Simulation and physical modelling of synchronous electric drive for electric and hybrid vehicles

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Abstract. The article presents the theoretical foundations of the device and the principle of control of a power electric drive. An overview of the main structural elements and the requirements for the electric drive are made. Power electric drive control systems using inverter converters are considered: frequency-current control based on a current inverter; frequency-current control based on a voltage inverter; direct torque control; vector field control. The main provisions of the use of simulation and physical modeling in the development of an electric drive are presented. On the basis of the previous analysis, the best solutions allowing modeling the electric drive have been selected. The choice of the element base has been substantiated and the development of a physical model has been carried out.

1. Introduction

Electric and hybrid transport is a promising area for further development of road vehicles. In the design of electric cars, instead of an internal combustion engine, an electric drive is used as an engine, and in a hybrid car, the electric drive is used to optimize the performance of the internal combustion engine and obtain better performance than a conventional vehicle. Progress in the development and design of electrically powered vehicles was facilitated by technological progress in various fields of science and technology: chemistry, mathematics, physics, power electronics and semiconductor technology, metallurgy and others. The range of vehicle types in which electric drive is used, expands every year. Many automakers benefit from having electric and hybrid vehicles, both passenger cars and trucks. Due to the fact that the process of developing requirements, creating an electric drive, developing an inverter and the most optimal control methods, testing, calibration and debugging are expensive and difficult processes, the creation of semi-natural simulation models is economically feasible and allows to shorten the development time, while increasing the quality of the final product. In order to develop a simulation and a physical model of a synchronous electric drive, as well as to research and develop control algorithms for an electric drive, it is necessary to solve a number of problems:

a) Analyze the composition of the synchronous electric drive.

b) Consider the principle of control of the synchronous electric drive

c) Develop a physical model of the synchronous electric drive.

d) Develop a simulation model of the synchronous electric drive.
2. Electric drive design
The electric drive includes a permanent magnet synchronous traction electric machine (motor-generator), a transistor inverter, a high-voltage storage battery, and a DC/DC voltage converter. The electric machine performs the functions of a starter for starting the internal combustion engine, a generator, a stabilizer for the internal combustion engine, an additional power unit when accelerating and driving uphill, as well as a traction motor when driving an electric drive. The inverter performs the functions of a commutator of the windings of electric machine when operating in motor mode and a controlled rectifier in generator mode. The high-voltage battery serves as a source of energy when the electric machine is operating in motor mode and a buffer storage when the electric machine is operating as a generator.

3. The composition of the synchronous electric machine with excitation from permanent magnets.
The choice of the design of the electric machine was determined by the requirements arising from its application, namely:

- The length of the electric machine should be minimal, since the electric machine is often installed on the same shaft with the internal combustion engine and automatic transmission;
- Weight is limited due to the general unit weight restrictions;
- The electric machine should not create excessive noise and vibrations during operation;
- The electric machine shall operate in a wide range of temperatures and pressure drops and withstand the temperature in the engine compartment (90 °C);
- The electric machine is to provide dual-band regulation - in the first section, regulation with constant torque, in the second - regulation with constant power - thus allowing limiting the current through the transistor switches of the inverter and limit losses in the steel of the magnetic circuit at high speeds due to weakening of the field.
- The range of rotation speed, in which the electric drive functions, is to be from 0 to 6500 rpm
- The maximum torque generated by the electric drive must be + -400 Nm.
- The error in the torque control of the electric drive is not more than +/- 2%.

Therefore, the design of an electric machine is to have:

- flat shape and the ratio of length to diameter, which do not exceed the level of values 0.25-0.3;
- the protrusion of the front parts of the winding of the electric machine is minimal, in order to place the electric machine on the same shaft with the automatic transmission and the internal combustion engine;
- high utilization of the torque in relation to the weight;
- high efficiency rates so as not to overheat the winding and magnets;
- materials providing high specific indicators of temperature impact;
- liquid cooling, providing thermal insulation against high external temperatures and efficient heat dissipation.

The analysis of these requirements and the existing experience of using electric machines as a motor-generator made it possible to select a simulation object in favor of a synchronous machine with permanent magnets built into the rotor package (IPM design) (Fig. 1).

Figure 1. Rotor design.
Preference has been given to a radial structure, which provides strength, better maintainability and lower cost, despite the fact that the end structure has better specific indicators in terms of mass and volume. To reduce the overhang of the front parts of the winding, the design with a toothed winding was chosen when the coil is wrapped around one tooth (Fig. 2). This design allows for low-waste technology, which lowers cost by reducing material consumption. The stator of such an electric machine is assembled from laminated cores (assembled from separate sheets) with coils wound on them with ordered turns. Assembly is carried out mortise and tenon. Since each core is wrapped separately, the winding density can be increased. Moreover, the manufacturability of winding is ensured by choosing the ratio of the number of poles and coils in such a way that all coils of the same phase are connected in parallel. This allows increasing the number of turns in the coil and winding in a wire of a relatively small diameter.

![Figure 2. Coil with a core.](image)

One of the well-known disadvantages of electric machines with toothed windings is the concentration of radial forces in the teeth, which creates bending forces in the yoke, which is the cause of increased noise and vibration compared to machines with distributed winding. To ensure the temperature range of operation in the electric machine, rare-earth magnets with the maximum allowable operating temperature of 180 °C are used. The electric machine operates as a part of a dynamic drive, therefore, a rotor position sensor, a resolver is installed in the electric machine, which makes it possible to form phase currents of a sinusoidal shape in the entire range of speed control. An inductor machine has been chosen as a resolver, since the excitation winding of the radial type in it lie in the same slots as the output (anchor) windings. This allows the design to be flat, in contrast to the classical resolver design, since there is no need for a rotating ring-wound transformer. In the classical design, the transformer is installed along the axis of rotation in series with the packages of the electrical machine itself, it serves to transmit high-frequency voltage to the excitation winding, which is installed on the rotor. Temperature control of the winding is carried out using a platinum resistance temperature sensor. Special mention should be made of the built-in magnet design applications.

On the one hand, a solution provides increased strength and manufacturability of the rotor, on the other hand, in comparison to an electric machine with surface-located magnets, it reduces the magnetic resistance on the path of the magnetic flux closure, since part of the flux - the leakage flux is closed through the surface section of the rotor electrical iron package, not passing through the magnets. Besides, a part of the flux, determined by the magnetomotive force of the anchor, is closed through the sections of iron between the magnets, bypassing the magnets, which consideranly reduces magnetic resistance, since the flux, passing through the gap, immediately enters the electrical iron, which has a conductivity one to two orders of magnitude greater than near air and magnet. It should be noted that the magnetic flux, passing between the magnets, passes, with no changes, along the q axis (Fig. 3), as a result, the inductance along the q axis turns out to be greater than along the d axis, this distinguishes such a machine from a classical synchronous
machine with pronounced poles. When looking at the system of equations for a synchronous machine in rotating axes $d$ and $q$, it becomes clear that the reactive component of the moment changes its character in comparison with the classical machine:

\[
\begin{align*}
U_d &= R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q \\
U_q &= \omega L_d I_d + R_s I_q + L_q \frac{dI_q}{dt} + \omega \Psi_M \\
M &= \frac{3}{2} (\Psi_M I_q + (L_d - L_q) I_d I_q)
\end{align*}
\]

(1)

Figure 3. Direction of axes $d$ and $q$ of the electric machine.

This feature leads to the situation when the demagnetizing current $I_d$ is added, additional reactive torque $\frac{3}{2} (L_d - L_q) I_d I_q$ appears, which is added to the active torque $\frac{3}{2} (\Psi_M I_q)$. As a result, the moment developed by the electric machine increases, and it can increase up to 10%, which shall be taken into account when controlling the electric machine. As it has been noted, in the IPM machine, the inductance is higher compared to synchronous machines with surface-located magnets, this facilitates the process of demagnetizing the electric machine at frequencies when the linear EMF of the open circuit exceeds the supply voltage, a lower demagnetizing current is required and the winding of the electric machine heats up less. The increased inductive resistance also reduces short-circuit currents, since they are directly proportional to the EMF of the open circuit and inversely proportional to the complex resistance. For a three-phase short circuit, the equations in the $d$ and $q$ axes are:

\[
\begin{align*}
0 &= R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q \\
0 &= \omega L_d I_d + R_s I_q + L_q \frac{dI_q}{dt} + \omega \Psi_M
\end{align*}
\]

(2)

As a result, even with long-term flow of short-circuit currents, the electric machine does not overheat catastrophically, and the short-circuit moment turns out to be less than the nominal one, since in addition to the relatively small value of the current vector, it is rotated by a significant angle relative to the EMF vector, and the moment is equal to their vector product. Thus, in the event of a short circuit, excessive braking torque will not be created, the driver will be able to react in time, and there will be no catastrophic heating of the electric machine.

4. Power inverter design

Let us consider the inverter, which is structurally composed in an aluminum die-cast case (Fig. 4), the power switches are a three-phase bridge assembled on an IGBT, made in the form of a module, a high-voltage film capacitor is installed in the DC link, the power switch drivers controlled by the processor are assembled on
a separate board. Input control signals are received via the interface data bus, feedback signals are signals from phase current sensors, from the voltage sensor in the DC link, from the rotor position sensor (resolver), from temperature sensors of the electric machine and the power module. In turn, the excitation winding of the resolver is powered by a special module in the processor in the form of a frequency modulated voltage.

Figure 4. Three-phase inverter converter.

The operating characteristics of the inverter driving the electric machine are as follows (values are given as an example for one of the known devices):
1. Maximum output current of the inverter 600 A;
2. Maximum input voltage 450 V;
3. Operating range of input voltages 240 - 400 V.

The transistors of the inverter are switched at a frequency of approximately 8 kHz, synchronously with the frequency of the excitation voltage of the resolver. This makes it easier to combat switching interference. Besides, a step-down DC/DC converter can be built into the inverter housing to supply 12 V to the automobile low-voltage network, the converter power is about 3 kW. The output voltage range is 9-16V according to ISO 16750-2. The converter operates at high frequency and allows the output voltage to be stabilized when the voltage on the high-voltage battery changes.

5. Electric drive control principle
Modern control of variable-voltage AC drives involves the use of the concept of vectors in one form or another, with the frequency-current control method, direct control of torque (DCT), vector field control (FOC) being the most interesting in application to electric drives of vehicles.

5.1. Frequency-current control
This method was developed by a group of Soviet electrical engineers headed by V.N. Brodovsky and Ivanov E.S. and was successfully used in high-precision drives for various purposes, including machine tools (Size 5-2M). The drive structure is shown in Figure 5.
Figure 5. Functional diagram of frequency-current control of a voltage inverter.

Figure 6. General block diagram of frequency-current control.

The main idea of this method is the "degeneration" of the equations of electrical equilibrium, when the inductances of the winding can be neglected, while the power source turns into a current source that directly forms the currents $I_q$ and $I_d$. As a result, the model of the electric motor is comes down to its representation in the form of an inertial link:

$$
\begin{align*}
    \Delta \omega^* & \rightarrow W_{SR} \\
    & \rightarrow \text{Frequency converter} \\
    & \rightarrow K_{FC} \frac{1}{1+\beta T_{FC}} \rightarrow \Delta \omega_0 \\
    & \rightarrow \text{Electrical part} \\
    & \rightarrow \frac{\beta}{p T_e + 1} \rightarrow \Delta T \\
    & \rightarrow \text{Mechanical part} \\
    & \rightarrow \frac{1}{J_p} \rightarrow \Delta I_0 \\
    & \rightarrow \text{Engine}
\end{align*}
$$

The state equations of the system can be written in the form:

$$
\begin{align*}
    \Delta \omega^* & = \Delta \omega_0 \\
    \Delta \omega_0 & = \%(\Delta T) \\
    \Delta I_0 & = \Delta \omega^* - \Delta \omega_0 \\
    \Delta I_0 & = \frac{1}{J_p} (\Psi_M I_q + (L_d - L_q) I_d I_q)
\end{align*}
$$

(3)
Since in a linear interpretation the torque is proportional to the current $I_q$, when the inductances along the d and q axes are equal, the current $I_d$ does not directly participate in the formation of the torque, the torque is actually set by setting the current $I_q$. The inertialless shaping of the current is achieved via the following process: the phase currents are obtained using regulators with hysteresis, to the input of which the current assignments obtained by the inverse Park transformation from the currents $I_q$ and $I_d$ are applied, the specified currents are compared with the signals from the phase of current sensors. Thus, the currents in the phases oscillate around the value defined by the control system, forming a current tube (Fig. 7).

In this case, the narrower the hysteresis, the more accurately the current setting is processed, the less the torque fluctuations associated with the current vector fluctuations caused by the current ripples, the less loss in steel, and the greater the loss in the keys. Therefore, the use of field switches, for example, on silicon carbide, is preferable. At high speeds, the influence of the EMF of rotation is affected, the phase current may lag, the introduction of the demagnetizing component of the current $I_d$ expands the control range in terms of speed. It should also be noted that the switching frequency of the keys depends on the rotational speed and changes during the period of the current change. The non-linear regulator increases the speed of the drive, since the electromagnetic constants are compensated.

In general, the following advantages of frequency-current control can be formulated:

4. High performance;
5. Almost no overshoot;
6. High accuracy of the task processing (used in precision drives);
7. There is no need to solve the equations of electrical equilibrium and take into account the values of the parameters;

The disadvantages of the frequency-current control method are:

8. The appearance of a phase shift - a delay in the formation of the phase current, which leads to deterioration in the processing of the task at high speeds;
   - Floating switching frequency of power switches depending on rotation frequency and current phase;
   - Increased noise of the floating spectrum at insufficiently high switching frequency;
   - A high switching frequency is required to reduce the ripple current.

5.2. Direct torque control.
This method was developed by ABB specialists and consists in the following: the voltage vector can occupy one of 6 positions, depending on the combination of open switches (this is somewhat reminiscent of the field-oriented control (FOC)), but the intermediate positions of the voltage vector are not formed. The flux is calculated through the integral of the voltage and compared with the desired one (calculated).
Moreover, the system detects the difference between the set torque and the actual torque. Depending on the signs of the difference between flows and moments, one of 4 positions of the voltage vector is selected; for this, the table of inclusions is used.

![Functional diagram of direct torque control](image)

**Figure 8.** Functional diagram of direct torque control.

The advantages of direct torque control are:
- High performance;
- Significantly simpler control system than FOC, since no coordinate system transformation and rotor position measurement are required;

The disadvantages of direct torque control are:
- High ripple of current and torque;
- Problems of stable operation at low speeds;
- Increased noise and vibration.

5.3. **Vector field control**

This control method was proposed in 1970 in Germany by Blaschke and Hasse and consists in spatial orientation of the current and flux vectors relative to each other by forming a voltage vector using an inverter, this control method combines well with with vector PWM.

This method is now the most widespread, including in a traction electric drive, thanks to its advantages:
- Increased control range and control accuracy;
- Smooth start and smooth rotation of the engine in the entire frequency range;
- Minimum ripple current, reduced noise level of the electric motor, constant switching frequency of power frequencies;
- Reduced losses in steel and increased efficiency;
- Good speed regulation accuracy.

However, this control system also has its drawbacks, which in some cases makes us turn to other control methods. The disadvantages include, first of all:
- The need to set the parameters of the electric motor;
- Great computational complexity;
- Tendency to speed fluctuations at constant load;
- The presence of higher EMF harmonics, causing fluctuations in the voltage vector, causes fluctuations in current and torque, which leads to fluctuations in speed;
- Sudden changes in the speed reference result in torque fluctuations. In some cases, if one needs to work out fast processes, one shall turn to frequency-current control (FCC) or direct torque control (DCT), but currently Field oriented control (FOC) is used as a control system in the drive. It should be noted that a number of methods have been developed that are hybrids of the described classical methods, and when choosing a control system, one should consider both positive and negative properties of the systems.

![General functional diagram of vector control](image)

**Figure 9.** General functional diagram of vector control.

### 6. Simulation and physical modeling of an electric drive

One of the most important aspects of the development of electric drives is the early detection of defects during the design process. The later the problem is discovered in the design process, the higher the cost of fixing it. Simulation and physical modeling of an electric drive is one of the techniques that allows an engineer to check the algorithms for controlling an electric drive in an ECU with a power inverter. The ECU of the power inverter is connected in a closed loop with the physical model of the controlled electric drive.

The developed control algorithm for the electric drive can be converted into program code and form the development environment and loaded into the ECU of the power inverter, and then the control algorithm can be checked on a real electric machine. This technique assumes that a real electric drive is available at the stage of the power inverter ECU and control algorithm design. Besides, the electric drive test bench requires a second electric drive (e.g. DC motor) that is connected to the motor under test as a drive to simulate a mechanical load. This is a sophisticated test bench system, but it is very effective in detecting problems early in the design process.

In cases where a physical drive is not available, is not created, or only expensive prototypes are available, at the stage of developing an ECU prototype with a power inverter, a simulation and physical model of an electric drive can be used. In such cases, the dynamometer, real power IGBT converter, and electric machine are replaced by a real-time physical and simulation model of the motor drive. This approach has several advantages. For example, a virtual electric drive can be tested in boundary conditions that would otherwise damage the real electric machine (active short circuit mode; operation at maximum power, maximum speed). What is more, the system for regulating the speed of the stand is simplified, since the simulated shaft speed is set by one signal in the simulation model, as opposed to using a real stand, where a second electric drive would have to be used to control the shaft speed. [5]
In cases where a physical drive is not available or only expensive prototypes are available only expensive prototypes, a simulation and physical model of the electric drive can be used during the prototype development phase of the power inverter ECU. In such cases, a dynamometer test bench, a real IGBT converter and an electric motor are replaced with the physical and real-time simulation model of the motor drive. This approach has several advantages. For example, the virtual electric drive can be tested in boundary conditions that would otherwise damage the real motor (active short-circuit mode; operation at maximum power, maximum speed). Moreover, the test bench speed control system is simplified because the simulated shaft speed is set by a single signal in the simulation model, as opposed to using a real test bench where the 2nd drive would have to be used to control the shaft speed.

Other advantages of using an electrical drive simulation and physical simulation system include the ability to easily study the effects of changes in electrical drive parameters on the ECU itself.

6.1. Physical model selection and development
The selection of the physical model concept is based, on the features of the electric drive under study: the type of electric drive rotor position sensor, the frequency of IGBT PWM keys, etc. The scheme of the physical model of the electric drive is presented below.
Figure 11. Functional diagram of the physical model of the electric drive.

The physical model of the electric drive is executed at the signal level and does not contain high-voltage circuits. The input and output signal circuits of the physical model are connected to the PCB or to the output connectors of the power inverter ECU.

Figure 12. Physical model of the electric drive.
PWM control signals for 6 power IGBT transistors are fed to the input of the PWM signal detector of the physical model (the maximum detection frequency of the PWM signal is up to 100 kHz; frequency detection accuracy: +/- 0.04% from 1 Hz to 10 kHz, +/- 0.4 %, 10 kHz to 100 kHz; frequency detector resolution 125 MHz).

For processing high-frequency signals from the PWM detector, programmable logic integrated circuits (FPGAs) containing a programmed simulation model of an electric drive are used. The advantage of using FPGAs is that the computation speed is about 850 ns. Along with a high-resolution, 16-bit, high-frequency DAC, this allows for highly accurate simulation of the operation of an electric drive. The disadvantages of using FPGAs include the inability to change the model programmed in the FPGA in real time. Selection and development of a simulation model.

The simulation model of the electric drive is implemented on FPGA and consists of 3 parts (inverter model, electric machine model, model simulating the external load on the inverter electric drive).

6.2. Inverter model
The task of the power inverter is to operate in a motor mode i.e. convert the voltage from the DC circuit from the high-voltage battery into alternating voltage on 3 phases of the electric motor to control rotation and torque; operation in generator or "regenerative" mode i.e. conversion of alternating voltage on the phases of the electric motor into direct voltage for charging the high-voltage battery and supplying high-voltage consumers (air conditioner compressor, step-down DC / DC converter for supplying 12V mains and charging 12V battery).

The inverter receives information from the sensors about the current position of the rotor of the electric motor, the magnitude of the voltage and current in the DC circuit, the magnitude of the phase currents. Based on this information on the vector control algorithms for the electric motor, the inverter performs the necessary conversions and calculates the required voltage value on the phases of the electric motor. The result of this calculation is the switching sequence of the IGBT transistors and the duty cycle for the PWM signal generated by the IGBT transistor drivers on the ECU board by the power inverter.

The inverter model includes a model of IGBT transistors (forward voltage drop across transistors, losses in conductors and reverse diodes are taken into account. These diodes turn on only in the dead time with logic that depends on the direction of the current (for example, if current flows into the load, then Lower diode turns on.) The inverter model can also operate in full rectifier mode without IGBT pulses. Depending on the motor speed and DC voltage, the drive can operate in the mode where the back EMF voltage of the motor causes the inverter to act as a controlled transistor rectifier.

The model allows to perform:

- Simulation of hardware failures (transistors always open or closed);
- Simulation of phase voltages U_Phase_X (X = U, V, W) and U_d, U_q;
- Simulation of phase voltages in no-load operating mode (all six inverter transistors open);
- Simulation of the torque from the field harmonic disturbance;
- DC voltage line modelling;
- Simulation of transistor voltages and current flowing through the transistors;
- Simulation of ohmic losses in transistors and diodes;

6.3. Electric machine model
The electric machine model is based on the analytical D-Q model, which uses the following equation to calculate [5]

\[
l_{abc} = [L]^{-1} \int (V_{abc} - \frac{d\psi_{abc}}{dt} - RI_{abc})dt
\] (4)
I_{abc} - stator current flowing in the stator coil  
\phi_{abc} - flux linkage (magnetic flux coupled to all turns of the coil)  
R - stator resistance  
V_{abc} - voltage across the stator windings

According to the model, all calculations are performed in the FPGA itself: the model uses the tables of reverse inductance and nominal back EMF speed stored in the FPGA. During the calculations, the real back EMF is determined by multiplying the nominal value by the actual speed. The gate signals of the power IGBT transistors of the inverter come from the inverter driver board to the input of the semi-natural simulation stand.

The model allows to perform:

- Simulation of phase currents I_{Phase_X} (X = U, V, W) and I_d, I_q;
- Counter EMF imitation;
- Consideration of the gearing torque when modeling the torque of the electric motor;
- Modeling ohmic losses.

6.4. A model that simulates an external load.

The model serves to simulate the rotation of electric field in the electric machine and the resulting torque, taking into account the external load.

7. Conclusion

The article analyzes the device of a synchronous electric drive with excitation from permanent magnets and substantiates the choice of the design of the electric machine, which is used to build the bench with a semi-natural model.

The composition of a 3-phase power inverter is analyzed and the characteristics necessary for operation in conjunction with an electric machine are determined.

The principle of electric drive control is considered. The field-oriented (FOC) method of control of a synchronous electric drive was as the one satisfying the requirements for the accuracy of torque control (the error in torque control should not exceed + -2% over the entire range of torque control).

The choice of principles and methods for modeling an electric drive have been substantiated. For a physical model of electric drive, the method for modeling an electric drive at the signal level without using high-voltage power circuits has been selected. An FPGA controller is selected as a computing core for the simulation model, which provides the required computation speed for the model.

The physical model of the electric drive that meets the requirements of the minimum error (model error no more than 5%) has been developed.

The simulation model of an electric drive that meets the requirements for the computation speed (model computation step of 850 ns) has been developed.

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