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Discounted Costs Range Criterion Modification for Controlled Asynchronous Electric Drives

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Abstract: A range criterion of discounted costs is proposed, which takes into account all costs for a speed-controlled asynchronous electric drive, including its price, costs of losses and maintenance, and amortization charges. It is also possible to take into account the cost and energy performance of matching transformers and gearboxes. Costs for reactive power compensation of both the first and second kind (due to the presence of harmonic components at the drive input) are taken into account. The latter requires determining the total harmonic distortion (THD) of the currents consumed by the drive. In the case of autonomous power systems, it is also necessary to determine the drive's supplying voltage non-linear distortion coefficients. Representing the discounted costs as the sum of initial capital investments and annual costs made possible taking into account the presence of inflationary processes. The control characteristics of the active power consumed by the drive, efficiency, power factor, and phase shift factor are constructed, which are dependencies on the rotation frequency in a certain control range at a specific load. It is proposed to calculate the drive's discounted costs criterion, depending on the operating mode of the load. According to the mode, the criterion is calculated as an average range in a certain range of speed control or is determined taking into account a given tachogram of speed changes. For the controlled asynchronous drive under consideration, the discounted costs are 4148 c.u. in the first case and 5139.3 c.u. in the second case. If inflationary processes are taken into account, the first case is 4219.4 c.u. and the second case is 5227.7 c.u., respectively.

Keywords: speed-controlled asynchronous electric drive; efficiency criteria; efficiency; power factor; non-linear distortion factor; discounted costs; operating conditions; experimental studies

Citation: Petrushin, V.; Plotkin, J.; Almuratova, N.; Mustafin, M.; Zharkymbekova, M. Discounted Costs Range Criterion Modification for Controlled Asynchronous Electric Drives. *Energies* **2023**, *16*, 5704. https://doi.org/10.3390/en16155704

Academic Editor: Chunhua Liu

Received: 5 July 2023
Revised: 23 July 2023
Accepted: 27 July 2023
Published: 30 July 2023

1. Introduction

The widespread introduction of controlled asynchronous electric drives (CAED) in all industries, in transport, in the utilities sector, and in agriculture, makes it necessary to consider their efficiency, determined by different criteria. These criteria can be used both in evaluating existing CAEDs and in developing new ones.

Mainly economic justifications are aimed to show the advantage of feedback over feed-forward controlled electric drives. At the same time, we need a cost indicator for a comparative assessment of several CAEDs in order to select the best option.

CAED is a source of harmonic currents (and in autonomous power systems also of harmonic voltages), which adversely affects the operation of other electrical energy consumers. This phenomenon determines electromagnetic compatibility and is taken into account when calculating the drive's power factor. It is advisable to use a CAED evaluating criterion, which would take into account electromagnetic compatibility, which is also characterized by the consumption of distortion power and its cost estimate.

The purpose of the proposed work is to substantiate the economic criterion that takes into account both the capital costs of CAED manufacturing and its operational costs. Such criterion is widely used in the evaluation of many technical objects, in particular, in the development of a series of electrical machines. One of the basic elements of CAED is an induction motor and to its design with the use of various criteria, a number of works are devoted [1–3]. It is reasonable to take into account inflationary processes when using the criterion of reduced costs. For this purpose, it should be modernized.

Calculation of such criterion can be carried out on the basis of experimental studies of CAED. The performed experiments make it possible to determine a number of electrical and power parameters. Oscillography of currents and voltages consumed by CAEDs allowed us to consider their harmonic spectrum and proceed to find their nonlinear distortion coefficients (THD). Their values significantly determine the operating costs in cases of certain EMC requirements related to inactive power consumption. Some works [4,5] relate the distortion power consumption to the value of the power factor. The present cost criterion depends significantly on the mode of operation of the CAED. Because of this, the values of the criterion under different operating modes should be considered.

2. Theoretical Definition of Criteria

The main CAED efficiency criterion is the efficiency factor η. Also, one of another CAED energy efficiency criteria is power factor χ. It determines the energy and electromagnetic compatibility of the drive with the power supply [6]. Meanwhile, the energy efficiency standards for CAED, as well as the standards of grid- [7] and converter-fed [8] AC motors, are solely based upon efficiency criterion. In some works, it is proposed to use the product of efficiency factors and power factors as an energy efficiency criterion [9–12]. Then, the efficiency of converting electrical energy in an electric drive can be determined based on the expression of mechanism active power:

$$P_{mech} = \sqrt{3} \cdot U_1 \cdot I_1 \cdot \chi_{ED} \cdot \chi_{tr} \cdot \eta_{IM} \cdot \eta_{red} \cdot \eta_{tr} \cdot \eta_{conv},$$

where I_1 is the drive current fed by line-to-line voltage U_1, and η_{IM}, η_{red}, η_{tr}, and η_{conv} is the efficiency of the asynchronous motor, matching gearbox, matching transformer, converter; χ_{ED} and χ_{tr} are the power factors of the drive and the transformer. Then the energy efficiency coefficient is defined as

$$k_{ef} = P_{mech} / \sqrt{3} \cdot U_1 \cdot I_1 = \chi_{IM} \cdot \chi_{tr} \cdot \eta_{IM} \cdot \eta_{red} \cdot \eta_{tr} \cdot \eta_{conv}.$$

A special feature of power factor determination for CAED is the presence in the energy balance (Figure 1) not only of reactive power Q_1, due to the phase shift angle of the main harmonics of current and voltage and also called reactive power of the first kind, but also of reactive distortion power D, due to the presence of higher harmonics and also called reactive power of the second kind [13,14]. S_1 and Q are auxiliary powers used to represent the balance.

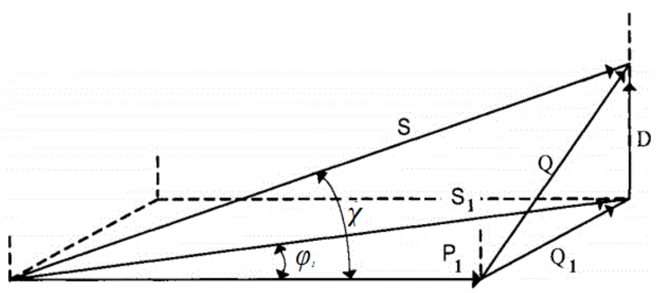

Figure 1. Balance of power consumed by CAED.

Considering a grid with an infinite power capacity, in which an undistorted three-phase voltage is applied to the distorting load, the expression for the electric drive's power factor will be [14]:

$$\chi = \frac{\cos\varphi_1}{\sqrt{1+THD_I^2}}.$$

In autonomous systems with distorted voltage, the power factor will be equal to [13]:

$$\chi = \frac{\cos\varphi_1}{\sqrt{1+THD_U^2+THD_I^2+THD_U^2\cdot THD_I^2}}.$$

Calculations of χ CAED present a certain complexity due to the variable spectrum of the higher harmonics, which depends upon control parameter, load, and also upon the converter settings (frequency control law, basic voltage, and frequency values of the converter, modulation frequency).

Based on Figure 1, reactive power Q_1 and distortion power D can be determined with a known active power P_1 consumed by the drive

$$Q_1 = P_1\cdot tg\phi_1,\ D = P_1\cdot\sqrt{tg^2\chi - tg^2\phi_1}.$$

In some cases, CAEDs may include gearboxes that match the torques of motors and loads. In this case, the performance characteristics of such a drive are largely determined by the parameters of the gearboxes [9,14].

The inclusion of matching transformers and gearboxes in CAED when considering static modes is taken into account as follows:

$$\begin{array}{ll} n_{mech} = \frac{n}{i_{red}}; & M_{mech} = M_{IM}\cdot i_{red}\cdot\eta_{red}; \\ P_{mech} = P_{IM}\cdot\eta_{red}; & \eta_{ED} = \eta_{IM}\cdot\eta_{red}\cdot\eta_{tr}\cdot\eta_{conv}, \end{array}$$

where i_{red} is the gear ratio of the gearbox, n and n_{mech} are the rotational speeds of motor and load; M_{IM} and M_{mech}—torques on the motor shaft and on load side; P_{IM} and P_{mech} are active mechanical powers on the motor shaft and on the mechanism. The matching transformer changes the mains voltage U_1 according to the transformation ratio k_{tr} to the drive supply voltage $U_2 = \frac{U_1}{k_{tr}}$.

The criteria can be characterized both by the range of the drive for a certain load, and the duration of operation at the speeds specified by the tachograms. The CAED operates in a certain range of rotational speeds, and this circumstance determines the specifics of the optimality criterion. It is justified to choose the mid-range efficiency criterion, which will ensure the minimization of energy losses in the entire control range from n_1 to n_2 [13]:

$$\eta_{cd} = \frac{1}{n_2-n_1}\cdot\int\limits_{n_1}^{n_2}\eta(n_i)\,dn.$$

Similarly, mid-range criteria for power factors, phase shift between the fundamental voltage harmonics and the current consumed by the drive can be used.

$$\begin{array}{l} \chi_{cd} = \frac{1}{n_2-n_1}\cdot\int\limits_{n_1}^{n_2}\chi(n_i)\,dn, \\ \cos\varphi_{1cd} = \frac{1}{n_2-n_1}\cdot\int\limits_{n_1}^{n_2}\cos\varphi_1(n_i)\,dn. \end{array}$$

If the time diagrams of the load operation are known, i.e., operating time at each speed, determined by the technological requirements for drive mechanisms, then the evaluation of these range energy criteria of the motor and drive must be carried out taking into account the motor operation duration at each point of control range

$$\eta_{dt} = \frac{\sum_i \eta(n_i) \cdot t_{n_i}}{\sum_i t_{n_i}}, \ \chi_{dt} = \frac{\sum_i \chi(n_i) \cdot t_{n_i}}{\sum_i t_{n_i}},$$
$$\cos\varphi_{1dt} = \frac{\sum_i \cos\varphi_1(n_i) \cdot t_{n_i}}{\sum_i t_{n_i}},$$

where t_{n_i} is the motor operation time at rotational speed n_i, and i is the number of the tachogram section. In the same way, k_{ef}. can be calculated.

It is advisable to use the control characteristics $P_1 = f(n)$ to calculate the active power consumed by the drive in the medium range or range, taking into account the given tachogram of the drive operation

$$P_{1cd} = \frac{1}{n_2 - n_1} \cdot \int_{n_1}^{n_2} P_1(n_i)\, dn, \quad P_{1dt} = \frac{\sum_i P_1(n_i) \cdot t_{n_i}}{\sum_i t_{n_i}}.$$

At the same time, the proposed criteria for efficiency, power factor and their product do not take into account some financial aspects, such as the cost of manufacturing and drive operation, inflation rate, etc. Such accounting is carried out using the discounted cost criterion (*RC*) [15], which can also be mid-range or range, taking into account the given tachogram of the drive

$$RC_{cd} = \frac{1}{n_2 - n_1} \cdot \int_{n_1}^{n_2} RC(n_i)\, dn, \quad RC_{dt} = \frac{\sum_i RC(n_i) \cdot t_{n_i}}{\sum_i t_{n_i}}.$$

When modifying the *RC* criterion of an electric drive [16,17], it is necessary to take into account the effect of inflationary processes upon the criterion, since the standard payback periods for the CAED are quite long (5–8 years). In the general case, when the total drive cost cep is known (in the general case, in addition to the cost of asynchronous motors and converters, it includes also the cost of matching transformers and gearboxes, as well as the cost of network chokes or filters) and the cost of money is constant, the value of the criterion is determined as

$$RC = \left(cep + C_{rpc1} + C_{rpc2}\right)[1 + (k_d + k_s)] + C_L,$$

where C_{rpc1} is the cost of reactive power compensation of the first kind; C_{rpc2}—the cost of reactive power compensation of the second kind; C_L is the cost of electricity losses per year; k_d is the share of depreciation expenses; k_s is the share of maintenance costs during operation of the drive. For CAEP, the values k_d = 0.065, k_s = 0.069 are taken to be the same as for general industrial IM.

Expressions C_{rpc1} and C_{rpc2} with a known time diagram of the drive operation have the form:

$$C_{rpc1} = c_{K1} \cdot k_{my} \cdot P_{1dt} \cdot [tg(\arccos\varphi_{dt}) - tg\varphi_0] \cdot t_{ED},$$

where c_{K1} is the cost of installing 1 kVAr reactive power compensating devices of the first kind; k_{my} is the coefficient of IM participation in the load peaks (in subsequent calculations, 0.25 is assumed); φ_0 is the angle of shift between the motor's current and voltage, at which the reactive power cannot be compensated (in subsequent calculations, tgφ_0 = 0.484 is assumed).

$$C_{rpc2} = c_{K2} \cdot k_{my} \cdot P_{1dt} \cdot \left\{ \sqrt{[tg(\arccos\chi_{dt})]^2 - [tg(\arccos\varphi_{1dt})]^2} - \right.$$
$$\left. tg[\arccos(\frac{1}{\sqrt{1 + THD_{ID}^2 + THD_{UD}^2 + THD_{ID}^2 \cdot THD_{UD}^2}})] \right\} \cdot t_{ED},$$

where c_{K2} is the cost of installing 1 kVAr compensating devices for reactive power of the second kind (in subsequent calculations, 10 is assumed).

The standards [18,19] determine the permissible values of the coefficients of non-linear distortion of currents THD_{ID} (in autonomous power systems and the permissible values of the coefficients of nonlinear distortion of voltages THD_{UD}).

In expressing the cost of active losses for a year with a known time diagram of the drive operation, $C_L = c_{ae} \cdot P_{1dt} \cdot (1 + a_r - \eta_{dt}) \cdot t_{ED}$ is used, where c_{ae} is the cost of 1 kWh (in subsequent calculations, 1 is taken); a_r is a coefficient that takes into account losses in distribution networks (0.04 is assumed in subsequent calculations); t_{ED} is the duration of the drive operation during the year (2000 h are assumed in subsequent calculations).

In the case when the timing diagram of the motor operation is not defined, the average range values of the present value components C_{rpc1}, C_{rpc2} and C_L, and are calculated using: η_{cd}, χ_{cd}, $\cos\varphi_{1cd}$ and P_{1cd}.

The expression of the considered criterion of the present value of the RAEP can be represented in a general form as

$$RC = K + \sum_{i=1\ldots T_n} Y_i,$$

where $K = cep + C_{rpc1} + C_{rpc2}$ is the initial investment and $Y_i = (k_d + k_s) \cdot (cep + C_{rpc1} + C_{rpc2}) + C_L$ is the annual cost. If inflation is not taken into account, then the value of annual costs is constant $Y_i = const$ and equal to the calculated value Y_i determined for the first year of operation. To take into account annual inflation, the expression of discounted costs is converted to the form

$$RC = K + Y_i \cdot \left[1 + (1 + d_{INF1}) + (1 + d_{INF1}) \cdot (1 + d_{INF2}) + \ldots + (1 + d_{INF1}) \cdot \ldots \cdot (1 + d_{INF(Tn-1)})\right] / T_n,$$

where d_{INF1}, d_{INF2}, d_{INF3}, etc. projected inflation rates in the current years of the payback period T_n.

Most often, for the purpose of simplification, the average inflation rate d_{INF} is set for the payback period and the inflation coefficient is calculated as follows:

$$k_{INF} = \frac{\sum_{m=0}^{Tn-1} \left(1 + \frac{d_{INF}}{100\%}\right)^m}{T_n},$$

where d_{INF} is the average annual inflation rate (in %).

3. Experimental Study of Controlled Asynchronous Electric Drive

On the experimental stand (Figure 2), studies were carried out [8] on the basis of which the calculations of the discounted costs of the CAED were further performed.

The considered CAED consists of a SEMITEACH-IGBT SKM50GB12T4 transistor frequency converter and an AIR71A2U3 asynchronous motor. The motor stator winding is star connected. The mains voltage during the experiment was 380 V at a frequency of 50 Hz. The frequency control law U/f = const was implemented. The converter had standard settings U_{nom} = 380 V and f_{nom} = 50 Hz. The pulse-width modulation frequency was set to 6 kHz. With the help of a digital device BORDO-421, to determine the powers and the required coefficients, oscillography of currents and voltages was carried out both from the side of the network and from the side of the motor.

The instruments were used to measure phase voltages of the network—$U = (U_a + U_b + U_c)/3$, currents—$I = (I_a + I_b + I_c)/3$, active P_1, and reactive (of the first kind) Q_1 powers consumed from the network by the drive at different frequencies (Table 1). The total power S was also calculated.

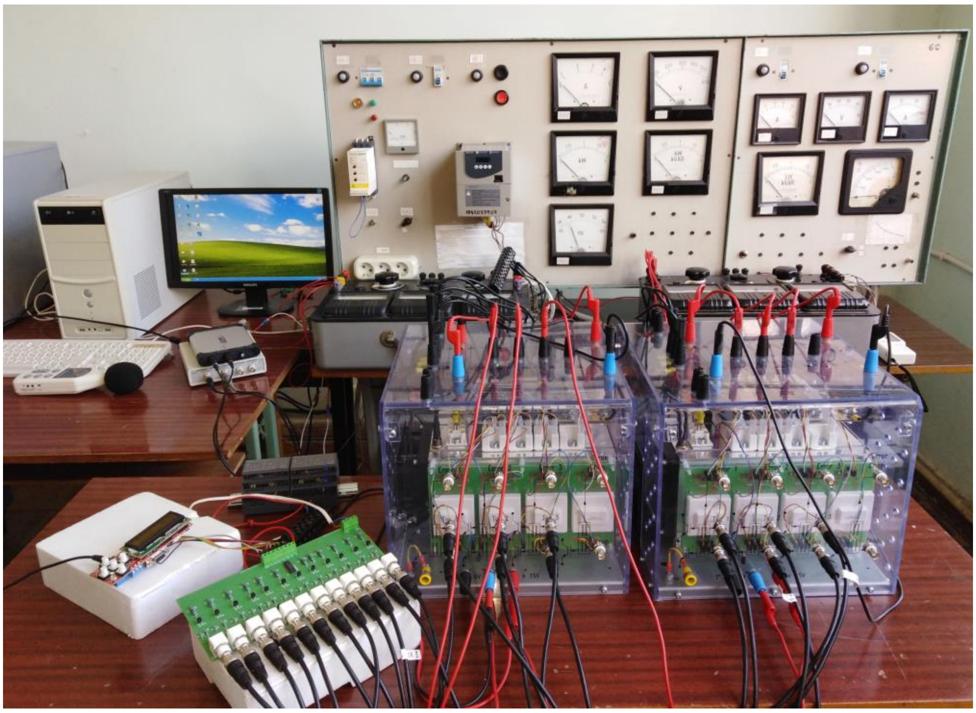

Figure 2. General view of the experimental stand with an adjustable asynchronous electric drive.

Table 1. Measured data at the drive input.

f, Hz	*U*, V	*I*, A	P_1, W	Q_1, Var	*S*, VA
20	217.7	0.393	111	110	256.8
25	217	0.475	145	90	309.2
30	217.3	0.97	265	80	632.4
35	216.3	1.07	330	130	694.9
40	216.3	1.35	440	150	873.3
45	216.7	1.67	530	160	1087.7
50	217	1.95	635	220	1265.5
55	216.3	2.21	740	250	1433.2
60	216	2.52	895	250	1629.7

To create a mechanical load, a synchronous generator of a type G250I1 is used, which is mounted on the same shaft with the motor, operating through a rectifier on the loading resistance (rheostat F-8221/315 with nominal data: P = 1.9 kW, U = 110 V, I = 20.5 A, R = 6.2 Ω). The generator field winding is supplied through a bridge rectifier from a single-phase transformer 220/17 V. The generator excitation current was 2.4 A. According to the scheme used, the generator is loaded up to 42 A, and IM, respectively, up to 2.4 A. It is possible to calculate the load on the induction motor shaft by the measured values of the generator parameters U_G and I_G (Table 2). At that, mechanical ΔP_{mech} and magnetic ΔP_{st} losses in the generator were taken into account.

Using the data in Table 2, it is possible to build a family of mechanical characteristics for a number of frequencies (Figure 3). The load characteristic is also given.

The results obtained made it possible to calculate a number of energetic parameters (Table 3).

Table 2. Data for motor shaft load calculation.

f, Hz	U_G, V	I_G, A	ΔP_{mech}, W	ΔP_{st}, W	n, rpm	T, Nm	P_2, W
20	13	2.8	25	31.3	1035	0.855	92.7
25	15.8	3.5	37	45	1356	0.967	139.7
30	20.7	4.5	45	60.5	1660	1.143	198.6
35	24.1	5.4	57	77	1959	1.287	264.1
40	28	6	68	104	2254	1.44	340
45	31.7	7	80	141	2548	1.659	442.9
50	35	7.9	94	181	2840	1.854	551.5
55	38	8.3	109	243	3082	2.068	667.4
60	40	8.8	123	303	3287	2.26	778

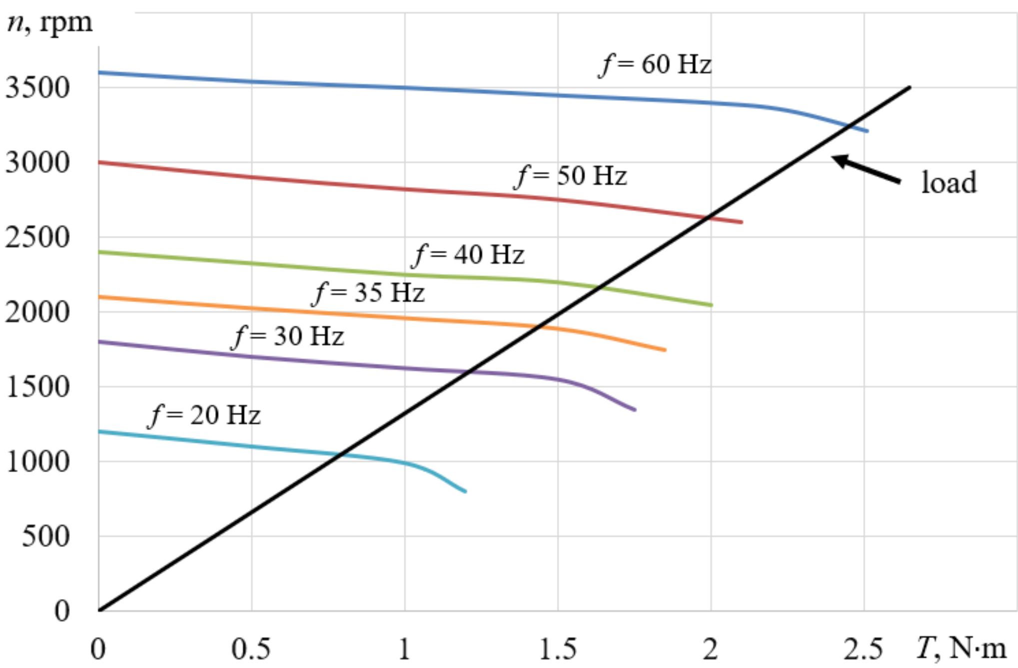

Figure 3. Mechanical motor characteristics at different supply voltage frequencies and load characteristics.

Table 3. The calculation of energetic parameters.

f, Hz	$\cos\varphi_1$, r.u.	THD_I, r.u.	χ, r.u.	η, r.u.
20	0.71	1.31	0.432	0.835
25	0.849	1.51	0.469	0.939
30	0.957	2.05	0.419	0.749
35	0.93	1.68	0.475	0.8
40	0.946	1.59	0.504	0.772
45	0.957	1.73	0.487	0.835
50	0.944	1.6	0.5	0.868
55	0.947	1.61	0.516	0.901
60	0.963	1.38	0.549	0.869

Control characteristics of efficiency factors, power, phase shift, and non-linear distortions of the current consumed by the drive of active power were experimentally obtained (Figures 4–6).

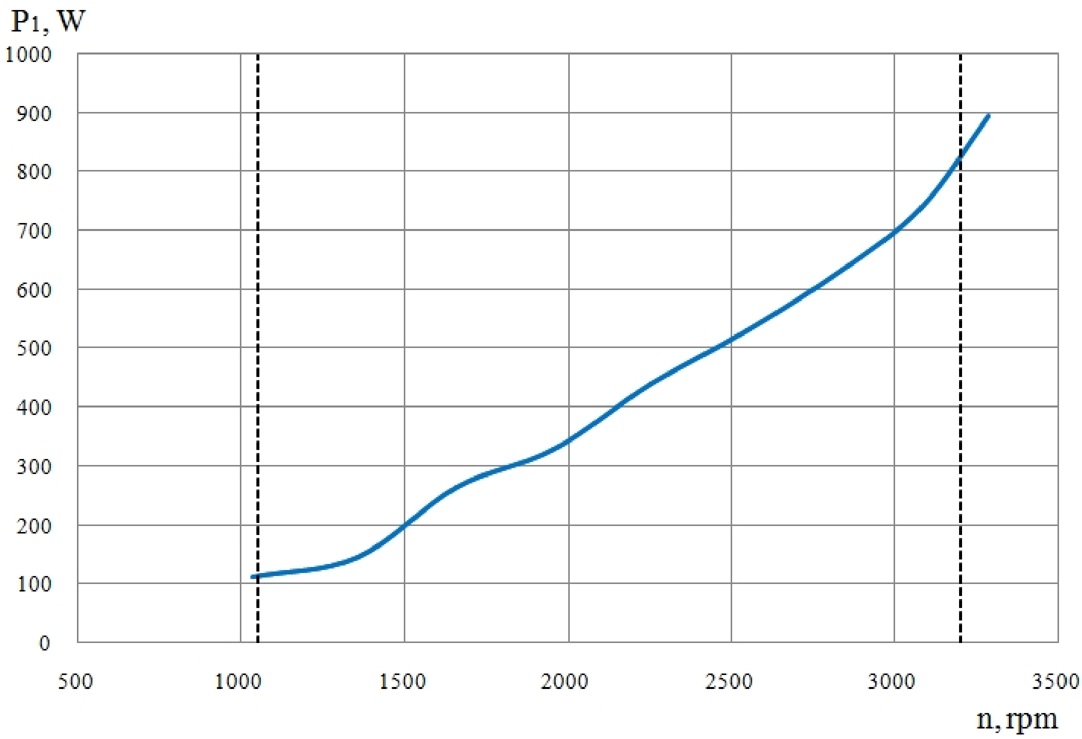

Figure 4. Drive active power consumption.

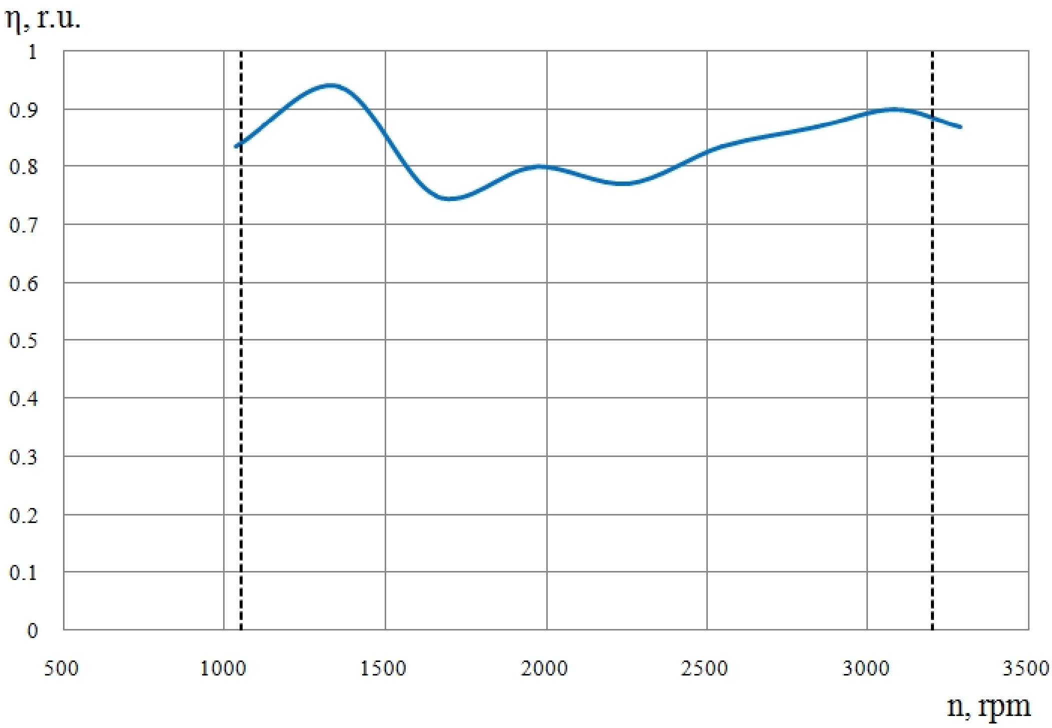

Figure 5. Drive efficiency.

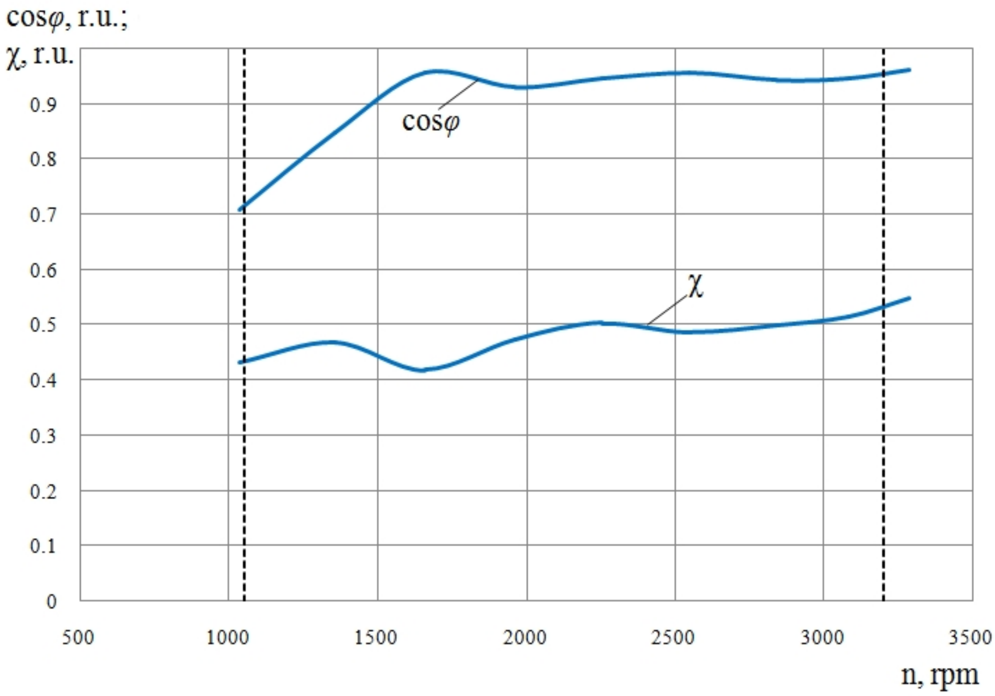

Figure 6. Drive power factors and phase shift.

Two modes of operation are considered. In one, the drive operates in the speed range of 1050–3200 rpm, and for this range, the average values of coefficients and active power consumed by the CAED are found. In the second, the drive operates on a tachogram (100 s - 1700 rpm, 300 s - 2000 rpm, and 200 s - 3000 rpm) and coefficients and consumed active power are calculated according to the corresponding expressions. It should be noted that in this case, reactive power compensation of the first kind can be omitted since tgφ1 is much less than 0.484. In other cases (for example, when using semiconductor voltage converters or cycloconverters), the need to compensate for both the reactive power of the first kind and the reactive power of the second kind must be taken into account. The cost of the drive is 300 USD. (the cost of the motor is 100 USD and the cost of the converter is 200 USD). If we take the average inflation rate of 5.3%, and the payback period T_H is 5 years, then the inflation coefficient k_{INF} will be equal to 1.112.

Calculation results are shown in Table 4.

Table 4. CAED criteria.

Drive Unit Options	Range Is Set	Tachogram Is Set	Range Adjusted for Inflation	The Tachogram Is Set Taking into Account Inflation
η	0.836	0.822	0.836	0.822
cep, c.u.	300	300	300	300
$\cos\varphi_1$	0.903	0.938	0.903	0.938
P_1, kW	0.41	0.45	0.41	0.45
χ	0.48	0.477	0.48	0.477
C_{rpc2}, c.u.	3210.3	4059	3210.3	4059
C_L, c.u.	167.3	196.2	167.3	196.2
K, c.u.	3510.3	4359	3510.3	4359
Y, c.u.	637.7	780.3	709.1	867.7
RC, c.u.	4148	5139.3	4219.4	5227.7

In calculations allowable coefficient of non-linear current distortion THD_{ID} = 20% was assumed.

4. Conclusions

- A cost indicator that allows a comparative evaluation of several CAEDs in order to select the best option is the discounted cost criterion.
- The discounted cost criterion must take into account the need to compensate for the reactive power of the second kind due to higher harmonics at the input of the drive.
- The operating mode of the load affects the calculation result of the drive's discounted cost criterion. In a certain speed control range, it is calculated as mid-range or is determined by taking into account the specified speed tachogram. For the regulated asynchronous electric drive under consideration, the reduced costs are 4148 c.u. in the first case and 5139.3 c.u. in the second case.
- Discounted costs criterion modification is related to the need to take into account inflationary processes. If inflationary processes are taken into account, then in the first case 4219.4 c.u. and in the second case—5227.7 c.u. are obtained, respectively.
- The proposed criterion can be used both in the process of drives operation, in the measurement of a number of their indicators, and in the development of new CAEDs with the calculation of these indicators in the design models.
- With the help of the proposed discounted costs criterion the use of various devices (network filters and chokes) for compensation of reactive powers of the first and second kind in controlled electric drives can be economically justified.

Author Contributions: Conceptualization, V.P., J.P. and N.A.; Methodology, V.P. and N.A.; Software, J.P.; Validation, M.M. and M.Z.; Formal analysis, N.A. and M.Z.; Investigation, V.P., J.P. and N.A.; Resources, N.A., M.M. and M.Z.; Writing—original draft, V.P.; Writing—review & editing, J.P.; Supervision, V.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP14869184).

Data Availability Statement: Data sharing not applicable. Created data is presented within the article itself.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

P_{mech}	mechanism active power
k_{ef}	energy efficiency coefficient
χ	power factor
THD_I	total harmonic distortion of current
THD_U	total harmonic distortion of voltage
CAED	asynchronous electric drives
η_{cd}	mid-range efficiency criterion
χ_{cd}	mid-range power factor criterion
$\cos \varphi_{1cd}$	mid-range shift coefficient criterion
η_{dt}	range criterion of efficiency taking into account the tachogram
χ_{dt}	range criterion of power factor taking into account the tachogram
$\cos \phi_{1dt}$	range criterion of the shift coefficient taking into account the tachogram
P_{1cd}	mid-range active power consumption
P_{1dt}	range active power consumption taking into account the tachogram
RC_{cd}	mid-range discounted costs
RC_{dt}	range discounted costs taking into account the tachogram
C_{rpc1}	cost of reactive power compensation of the first kind
C_{rpc2}	cost of reactive power compensation of the second kind

C_L	cost of active losses
K	capital expenditures
cep	drive cost
Y_i	annual operating costs
d_{INF}	annual inflation coefficient
k_{INF}	average inflation coefficient

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