Study of the effectiveness of a variable frequency drive of an induction motor

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Abstract **- The results from a study of the effectiveness of a variable frequency drive of an induction motor, are presented in the paper. The electric power savings when regulating the voltage and the output frequency of the frequency converter are analysed. The power losses when varying the angular speed and the load, and also the efficiency of the obtained power drive system, are determined.**

Keywords - energy efficiency, variable frequency drive, induction motor, energy losses.

I. Introduction

Energy savings, particularly the rationalization of production, distribution, and consumption of all types of energy have become one of the main directions of development in the technical policy of all developed countries in the world for the past 20 years. This is due, first of all, to the limited and non-renewable nature of all major energy resources, secondly to the ever-increasing complexity and costs of their production, and thirdly, to the emerging global environmental problems.

Studies and analyses of losses in the production, distribution, and consumption of electricity show that the decisive share of losses - over 90% - is in area of energy consumption, while the losses in the transmission of energy account for about 10% of total losses. It's obvious that the main efforts in the field of energy efficiency should concentrate mainly on the consumption of electrical energy [1].

The main consumer of electrical energy in the industry is the induction motors, operating at a constant speed - without speed control, consuming more than 65% of the total energy consumed. They are the main focus of global technical and legislative organizations working in the field of energy efficiency in the industry.

Variable frequency drives reduce energy consumption, improve performance characteristics, and extend the operating lifetime of the units and systems in which they, are installed. This is achieved by continuously adjusting the frequency and the RMS value of the output voltage, whereby the motor operates with high efficiency and power factor cosφ.

Expert estimates suggest that the use of variable frequency (adjustable) electrical drives is economically viable at 25 to 50 percent of all technological facilities, but currently only used in about 10% of them. According to these estimates, up to 60% (16 TWh) of the annual increase in electricity consumption, in the industrial sector for EU countries can be covered by the use of variable frequency drives. Assuming that CO_2 emissions are 0,28307 kg/kWh, the savings on this indicator will be 5,27 million tonnes of CO_2 per year.

The paper gives the results of a study of the effectiveness of a variable frequency drive with an induction motor. The electric power savings in the regulation of the voltage and the output frequency of the frequency converter, are analysed.

II. Regulatory documents in the field of energy efficiency and ecodising of electric drives

Regulations and standards related to energy efficiency are gradually intensified throughout the world. The Ecodesign Directive is the legislative framework that currently sets requirements for all energy-related products in the utility, commercial, and industrial sectors of the entire European Union. Its aim is to ensure that manufacturers reduce energy consumption and environmental impact of their products by establishing minimum requirements for energy efficiency, which are gradually being strengthened. The European Commission has identified energy efficiency in industry as a key aspect of the 2030 strategy - reducing CO_2 emissions by 40% across Europe. As a measure to implement the strategy the minimum energy classes, of newly commissioned electric motors and power electronic converters, are limited as indicated in Table 1 [2].

TABLE I. Minimum energy classes of electric motors and power electronic converters for the period until 2023

Minimum energy class	For electric motors	For power electronic converters
To July 2021	IE3	IE2
To July 2023	IE4 for motor with rated power from 75 to 200 kW	IE2

The standard EN IEC 61800-9-2:2017 specifies the energy efficiency indicators of power electronic converters so-called complete drive modules (CDMs), power drive systems (PDSs) and motor starters used for electric motors with power ratings of 0,12 kW to 1000 kW. This standard presents a methodology for determining the losses of the complete drive module and the power drive system and defines the IE class of power electronic converters and the IES class of power drive systems. The methodology is based on the use of a reference power drive system (RPDS), consisting of a reference drive module (RCDM) and a reference motor (RM). This makes it easy to compare energy

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performance across different drive module topologies and different strategies for its control [3].

The power, required to drive the working machine, can be defined for each operating point of its torque-speed characteristic as:

$$P_i = M_i \omega_i , \qquad (1)$$

where: M_i is the torque in the *i-th* operating point;

ω_i - angular speed in the *i-th* operating point.

For the determination of the power losses, it's sufficient to know the relative power losses in the drive system in the specific operating points, which are eight in number (Fig. 1). These operating points are determined based on the specific features of the torque-speed curves of the technological aggregates.

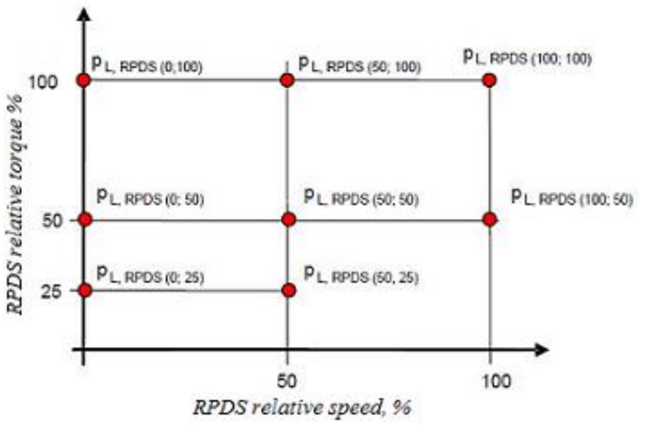

Fig. 1. Operating points for determining relative power losses in a reference power drive system

The relative power losses in the particular operating points, with the exception of the operating point at rated speed and torque, are determined by using the equation:

$$p_{L,RPDS} = \frac{p_{L,RM} P_{r,RM} + p_{L,RCDM} S_{r,RCDM}}{P_{r,RM}} , \qquad (2)$$

where: $P_{r,RM}$ is the rated power of the reference motor;

$S_{r,RCDM}$ - rated apparent power of the reference complete drive module;

$p_{L,RM}$ - relative power losses in the reference motor ;

$p_{L,RCDM}$ - relative power losses in the complete drive module.

The relative power losses at rated speed and torque are determined by the following equation:

$$p_{L,RPDS\,(100,100)} = \frac{p_{L,RM\,(100,100)} P_{r,RM}\, x + P_{LCDM(90,100)}}{P_{r,RM}} , \qquad (3)$$

where: $P_{LCDM(90,100)}$ are the power losses in the reference complete drive module working at an output frequency of 90% of the rated motor frequency and current equal to the rated current of the motor;

x is the coefficient taking into account the operation of the motor with a voltage different from the rated one $x = U_{r,Mot} / U_{CMD,fund}$;

$U_{r,Mot}$ - rated motor voltage;

$U_{CMD,fund}$ - fundamental component of the output voltage of the drive module.

The specific operating points of the reference complete drive module cannot be represented by angular speed and torque, because quantities at the output of the module are electrical - current and voltage. Furthermore, the output voltage of the drive module is limited to 90% of its rated value, in order to avoid the operation of the inverter in the over-modulation mode.

The definition of the energy classes, of the complete drive module and the power drive system, is done by comparing the relative losses in them with those in the reference elements and systems with the corresponding power rating. In the case of complete drive module, the class IE1 is considered to be the reference class, and in the case of power drive systems, the reference class is IES1. The determination of the energy classes, of the drive modules and power drive systems, is illustrated in Fig. 2 and Fig. 3.

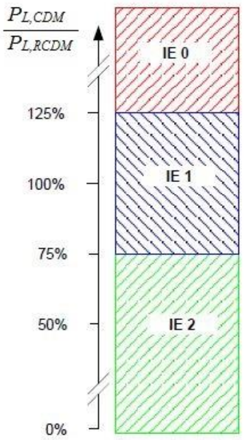

Fig. 2. Determination of the energy class of the complete drive module

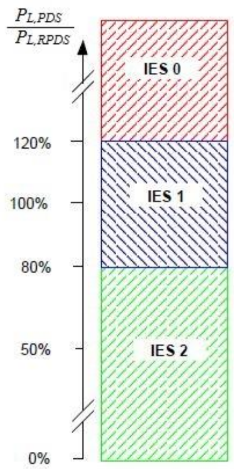

Fig. 3. Determination of the energy class of the power drive system

III. CHARACTERISTICS OF THE OBJECT OF STUDY

The object of the survey is a variable speed drive with a three-phase squirrel cage induction motor. The scheme, of the variable speed drive, is shown in Fig. 4.

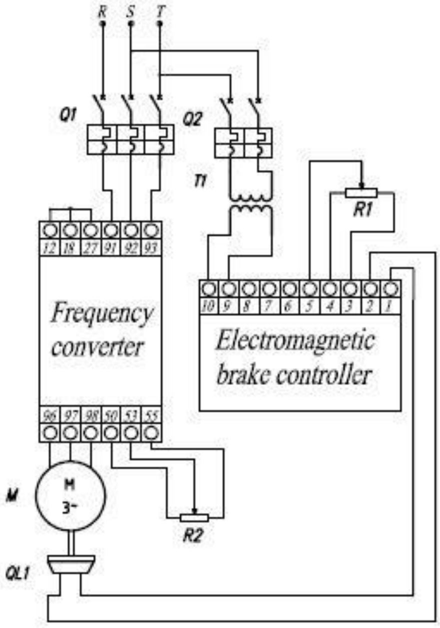

Fig. 4. Scheme of the studied variable speed drive

The elements of the studied adjustable electric drive and their rated parameters are as follow:

- Induction motor AO90S-4 – $P_r = 1{,}1kW$, $U_r = 400/230V$, $I_r = 2{,}8/4{,}9A$, $f_r = 50Hz$, $n_r = 1410\min^{-1}$, $\cos\varphi = 0{,}8$.
- Frequency converter Danfoss VLT HVAC FC102 – Input parameters: $U_{r,in} = 3\times380 \div 480V$, $I_{r,in} = 2{,}7/2{,}6A$, $f_{r,in} = 50/60Hz$; Output parameters: $U_{r,out} = 3\times0 \div U_{r,in}\,V$, $I_{r,out} = 3/2{,}7A$, $f_{r,out} = 0 \div 590Hz$.
- Electromagnetic brake Warner electric ERD P35 - $M = 35Nm$, $U_r = 24VDC$, $I_r = 1A$.
- Electromagnetic brake controller FP-25.1 - $U_r = 24VDC$ $U_{c,in} = 0 - 10VDC$, sensitivity $\delta U = 10mV$, maximum power consumption 30W.

The used frequency controller offers a large set of tuning parameters directly affecting the energy efficiency of the electric drive. It is designed to control both induction motors and synchronous permanent magnet machines, offering two control methods - scalar (Volt/Hz) control and field-oriented vector control. Moreover, it allows for obtaining constant or variable torque with or without automatic energy optimization (AEO).

When using linear mode ($U/f = const$) scalar control, the maximum electric drive efficiency is obtained at rated slip s_r and load M_r values. In heating, ventilation, and air conditioning (HVAC) systems for which the frequency controller is intended, mechanisms running at low load and reduced speed are often encountered. In such operating mode, the slip values are much lower than the rated value, but at the same time, the motor operates with its full magnetizing current and magnetic flux, respectively. High values of current and magnetic flux cause large losses in the windings and the magnetic cores and reduce the overall efficiency of the drive system. To overcome this disadvantage of the linear mode scalar control it is combined with automatic energy optimization (AEO). The AEO algorithm is based on maintaining a constant overload capacity when changing the load of the motor (Fig. 5).

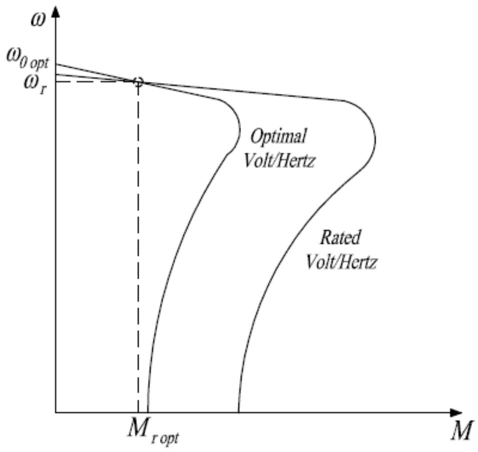

Fig. 5. Torque-speed characteristics when using automatic energy optimization

For loads smaller than the rated one, the motor supply voltage is reduced, thereby reducing the magnetic flux. This changes the motor torque so that the load torque is equal to the rated torque of the motor running on the optimal Volt/Hz curve. At the same time, in order to maintain the operating point of the system, the frequency reference f_{ref} is increased so that the angular speed at the optimal characteristic corresponds to the rated slip:

$$\Delta f_{ref} = f_{ref}(s_r - s)\,, \tag{4}$$

where: s is the slip when working on the rated Volt/Hz curve.

The automatic energy optimization greatly improves the efficiency of the drive system, but it also has its limitations stemming mainly from system stability at low speeds [4, 5].

The settings of the frequency converter with which the study was performed are listed in Table. 2.

TABLE II. SETTING OF THE FREQUENCY CONVERTER

Parameter name	Set-up
Configuration mode	Open loop
Motor construction	Asynchronous
Torque characteristics	Variable torque (VT) - Auto Energy Optimization
Slip compensation	0%
Minimum AEO frequency	10 Hz
AEO minimum magnetization	40%
VT Magnetization at low speed	66%
Cosφ	0,69
Switching pattern	60°AVM
Switching frequency	5 kHz
Overmodulation	Off

The choice of these settings has been made considering the expected speed adjustment range under actual operating conditions, as well as maintaining the stability and overload capacity at low speeds.

IV. Research and Results Analysis

Measurements were carried out at different frequencies of the supply voltage, which correspond to the expected speed control range. The motor is laden by means of the electromagnetic brake, by varying the control voltage $U_{c,in}$ of its controller in the range from 0 to 4V for each of the frequencies. With this method of measurement, the savings of electrical power (energy), by regulating the voltage when operating at a constant speed and variable load, can be determined. It is also possible to determine the saving of electrical power (energy) from regulating the frequency when the drive system is operating with variable speed at different loads.

A. Power (energy) savings from regulating the motor voltage

For the determination of the power savings, by regulating the voltage, the power consumed by the drive system, has been measured when the motor is fed directly from the mains (DOL fed), and when the motor is fed from the frequency converter (FC fed). The results, from the measurements, are presented in Table 3.

TABLE III. Electrical Power Savings from Voltage Regulation

$U_{c\ in}$, V		0	1	2	3	4
Directly fed 50Hz	U_M, V	400				
	I, A	1,9	2,05	2,2	2,43	2,8
	P, kW	0,208	0,293	0,473	0,768	1,162
Frequency converter fed - 50Hz	U_M, V	156,1	188,8	271,8	339	388
	I, A	0,57	0,9	1,38	1,89	2,44
	P, kW	0,07	0,2	0,44	0,76	1,15
Power savings	*ΔP, kW*	0,138	0,093	0,033	0,008	0,012
	ΔP, %	66,35	31,74	6,98	1,04	1,03

The variation of power consumption, at different load values (control voltage $U_{c\ in}$), is shown in Fig. 6.

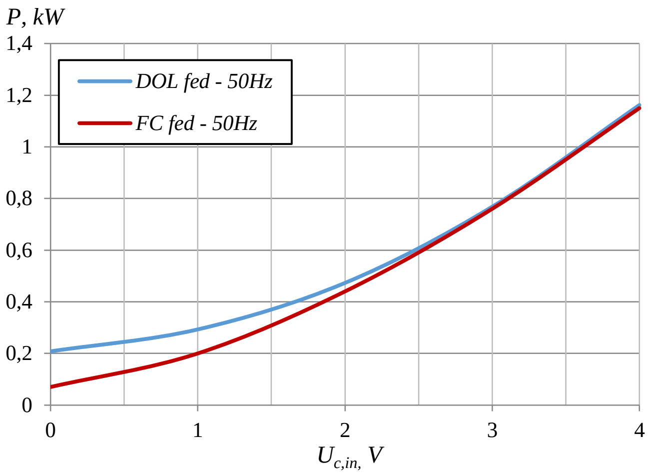

Fig. 6. Change of power consumption in voltage regulation

Fig. 6 shows that the real economy of electric power is obtained at $U_{c,in} \leq 2{,}5V$, which is equivalent to 50% of the rated torque of the motor. Power savings achieved through voltage regulation reach 66,35% when the motor idling. The reduction of power losses in the motor is due to the implementation of the automatic energy optimization algorithm.

For aggregates operating in large inter-operative periods during which the motor is idling or running with low load, voltage regulation can lead to significant energy savings.

B. Power (energy) savings from regulating the frequency

For the determination of electric power savings, due to frequency regulation, four measurements at different frequencies of the supply voltage - 50Hz, 45Hz, 40Hz, and 35Hz are carried out. The input control voltage of the controller of the electromagnetic brake is changed in a range from 0 to 4V. The results of the measurements at the maximum and minimum values of the output frequency of the frequency converter are given in Table 4 and Table 5.

TABLE IV. Results from the Measurements at an Output Frequency of 50 Hz

f=50Hz; n_S=1500 min^{-1}					
$U_{c\ in}$, V	0	1	2	3	4
I, A	0,57	0,9	1,38	1,89	2,44
P, kW	0,07	0,2	0,44	0,78	1,15
U_M, V	155,5	188,8	271,8	339	388
M, Nm	0,3	1,1	2,5	4,3	6,6
M, %	4	15	34	59	89
n, min^{-1}	1410	1410	1410	1410	1410

TABLE V. Results from the Measurements at an Output Frequency of 35 Hz

f=35Hz; n_S=1050 min^{-1}					
$U_{c\ in}$, V	0	1	2	3	4
I, A	0,56	1	1,52	2,01	2,51
P, kW	0,04	0,17	0,38	0,62	0,88
U_M, V	109,6	149,9	212,4	242,9	247,7
M, Nm	0,3	1,4	3,1	5	7
M, %	4	18	41	66	94
n, min^{-1}	991	991	991	991	991

The results for the achieved electric power savings by frequency regulation are shown in Table 6.

TABLE VI. Results for the Achieved Power Savings

$U_{c,\ in}$, V	0	1	2	3	4
$\Delta P_{35\ Hz/50\ Hz}$ kW	0,03	0,03	0,06	0,16	0,27
$\Delta P_{35\ Hz/50\ Hz}$ %	42,86	15	13,64	20,51	23,48
$\Delta P_{40\ Hz/50\ Hz}$ kW	0,025	0,04	0,04	0,11	0,16
$\Delta P_{40\ Hz/50\ Hz}$ %	35,71	20	9,09	14,1	13,91
$\Delta P_{45\ Hz/50\ Hz}$ kW	0,02	0,04	0,01	0	0,09
$\Delta P_{45\ Hz/50\ Hz}$ %	28,57	20	2,27	0	7,83

The change of the stator current, at the considered frequency and load values, is shown in Fig. 7.

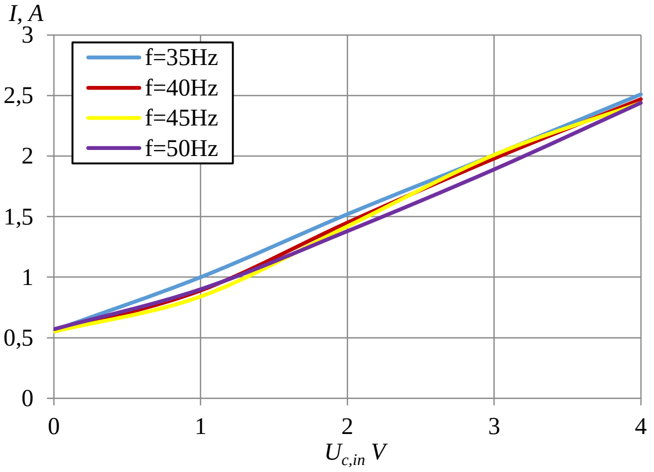

Fig. 7. Change of the stator current at different supply frequencies

As can be seen from Fig. 7, the stator current remains relatively the same for different values of the supply frequency and the load of the motor. When working on idle mode, the motor current is reduced by 70% compared to that of the case of direct power supply. Maintaining a constant current value at different frequencies is realized by maintaining the ratio $U/f = const$ and the AEO algorithm at different load values.

Fig. 8 shows the change in power consumption for the minimum and maximum values of the supply voltage frequency.

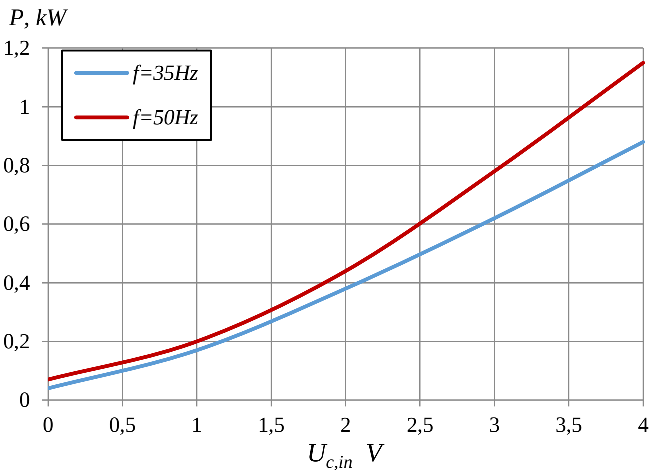

Fig. 8. Change in power consumption by regulating the supply voltage frequency

Power savings realized by regulating the supply voltage frequency reach up to 42,86% for the selected speed control range. This savings is due to the implementation of the frequency regulation principle, which leads to reducing the iron losses, and friction and windage losses.

C. Determination of power losses in the power drive system

For determination of the losses in the drive system, the losses in the motor and the frequency converter at specific operating points defined in standards EN 60034-2-3 and EN 61800-9-2, have been measured.

Table 7 shows the results obtained when determining the losses in the motor, the drive module, and the power drive system when operating at the separate operating points.

TABLE VII. POWER LOSSES IN THE DRIVE SYSTEM

Operating point		**Power losses in the motor**	**Power losses in the drive module**	**Power losses in the power drive system**	**Efficiency of the power drive system**
ω/ω_r, %	M/M_r, %	ΔP_M, W	ΔP_{CDM}, W	ΔP_{PDS}, W	η %
0	25	57	10	67	7,6
0	50	82	11	93	10,5
0	100	48	24	72	23,4
25	25	62	10	72	48,8
25	100	153	28	181	60,3
50	25	75	10	85	61,7
50	50	132	13	145	65,5
50	100	225	31	256	68,2
90	50	171	14	185	72,8
90	100	271	38	309	76,2
100	50	181	14	195	73,8
100	100	269	38	307	78,2

The data shows that most of the total power losses occur in the motor, while the power losses in the drive module only reach 14,9% of the total losses.

Fig. 9 shows the change of the power losses in the drive system as a function of the angular speed and the load torque.

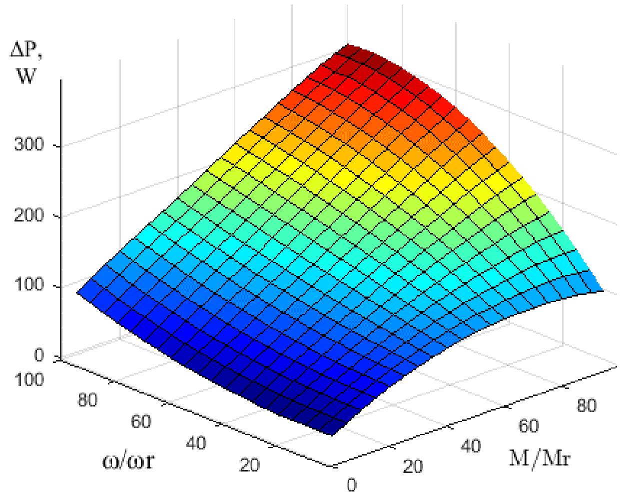

Fig. 9. Change of power losses in the drive system

The change of the efficiency of the power drive system as a function of the angular speed (output frequency of the drive module) is shown in Fig. 10. Three cases with different load torques, respectively 25%, 50%, and 100%, are considered.

Apparently, the efficiency of the power drive system remains high over a wide range of load and angular speed variations. For the drive system under consideration, the overall efficiency of the drive module is 97,3%, and the efficiency of the power drive system is 70,1%. These values correspond to the energy classes IE2 for the drive module and IES1 for the power drive system.

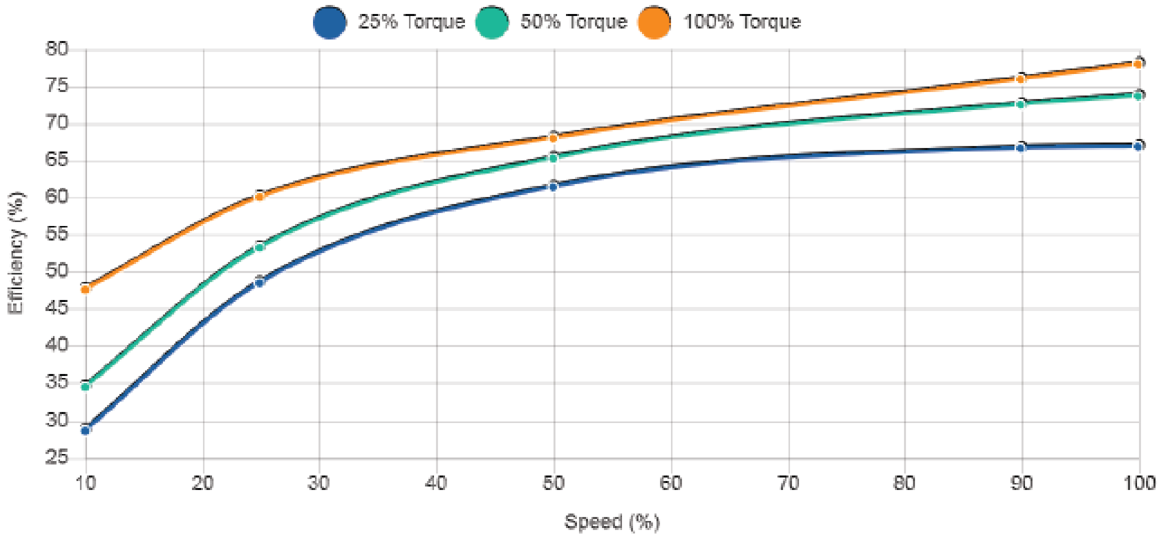

Fig. 10. Efficiency of the power drive system

V. Conclusion

Electric drives built based on frequency converters have high energy and performance characteristics, and possibilities for saving electricity. The conducted study shows that for aggregates working with variable load and angular speed, the use of a frequency converter can lead to the following savings in electrical power:

- 66,35% by implementing only AEO;
- 42,86% when implementing only the frequency regulation principle;
- 80,76% in the implementation of the AEO together with the frequency regulation principle.

The selection of the appropriate values of the setting parameters is crucial for ensuring the stable operation of the electric drive and realizing the greatest possible saving of energy.

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References

[1] Ilinskiy N. F., Moskalenko V. V., Electric drives energy and resource saving, Academia, Moscow, 2008, ISBN 978-5-7695-2849-1.

[2] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products.

[3] EN IEC 61800-9-2: 2017 Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters.

[4] Lee K., Zhai P., Ruchti T., Haberkorn B., Zhou J., Optimal Energy Efficiency Evaluation in Induction Machines Driven by Adjustable Speed Drives under EN 50598–2 and IEC 61800-9-1 Standards, 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 2018, DOI 10.1109/ECCE.2018.8558445.

[5] Cabezas Rebolledo A., Anibal Valenzuela M., Expected Savings Using Loss-Minimizing Flux on IM Drives—Part I: Optimum Flux and Power Savings for Minimum Losses, IEEE Transactions on Industry Applications, Vol. 51, Issue 2, 2015, pp 1408-1416, 2015, DOI: 10.1109/TIA.2014.2356643