction electric locomotives and determining of the energy efficiency of electric drives.

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