Design Criteria and Range Limits in The Development of Controlled Induction Motors

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Abstract: Automated design optimization of controlled induction motors for a variety of design tasks in two ranges criteria is performed. Design tasks include consideration of both static and dynamic modes. The changes in variable motor parameters according to the selected criteria and design tasks are defined. A modification of the criteria of electric drive given costs is proposed by using of operation significance coefficient. This allows reconciling of the maximum of mid-range efficiency and the minimum of mid-range resulted expenses. Analysis of the effect of inflation coefficient on the value of the reduced costs objective function is carried out. The classification of a design range limits applicable to the development of controlled induction motors is offered. The applying of range limitations in the automatic optimization design program of controlled induction motors is described. The use of range limitations affects the results of the design synthesis of controlled induction motors.

Keywords: controlled induction motor; automated design optimization; mid-range efficiency; reduced costs criterion; design range limit

1. Introduction

Using of controlled-speed electric drives in all industries and on a transport makes possible rationally control technological processes at minimization of consumption of energy resources. To analyze the operation and to design of induction motors (IM) in controlled electric drives it is necessary joint consideration of converters, motors and mechanisms, as well as, if necessary, matching transformers and reducers. In the software product DIMASDrive [2] controlled electric drive is represented with a complex mathematical model, which includes models of all its elements [1].

Using of standard commercially available induction motors in electric drives with frequency speed control is not optimal according to the criteria of mass, size, cost and energy efficiency. Therefore, for specific industrial electric installations specific controlled induction motors (CIM) must bee designed with considering of their mode of operation, the nature of the load and dependence of the load on the motor speed [3, 4, 5]. IM of general industrial use are designed for continuous operation with constant speed and load torque. CIM should be designed to work in a given speed range, taking into account changes in the load. In their development the number of calculations increases significantly.

The material, energy and labor resources necessary for the production and operation of CIM should be used with maximum efficiency, which can be ensured only when they are designed and optimized on the basis of scientifically based criteria.

In connection with rising of energy cost the series of general-purpose IM with high energy efficiency are currently being designed and produced [6]. Many industrial installations also require of specialized CIM with high values of efficiency, although the price of these motors increases.

In the DIMASDrive program, project limitations are accounted for. When designing electrical machines, restrictions are divided into constructive and functional. When designing the

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IM series 4A, 4AI, AI, functional limitations were applied, which are determined by the requirements of the standards (permissible values of starting and maximum moments, inrush current, winding temperature) and reliability requirements (rate of temperature rise in short-circuit mode) [7,8].

2. Statement of problem

In general, when designing of CIM as the design criteria may be used weight, dimensions, motor cost, mid-range resulted expenses on manufacturing and operation (RC), mid-range energy performance (efficiency and power factor) or generalized criterion may be applied, taking into account all of these criteria. Similar design criteria can also be used for the entire regulated electric drive.

Design results vary with different used criteria or their various components in the consolidated criteria, and also depend on the importance given by the coefficients of these components. When calculating the criteria may be taken into account their value in a transitional mode. This approach allows to design for both modes of operation, in which the duration of transients is significantly shorter than the steady state operation, and for modes with comparable values of the durations indicated above. Thus, it is possible to define several design problems that are described as running time at a certain load, and as the duration of operation at predetermined speeds.

If the mid-range efficiency is used as the design criterion, it will be provided the design of energy-saving CIM.

Mid-range power design criteria [9] should reflect the energy performance in all speed control range from a minimum value n_1 to a maximum value n_2. They are defined as equivalent average for that range. The same applies to the generalized criterion of the given costs, which takes into account the cost of manufacturing and operating costs. Due to the fact that the cost depends on the motor efficiency and power factor, generalized criterion of resulted expenses assumes different values at different points of speed control range and it is advisable to determine an equivalent average value for the whole range.

Efficiency and motor power factor calculated as average values for a control range of motor speed.

$$\eta_{aIM} = \frac{1}{n_2 - n_1} \int_{n_1}^{n_2} \eta_{IM}(n)\, dn, \tag{1}$$

$$\cos\varphi_{1aIM} = \frac{1}{n_2 - n_1} \int_{n_1}^{n_2} \cos\varphi_{1IM}(n) \cdot dn. \tag{2}$$

Full range criterion of annual resulted expenses of the motor.

$$RC_{IM} = (ced + C_{rpc})[1 + T_S(k_{de} + k_S)] + CL_{IM}, \tag{3}$$

where ced is the full cost of the motor; C_{rpc} is the costs for compensation of reactive power; CL_{IM} is the cost of power losses for the year; T_s is the standard motor payback period, years; k_{de} is the share of expenditures for depreciation expenses; k_s is the share of expenditures for service at motor maintenance.

We assume for the controlled induction motors the same meanings as for general-purpose motor series $T_s = 5$ years, $k_{de} = 0.065$, $k_s = 0.069$ [4].

$$RC_{IM} = 1.67(ced + C_{rpc}) + CL_{IM}, \tag{4}$$

$$C_{rpc} = C_{cre} P_1 (tg\varphi_1 - 0.484), \tag{5}$$

$$CL_{IM} = C_{cae} P_{1IM} (1.04 - \eta_{IM}), \tag{6}$$

where C_{cae} is the coefficient taking into account the value of the active energy losses, is the product of the value of 1 kW·h of electricity during the life of the motor ($C = 0.13$ c.u. for kW·h), the number of hours of motor operation during the year (T_{year} = 2100), the number of years between overhauls (5) and coefficient of the relative motor load (K_L =0.8), C_{cre} is the coefficient taking into account the cost of reactive energy compensation is the product of the value of 1 kVAr reactive power compensation devices (10 c.u. for 1 kVAr), the coefficient of participation of the motor at the maximum load of the system (0.25).

$$RC_{aIM} = \frac{1}{n_2 - n_1} \int_{n_1}^{n_2} RC_{IM}(n) \cdot dn. \qquad (7)$$

When using CIM as a part of modern variable frequency electric drives (CED) because of the drive power factor proximity to 1 component corresponding to the cost of the reactive energy compensation can be excluded from the expression RC of electric drive.

$$RC_{CED} = cep\,[1 + T_S(k_{de} + k_S)] + CL_{CED}, \qquad (8)$$

where cep is the full cost of the electric drive,

$$C_{CED} = C_{cae} P_{1CED}(1.04 - \eta_{CED}). \qquad (9)$$

The values of the coefficients and costs, as well as hours and years where used the same as in (3) - (6).

$$RC_{aCED} = \frac{1}{n_2 - n_1} \int_{n_1}^{n_2} RC_{CED}(n) \cdot dn. \qquad (10)$$

If the tachogram for industrial installation is defined and the time of motor's working at each speed is known, the evaluation of range energy criteria for the motor and for the electric drive must be carried out taking into account the duration of the motor's operation at each speed.

$$\eta_a = \frac{\sum_i \left(\eta(n_i) \cdot t_{n_i}\right)}{\sum_i t_{n_i}}, \qquad (11)$$

$$\cos\varphi_{1a} = \frac{\sum_i \left(\cos\varphi_1(n_i) \cdot t_{n_i}\right)}{\sum_i t_{n_i}}, \qquad (12)$$

where t_{n_i} is the time of motor's operation with rotation frequency n_i , i is the sequence number of the tachogram's sector.

Mid-range resulted expenses

$$RC_a = \frac{\sum_i \left(RC(n_i) \cdot t_{n_i}\right)}{\sum_i t_{n_i}}. \qquad (13)$$

For solution of design problems for CIM standard methods and computer-aided design software, designed for IM of general industrial use, can not be applied. It should be a joint consideration of converters, motors and loads [10,11]. In the design system it is necessary to use a complex mathematical model of the entire system of electric drive and not just a model of the motor, as is done in the design of IM for general industrial use [12].

In the development of CIM it is advisable to use the mid-range criterion of motor's efficiency and the mid-range criterion of resulted expenses of electric drive [13].

3. The results of investigation

Let us consider the solution of the three project tasks on the basis of serial induction motor 4A160S4. The stator winding is connected to a "star" and is powered by a frequency converter

(Altivar 58, 1500 c.u., 15 kg, η_c=0.94) with frequency control law U/f = const. The motor runs at a constant active torque load of 75 N·m. As variable parameters were selected stator packet length (L) and the frequency at which the stator winding (SW) is projected. The change in frequency (f) involves the automatic change in the number of SW turns (w_1), the effective conductor cross-section (q_{ef}), the diameter of the winding wire (d_w).

The first design task involves optimization of the motor design for a specific control range. In this case, we chose the range of 300 - 1900 rpn. Ranges of the variable parameters are from 0.8 to 1.2 of baseline values. Table 1 shows the values of design criteria and design changes by using two selected design criteria.

Table 1. The design criteria and design changes

Motors / Indicators and parameters	Serial	Optimized by criterion η	Optimized by criterion RC_{CED}
η_a IM,%	83.43	85.54	85
RC_a IM, th. c.u.	2.143	2.114	2.101
Mass IM, kg	120	132	127
Value IM, c.u.	651	710	683
Mass CED, kg	135	147	142
Value CED, c.u.	2.151	2.210	2.183
RC_a CED, th. c.u.	4.709	4.678	4.664
η_a CED, %	81.8	83.86	83.34
L, mm	130	155	145
f, Hz	50	58.54	55.47
w_1	112	96	101
q_{ef}, mm^2	2.45	2.87	2.72
d_w, mm	1.33	1.43	1.38

Table 2. The design criteria and design changes

Motors / Indicators and parameters	Serial	Optimized by criterion η	Optimized by criterion RC_{CED}
η_a, IM %	75.13	80.5	80.15
RC_a IM, th. c.u.	2.603	2.349	2.304
Mass IM, kg	120	129	121
Value IM, c.u.	651	696	654
Mass CED, kg	135	144	136
Value CED, c.u.	2.151	2.196	2.154
RC_a CED, th. c.u.	5.169	4.915	4.864
η_a CED, %	73.66	78.92	78.58
L, mm	130	150	134
f, Hz	50	59.62	59.94
w_1	112	94	93
q_{ef}, mm^2	2.45	2.92	2.94
d_w, mm	1.33	1.43	1.43

The second project involves the task of optimization design of CIM to work for a given motor speed change chart (see Figureure 1), excluding transients.

Table 2 shows the values of design criteria and design changes by using two selected design criteria.

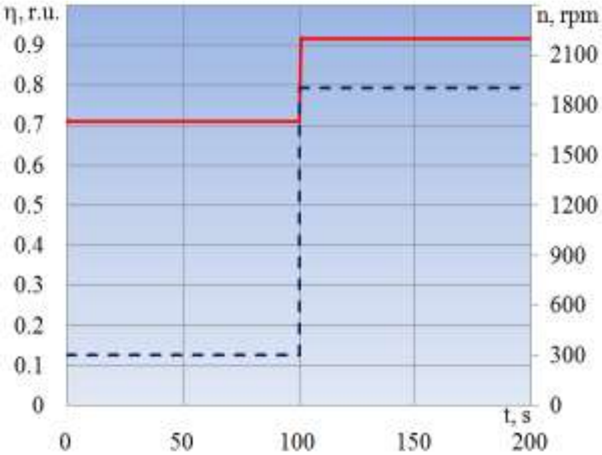

Figure 1. Characteristics of a rotational speed (---) and efficiency (-) of baseline motor for the second design task

The third project involves the task of optimization design of CIM to work for a given motor speed change chart (see Figure 2), including transients.

Table 3 shows the values of design criteria and design changes by using two selected design criteria.

Table 3. The design criteria and design changes

Motors / Indicators and parameters	Serial	Optimized by criterion η	Optimized by criterion RC_{CED}
η_a IM, %	76.65	80.4	77.78
RC_a IM, th. c.u.	1.173	1.090	1.088
Mass IM, kg	120	121	130
Value IM, c.u.	651	652	702
Mass CED, kg	135	136	145
Value CED, c.u.	2.151	2.152	2.202
RC_a CED, th. c.u.	3.678	3.594	3.593
η_a CED, %	75.15	78.62	76.5
L, mm	130	133	153
f, Hz	50	59.94	59.51
w_1	112	93	94
q_{ef}, mm^2	2.45	2.94	2.92
d_w, mm	1.33	1.43	1.43

Figure 2. Characteristics of a rotational speed (---) and efficiency (-) of baseline motor for the third design task

The full range efficiency criterion does not take into account the financial aspects: the costs of manufacturing and operating the engine and electric drive, the inflation rate, and so on. Normative payback periods for CIM are long enough (5-8 years). Therefore, in the modification of the criterion of electric drive's resulted expenses [5, 14] it is necessary to take into account the effect of inflation. During the motor life time the energy component of reduced costs several times higher than the cost component associated with capital costs. Therefore, optimization of the energy component is paramount.

To use the modified criterion of electric drive's resulted expenses it must be agreed with the criterion of efficiency, that is to make closer extremums of objective functions. For this we use the coefficient of operation significance k_{os}. It is also advisable to take into account the inflation factor k_{inf} in the modified criteria of resulted expenses [14]. Modification of the full range criterion of annual resulted expenses for the design of general-purpose IM was carried out in a similar way.

In view of the above expression for the modified criterion of resulted expenses is given by

$$RCm_{CED} = \frac{cep\,[1+T_S\cdot(k_{de}+k_S)]}{k_{os}} + CL_{CED}\cdot k_{\inf}. \quad (14)$$

The coefficient k_{inf} is calculated as follows:

$$k_{\inf} = \frac{\sum_{m=0}^{T_S-1}\left(1+\frac{d_{\inf}}{100\%}\right)^m}{T_S}, \quad (15)$$

where d_{inf} is the the average rate of annual inflation, %.

The coefficient k_{os} for harmonizing the maximum efficiency and minimum of the resulted expenses is determined by dividing the value of unmodified RC by the value of the cost of active energy losses of the base motor. It is equal to 3.94 for calculations performed for the motor 4A160S4.

The stator winding is connected to a "star" and is powered by a frequency converter (Altivar 58, 1500 c.u., 15 kg, η_c = 0.94) with frequency control law U/f = const. The motor runs at a constant active torque load of 75 N·m. To find the extremes of the criteria of efficiency and RC calculation was performed using DIMASDrive program. As variable parameters were selected the stator packet length (L), mm, and the frequency at which SW is projected, which ranges from 45 to 55 Hz. The change in frequency (f) involves the automatic change in the number of SW turns (w_1), the effective conductor cross-section (q_{ef}), the diameter of the winding wire (d_w).

The maximum of mid-range efficiency is obtained at values f = 52.5 Hz, L = 143.3 mm (see Figureure 3).

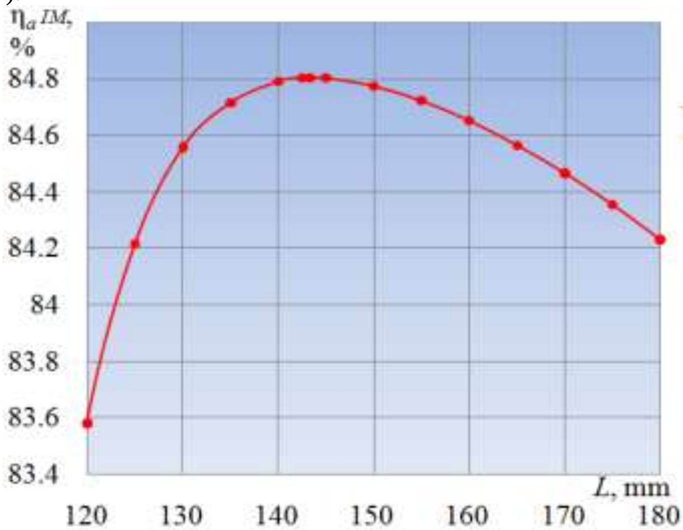

Figure 3. The efficiency versus L with f = 52.5 Hz

The minimum of mid-range resulted expenses obtained when f = 52.5 Hz, L = 128.3 mm (see Figure 4).

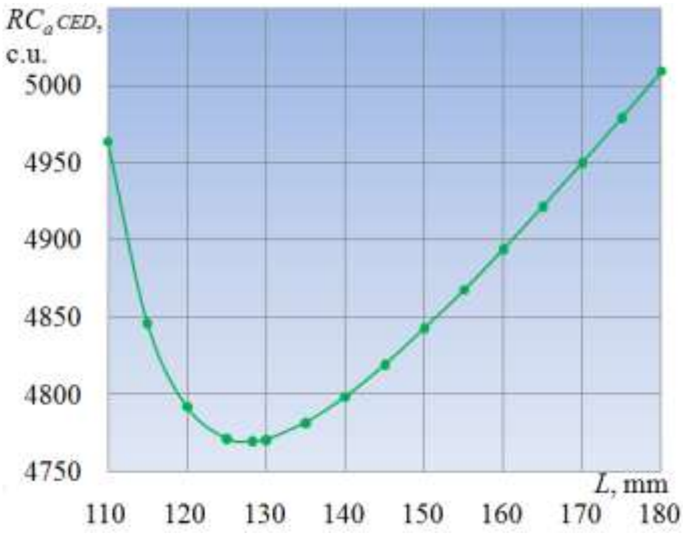

Figure 4. RC versus L with f = 52.5 Hz

Calculations using the traditional expressions for RC showed a significant divergence values of the length of the machine, which match the maximum efficiency and minimum RC.

Extremums of criteria (11) and (14) depend only on the varying variables corresponding to the mass, size, cost. When the coefficient k_{os} = 3.94 is introduced, the extremums suit to each other. Position of modified criterion's (14) extremum is shown in Figure 5.

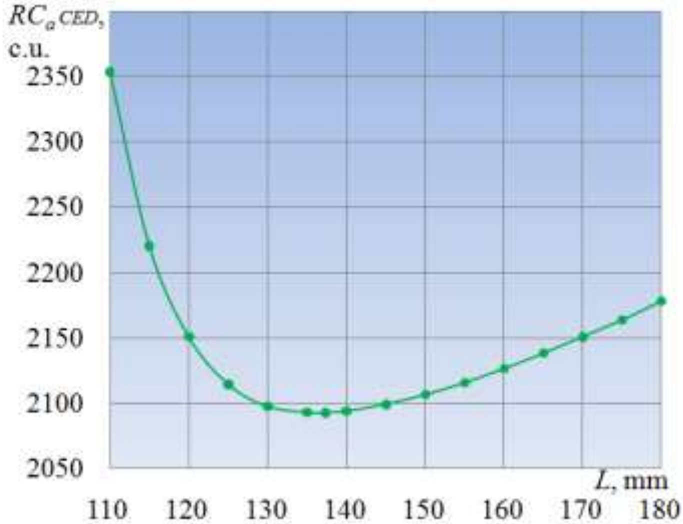

Figure 5. RCm_{CED} versus L with f = 52.5 Hz and k_{os} = 3.94

Comparison of standard and optimized motors and optimized motor by a factor of k_{os} presented in Table 4. In the process of optimizing a design range limit temperature of the stator winding and bearing shields were taken into account. In all variants of the design calculations winding wire diameter (d_w) remains constant.

Table 4. Comparison of the motor 4A160S4 modifications

Motors / Indicators and parameters	Serial	Optimized by criterion RC_{CED}	Optimized by criterion η	Optimized by modified criterion RC_{CED}
RC_a CED, th. c.u.	4.799	4.769	4.811	2.092
η_a CED, %	82.5	82.8	83.14	83.1
η_a IM, %	84.13	84.46	84.8	84.77
$cos\varphi$ IM, r.u.	0.888	0.857	0.897	0.886
Mass IM, kg	119.3	118.5	126.1	123.1
Value IM, c.u.	644.3	640.5	678.6	663.4
Volume IM, dm^3	9.62	9.49	10.6	10.16
f, Hz	50	52.5	52.5	52.5
w_1	112	107	107	107
q_{ef}, mm^2	2.45	2.57	2.57	2.57
L, mm	130	128.3	143.3	137.3

With the following initial data: k_{os} = 3.94, d_{inf} = 5.3%, T_s = 5 years for the project objectives discussed above the value k_{inf} = 1.112 was calculated. To test the effect of k_{inf} on the RC criterion, calculations were performed in which the stator length L varied in the range from 110 to 180 mm at a frequency f = 52.5 Hz.

As can be seen from Figure 6, the position of the RC extremum has not changed and corresponds to f = 52,5 Hz and L = 137.3 mm.

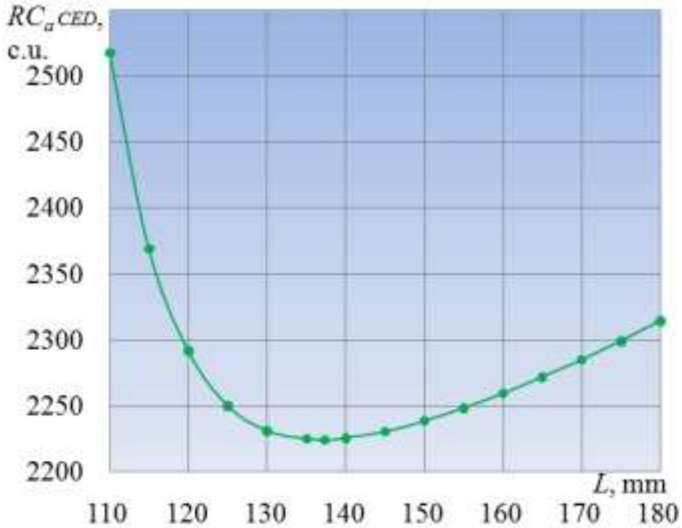

Figure 6. RCm_{CED} versus L with f = 52.5 Hz, k_{os} = 3.94 and $k_{\inf}$ = 1.112

The numerical value of the minimum resulted expenses increased from 2092.5 to 2224.2 c.u. taking into account the inflation rate of 6.3%.

The work of IM in CED is characterized by a change in motor speed n in the preset limits and on given laws, changes in amplitude and frequency of the motor supply voltage, the influence of the higher harmonic components of the voltage on the electromagnetic and thermal processes in the motor [5,15]. Therefore, more accurate mathematical models of electromagnetic, electromechanical, power, and heating processes in steady state and transient motor operating modes are being used, additional magnetic losses, mechanical and vibroacoustic performance are being calculated. IM in a number of CED is powered by polyharmonic voltage with variable parameters.

When designing the CED functional limitations, which include mechanical, thermal, dynamic and vibroacoustic, must be satisfied in the entire control range [5].

The maximum values of the considered indicators are limited by factors such as temperature, noise, vibration, etc. Minimum values of the indicators are limited by overload capacity, the duration of the transition process, the maximum value of the currents and torque in transients, etc. Vector of limitations.

$$[\mathbf{L}(n)] = \begin{bmatrix} \theta_S(n) \\ k_M(n) \\ BT(n) \\ \vdots \end{bmatrix},$$

where $\theta_s(n)$ is the excess of the stator winding temperature above the ambient temperature, $k_M(n)$ is the factor of overload capacity, $BT(n)$ is the stiffness of the mechanical characteristic.

The system of limits is presented in the form of two vectors - the maximum $[\mathbf{L_{max}}]$ and minimum $[\mathbf{L_{min}}]$ allowable values of functional indicators. At the same time in the whole range of the speed control from n_{min} to n_{max} should be satisfied:

$$[\mathbf{L_{max}}]_k > [\mathbf{L}(n)]_k > [\mathbf{L_{min}}]_k,$$

where k = 1, 2, … m, a m is the number of limitations.

Functional limitations should be automatically taken into account at the step of automated selection and in step of design optimization [16].

Window of setting of the design limitations in the program DIMASDrive is shown in Figure 7. Induction motors can be designed, different in design, degree of protection, a method of cooling. It is possible to inclusion in the system design model the most common models of semiconductor converters and consideration of different types of control.

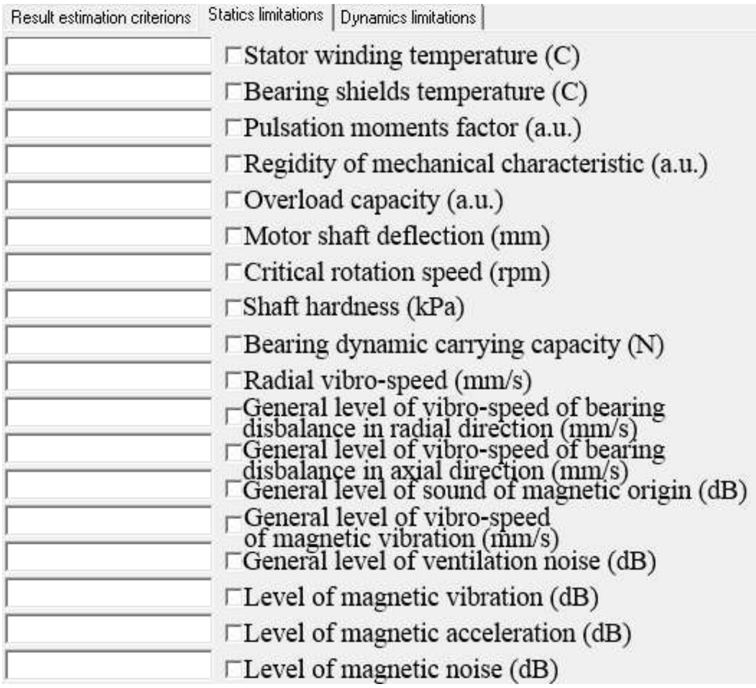

Figure 7. Window of setting of the design limitations

4. Conclusions

The results of the optimization design (the value of design changes) are different depending on the selected design criteria. Extremums of design criteria, depending on the variable parameters are not the same.

Calculations using the traditional criterion of expression resulted expenses showed a significant difference between the values of the length of the machine, which corresponds to the maximum of range efficiency and minimum of resulted expenses. To bring together these extremums the coefficient of operation significance was used in the modified criteria of resulted expenses. The value of the minimum of the modified criterion of resulted expenses becomes less than that of the unmodified.

Inflation factor determines only the value of resulted expenses, without affecting the relative position of the minimum regarding to the length of the machine. Inflation factor determines only the value of resulted expenses, without affecting the relative position of the minimum regarding to the length of the machine. However, the value of resulted expenses increases and the inflation factor to consider when designing.

Optimization design based on a modified criterion of resulted expenses for various design tasks, power and design performances of IM can be carried out in a similar way.

Accounting limitations significantly affects on the results of the project synthesis of IM. The most important limitation is the temperature, but the mechanical, dynamic and vibroacoustic limitations may also be used in some cases. Limitations of indicators of mechanical characteristics are advisable to use in the synthesis of controlled electric drive.

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