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Influence of the electricity quality on the energy characteristics of agricultural machines

***Abstract**. With a decrease and asymmetry of voltage, energy losses in electric drives of agricultural machines increase, and their productivity decreases. Therefore, the specific consumption of electricity increases, the limits of its change are determined by the mechanical characteristics of the working machine and the stiffness coefficient of the mechanical characteristics of the electric motor. It changes most significantly in machines with fan mechanical characteristics, the least – in machines with hyperbolic mechanical characteristics.*

***Streszczenie.** Wraz ze spadkiem i asymetrią napięcia zwiększają się straty energii w napędach elektrycznych maszyn rolniczych, a ich wydajność maleje. Dlatego wzrasta specyficzne zużycie energii elektrycznej, granice jego zmiany są określone przez właściwości mechaniczne pracującej maszyny i współczynnik sztywności właściwości mechanicznych silnika elektrycznego. Zmienia się ona najbardziej w maszynach o charakterystyce wentylatorowej, najmniej w maszynach o hiperbolicznej charakterystyce mechanicznej. (**Wpływ jakości energii elektrycznej na charakterystyki energetyczne maszyn rolniczych**)*

Keywords: voltage deviation, voltage asymmetry, productivity, technological characteristics of a working machine.
Słowa kluczowe: odchylenie napięcia, asymetria napięcia, wydajność, charakterystyka technologiczna pracującej maszyny.

Introduction

The low quality of electrical energy causes both a loss of active power and a reduction in the service life of electrical equipment, as well as a decrease in the technological installations productivity of and the manufactured products quality [1, 2].

Although according to EN50160, the voltage deviation should be within ±10%, but in reality these indicators can differ significantly from the norm, for example, in Ukraine the voltage deviation is from -20% to +30% [3].

As the conducted studies have shown, voltage deviations (in 68% of cases) and voltage asymmetry (in 38% of cases) have the greatest impact on electric drives of agricultural machines [4].

It has now been established that when the voltage changes, the torque of three-phase asynchronous electric motors [5, 6], the power consumed by them and the service life of the winding insulation [7, 8] change. A significant decrease in voltage can lead to the stoppage of the electric motor or the impossibility of starting it [9]. Voltage asymmetry leads to a decrease in the torque of an asynchronous motor and an increase in energy losses [10], motor vibration [11], as well as additional heating of the rotor and stator, which leads to rapid aging of the insulation and a decrease in motor power [12, 13].

Voltage deviations and asymmetries lead to changes in the speed and productivity of agricultural machines [14].

Since electric drives are the largest consumers of electricity, much attention is currently being paid to reducing energy losses in electric drives and the energy intensity of products. Therefore, an urgent task is the study of energy losses when the power quality indicators deviate from the nominal values.

Research Methods.

The study of the electric motor mechanical characteristics at different voltage values was carried out when the windings of the stator motor were connected in a "star" and "delta".

During experimental studies of the voltage asymmetry effect on the asynchronous motor mechanical characteristics, a rheostat was turned on in one of the stator phases. The voltage was measured by voltmeters in each phase of the motor and the voltage asymmetry coefficient was determined in the reverse sequence.

The motor load under study was a DC machine with independent excitation, the angular speed of which was regulated by the "generator-engine" system. The rotation frequency of the electric motor was measured with a tachogenerator, and the current of the loading machine was measured with an ammeter, which was used to determine the motor torque.

The influence of voltage deviation on power losses in asynchronous motors.

In the stable mode of operation with voltage deviation, the mechanical characteristics of an asynchronous motor in the working area have the form [15, 16]

(1) $$M_m = \beta_m U_*^2 (\omega_0 - \omega),$$

where M_m is the moment of the motor, N· m; β_m - mechanical characteristic stiffness, N· m· s; $U^* = U/U_n$ - voltage in relative units; ω_0-synchronous angular speed, c^{-1}; ω is a given angular speed, c^{-1}.

In the stable mode of operation, the mechanical characteristics of the electric motor on the working area with voltage asymmetry are described by the dependence:

(2) $$M_m = \beta_{ma*} \beta_{mn} (\omega_0 - \omega),$$

where $\beta_{ma*} = \beta_{ma}/\beta_{mn}$ is the mechanical characteristic stiffness with voltage asymmetry in relative units; β_{ma} is the mechanical characteristic stiffness of the electric motor with voltage asymmetry; β_{mn} is the mechanical characteristic stiffness of the of the electric motor at the nominal symmetrical voltage, N·m·s.

Most of the agricultural machines mechanical characteristics of agricultural machine are described by the equation [15]

(3) $$M_s = M_0 + (M_{sn} - M_0)\left(\frac{\omega}{\omega_n}\right)^x,$$

where M_s is the moment of static resistance of the working machine at a given angular speed, N· m; M_0 – initial moment, N· m; M_{sn} – moment of static resistance at nominal angular speed, N·m; ω and ω_n – set and nominal value of angular speed, s^{-1}; x is a degree indicator.

Then in the established mode of operation

(4) $$M_m = M_0 + (M_{sn} - M_0)\omega_*^x,$$

where $\omega^* = \omega/\omega_n$ is the angular speed in relative units.

As shown by the conducted experimental studies, with a decrease and asymmetry of the voltage, the mechanical characteristic stifiness and the motor angular speed decrease (Fig. 1).

At the same time, motor slip increases, accordingly, and variable power losses.

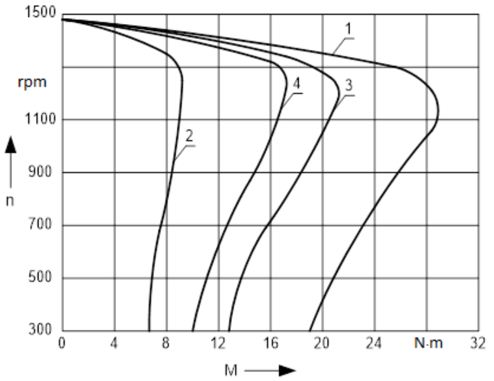

Fig. 1. Mechanical characteristics of a three-phase asynchronous electric motor: 1 – natural; 2 – at reduced voltage by √3 times; 3 – with a voltage asymmetry coefficient of 0.86; 4 – with a voltage asymmetry coefficient of 0.8

In an asynchronous motor, permanent losses include mechanical losses, losses in the steel of the stator and rotor, losses in the stator winding from the magnetizing current.

Mechanical losses are determined by the approximate formula:

(5) $$\Delta P_m = \Delta P_{mn}\omega_*^2,$$

where ΔP_{mn} are mechanical losses at nominal speed.

When the voltage is deviated, the expression for losses in steel due to eddy currents and hysteresis has the form:

(6) $$\Delta P_{st} \approx \Delta P_{st1n}U_*^2\left(1 + s^{1,3}\right) \approx \Delta P_{st1n}U_*^2,$$

where ΔP_{st1n} are the losses in the stator steel at the nominal values of the frequency and voltage.

Variable power losses when the supply voltage of an asynchronous electric motor changes

(7) $$\Delta P_v = \Delta P_{v2} + \Delta P_{v1} = \left(1 + \frac{R_1}{R_2^/}\right)M_m(\omega_0 - \omega),$$

where ΔP_{v2}, ΔP_{v1} are variable power losses in the rotor and stator circuits; R_1 – active resistance of the rotor winding; $R_2^/$ is the resistance of the rotor winding reduced to the stator winding.

When the supply voltage deviates from working machines with a constant moment of static resistance, variable power losses in an asynchronous motor

(8) $$\Delta P_v = \left(1 + \frac{R_1}{R_2^/}\right)\frac{M_s^2}{\beta_m U_*^2},$$

or

(9) $$\Delta P = \Delta P_{vn}/U_*^2,$$

where ΔP_{vn} are variable power losses at rated voltage.

Thus, the asynchronous motor variable power losses are inversely proportional to the square of the voltage.

When the voltage is reduced, the constant power losses decrease. Since they are much smaller than variable losses, when the voltage is reduced, the power losses will increase, and when the voltage increased, the power losses will decrease (Fig. 2).

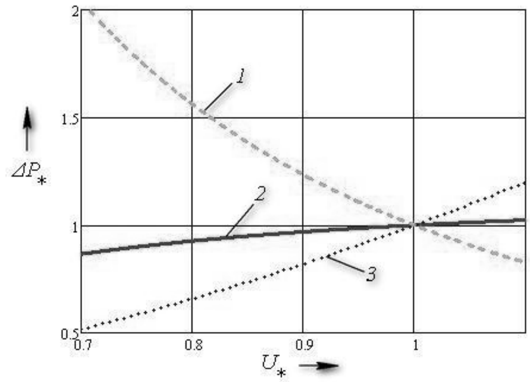

Fig. 2. Change in power losses in the electric motor of the belt conveyor during voltage deviation: 1 – variable losses; 2 – mechanical losses; 3 – losses in steel

When the supply voltage is asymmetric, variable power losses in an asynchronous motor:

(10) $$\Delta P_v = \left(1 + \frac{R_1}{R_2^/}\right)\frac{M_s^2}{\beta_{ma}}.$$

As follows from expression (10), variable power losses increase with voltage asymmetry, although constant losses decrease somewhat.

The influence of voltage deviation on the energy indicators of the electric drive.

The energy assessment of the agricultural machines electric drive in case of deviation and asymmetry of voltage is expedient to be carried out according to the specific consumption of electricity, which is determined by the formula:

(11) $$q = P_1/Q,$$

where q is specific electricity consumption, kWh/m^3; P_1 – power consumed by the motor from the network, kW; Q – productivity, m^3/h.

In relative units, expression (11) can be written as:

(12) $$q_* = \frac{P_2 + \Delta P_c + \Delta P_v}{P_{2н} + \Delta P_{cn} + \Delta P_{vn}}\cdot\frac{Q_n}{Q} = \frac{P_2 + \Delta P_{vn}(\alpha + \Delta P_v/\Delta P_{vn})}{P_{2n} + \Delta P_{vn}(\alpha + 1)}\cdot\frac{Q_n}{Q},$$

where P_{2n} and P_2 are, respectively, power on the motor shaft at nominal and non-nominal voltage, W; ΔP_{cn} and ΔP_c – constant losses, W; ΔP_{vn} and ΔP_v – variable losses, W; α is the loss coefficient.

For working machines with a constant moment of static resistance (x=0) (belt and scraper conveyors, vacuum pumps), productivity and power are directly proportional to angular velocity.

Dividing the numerator and denominator of expression (12) by P_{vn} and taking into account that

(13) $$P_2/P_{2н} = M_c\omega/M_c\omega_н = \omega_*,$$

(14) $$\Delta P_н = P_{2н}\frac{1-\eta_н}{\eta_н} = \Delta P_{vн}(\alpha_н + 1),$$

where η_n is the motor efficiency at nominal voltage, we will get

(15) $$q_* = \frac{\omega_* + \frac{1-\eta_n}{\eta_n}\cdot\frac{(\alpha + 1/U_*^2)}{(\alpha_n + 1)}}{\omega_*\left(1 + \frac{1-\eta_n}{\eta_n}\right)} = \eta_n + \frac{1-\eta_n}{(\alpha_n + 1)}\cdot\frac{(\alpha + 1/U_*^2)}{Q_*}.$$

Thus, a decrease in voltage causes an increase in the specific consumption of electricity in machines with a constant moment of static resistance, and an increase in voltage - a small decrease.

For machines with fan mechanical characteristics (*x*=2) (pumps, fans), the initial torque is small, so it can be neglected. Then the expression for motor slip will be written as

(16) $$s = \frac{K_l s_n \omega_*^2}{U_*^2},$$

where K_l is the motor load factor.

Taking into account (16) variable power losses

(17) $$\Delta P_v = \left(1+\frac{R_1}{R_2^{/}}\right)\beta_m U_*^2 \omega_0^2 s^2 = \left(1+\frac{R_1}{R_2^{/}}\right)\frac{\beta_m \omega_0^2 K_l^2 s_n^2 \omega_*^4}{U_*^4},$$

or

(18) $$\Delta P_v = \Delta P_{vn} \omega_*^4 / U_*^4 .$$

Fan and pump performance is directly proportional to angular speed:

(19) $$Q = Q_n \omega_* ,$$

and the power is proportional to the cube of the angular speed:

(20) $$P_2 = P_{2n} . \omega_*^3 .$$

Then, after transformations, expression (12) will have the form:

(21) $$q_* = \eta_n Q_*^2 + \frac{1-\eta_n}{(\alpha_n+1)} \cdot \frac{(\alpha U_*^2 + Q_*^4 / U_*^4)}{Q_*}.$$

It follows from dependence (21) that a decrease in voltage in machines with a fan mechanical characteristic causes an increase in the specific consumption of electricity, and an increase in it causes a slight decrease (Fig. 3).

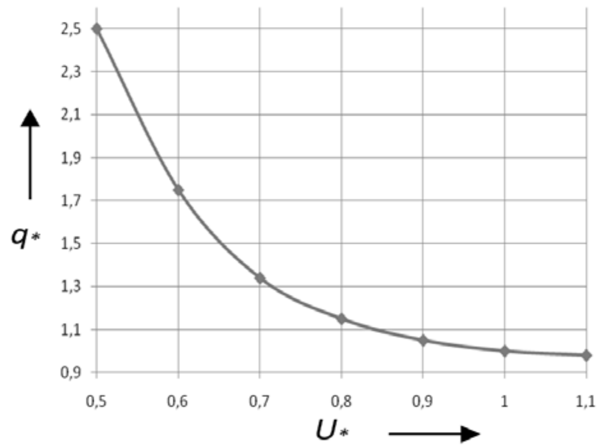

Fig. 3. Dependence of specific electricity consumption of ventilation units on voltage

Machines with hyperbolic mechanical characteristics (*x*=-1) (bucket and screw conveyors, light and medium metalworking machines) work with constant power. The expression for the specific power consumption for this group of machines can be obtained by dividing the numerator and denominator of expression (12) by P_{2n} and taking into account (14):

(22) $$q_* = \frac{1+\frac{1-\eta_n}{\eta_n}\cdot\frac{(\alpha U_*^2+1)}{(\alpha_n+1)}}{Q_*\left(1+\frac{1-\eta_n}{\eta_n}\right)} = \frac{\eta_n}{Q_*} + \frac{1-\eta_n}{(\alpha_n+1)} \cdot \frac{(\alpha U_*^2+1)}{Q_*}.$$

As follows from formula (22), the specific power consumption for bucket and screw conveyors does not decrease significantly when the voltage is deviated.

The influence of voltage asymmetry on the energy characteristics of agricultural machines

For working machines with a mechanical characteristic that does not depend on the angular speed (*x*=0), expression (4) can be written as follows:

(23) $$\beta_m \beta_{ma*}(\omega_0 - \omega) = M_{sn} = K_l \beta_n (\omega_0 - \omega_n).$$

From expression (23), we obtain the dependence for motor slip:

(24) $$s = \frac{K_l s_n}{\beta_{ma*}}.$$

Then the variable power losses can be written as:

(25) $$\Delta P_v = \left(1+\frac{R_1}{R_2^{/}}\right)\beta_m \beta_{ma*} \omega_0^2 s^2 = \left(1+\frac{R_1}{R_2^{/}}\right)\frac{\beta_m \omega_0^2 K_l^2 s_n^2}{\beta_{ma*}},$$

or

(26) $$\Delta P_v = \Delta P_{vn} / \beta_{ma*} .$$

After the transformations, we get the expression for the specific power consumption:

(27) $$q_* = \eta_н + \frac{1-\eta_н}{(\alpha_н+1)} \cdot \frac{(\alpha_a + 1/\beta_{\partial a*})}{Q_*}.$$

For machines with a linear mechanical characteristic (x=1), expression (4) will have the form:

(28) $$\beta_m \beta_{ma*}(\omega_0 - \omega) = M_{sn}\omega_* = K_l \beta_m (\omega_0 - \omega_n)\omega_* .$$

From expression (28), we obtain the dependence for motor slip:

(29) $$s = \frac{K_l s_n \omega_*}{\beta_{ma*}}.$$

Then the variable power losses can be written as:

(30) $$\Delta P_v = \left(1+\frac{R_1}{R_2^{/}}\right)\beta_m \beta_{ma*} \omega_0^2 s^2 = \left(1+\frac{R_1}{R_2^{/}}\right)\frac{\beta_m \omega_0^2 K_l^2 s_n^2 \omega_*^2}{\beta_{ma*}},$$

or

(31) $$\Delta P_v = \Delta P_{vn} \omega_*^2 / \beta_{ma*} .$$

In working machines with a linear mechanical characteristic, the power is directly proportional to the square of the angular speed:

(32) $$P_2 = P_{2n} . \omega_*^2 .$$

Then after transformations we get:

(33) $$q_* = \eta_n Q_* + \frac{1-\eta_n}{(\alpha_n+1)} \cdot \frac{(\alpha + Q_*^2 / \beta_{ma*})}{Q_*}.$$

In machines with fan mechanical characteristics (*x*=2), expression (4) can be written as follows

(34) $$\beta_m \beta_{ma*}(\omega_0 - \omega) = M_{sn}\omega_*^2 = K_l \beta_m (\omega_0 - \omega_n)\omega_*^2 .$$

From expression (34), we obtain the dependence of motor slip on voltage asymmetry:

(35) $$s = \frac{K_l s_n \omega_*^2}{\beta_{ma*}}.$$

Then the variable power losses can be written as:

(36) $$\Delta P_v = \left(1+\frac{R_1}{R_2^{/}}\right)\beta_m \beta_{ma*} \omega_0^2 s^2 = \left(1+\frac{R_1}{R_2^{/}}\right)\frac{\beta_m \omega_0^2 K_l^2 s_n^2 \omega_*^4}{\beta_{ma*}},$$

or

(37) $$\Delta P_v = \Delta P_{vn} \omega_*^4 / \beta_{ma*} .$$

After transformations, we get:

(38) $$q_* = \eta_n Q_*^2 + \frac{1-\eta_n}{(\alpha_n+1)} \cdot \frac{(\alpha + Q_*^4 / \beta_{ma*})}{Q_*}.$$

For machines with a hyperbolic mechanical characteristic (*x*=-1), expression (4) can be written as follows:

(39) $$\beta_m \beta_{ma*}(\omega_0 - \omega) = M_{sn} / \omega_* = K_l \beta_m (\omega_0 - \omega_n) / \omega_*.$$

From expression (39), we obtain the dependence for motor slip:

(40) $$s = \frac{K_l s_n}{\beta_{ma*} \omega_*}.$$

Then the variable power losses can be written as:

(41) $$\Delta P_v = \left(1 + \frac{R_1}{R_2^{/}}\right) \beta_m \beta_{ma*} \omega_0^2 s^2 = \left(1 + \frac{R_1}{R_2^{/}}\right) \frac{\beta_m \omega_0^2 K_l^2 s_n^2}{\beta_{ma*} \omega_*},$$

or

(42) $$\Delta P_v = \Delta P_{vn} / \beta_{ma*} \omega_*.$$

The productivity of the bucket and screw conveyor can be roughly considered directly proportional to the square of the angular speed:

(43) $$Q = Q_n \omega_*^2 ,$$

and the power remains unchanged.

After transformations, we get:

(44) $$q_* = \frac{\eta_n}{Q_*} + \frac{1-\eta_n}{(\alpha_n+1)} \cdot \frac{(\alpha + 1/\beta_{ma*}\sqrt{Q_*})}{Q_*}.$$

From the given dependences for the consumption of electric power with voltage asymmetry, it follows that the voltage asymmetry causes an increase in the specific power consumption, as the mechanical characteristics stiffness of the electric motor and the performance of the machine decrease.:

Conclusions

With a decrease and asymmetry of the voltage, the stiffness of the mechanical characteristics of the asynchronous electric motor, the angular speed decreases and motor slip increases. At the same time, variable power losses increase and the productivity of agricultural machines decreases.

When the voltage deviates, the specific power consumption changes, which depends on the mechanical characteristics of the working machine. When the voltage is reduced by 20%, the specific electricity consumption of conveyors increases by 11%, fans – by 15%, pumps – by 12%, and pumps – by 0.5%.

With voltage asymmetry, power losses increase and the productivity of the working machine decreases. As a result, the specific losses of electricity in the electric drives of agricultural machines increase with the increase of the voltage asymmetry factor..

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