Improving the efficiency of a variable frequency asynchronous electric drive

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Abstract. Asynchronous electric drives hold leading positions in the global structure of electricity consumption. That’s why the development and implementation of an energy-efficient asynchronous electric drive are always economically feasible and important. The aim of this article is to develop an algorithm to minimize losses of asynchronous electric drive power. The article offers methods to optimize the level of losses in the winding of an electric motor, powered in a steady-state mode by a frequency converter with a scalar control. The substitution scheme for an asynchronous electric drive is considered as a consistent set of conductivities for the stator and rotor wirings. The research tasks were solved based on theoretical and experimental methods, including mathematical and physical simulation of studied processes using modern measuring and computation devices as well as statistic treatment of experimental data. The article offers methods to minimize the losses of power in the winding of an electric motor, powered in a steady-state mode by a frequency converter with a scalar control. The offered method is significantly different in that it uses the substitution for an asynchronous electric drive expressed as a consistent set of conductivities for the stator and motor wirings and the use of the energy efficiency ratio which determines the losses of power in an asynchronous drive for assessing the efficiency of a drive. The main principle for optimal frequency control of an asynchronous engine in terms of energy efficiency was formulated. The laboratory bench for studying the modes of frequency-controlled electric drives was built. The tested drive AIR100S4 showed an increase in energy efficiency ratio from 0.59 to 0.67.

1. Introduction

The optimization of frequency-controlled asynchronous electric drive modes means achieving the extremum of a quality function (optimality criterion). Power losses are one of the important criteria to assess the quality of asynchronous electric drive in terms of energy efficiency and reliability. The requirements for losses optimization are applicable for an electric motor, a frequency controller and an electric drive as a whole.

The energy conversion efficiency of standard frequency converters is 0.96-0.98%. That’s why one of the ways to solve the task of reducing energy consumption by an electric drive is increasing the energy conversion efficiency of a drive itself.

Let’s review the task of optimization for a frequency-controlled electric drive in terms of power losses in an asynchronous motor, which mainly works in the operation mode with a steady or slowly changing moment of the load.

In practice, there are quite simple algorithms that provide a working mode of a drive with the minimal
current or with the maximum ratio of an electromagnetic moment to the current of a stator. Although such algorithms increase the energy conversion efficiency of a drive, they don’t provide the optimal level of losses in it.

The maximum efficiency of an asynchronous drive in a steady-state mode can be achieved using optimal control laws with respect to the minimization of losses. Such laws are formulated in many works. Although some of them are appropriate for practical implementation, there is no universal approach to solve the problem. Thus, the synthesis of scalar control systems that provide the minimal value of one or another criterion of energy efficiency is very important.

2. Methods and materials

When studying the steady-state work modes of an asynchronous drive, it is important to know the decrease in current on separate resistors of a substitution scheme and phase currents, their active and inductive components, that are used to define active and reactive power, power ratio and other components of operational characteristics of an asynchronous drive. Thus, it is proposed to express the scheme for asynchronous drive substitution as a set of consecutive conductivities: active and inductive.

Using electrical engineering formulas of transformation in electrical circuits, the inverted L-shape scheme of asynchronous drive substitution with a set of resistors, represented in Figure 1, can be changed into a similar scheme with a set of conductivities, represented in Figure 2 [1, 2].

![Figure 1](image1.png)

**Figure 1.** Inverted L-shape scheme of asynchronous drive phase substitution.

![Figure 2](image2.png)

**Figure 2.** The scheme of one asynchronous drive phase substitution, expressed in the conductivities of a rotor and stator.

The conductivities of a substitution scheme for one phase of an asynchronous motor expressed via the conductivity of a stator and a rotor are determined based on the substitution scheme in figure 2:
- active conductivity of a magnetizing circuit:
  \[ q_1 = \frac{R_0}{R_1^2 + X_0^2} = \frac{R_0}{Z_1^2} \]  
  (1)

- inductive conductivity of a magnetizing circuit:
  \[ b_1 = \frac{X_0}{R_1^2 + X_0^2} = \frac{X_0}{Z_1^2} \]  
  (2)

- inductive conductivity of dispersion in a circuit of a rotor:
  \[ b_{2s} = \frac{X_{2k}}{(R_1 + R_2/s)^2 + X_{2k}^2} = \frac{X_{2k}}{Z_{2k}^2} \]  
  (3)

- active conductivity of a rotor circuit used to determine the losses of active power in the phase:
  \[ q_{2k} = \frac{R_1 + R_2}{(R_1 + R_2/s)^2 + X_{2k}^2} = \frac{R_2}{Z_{2k}^2} \]  
  (4)

- active conductivity of a rotor circuit used to determine the active current component, and power when transforming electric power in mechanical:
  \[ q_{2s} = \frac{R_2 \cdot (1 - s)/s}{(R_1 + R_2/s)^2 + X_{2k}^2} = \frac{R_2 \cdot (1 - s)/s}{Z_{2k}^2} \]  
  (5)

where \( s \) is a motor slip.

The total value of conductivities of one asynchronous drive phase: inductive \( b \), active \( q \) and full \( y \) based on the following formula:

\[ b = b_1 + b_{2s} \]  
(6)

\[ q = q_1 + q_{2k} + q_{2s} \]  
(7)

\[ y = \sqrt{q^2 + b^2} \]  
(8)

Active and inductive conductivities of a phase can be used to determine the corresponding powers.

The standard assessment of asynchronous drive efficiency using the energy conversion efficiency method can’t fully show the energy characteristics of a drive. The assessment of drive characteristics based on energy conversion efficiency means that an electric drive is treated only as a converter of electric energy, but not as a consumer. This brings forward the idea of combining \( \eta \) and \( \cos \varphi \) in one criterion [3]. One such criterion sometimes comes in the form of a product of energy conversion efficiency and \( \cos \varphi \):

\[ \xi = \cos \varphi \times \eta \]  
(9)

However, this combination is not appropriate, as its components have different definitive ratios.

In the general case, the energy conversion efficiency is determined as the ratio of energy at the output of an asynchronous drive \( P_{2s} \) in relationship to the energy consumed at the input \( S \).

Using this definition and the substitution scheme, expressed in the conductivities of a stator and a rotor presented earlier, we can find expressions to determine the efficiency of asynchronous drive:

\[ \eta_{ad} = \frac{P_{2s}}{S} \]  
(10)

Based on the formulas 1–8 we can write expression 10 in the following way:

\[ \eta_{ad} = \frac{U_{2s}^2 \cdot q_{2s}}{U_{2s}^2 \cdot y} = \frac{q_{2s}}{y} \]  
(11)

It should be noted that expression 11 can be achieved by multiplying energy conversion efficiency and \( \cos \varphi \) for the substitution scheme, expressed in the conductivities of a stator and a rotor:

\[ \cos \varphi = \frac{P}{S} = \frac{U_{2s}^2 \cdot q}{U_{2s}^2 \cdot y} = \frac{q}{y} \]  
(12)
Using 12 and 13 in 9 we get:

$$
\xi = \cos \phi \times \eta = \frac{q \cdot q_{2s}}{y \cdot q} = \frac{q_{2s}}{y}
$$

Based on what has been said we offer to use the minimal value of full losses of drive power as an indicator of asynchronous drive efficiency in a steady-state mode of operation. The value is determined by the ratio of active conductivity of a rotor circuit $q_{2s}$ in relationship to full conductivity $y$, expression 11. Let’s determine this ratio as a coefficient of energy efficiency $k_{en}$, expressed in relative units:

$$
k_{en} = \frac{q_{2s}}{y}
$$

Based on what has been said it is possible to say that an optimal control system of an asynchronous drive should be designed based on the maximum value of energy efficiency ratio that takes treats an asynchronous drive as both converter and a consumer of electric energy:

$$
k_{en} = \frac{q_{2s}}{\sqrt{(q_1 + q_{2k} + q_{2s})^2 + (b_1 + b_{2s})^2}}
$$

Let’s write formula 16, using the values of conductivity for an asynchronous drive in compliance with 1–8 formulas:

$$
k_{sn} = \frac{R_2 \cdot (1 - s)/s}{(R_1 + R_2/s)^2 + 4\pi^2 \cdot f^2 \cdot L_i^2} + \frac{R_1 + R_2}{R_1^2 + 4\pi^2 \cdot f^2 \cdot L_i^2} + \frac{R_2 \cdot (1 - s)}{R_1^2 + 4\pi^2 \cdot f^2 \cdot L_i^2} + \frac{2\pi \cdot f \cdot L_{2k}}{R_1^2 + 4\pi^2 \cdot f^2 \cdot L_i^2} + \frac{2\pi \cdot f \cdot L_{2k}}{R_1^2 + 4\pi^2 \cdot f^2 \cdot L_i^2} + \frac{2\pi \cdot f \cdot L_{2k}}{R_1^2 + 4\pi^2 \cdot f^2 \cdot L_i^2}
$$

Formula 17 shows that the energy efficiency ratio of an asynchronous drive is determined by the parameters of a substitution scheme, the frequency of supply voltage and the value of slip.

Let’s determine the value of rotor slip in extremum points by assigning the first derivative to zero:

$$
d(k_{en}) = 0
$$

The solution of this equation results in the dependency of critical slip from the ratio of energy efficiency:

Analysing formula 19, it can be concluded that an asynchronous drive will work with minimal losses

$$
s_{k_{sn}} \left(\frac{R_2}{R_1} \cdot X_{2k} + R_1 \cdot X_0 + R_0 \cdot R_1 \cdot X_{2k} + R_1 \cdot X_0 + X_0 \cdot X_{2k} + X_0^2 \cdot X_{2k}^2\right)
$$

if we change the voltage and frequency of supply voltage in such a way that the slip of an asynchronous drive will be equal to a critical value $s_{k_{sn}}$ for a set frequency. (The critical value for AIR100S4 drive, studied in this research, the critical value is equal to $s_{k_{en}} = 0.0978$ with power-line frequency equal to
The asynchronous drive was studied in compliance with the substitution scheme with fixed parameters. That’s why the value of slip doesn’t depend on the value of supply voltage amplitude.

3. Results
The optimal criterion was verified using a specially designed laboratory bench. The electrical circuit of this bench is represented in figure 3.

![Figure 3. The electric circuit for testing the asynchronous drive working together with the frequency converter.](image)

![Figure 4. Test bench for AIR100S4 drive.](image)

The experiments were carried out in the laboratory of the electric engineering department in Izhevsk Academy of Agriculture.

The experiment was aimed at analysing the precision of a mathematical model for an asynchronous drive in static modes as well as the verification of optimal slip existence based on the criterion of minimal power losses.

The laboratory bench includes the following facilities:
- an asynchronous drive AIR100S4, 3 kW rated power, 380 V rated voltage, 7.3 A nominal current, rated rotation frequency 1 410 min⁻¹;
- a DC generator P41UHL4, 3.2 kW rated power, 220 V rated voltage, 18.5 A nominal current, rated rotation frequency 1 500 min⁻¹;
- a frequency converter, type MRS 311, 380 V three-phase supply voltage, 45 – 66 Hz supply voltage frequency, 3.0 kW power, 0 – 380 V output voltage, 0.5 – 200 Hz output frequency, output nominal current 9 A.
- Electronic rev counter TEMP-4 to measure the rotation frequency.
- Measurement set K-505. The set is used to measure the three-phase voltage, current, and power at the output of a converter (drive supply). The set consists of a voltmeter and an ammeter of the electromagnetic system and a power meter of the electrodynamic system with variable limits of measurement. These devices help to measure voltage, currents and active power of phases in the stator wiring.
- R₁ resistor is used to change the load created by a DC generator of an asynchronous drive.
- TV (АОМН 40-220-75) autotransformer allows to adjust the varying voltage and the control limits of a secondary voltage are 0–240 V.

The equipment was configured and the feasibility of a working bench was tested. The tests showed that the bench can be used to test the asynchronous drive working together with the frequency converter
in the limits of their rated loads.
The asynchronous drive was tested in compliance with methods written in GOST 11828 Rotating electrical machines. General test methods; GOST 25941 Rotating electrical machines. The techniques for measuring losses and energy transformation efficiency; GOST 7217 Three-phase asynchronous engines. Test methods [4–8].
The experimental studies were carried out using a laboratory bench. The offered control method of an asynchronous drive helps to increase the energy efficiency ratio of an asynchronous drive. The tested drive AIR100S4 showed an increase in energy efficiency ratio from 0.59 to 0.67.

4. Discussion
The article offers methods to minimize the level of losses in the winding of an electric motor, powered in a steady-state mode by a frequency converter with a scalar control. The offered method is significantly different in that it uses the substitution for an asynchronous electric drive expressed as a consistent set of conductivities for the stator and motor wirings and the use of the energy efficiency ratio which determines the losses of power in an asynchronous drive for assessing the efficiency of a drive. The designed method uses the possibility to change the ratio of inductive and active components of asynchronous drive current in the limits of rated phase current by simultaneously using the electric line voltage, powering the phase of a drive and using the rotor slip. Thus, it is possible to change the energy efficiency of an asynchronous drive.

5. Conclusion
The main principle for optimal frequency control of an asynchronous engine in terms of energy efficiency was formulated.
The laboratory bench for studying the modes of frequency-controlled electric drives was built. It supports the adequacy of mathematical models and helps to experimentally verify the optimal parameters for adjusting the rotating speed found during the research.
The tested drive AIR100S4 showed an increase in energy efficiency ratio from 0.59 to 0.67.

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