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Study of Energy Indicators and Features of Propulsion System Main Components of Electric Vehicle Using Mathematical Simulation

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Abstract

Objectives: To calculate the energy performance of the Electric Propulsion System (EPS) using the mathematical simulation and analysis of the obtained characteristics, taking into account the use of various types of electric motors. **Method/ Statistical Analysis:** The method of model-oriented programming was used to study the necessary parameters, by which the two mathematical models in Matrix Laboratory (Matlab) / Simulink were built. It allowed the calculations in a short time and a detailed analysis of the results. While building up the mathematical models of electric motors, the vector control was implemented, as based on the method of vector representation in variables of states in a space (Field oriented control). **Findings:** In addition to mathematical description of the motors, the article represented the mathematical model of the inverter on IGBT transistors required for commutation of the traction motor, lithium-ion battery as well as all major components required for proper system operation. This article discusses two of the most often used type of contactless AC machines - asynchronous motor with squirrel-cage rotor (Induction motor) and a synchronous motor with permanent-magnet excitation (Permanent Magnet Synchronous Motor). Because of mathematical simulation, the assessment of the energy parameters of two systems was carried out. Analysis of the obtained results allowed the identification of characteristic points in driving cycle, defining the minimum requirements for mechanical, electrical and power parameters of the electric propulsion of the electric vehicle on condition of implementation of the cycles reviewed. Because of the traction and energy calculation, the consumption values of electric energy for the electric power source were obtained, including the amount of energy regeneration. **Application/improvement:** These methods of mathematical models are universal and can be applied to various types of transport, from electric vehicles to electric trucks and electric buses.

Keywords: Battery, Electric Vehicle, IGBT Inverter, Induction Motor, Permanent Magnet Synchronous Motor, Vector Control

1. Introduction

The modern electric vehicle is a high-tech vehicle. The high technological and energy requirements are applied to the electric propulsion. While selecting a traction motor for an electric vehicle, the question arises, what type of electric motor to give preference. The main indicators can serve as a cost of the electric motor, power characteristics and complexity of control. Two types of electric motors are widely distributed on the market: asynchronous motor with squirrel cage and synchronous motor with permanent magnet excitation. These types of motors are used in all mass-produced electric vehicles. The electric motors have their own advantages and disadvantages. Thus, the synchronous motor has a higher cost due to the use of permanent magnets based on the rare earth materials. In addition, this motor is limited by power due to the temperature characteristics. In turn, its advantages can be characterized by high power characteristics at sufficiently small weight and size as compared to the

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asynchronous motor. The vector control can be used when controlling the motor in both cases, with the regulation of the electromagnetic motor torque. The calculation and assessment of energy performance achieved by creating the mathematical models of components of traction electric equipment and implementing the vector control both synchronous and asynchronous motors.

The study of energy performance and characteristics of the main components of the propulsion system of the electric vehicle allows the comparison of electric motors of various designs with each other and make a choice based on the required performance indicators of electric motor, results of traction and energy calculation and analyses of electric motor through driving conditions.

The mathematical simulation allows the determination of the necessary energy parameters of the traction components and fully, to introduce the functional characteristics of an electric vehicle. A need to build a mathematical model is determined by the complexity of real tests of the vehicle as well as restrictions on time and material costs. Furthermore, the mathematical model allows the more detailed description of the control processes for traction electrical equipment as well as finds a suitable component nomenclature for its implementation. The contemporary mathematics provides extremely powerful and universal means of study. The usage of data mining to extract the original data from specification of manufacturers can help to accelerate the calculations[1]. When building a mathematical model, it requires mathematical formalization of the object, assuming that the features and details of the object can be associated with suitable adequate mathematical concepts: figures, functions of matrix etc. The links and relations, detected and anticipated in the vehicle between its individual parts and components can be recorded using the mathematical relations: equalities, inequalities and equations.

2. Concept Headings

2.1 Determination of Required Functional Performance of Electric Propulsion

The article proposed for the purposes of computational researches the comprehensive mathematical model of electric vehicle based on the mathematical description of mechanical, electrical, and energy parameters of Electric Propulsion System (EPS) key components and the vehicle as a whole. The functional diagram of a comprehensive mathematical model is the electric vehicle provided in Figure 1.

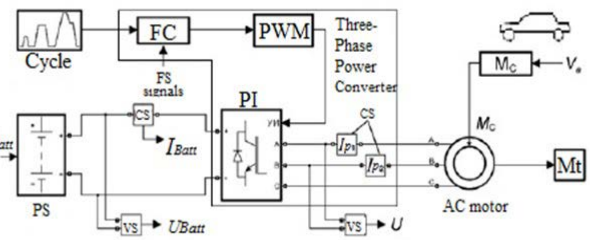

Figure 1. Flow sheet of comprehensive mathematical model of electric vehicle.

The comprehensive mathematical model of electric vehicle includes:

- model of electric power source of battery pack (Power Source);
- model of AC motor (AC motor);
- model of three phase power converter (Three Phase Power Converter);
- control system for power inverter (PI – Power inverter), including the control signal amplifier – functional converter (FC – Functional Converter) with input signals of feedback sensors (FS – Feedback Sensors) and unit of pulse width modulation (PWM – Pulse Width Modulation);
- driving cycle setting unit (Cycle);
- resisting moment valuator (Mc) on the shaft of AC motor in function of characteristics and speed of the motor vehicle;
- data exchange units and measuring units of AC motor and PI parameters (MT–measurement).

The main input data for model of electric vehicle are as follows:

- technical characteristics of the vehicle, including weight, the radius of the wheel, the front projection area, rolling resistance factor, aerodynamic factor, efficiency, moment of inertia of vehicle reduced to the shaft of AC motor;
- equivalent circuit parameters of electric motor;
- characteristics of traction battery (type, nominal voltage, charge-discharge characteristics, efficiency at charge and discharge);
- standard driving cycle, allowing the correct assessment of system energy characteristics[2].

2.2 Basic Provisions to Build Mathematical Model

The mathematical simulation was carried out in the Matlab (Simulink) software. While building a mathematical model, the individual sub-models of EPS components were generated, which were previously described.

2.3 Mathematical Model of Electric Power Source

One of the classic versions of function approximation *f (SOC)* is the equation of Shepherd (Shepherd model), which modification for the lithium-ion battery has the form:

Discharging function ($i^*>0$)

$$f_1(it,i^*,i) = E_0 - K\cdot\frac{Q}{Q-it}\cdot i^* - K\cdot\frac{Q}{Q-it}\cdot it + A\cdot\exp(-B\cdot it) \quad (1)$$

Charging function ($i^*<0$)

$$f_2(it,i^*,i) = E_0 - K\cdot\frac{Q}{it+0{,}1\cdot Q}\cdot i^* - K\cdot\frac{Q}{Q-it}\cdot it + A\cdot\exp(-B\cdot it), \quad (2)$$

where $f_1$and $f_2$are battery energy;$E_0$is constant of voltage, B;K is constant of polarization, Ah^{-1} (polarization resistance); I is current of battery, A;it is extractable capacity, A h; Q is maximum capacity of battery; A is exponential function of voltage, V;B is exponential function of capacityAh^{-1};

The factors E_0, K,A, Bare calculated on the basis of characteristic points of battery discharge curve which are contained in the technical documentation, and Q is the total charge passed to or from battery for a time t:

$$Q = \int_0^t I(t)dt \quad (3)$$

The battery charging rate is calculated according to formula:

$$SOC = 100\left(1 - \frac{1}{Q}\int_0^t i(t)dt\right) \quad (4)$$

- Description of mathematical model of traction electric machine

The Sim Power Systems software has a ready block, which describes these equations for lithium-ion battery. Table 1 provides battery packs characteristics, which were used in the mathematical model.

Table 1. Battery pack parameters

Nominal voltage (V)	400
Rated capacity (Ah)	80
Initial state-of-charge (%)	100
Maximum capacity (Ah)	84
Cut-off Voltage (V)	300
Fully charged voltage (V)	461.44
Nominal discharge current (A)	40
Internal resistance (Ohms)	0.05

2.4 Mathematical Model Squirrel-Cage Motor

This model is based on the equivalent circuit shown in Figure 2.

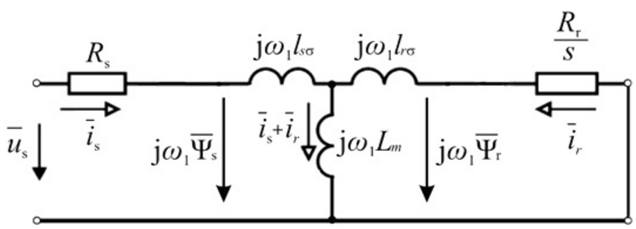

Figure 2. Equivalent circuit of asynchronous machine.

The vector equations for winding voltages of asynchronous machine can be graphically represented by electric circuit diagram. Expressing terms, included in the vector equations, $\frac{d\bar\Psi_s}{dt}, \frac{d\bar\Psi_r}{dt}$ it is obtained[3]:

$$\begin{aligned}\bar u_s &= \bar i_s R_s + \frac{d}{dt}(L_s\bar i_s + L_m\bar i_r) + jw_k\bar\Psi_s,\\ \bar u_r &= \bar i_r R_r + \frac{d}{dt}(L_r\bar i_r + L_m\bar i_s) + j(w_k - w)\bar\Psi_r\end{aligned} \quad (5)$$

where $\bar\Psi_s$, $\bar\Psi_r$ are vectors of current linkage of stator and rotor, accordingly;$\bar u_s, \bar u_r$ are vectors of voltages on stator and rotor windings;$\bar i_s, \bar i_r$ are vectors of currents in stator and rotor windings; R_s, R_r are active resistances of stator and rotor windings; L_s, L_r are total inductions of stator and rotor windings; L_m – mutual induction of stator and rotor windings (total induction of stator winding from the main magnetic flux);$\omega_к$– angular velocity of coordinate system;ω– angular velocity of rotor speed of the electric machine with one pair of poles.

The equations of asynchronous machine in steady-state mode have a form:

$$\bar{u}_s = R_s \bar{i}_s + jw_1 l_{s\sigma} \bar{i}_s + jw_1 L_m (\bar{i}_s + \bar{i}_r),$$
$$0 = \frac{R_r}{s} \bar{i}_r + jw_1 l_{r\sigma} \bar{i}_r + jw_1 L_m (\bar{i}_s + \bar{i}_r) \qquad (6)$$

To determine a slip and angle of effective rotation θ, it is necessary to use the following equations:

$$\theta = \int_0^t (w_r + w_m) \qquad (7)$$

Where w_r is rotation speed of field; w_m is mechanical frequency of rotor speed.

For the system of equations written with respect to the stator current and the rotor flux linkage in the coordinates (x, y) we make a transition into an orthogonal coordinate system (d, q), oriented along the vector of the rotor flux linkage[2]. In this case $w_k = w_\psi, \Psi_{rq} = 0, \Psi_{rd} = \Psi_r$

$$w_\psi = w + w_s = w + \frac{L_m}{T_r}\frac{I_q}{\Psi_r} \qquad (8)$$

$$M_e = \frac{3}{2} Z_p \frac{L_m}{L_r} \Psi_r I_q \qquad (9)$$

The mathematical model of asynchronous machine in orthogonal coordinate system is shown in Figure 3.

In steady-state motor operating conditions, all converted variables are constants. In this regard, this system of equations is very convenient for the calculations of processes in the machine and for the synthesis of a vector control system in coordinates (d,q).

The saturation effect of magnetization circuit in the drive operating conditions can vary up to 30%. The flux linkage shall be regulated to compensate the saturation in the following modes:

1) While drive is operating at speeds exceeding the nominal value (in the second zone of speed regulation at the power constant mode), a weakening of the field occurs;

2) When optimizing the energy drive power, it is required to regulate the flow of the magnetization as a function of the load;

To account for the saturation effect it is used one of the following methods: the method of static inductances or method of dynamic inductances. At the synthesis of the drive control systems it is typically used the method of static inductances giving sufficiently high accuracy in the description of dynamic processes. In this method, the non-linearity of the magnetization circuit is preset by the tabular or by analytical approximation.

Figure 4 shows model in Matlab Simulink software. The library model of asynchronous motor is used as a model of electric motor. The motor parameters are shown in Table 2.

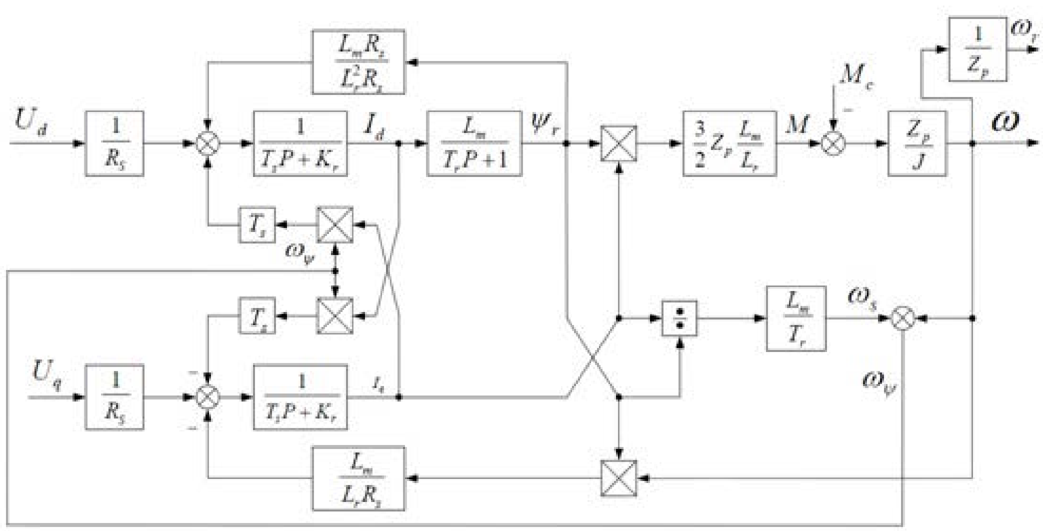

Figure 3. Structural diagram of asynchronous machine in coordinates (d, q).

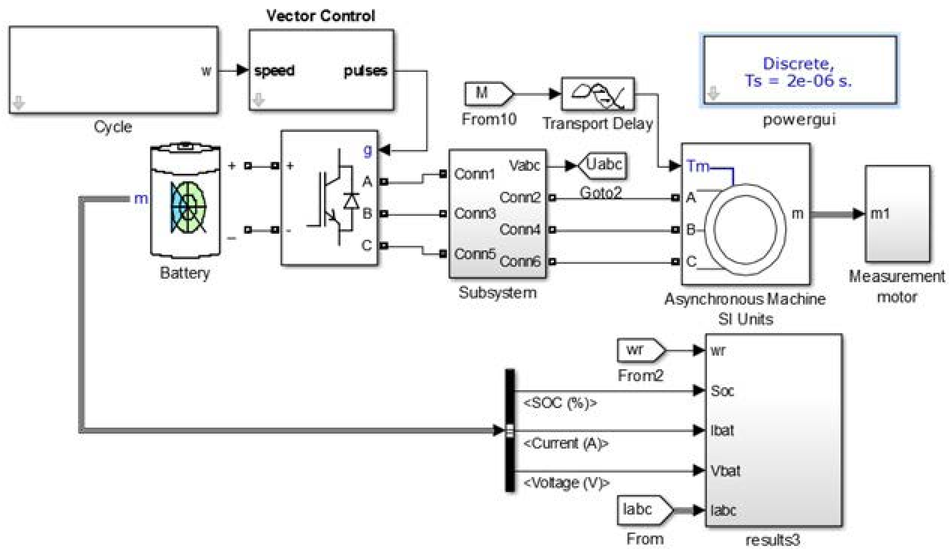

Figure 4. Mathematical model of system with IM in simulink software.

Table 2. IM motor parameters

Nominal power,	160 kW
voltage (line-line)	400 V
frequency	50 Hz
Stator resistance, Rs	0.01379 Ohm
Stator inductance,Lls	0.000152 H
Rotor resistance,Rr'	0.007728 Ohm
Mutual inductance,Lm	0.00769 H
Pole pairs, p	2

2.5 Mathematical Model of PMSM

To simplify the mathematical description of the motor, it is used the coordinate system d-q, rigidly linked with the rotor. Here, axis d is aligned with the direction of the rotor magnetic field. In this case, the operator equations, which describe the electromagnetic and electromechanical processes in the valve motors, have the form:

$$U_d = R(T_d s + 1)i_d - wL_q i_q \quad (10)$$

$$U_q = R(T_q s + 1)i_q - wL_d i_d + \Phi_0 w$$

In equations 10 U_d, U_q, *id, iq* are projections of voltage and stator current on axis, $0_Y$is projection of rotor flux linkage to axis d, $Td = \frac{L_d}{R}, T_q = \frac{Lq}{R}, Ld, Lq$ are time constants and induction of stator winding along longitudinal and transverse axes, R is resistance of stator winding[4]. Mathematical model Mathematical Model of votor in rotation coordinate system

Is shown in Figure 5 and Figure 6. Mathematical model of system with PMSM motor in Simulink software is shown in Figure 7.

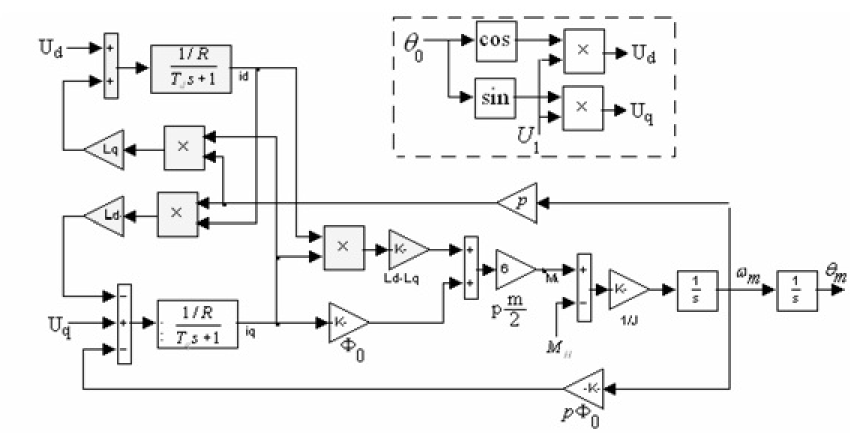

Figure 5. Structural diagram of motor in fixed coordinate system.

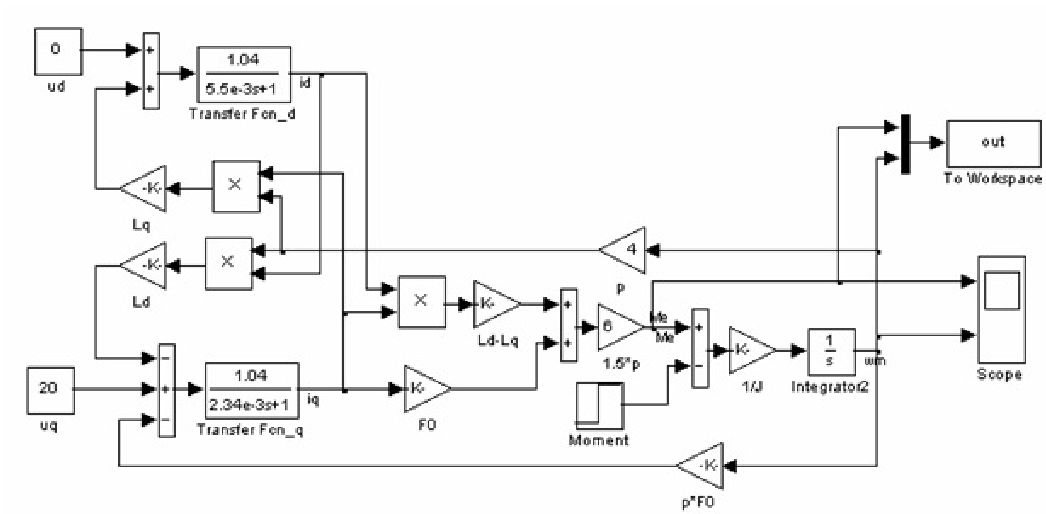

Figure 6. Mathematical model of motor in rotation coordinate system.

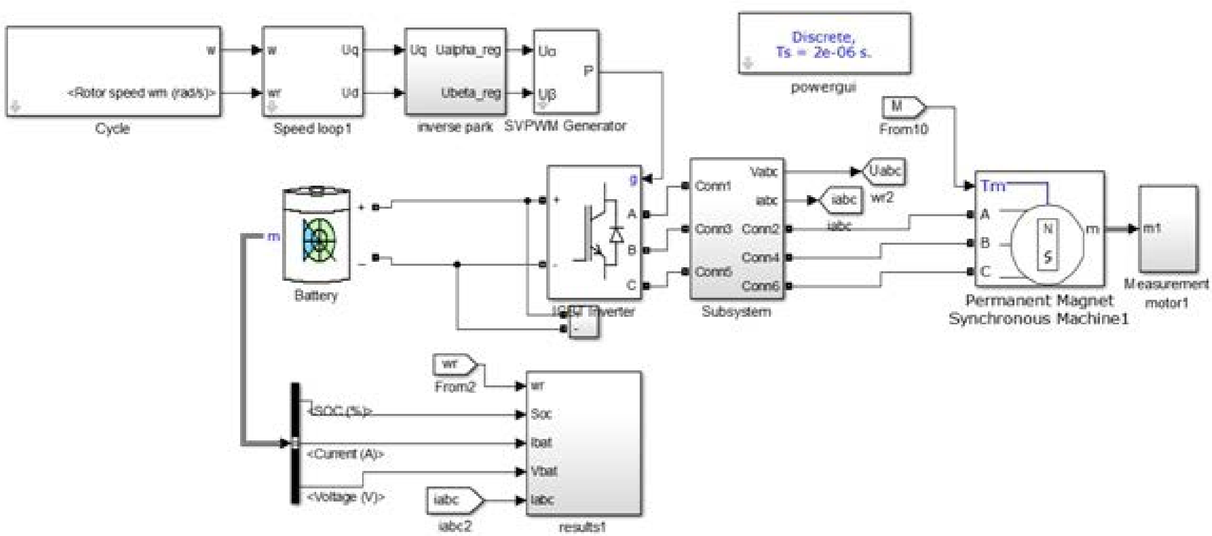

Figure 7. Mathematical model of system with PMSM motor in simulink software.

While describing the PMSM model, the designations of parameters and variables are used as assumed in Sim Power System package[4].

$$\frac{di_d}{dt} = \frac{1}{L_d}u_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}pw_r i_q \qquad (11)$$

$$\frac{di_q}{dt} = \frac{1}{L_q}u_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}pw_r i_d - \frac{\lambda p w_r}{L_q} \qquad (12)$$

$$T_e = 1{,}5p[\lambda i_q + (L_d - L_q)i_d i_q]\ , \qquad (13)$$

Where i_d, i_q, u_d, u_q are amplitudes of current and voltage of stator along axes d, q; λ is amplitude of permanent magnet flux of rotor coupled to the stator winding, Wb; T_e is electromagnetic moment, Nm; w_r is angular velocity of rotor speed, rad/sec; L_d, L_q are inductions along axes d, q, H; R is stator resistance, Ohm; pis a number of pole pairs.

The motor parameters were measured on real motor (Table 3).These parameters are entered to PMSM block.

Table 3. Motor parameters

Nominal power	160 kW
Stator phase resistance, Ohm	0.01087
Armature inductance (H)	0.00021
Torque constant	1.414
viscous damping	0.028
Pole pairs	6
Flux linkage	0.15711

2.6 Mathematical Model of Traction Inverter

Three-phase stand-alone inverter consists of three single-phase single arm inverters, connected in parallel to a single power source. The load of such inverter is turned on either as per "star" or as per "triangle" scheme. As in the first and in the second case, the switching of transistor keys of each phase of the inverter causes a change of voltage in all phases.

Most stand-alone inverters are designed as two-phase and three-phase symmetrical power sources. This allows the presentation of such sources as resulting (generalized) spatial vector.

The frequency converter is running at the stator winding of the asynchronous motor is shown in Figure 8.

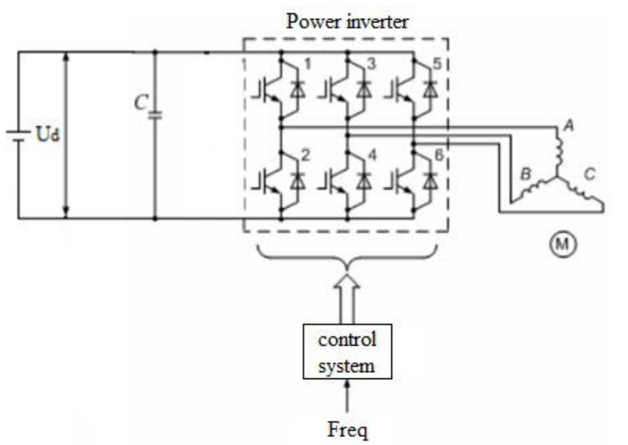

Figure 8. Structure of frequency converter with DC source and controlled amplifier.

It includes a Stand-alone Voltage Inverter (SVI) with Inverter Control System (ICS) and a Current Source (CS). The pattern of power section of the inverter consists of six controlled keys indicated in the Figure by the numbers 1 ... 6. These keys have two-way conductance. Keys are performed on transistors ensuring a current flow towards from the battery pack to the traction motor. The back conductance is ensured by reverse current diodes switched on in parallel to transistors. Using these diodes, it is built up the chain for reverse current flow during commutation of transistors in the regenerative mode.

The inverter model in Simulink software is shown in Figure 9. The Matlab library has a block "IGBT / Diode", which describes the macro model of a real device. This block does not describe the geometry or complex physical processes, but is able to implement the pulse width modulation algorithms for motor control. Six blocks are connected in a bridge circuit similar to Figure 8. The RLC circuit is connected to the inverter DC circuit, which is necessary for smoothing the switching of transistors as well as to improve operation of the inverter in whole.

3. Method and Results

3.1 PMSM Control

There are several ways to control a synchronous motor with permanent magnets. For a purpose of control, the prerequisite is to set the rotor position sensor, which determines the angle of rotation of the rotor. The vector

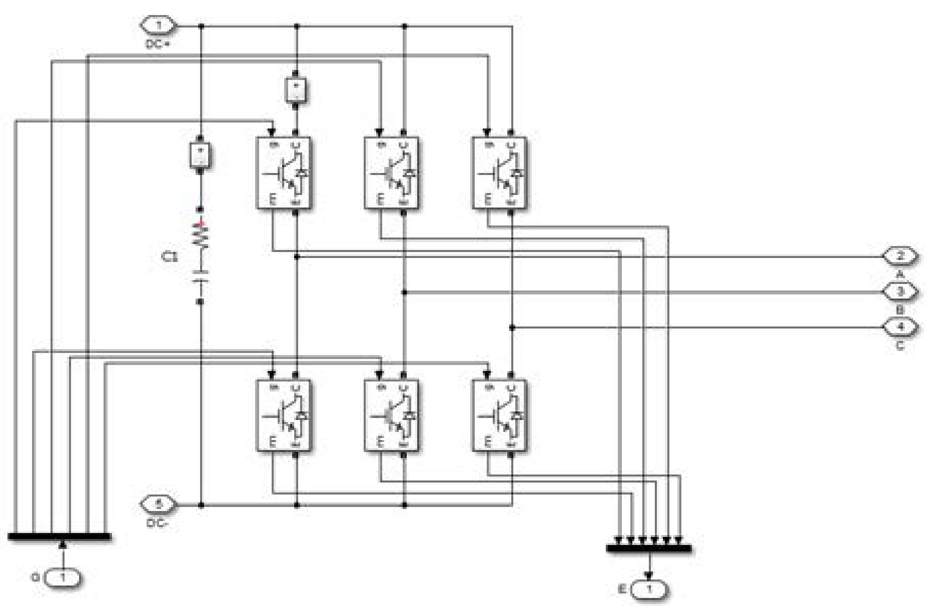

Figure 9. Mathematical model of traction inverter in simulink software.

control method is the most optimal for high-torque motors, since inertia of the entire vehicle is brought directly to the motor shaft.

The currents, flows, AC motor voltage can be represented as vectors in a certain coordinate system. In function of a ratio of the coordinate system that describes the processes, occurring in the motor will have a different look. To obtain the actual values of I_d and I_q current, it is necessary to use the coordinate transformation. For this purpose, the phase currents at the output of inverter shall be measured.

The rotating magnetic field is generated during motor operation that is actually, rotating magnetic flux exists physically. It can be divided into components, coupled with the stator and rotor flux and magnetizing flow and scattering flow, which are closed only through the stator or rotor. It can be assumed that the three-phase fixed coordinate system is oriented on the stator, and its axes coincide with the electric axes of the respective electric motor windings.

After conversion, these currents are compared with the required and at output of PI controllers the vector voltage U_q and U_d are obtained. For vector control, it is necessary to go back into the stationary system αβ. For this, it will be used the Park inverse transformation.

$$\begin{aligned} U_\alpha &= U_d \cdot \cos(\theta_e) - U_q \cdot \sin(\theta_e) \\ U_\beta &= U_d \cdot \sin(\theta_e) + U_q \cdot \cos(\theta_e) \end{aligned} \quad (14)$$

The system rotation is taken into account by the above formulas of coordinate transformations, measuring or calculating the angle of rotation relative to the fixed coordinate system[5].

Figure 10 shows the implementation of the control system in Matlab Simulink software. The "speed control" block contains a PI-controller and the block of error transformation between the motor shaft speed preset in a cycle and the actual rotation speed measured by the speed sensor. The currents i_a and i_b are measured by the current sensors, and then using coordinate transformations they are compared with the reference signals. The sub pattern implemented three PI - controllers, one high-speed ("speed control" block) block and two current blocks (PI controllers "Regiq" and "RegId"). The speed controller is a PI controller that reads the error between the preset motor rotation speed and actual speed. The pattern of "speed control" block is shown in Figure 11.Besides current regulation I_q during operation of motor at frequencies above the rated values, it is necessary the regulation of current I_d, which change shifts the general vector and allows an increase of the torque at motor engine speeds.

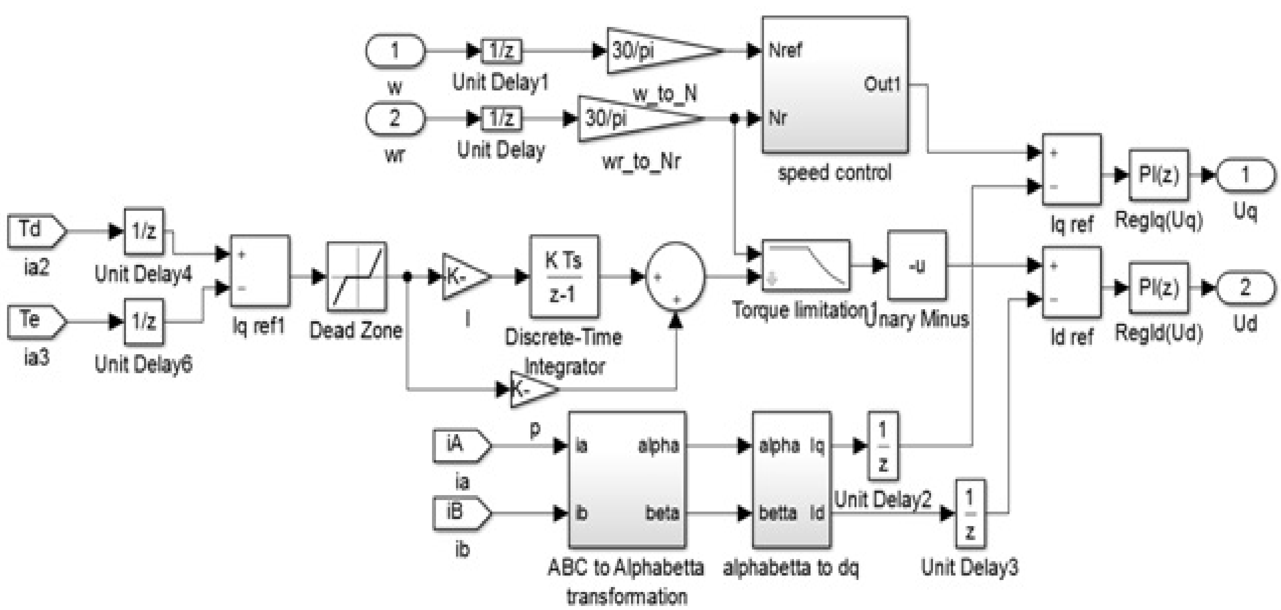

Figure 10. Structural control diagram for PMSM in Matlab software.

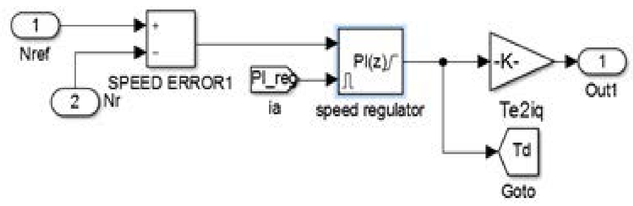

Figure 11. Subsystem of speed control unit.

PI controller increases signal to a value required to achieve the necessary moment until the error does not become minimum. PI controller is one of the most versatile regulators. In fact, PI controller is a P - controller with an additional integral component. I - component, which complements algorithm, is needed, first, to eliminate static error, which is characteristic of a proportional controller. Inherently, an integral part is cumulative and thus allows that the PI controller accounts the previous history for a given time of change in the input value. The output signal formula is as follows:

$$U(t) = P + I = K \cdot \varepsilon(t) + \frac{1}{T_u}\int_0^t \varepsilon(t)dt, \quad (15)$$

where: U(t) is output signal;Pis proportional part; I is integral part; K is proportion factor; T_u is integration constant; $\varepsilon(t)$ is the error signal, a difference between the feedback signal (input control signal).

The set-up of PI controller is implemented through auto-tuning. PI controller block has "Tune" button. After several restarts of system and transient process test between rotation speed (preset and real),the controller itself will put rates, the current controllers are adjusted by the same way.

To ensure the rated capacity through the whole rotation speed range, change of current I_d shall be adjusted by start-up of model and compilation of data tables (Lookup table), which shall contain a current dependence on rotation frequency of the motor shaft.

The output signal from the PI controller is the torque required to overcome the resistance of the vehicle motion, inertial forces, and to ensure the required acceleration. Torque signal is translated into a value of current i_q by the formula:

$$I_q = \frac{2Te}{3p \cdot \lambda}, \quad (16)$$

where λ is flux linkage.

After calculating the current I_q, a signal enters the input of a current controller, where it is compared with the current value. The current I_d is calculated by comparing the torque received at output from speed controller with the motor torque. In case, when at large rotation speed, engine has not enough torque, a difference between the moments enters to the input of the PI controller I_q. The "Dead zone" block is required to reset signal, if the difference is insignificant and for a purpose, that controllers do not affect each other. Furthermore, the "Torque limitation" block does not allow a change of the current I_d before reaching the nominal speed of the rotor.

3.2 IM Control

The flow is not measured or calculated in control system and it is generated by setting the other variables (Figure 12). The motor is represented as a mathematical model in the rotating coordinate system (α, β). The frequency converter is also presented with inverter controlled by current of frequency converter. A system with indirect orientation by field does not contain measurement nodes or calculation of flux linkage of rotor. The required signals for setting the stator current components are generated based on preset values of flux linkage values Ψ_{rz} and electromagnetic torque. At determination of preset values of currents, the mathematical description of motor is used as a structural scheme with orientation of vector $\vec{\Psi}_r$ along axis d.

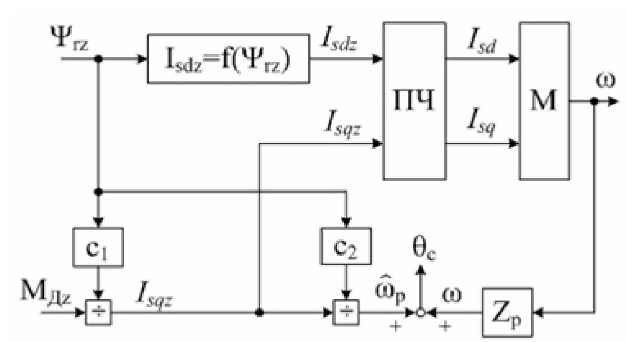

Figure 12. Drive structure with indirect orientation by field.

The implementation of control system in the Matlab mathematical medium shown in Figure 13.

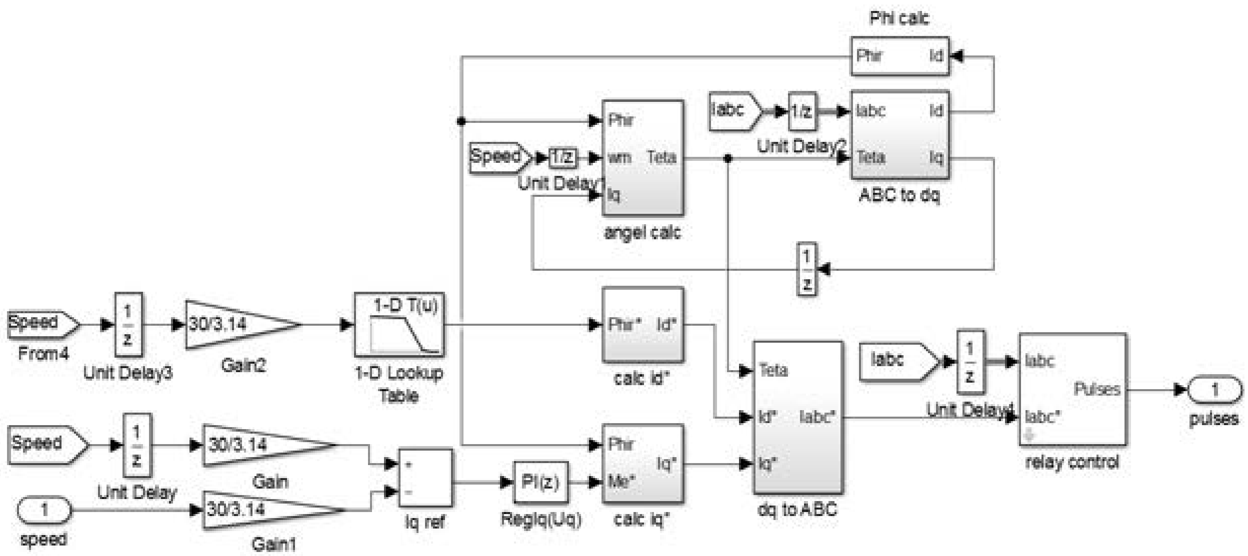

Figure 13. Control system of IM in simulink software.

As for the PMSM control for IM vector regulation, the coordinate converters and PI controller of speed are required.

To enable the proper operation of IM control system, it is necessary to use the coordinate transformation of the phase currents in the d_q system. Control of the motor torque is regulated by current iq, which is directly connected to the stator current. To build properly a value of the control signal is i_q, it needs to create a feedback of electric drive and control system.

The parameters for feedback control are as follows:

- Angular frequency of rotor speed w_r;
- Phase currents I_a, I_b, I_c.

$_{wr}$ is a signal to preset torque T_e, which is obtained by comparison of rotation frequency set in the driving cycle with actual frequency of rotor speed. Using integrator, which takes away from $w_{cycle,}$ the obtained value w_r a difference is found. This signal is delivered to input of the PI controller.

The signal after PI controller enters the measuring unit of current I_q. This unit calculates the current Iq according to the following formula:

$$I_q = \frac{2}{3} \cdot \frac{2}{p} \cdot \frac{L_r}{L_m} \cdot \frac{T_e}{\Psi} \quad (17)$$

In turn, the current Id as well as at PMSM regulation starts to change when motor leaves the nominal rating. By model launching, the data table of flux linkage is built which depend on the rotation speed of motor. After that the current Id is calculated by formula

$$I_d = \frac{\Psi'}{L_m} \quad (18)$$

For the calculation of rotor position, it is necessary to create a closed system, which will compare the rotor speed with the rotation speed of the stator electric field. As a result, the angle is found according to formula 7.

The rotation speed of electric field is found by the following formula:

$$w_s = \frac{L_m \cdot I_q}{T_r \cdot \Psi} \quad (19)$$

where $Tr = \frac{L_r}{R_r}$ -is time electric constant of rotor; Ψ is flux linkage; $L_r = L_{r\mu} + L_m$ is a total induction of rotor winding.

The flux linkage is calculated in "Phi calc" block:

$$\Psi = \frac{L_m I_d}{(1+Tr)} \quad (20)$$

After the measuring unit, signals come to the converter of coordinates of dq-ABC, which translates back into a three-phase signal[6]. Then, using the relay controller, the currents are compared with the current value of the phase. The difference between the currents enters to the hysteresis controller which generates a PWM signal for the inverter.

The application of the principles of relay-vector generation of control algorithms of voltage inverter for closed tracking loop of the instantaneous values of the stator current error allows the significant improvement of speed and reduces the sensitivity (without compulsory modulation).

The current control of a stand-alone inverter is a method of control using a feedback by current. Figure 14 shows the principle of the hysteresis modulation. By coordinate transformation, the controller generates sinusoidal currents of required amplitude and frequency, which are compared with the actual stator currents. When the current exceeds the upper threshold of switching, the lower switch of inverter arm is disabled and upper switch is enabled, whereby current returns to the threshold limit. Thus, the current value of the current is monitored and controlled within preset values. The amplitude and frequency of pulsations is determined by the parameters R, L of load and width of hysteresis loop of the relay element.

The components of discrete control vector are generated according to the equations:

$$S_{Ij} = \begin{cases} 1, if\,\Delta I_j + S_{Ij}\cdot\delta \geq 0 \\ -1, if\,\Delta I_j + S_{Ij}\cdot\delta < 0 \end{cases} \quad (21)$$

$$\Delta I_j = I_{szj} - I_{sj}\,; \quad (22)$$

$$\vec{U}_y = \vec{S}_I\,, \quad (23)$$

where $j = a,b,c$; δ is a hysteresis of current relay controller; $\vec{S}(S_{Ia}, S_{Ib}, S_{Ic})$ is vector discrete function of the current errors; I_{szj}, I_{sj} are components of vectors for preset and actual current of stator ($\vec{I}_{sz}(I_{az}, I_{bz}, I_{cz})$ and $\vec{I}_s(I_a, I_b, I_c)$, accordingly).

The pulse distributor (PD) distributes the control signals on six keys of the inverter, taking into account the generation of delays in switching the keys of one phase.

The implementation of current relay circuit for three phases is shown in Figure 15.

The input signals of model are not real values, but the preset values of the components of the stator current vector in the coordinate system (d, q). This implies that in all operating modes of the drive, the stator current vector corresponds to present value with accuracy up to a small value determined by the hysteresis of the relay controller. In other words, in all drive operating modes (including dynamic) it shall be fulfilled the conditions of existence of the sliding mode in the relay current circuit:

$$U_d > \sqrt{3}\left|\sigma L_s \frac{dI_{zj}}{dt} + R_s I_j + \frac{L_m}{L_r}\frac{d\Psi_{rj}}{dt}\right|, \quad (24)$$

Where L_s, R_s, is induction and active resistance of stator phase; $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is scattering index; j= a, b, c

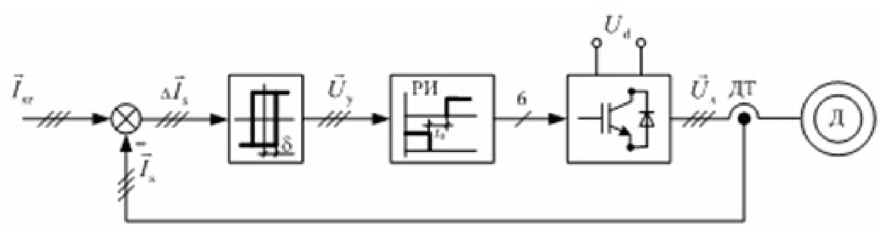

Figure 14. Structural diagram of current relay circuit.

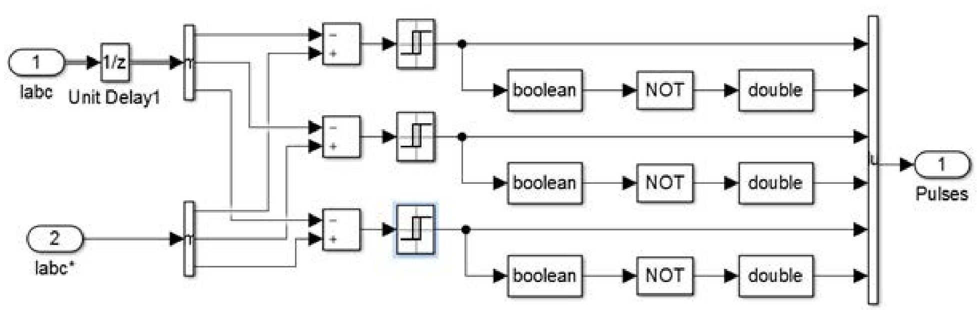

Figure 15. Implementation of current relay circuit in simulink software.

The formula 24 shows that the conditions of existence of the sliding mode impose restrictions not only for real variables of motor (stator current, rate of change of the rotor flux linkage), but also the derivative of current of presetting. It can be achieved by consistent inclusion in channels of generation of I_{dz} and I_{qz} of additional elements that implement algorithms of nonlinear speed limitation of their change. However, the electric drive is able to operate without above amendments, because the intervals of fallout of the current circuit from sliding mode at gradual change of setting are short-term (fractions of a millisecond), and status observer has the properties of a low-pass filter.

To bring the resistance moment to the shaft of the motor, it is necessary to generate a calculation block of all resistance forces.

This block includes:

- rolling resistance force of car wheels;
- resistance force to motion on the rise;
- air resistance force.

The value of vehicle linear speed is put on the input of block. The remaining parameters are entered as constants or as variable and configurable values.

These forces are added together and divided by the radius of the wheel. In addition, the radius shall be multiplied of transmission efficiency in the denominator. The block output is connected to block input of the motor.

At study of EPS of electric vehicle it shall be considered the moment of inertia of the propulsion system that enables the moment of inertia of the traction motor rotor, moment of inertia of vehicle reduced to electric motor shaft and mechanical transmission components.

In general case, the moment of inertia reduced to the traction motor shaft can be determined by the following expression:

$$J = J_{AC} + \frac{J_{EV} + J_{TR}}{i_{TR}^2 \cdot \eta_{TR}}\ , \qquad (25)$$

where J_{AC}, J_{EV}, J_{TR} is, respectively, moments of inertia of AC motor, motor vehicle, mechanical transmission assemblies, kg·m2; η_{TR}, i_{TR} is, respectively, the efficiency and the transmission gear ratio (total transmission ratio of AC motor to the wheels, which may include a transmission number of main gear and the intermediate gear, if necessary).

As a result of calculation, the final moment of inertia of both motors was 10,563 kg·m^2. The equality of the moments of inertia will allow the more accurate comparison of system characteristics, because dynamic performance will be equal during driving on a cycle.

3.3 Comparison of Traction and Dynamic Analysis Results of PMSM and IM

The traction and dynamic analysis was carried out in several cycles of standard (ECE 15, EUDC, HFEDS, NYCC) cycles, these cycles assume driving mode not only in the steady-state motion of the vehicle, but also with fast accelerations and speeds. The calues of speed and acceleration in cycles are shown in Figure 16

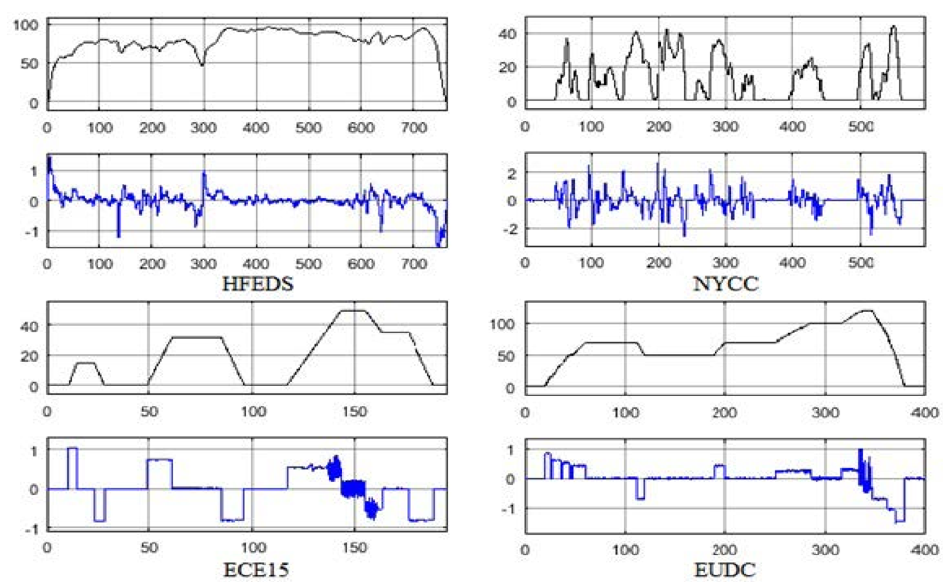

Figure 16. Speed and acceleration in cycles: ---- acceleration; ---- speed.

The input data of vehicle for the traction and dynamic analysis are provided in Table4.

Table 4. Input data for analytical studies and mathematical simulation for base motor vehicle and traffic conditions

Parameter	Designation	Value
Weight of vehicle, kg	G	1748(full) 1440(unladen)
Area of frontal projection of vehicle, m^2	S_a	2,2
Aerodynamic drag factor, p.u.	Cx	0,3
Wheel radius of vehicle, m^2	r_k	0,323
Efficiency of mechanical transmission, p.u.	η_{MT}	0,96
Final drive gear ratio, p.u.	I_{MG}	4,3
Angle of inclination of road, degree	α	0
Airdensity, kg/m^3	ρ	1,2

To compare two systems, the values of maximum consumed powers on the shaft were found (Figure 17).

To enable an analysis of obtained data, efficiency diagrams in cycles were also built (Figure 18).

The data show that at low values of vehicle acceleration, IM efficiency is higher than PMSM. In turn, at significant accelerations and high speeds, the PMSM efficiency becomes higher. PMSM shows high performance in heavy traffic and nominal operating conditions, while IM shows high performance at low speeds and low torque values. Figure 19 shows a diagram of specific energy consumption in the driving cycle. IM was more effective in the cycle with low speeds and accelerations. The PMSM has lower consumption in intense cycles.

Table 5 provides summary table for parameters, which can be obtained at mathematical simulation of the EPS, including PMSM.

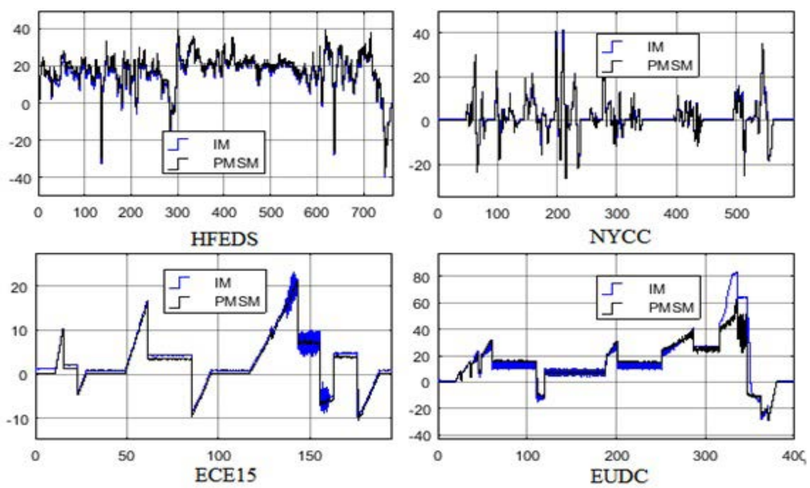

Figure 17. Consumed power of electric motor in cycles.

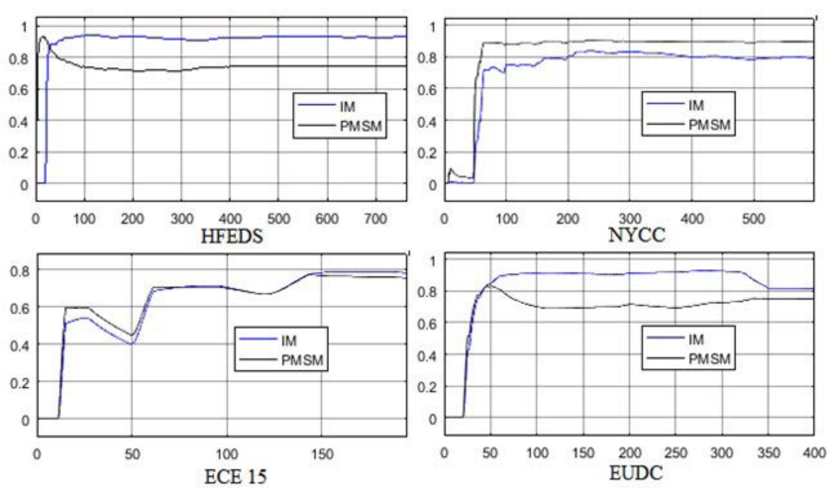

Figure 18. System efficiency in cycles.

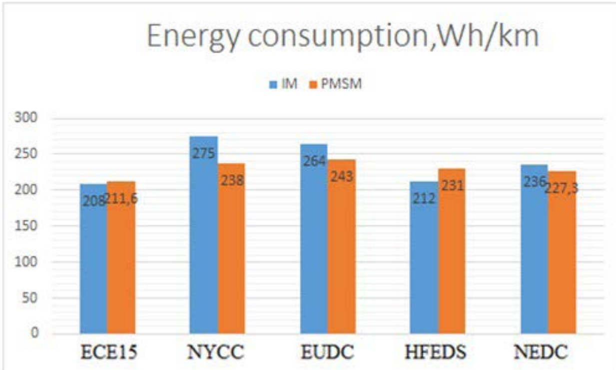

Figure 19. Specific energy consumption in cycles for two systems, taking into account for regeneration.

This table does not show all parameters that can be calculated by mathematical simulation. In addition to the energy performance resulting from mathematical simulation, the mathematical models are able to calculate the duration of operation for all EPS components, both in stationary and in emergency conditions. This allows selecting the necessary components for wires, fuses, and other peripheral equipment throughout the system.

4. Discussion

The mathematical simulation of EPS of electric vehicle in MATLAB software allows the determination both speed characteristic as well as assessment of the dynamic characteristics in a various external impacts. Also it can assess the dynamics of the vehicle at simulation of driving on the various traffic cycles and define energy efficiency of traction electric drive. The studies have shown that PMSM consumes less energy at driving cycles pertinent to the electric vehicle. In turn, the IM has also shown to be effective. In general, both motors correspond to the operating conditions of electric vehicle. However, the asynchronous motor has usually large dimensions and weight at the same power and energy parameters. It shall be taken into account for a more accurate calculation of the energy performance. Besides, the model did not take into account the temperature characteristics, because standard cycles do not involve high driving modes. Nevertheless, the obtained results can be used to generate the performance requirements to EPS characteristics of experimental prototype of electric vehicle, including AC

Table 5. Parameters of control cycles and simulation results for electric vehicle drive with PMSM/IM

Parameter	Driving cycles				
	Urban traffic		Suburban traffic		Mixed traffic
	ECE	NYCC	EUDC	HFEDS	NEDC
Maximum speed in cycle, km/h	50	45	120	96	120
Maximum acceleration in cycle, m/sec^2	1,0	2,7	0,83	1,5	1,0
Cyclelength, sec	195	598	400	765	1180
Range in cycle (theoretical), m	1013	1898	6955	16512	11007
Maximum power on shaft of traction motor P_2, kW	19,3	39,5	48	36,5	39,5
Maximum consumed power of traction motor P_1, kW	21.26/23	41,6/ 41,1	63/84	40/38,8	63/84
Maximum torque of traction motor M_{max}, N·m	168	400	138	227	168
Maximum rotation speed of shaft of traction motor, rpm	1765	1574	4235	3402	1765
Maximum operating current of phase of traction motor, A	170/150	220/ 200	600/ 950	160/ 165	600/ 950
Maximum discharge current of battery pack, A	46/51	90,9/ 90,4	139/ 191	86/85	139/ 191
Maximum charge current of battery pack in regenerative braking mode, A	23/21,5	58,4/ 57	62	81/84	62
Electric energy consumption W_1, W·h	171,1/ 157	446,8/ 520	1691/ 1839	3820/ 3506	2375,4/ 2467
Useful energy (on shaft of motor-generator) W_2, W·h	149,3	398,9	1315	2842	1912,2
Regeneration energy $W_{reg.}$ relatively to total consumption of battery pack W_B in cycle, %	34/35	46/37	10/8,3	3,5/4,2	44/43,3
Specific energy consumption of battery pack, W·h/km	211/ 208	238/ 275	243/ 264	231/ 212	227/ 236

motor parameters, the traction battery and the traction voltage converter.

5. Conclusion

The article describes the main methods for the building of a mathematical model of the traction electric drive, allowing the analysis of the processes occurred during the operation of an electric vehicle in different driving conditions. The results of calculations have become mechanical and power characteristics that are required for the initial choice of the component base for an electric vehicle. During calculations, it is possible to change not only the driving modes, but also the characteristics of each of the components. The obtained results show the high efficiency of PMSM and IM, which differ in performance in function of driving conditions.

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