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Development of an Adapted Theoretical Model for Increasing the Energy Efficiency of Induction Motor Drives

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***Abstract*—The paper presents a developed adapted theoretical model for increasing the energy efficiency of induction motor drives. The model uses input/output parameters that provide practical opportunities for a wide scope of applications and improved conditions for implementation of energy efficiency measures. The study performed confirms the applicability of characteristics of induction motors, contained in a selected software product, for contactless measurement of the active power. The analytical description and mathematical modelling, supported by 36 simulation scenarios, justify the development of the target-adapted model. The plotted regression relationships demonstrate high accuracy with an average coefficient of determination of 0.999. The study recommends measures for increasing the load on the drives and implementing energy-efficient motors that demonstrate significant energy savings. The simulation model proposes an algorithm that provides a basis for creating specialized software products for automation of scientific research and conducting of energy audits.**

***Index Terms*—Modelling, energy efficiency, induction motor drives, energy efficiency measures**

I. INTRODUCTION

Electric energy efficiency is an area that is subject to policies, strategies, regulations and government requirements. It is a relevant and intensive scientific field in which a large number of research and implementations are carried out. These are linked to the publication work of researchers at regional and global level. Significant results are being achieved in terms of the research methods and the acquisition of new experimental data.

Despite systematic efforts, many studies show low levels of efficient consumption of electrical energy by production machines and processes employed in practice. Hence, the need arises to look for new approaches that are adapted for the energy managers and precondition the increase and implementation of energy efficiency measures at these sites. Given the relevance of the problem at hand, a comprehensive literature review [1] was published in the Energies Journal in 2023, providing guidelines for its solution. The development presented in this paper is a direct continuation of the stated literature review. The analysis of the status in the scientific field to which the development presented in this paper belongs is set forth in the same publication [1].

The development that we are presenting with this paper is in the field of the energy efficiency of induction motor drives. A comprehensive overview of the related works in this field is given in a recent review article [1] that covers 151 references most of which are published after 2021 (see Table I). This overview and one more contemporary review article [2] identify the research gaps and present a formulated scientific problem in the considered field. The gaps are connected with the development of models tailored for energy managers to boost the efficiency of induction motor-driven systems and the machines they power. These models are intended to guide the choice and evaluation of scientifically grounded strategies for improving energy use in industrial settings.

TABLE I: SUMMARY OF SOME THEMATIC LITERATURE SOURCES ANALYZED IN A REVIEW ARTICLE [1] IN THE FIELD OF THE ENERGY EFFICIENCY OF INDUCTION MOTOR DRIVES

No.	Lead author	Subject area/Core contribution
1	S. Foti	Application of "open end" windings in directly grid-connected constant- speed induction drives [3]
2	M. Dems	Design improvements of induction motors to increase the efficiency when operating at reduced frequencies [4]
3	C. Subramani	Motor design improvements using software [5]
4	A. Dominic	Improvement of the rotor magnetic flux of the induction machine [6]
5	N. Shukla	A hybrid algorithm for increasing the efficiency of induction motors at loads below the rated ones [7]
6	X. Sun	An optimized induction motor with variable number of active poles [8]
7	H. Mao	Dynamic number of poles for energy-efficient induction motors [9]
8	O. Iegorov	Optimization of winding parameters [10]
9	A. Bruno	An online algorithm for minimizing the losses through estimation of the optimum magnetization flux of an induction motor [11]
10	C. Jung	Adaptive loss control of induction motor drives [12]
11	W. Syed	Filtering the harmonics and power factor improvement of an induction motor drive by a fuzzy logic controller [13]

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12	P. Patel	Induction motor drive control unit with inverter recuperative braking capability [14]
13	A. Ahmed	Frequency control for composite pump units [15]
14	M. Baranidharan	Methodology for the rotational speed regulation of pump units in parallel [16]
15	C. Graciola	Increasing energy efficiency through scalar control of the induction motor [17]
16	G. Balasubramanian	Ventilation system performance regulation by frequency converter [18]
17	H. Xiao	Adjusting the phase of the supply voltage of a centrifugal fan with constant speed [19]
18	H. Hesar	Methodology for online energy efficiency control [20]
19	A. Krasteva	Weather factors and energy efficiency of water supply systems [21]

This research provides a justification for an adapted theoretical model for increasing the energy efficiency of induction motor drives with an analytically-based selection of measures for its improvement. This justification addresses the research gaps stated above and it is a possible solution of the identified scientific problem.

II. STRUCTURE AND INPUT/OUTPUT PARAMETERS OF THE MODEL

The increase of the energy efficiency of systems provided with induction motor drives is subject to regulatory requirements, with established activities and practices having been applied in this field. To improve the results of these processes, some challenges need to be overcome. These are identified as organizational challenges, and sometimes there is a lack of possibility to obtain experimental data from the necessary measurements, as well as lack of accessible, adapted and comprehensive information on energy-saving potential [1, 22]. Therefore, approaches should be sought to overcome these challenges through science-based theoretical models and tools based thereon.

The following is a list of the main requirements applied to the models:

- The convenient acquisition of measurement data about the actual power consumption of individual drives that has no significant impact on production processes;
- The introduction of a minimum amount of data available to energy managers;
- The possibility of automated selection of a recommended and justified energy-saving measure.

In response to these requirements, Fig. 1 shows the structure and input/output parameters of an adapted model for the synthesis and justification of energy-efficiency improvement measures. The following variables are used in Fig. 1: P_n, U_n, f_n, n_n and I_n – the shaft power, voltage, frequency, angular rotor speed and current at the nominal (rated) operation of the induction motor, respectively; η, P_2 and I – the efficiency coefficient, shaft power and current in the actual operating mode, respectively.

Block 1 of the block diagram is fundamental. It provides the computation of the proposed adapted model for enhancing energy efficiency and consists of two sub-blocks. These are block 3, which provides information on certain operational and energy characteristics of the drives' induction motors, and block 2, which processes the input information for the model. This information is input through entry blocks 4, 5, and 6. Block 4 serves to provide information on the drive's consumed current, obtained through measurement, as well as on the duration of operation in a steady-state and a characteristic mode. The duration is entered by energy managers. Block 4 supplies information for two operational modes - the actual observed production mode and the mode with an increased load (the optimal mode). Block 5 provides information on the measured current during testing of the drive in idle mode. Block 6 contains information on the nameplate data of the motors, recorded by the energy managers. Based on the submitted input information and performed processing, output criteria and indicators are obtained. These are presented in blocks 7 and 8. Block 7 presents information on potential energy savings from the application of energy-saving measures included in the model. Block 8 points the measure with maximum savings.

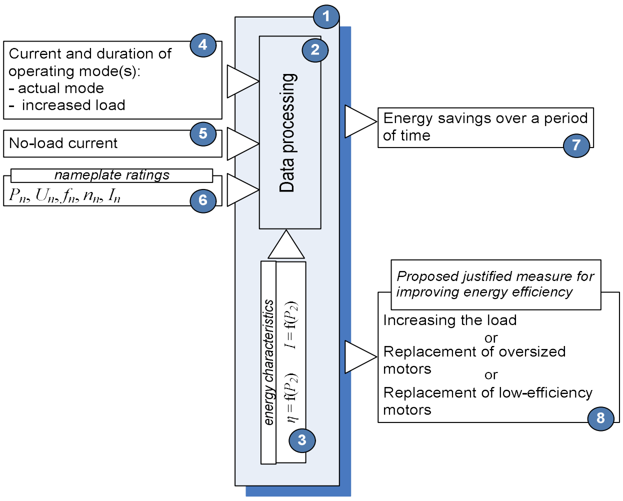


Fig. 1. Block diagram and input/output data and parameters of an adapted model for increasing the energy efficiency of induction motor drives.

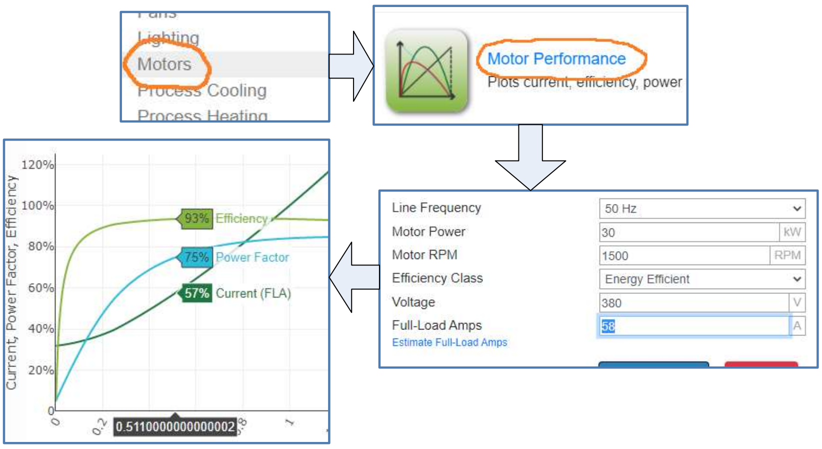
The input parameters of the adapted model consist of the nameplate data of the electrical machine and measurement data. The rated values of the induction motor parameters refer to power, voltage, frequency, angular speed and rated current, as energy managers can take these from the machine nameplates without any need for available technical documentation.

This choice favours to a great extent the application of the proposed model. A further level of adaptability can be achieved by simplifying the measurement methodology. In this respect, previous research experience shows [23], [24] significant or insurmountable hindrances in measuring the active power consumption of individual electric drives in industrial sites due to technological and organizational factors. It is therefore required that the assessment of the load and energy losses of the objects is done by measuring the current consumed in actual operating mode and during no-load operation, which can be performed conveniently with portable contactless devices without breaking the power circuit. It is possible to determine the active power on the basis of the measurement data and by using the energy characteristics of the motors. Following the processing of the input data, and for a period selected by the energy manager, the model generates energy savings as a result of three energy efficiency measures applicable in particular to drives with only slightly changing and continuous loads:

- Bringing the actual load closer to the optimum level;
- Reducing the idling level by replacing oversized motors;
- Implementing energy-efficient motors with improved efficiency.

A justified proposal is made for an energy-saving measure after taking into consideration the results of the energy savings.

In order for the presented model to function, reliable information on the energy characteristics $\eta=f(P_2)$ and $I=f(P_2)$ of induction motor drives is needed. This information should include a wide range of motors of various energy classes and parameters. For this purpose, it is appropriate to use the comprehensive database of the accessible software product MEASUR [25], developed by the US Department of Energy (Fig. 2). The product contains graphical and tabular data of the demanded characteristics, taken at average value and plotted for different energy classes in relative units in respect to the rated data of the machines.



Line Frequency 50 Hz
Motor Power 30 kW
Motor RPM 1500 RPM
Efficiency Class Energy Efficient
Voltage 380 V
Full-Load Amps 58 A
Estimate Full-Load Amps

Fig. 2. Graphical environment for user interaction and stages of plotting the energy characteristics of induction motors using a specialized software product.

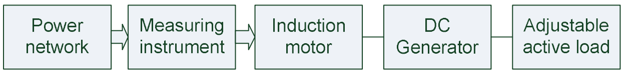


Fig. 3. Generalized block diagram of experimental setups for recording operating modes of different induction motors.

Fig. 4. General view of the connection diagram of power quality analyser for studying the electric power of induction motors.

It is interesting to determine how accurately the active power is assessed by applying the approach described above. In order to analyse the measures of variations of the target variables and the corresponding errors, a variant-based study was performed in laboratory conditions. A generalized block diagram of the used experimental setup is shown in Fig. 3. The investigated electric drives are supplied by the power network. A specialized measuring instrument (LEM Analyst 3Q) is connected at the input of the studied induction motors. The motors feed mechanical power to separately-excited DC generators. The load of the generators and of the motors can be changed by adjustable active loads where the mechanical power turns to heat. A photograph of the connected instrument is given at Fig. 4.

A cage-rotor induction motor type A090S-4 with a rated power of 1.1 kW and rated rotational speed of 1410 min^{-1}, another cage-rotor induction motor type A0 100L-4 with a rated power of 2.2 kW and rotational speed of 1430 min^{-1}, and a wound-rotor induction motor type MT-11-6 with a power of 2.2 kW and rotational speed of 885 min^{-1} were studied. The experiments consisted in the parallel measurement, at a 30s-interval, of the consumed active power using a LEM Analyst 3Q power quality analyser and the current consumed by the motor with two types of digital clamp meters, namely the auto-range MS2102 and the manual-range UT202A. Based on the data of the motors and the current consumption taken from the database mentioned above, the active power values to be compared were determined. The results of the laboratory experiments and processed data are presented in Table II, Table III, Table IV and Fig. 5. The following notations are used in the tables: P_{1n} is the active power consumed at the nominal operation of the induction motor; P_{aev} is the active motor power measured with a power quality analyser; $P_{ak\text{-}a}$ and $P_{ak\text{-}r}$ are the active motor power determined on the basis of the motor energy characteristics and the current consumption data measured, with an auto-range and a manual-range clamp ammeter, respectively; ε is the relative error in the determination of the active power using the energy characteristics of the motors (P_{aev} is considered as an accurate value and P_{ak-a} and P_{ak-r} are the approximate values).

TABLE II: DATA OF THE ACTIVE POWER IN KW OF A CAGE-ROTOR INDUCTION MOTOR TYPE A090S-4 UNDER DIFFERENT OPERATING MODES

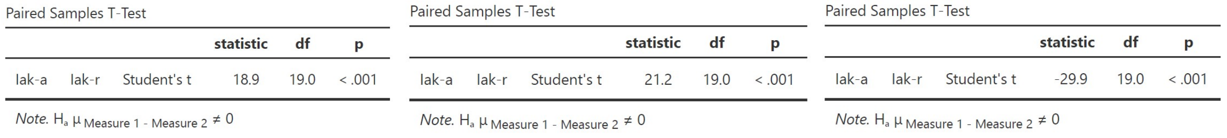
№	60 % P_{1n}			100% P_{1n}		
	P_{aev}	P_{ak-a}	P_{ak-r}	P_{aev}	P_{ak-a}	P_{ak-a}
1	0.802	0.874	0.846	1.135	1.143	1,122
2	0.800			1.135		
3	0.798			1.135		
4	0.797			1.135		
5	0.795			1.133		
6	0.794			1.131		
7	0.792			1.131		
8	0.791			1.130		
9	0.789			1.128		
10	0.788			1.129		
11	0.789			1.126		
12	0.789			1.124		
13	0.784			1.125		
14	0.783			1.123		
15	0.781			1.122		
16	0.780			1.123		
17	0.779			1.121		
18	0.778			1.121		
19	0.778			1.120		
20	0.777			1.120		
ε, %		10.93	7.35	–	1.30	-0.53

TABLE III: DATA OF THE ACTIVE POWER IN KW OF A CAGE-ROTOR INDUCTION MOTOR TYPE A0 100L-4 UNDER DIFFERENT OPERATING MODES

№	55 % P_{1n}			70 % P_{1n}			80 % P_{1n}		
	P_{aev}	P_{ak-a}	P_{ak-r}	P_{aev}	P_{ak-a}	P_{ak-a}	P_{aev}	P_{ak-a}	P_{ak-r}
1	1.466	1.460	1.502	1.865	1.809	1.823	2.191	2.028	2,069
2	1.460			1.858			2.186		
3	1.456			1.853			2.185		
4	1.454			1.851			2.181		
5	1.446			1.849			2.180		
6	1.446			1.847			2.179		
7	1.447			1.846			2.175		
8	1.444			1.845			2.172		
9	1.441			1.842			2.171		
10	1.437			1.840			2.168		
11	1.436			1.839			2.166		
12	1.436			1.839			2.166		
13	1.435			1.839			2.165		
14	1.434			1.837			2.163		
15	1.433			1.837			2.16		
16	1.432			1.237			2.159		
17	1.431			1.833			2.158		
18	1.428			1.830			2.158		
19	1.428			1.829			2.156		
20	1.429			1.829			2.158		
ε, %		1.34	1.20	–	-0.17	0.58	–	-6.53	-4.68

TABLE IV: DATA OF THE ACTIVE POWER IN KW OF A WOUND-ROTOR INDUCTION MOTOR TYPE MT-11-6 UNDER DIFFERENT OPERATING MODES

№	70 % P_{1n}			85 % P_{1n}		
	P_{aev}	P_{ak-a}	P_{ak-r}	P_{aev}	P_{ak-a}	P_{ak-a}
1	1.866	2.158	2.263	2.319	2.263	2,384
2	1.866			2.312		
3	1.857			2.315		
4	1.873			2.313		
5	1.858			2.307		
6	1.873			2.305		
7	1.874			2.312		
8	1.874			2.310		
9	1.864			2.303		
10	1.858			2.302		
11	1.864			2.302		
12	1.873			2.295		
13	1.871			2.286		
14	1.854			2.293		
15	1.877			2.294		
16	1.870			2.292		
17	1.871			2.291		
18	1.855			2.290		
19	1.871			2.292		
20	1.867			2.288		
ε, %		15.58	21.23	–	-1.64	3.60



Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	18.9	19.0	< .001

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	21.2	19.0	< .001

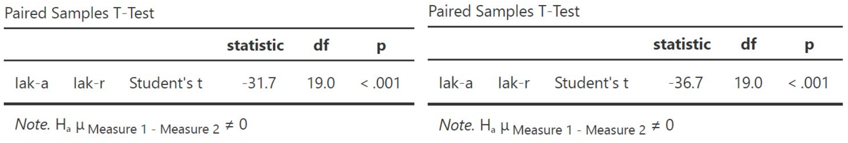
Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	-29.9	19.0	< .001

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

AO90S-4 60 % P_{1n} **AO90S-4** 100% P_{1n} **A0 100L-4** 55 % P_{1n}



Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	-31.7	19.0	< .001

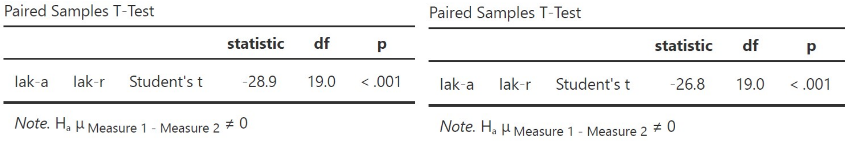
Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	-36.7	19.0	< .001

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

A0 100L-4 70 % P_{1n} **A0 100L-4** 80 % P_{1n}



Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	-28.9	19.0	< .001

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

Paired Samples T-Test

			statistic	df	p
Iak-a	Iak-r	Student's t	-26.8	19.0	< .001

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} \neq 0$

MT-11-6 70 % P_{1n} **MT-11-6** 85 % P_{1n}

Fig. 5. Results of null hypothesis testing by comparing two average values of the current consumption measurements of different types of induction motors.

The results of the null hypothesis testing (see Fig. 5) in the analysis of the average values of current measurements were obtained using the software product Jamovi 2.3.28. The statistical analysis was performed using the Student's t-test. This test is usually used to compare mean values between two groups and is especially useful when the samples are small and the population standard deviation is not known. In this case, the statistic value represents the t-value of the t-test. This value indicates the difference between the mean values of the two groups, adjusted for the standard error. The degrees of freedom in the performed analysis were nineteen. The results revealed that the probability p in testing this hypothesis for each of the experiments was less than 0.001. A general conclusion could therefore be drawn with a high level of assurance that the differences observed in motor current measurements taken with two types of clamp meter were statistically significant and the type of these devices had a significant effect on the accuracy of the results.

It can be seen in Table II, Table III and Table IV that the relative error was on average 1.41 times greater when the current was measured with an automatically-ranging clamp meter.

When determining the active power of the two squirrel-cage induction motors being studied, the modulus of relative error ranged from 0.17% to 10.93% with an average level of 3.46%. For the 2.2 kW motor, this modulus did not exceed 7% in all the experiments carried out. In the case of the studied wound-rotor motor, the error spread was 22.87 % and the average value was close to 10 %.

The proposed adapted model is aimed at studying the energy efficiency of induction motor drives operating in practice, in terms of justifying potential measures for enhancing it. For tasks of this nature, an admissible error value of about 15% to 20% is reported in literature [26, 27].

III. ANALYTICAL DESCRIPTION

The analytical description of the adapted model is intended to define the mathematical relationships and expressions with the help of which, with given input values, the target outputs for increasing the energy efficiency are determined. The description can be divided into three stages. These stages are: obtaining the consumed active power using the measurement data for the current, variant calculation of energy savings for a given time period and given energy efficiency measure, and comparison of the values in order to find the highest-efficiency measure.

Two approaches can be employed to express the active power as a function of the motor current. The first involves taking the readings of the efficiency value, while the second approach uses power factor data.

The first approach mentioned may be described as follows. If the motor current I is known, the mechanical power P_2 of the machine shaft is determined by the formula $I = f(P_2)$. Once the power is found, the $\eta = f(P_2)$ relationship can be used to find the η efficiency factor for the operational mode under consideration. Further on, the approach uses the mathematical relationship known as

$$P_1 = \frac{P_2}{\eta}, \tag{1}$$

which is used to calculate the wanted active electrical power P_1.

For the application of the second approach, the curves of the power factor $\cos\varphi$ and the motor current $\cos\varphi = f(P_2)$ and $I = f(P_2)$ are required. The two curves are compared on a common coordinate system, and given the value of the current I, $\cos\varphi$ is found for the motor load under consideration. The active power is obtained by the known expression for symmetrical three-phase circuits

$$P_1 = \sqrt{3} U_n I \cos\varphi, \tag{2}$$

where U_n is the nominal line supply voltage taken from the nameplate of the drive induction motor.

The active power P_1 can be obtained for any operating mode of the induction drive, including idle mode, rated mode, overload up to $1.2P_n$ or underload mode.

The adapted model concerned covers the energy efficiency measures that involve increasing the drive load, replacing oversized motors and replacing properly sized motors of a low energy class with ones of higher efficiency. The first of the listed measures does not require capital expenditure and is characterised by a reduction in the technological operating time of the drive.

It has been proven [28] that the electrical energy savings from the implementation of a potential energy-saving measure can be reliably determined on the basis of the actual level, the idling level and the optimum level of power consumption of the induction motor drives.

The formula for calculation of the electrical energy saved ΔW_{pn} by increasing the actual load of the drive in this case will be:

$$\Delta W_{\mathrm{pn}} = P_{1.\mathrm{ph}} (t_{\mathrm{d}\Sigma} - t_{\mathrm{opt}}), \tag{3}$$

where $P_{1.\mathrm{ph}}$ is the active power consumed by the induction motor drive in idle mode; $t_{\mathrm{d}\Sigma}$ is the cumulative running time of the drive in the actual operating mode under study; t_{opt} is the running time reduced after increasing the drive load.

Formula (3) is based on the condition of preserving the rectangle of the useful energy component and requires technological capabilities to increase the active power consumed by the drive. By applying this formula, the optimum time t_{opt} can be determined by the following relationship:

$$t_{\mathrm{opt}} = \frac{W_{\mathrm{pol}}}{P_{1.\mathrm{opt}} - P_{1.\mathrm{ph}}}, \tag{4}$$

where W_{pol} is the useful electricity consumption; $P_{1.\mathrm{opt}}$ is the active power consumption, determined following an optimum increase of the drive load.

The consumed useful electrical energy W_{pol} depends on the difference between the level at idling and the actual consumption level of the drive under load:

$$W_{\text{pol}} = (P_{\text{1.d}} - P_{\text{1.ph}}).t_{\text{d}\Sigma}\,, \tag{5}$$

where $P_{1.d}$ is the active electrical power consumed in the actual operating mode.

As it is known, the active power consumed by an induction motor drive decreases as the operating efficiency of the drive motor increases. This decrease is observed both in the idle mode of the drive and when under load (Fig. 6).

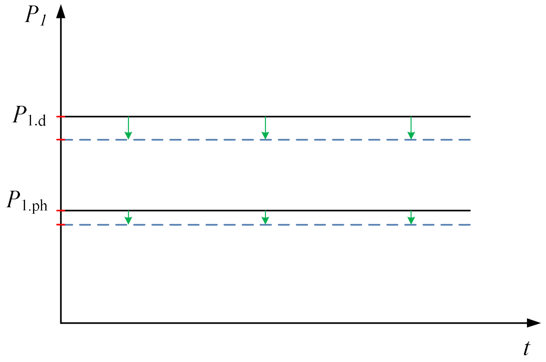


Fig. 6. Changes in the power consumption levels of induction motor drives as a result of the increased operating efficiency of the drive motor.

On the other hand, an increase in the operating efficiency can generally be achieved by two approaches, particularly by the use of an induction motor of a higher energy class with better energy characteristics and the use of a motor of the same energy class but with a lower rated power. The second approach becomes possible with the increase in the motor load.

Before determining the energy savings as a result of the replacement of oversized motors, it is necessary to obtain the mechanical power $P_{2.d}$ of the shaft through the current of the existing motor measured in the actual operating mode of the drive. To this end, the operating characteristic curve $I = f(P_2)$ is used. The rated power P'_n of the replacement motor can then be determined according to the term

$$P'_n \geq P_{\text{2.d}} \tag{6}$$

and the motor with power rating closest to the $P_{2.d}$ power is selected.

Using the found mechanical power value $P_{2.d}$, and after taking the efficiency value η'_{pd} from the curve $\eta = f(P_2)$ of the replacement motor, the new reduced active power consumption $P'_{\text{1.d.pd}}$ of the drive can be determined:

$$P'_{\text{1.d.pd}} = \frac{P_{\text{2.d}}}{\eta'_{\text{pd}}}. \tag{7}$$

In this case, the electricity saved ΔW_{pd} after replacing the oversized motor can be recorded as

$$\Delta W_{\text{pd}} = (P_{\text{1.d}} - P'_{\text{1.d.pd}})t_{\text{d}\Sigma}\,. \tag{8}$$

A similar analytical description is the one concerning the study of the energy efficiency measure using a motor of a higher energy class. The mechanical power $P_{2.d}$ taken from the curve $I = f(P_2)$, and the rated power P_n of the existing motor, remain unchanged, while the electricity ΔW_{ed} saved by the use of that motor is determined from the analogous relationships

$$P'_{\text{1.d.ed}} = \frac{P_{\text{2.d}}}{\eta'_{\text{ed}}} \tag{9}$$

and

$$\Delta W_{\text{ed}} = (P_{\text{1.d}} - P'_{\text{1.d.ed}})t_{\text{d}\Sigma}\,, \tag{10}$$

where $P'_{\text{1.d.ed}}$ is the active electrical power consumption reduced as a result of the increased efficiency value of the replacement induction motor of a higher energy class; η'_{ed} – the efficiency factor taken from the curve $\eta = f(P_2)$ of the same motor.

The selection of the energy-efficiency improvement measure with the highest savings of electrical energy over the specified time period is made according to the term

$$\Delta W_{\text{pn}} > \Delta W_{\text{pd}} > \Delta W_{\text{ed}}\,. \tag{11}$$

Based on the presented analytical description and on the conducted mathematical analysis, a flow chart for the operation of the proposed adapted model can be compiled. The chart is given on Fig. 7.

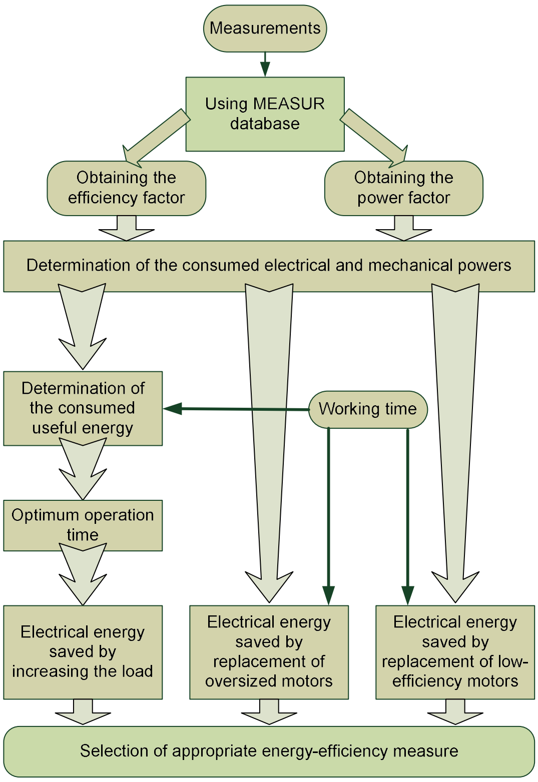


Fig. 7. Flow chart of a theoretical model for increasing the energy efficiency of induction motor drives.

Given the nature of the developed theoretical model, any preconditions for an analytical description of grouped induction drives are practically missing.

In order to successfully apply the theoretical model, the following assumptions are adopted:

- the investigated induction motor drives have steady state and typical modes of operation;
- the rotational speed of the induction motors of the drives is not changed by frequency converters.

IV. IT SUPPORT

The IT support of the proposed adapted model is of key importance for its operational performance and further enhancement of its practical applications. The support must cover the available approaches for finding the active motor power using the current consumption value, as well as extensive information on motor efficiency characteristics. These requirements are met by the Measur software database referred to in Section II above. The data it contains allows retrieval of comprehensive information and modelling of virtually any range of available induction motors.

As an example, we will present here the mathematical modelling of the relationship $P_1 = f\ (I_{avg})$ whereby the consumed active power P_1 can be calculated through the average value I_{avg} of the motor current measured by the contactless method. The modelling presents the coefficient of determination R^2 and covers motors of all three energy classes IE1, IE2 and IE3, made by one of the major manufacturers in Central and Eastern Europe, Elprom Troyan. The results are summarized in Table V, Table VI and Table VII.

TABLE V: MODELLED REGRESSION RELATIONSHIPS DATA IN THE IT SUPPORT OF AN ADAPTED MODEL FOR INCREASING THE ENERGY EFFICIENCY OF IE1-INDUCTION-MOTOR DRIVES

№	**Motor**		**Regression model**	R^2
	Type	Nominal power, kW		
1	T80B-2	1.1	$P_1 = -0.1463.I_{avg}^4 + 1.1668.I_{avg}^3 - 3.3178.I_{avg}^2 + 4.568.I_{avg} - 1.819$	0.9939
2	T80C-2	1.5	$P_1 = -0.0719.I_{avg}^4 + 0.7947.I_{avg}^3 – 3.1753.I_{avg}^2 + 6.0347.I_{avg} - 3.5395$	0.9972
3	T90S-2	1.5	$P_1 = -0.0605.I_{avg}^4 + 0.6663.I_{avg}^3 - 2.6555.I_{avg}^2 + 5.1506.I_{avg} - 2.9698$	0.9971
4	T90L-2	2.2	$P_1 = -0.0212.I_{avg}^4 + 0.3388.I_{avg}^3 - 1.9765.I_{avg}^2 + 5.6176.I_{avg} - 4.8827$	0.9961
5	T90LB-2	3.0	$P_1 = -0.0085.I_{avg}^4 + 0.1721.I_{avg}^3 - 1.2733.I_{avg}^2 + 4.7619.I_{avg} - 5.2373$	0.9992
6	T100L-2	3.0	$P_1 = -0.0085.I_{avg}^4 + 0.1721.I_{avg}^3 - 1.2733.I_{avg}^2 + 4.7619.I_{avg} - 5.2373$	0.9992
7	T100LB-2	4.0	$P_1 = -0.0038.I_{avg}^4 + 0.0988.I_{avg}^3 - 0.9251.I_{avg}^2 + 4.4413.I_{avg} - 6.1736$	0.9993
8	T112M-2	4.0	$P_1 = -0.0018.I_{avg}^4 + 0.0538.I_{avg}^3 - 0.5757.I_{avg}^2 + 3.3249.I_{avg} - 5.0478$	0.9993
9	T112MB-2	5.5	$P_1 = -0.0013.I_{avg}^4 + 0.0483.I_{avg}^3 - 0.6695.I_{avg}^2 + 4.6209.I_{avg} - 9.3076$	0.9995
10	T132SA-2	5.5	$P_1 = -0.0013.I_{avg}^4 + 0.0483.I_{avg}^3 - 0.6695.I_{avg}^2 + 4.6209.I_{avg} - 9.3076$	0.9995
11	T132SB-2	7.5	$P_1 = -0.0013.I_{avg}^4 + 0.0483.I_{avg}^3 - 0.6695.I_{avg}^2 + 4.6209.I_{avg} - 9.3076$	0.9995
12	T132MA-2	9.2	$P_1 = -0.0002.I_{avg}^4 + 0.0099.I_{avg}^3 - 0.2202.I_{avg}^2 + 2.7802.I_{avg} - 8.5692$	0.9991
13	T132MB-2	11.0	$P_1 = -0.0001.I_{avg}^4 + 0.0076.I_{avg}^3 - 0.1998.I_{avg}^2 + 2.9244.I_{avg} - 10.397$	0.9997
14	T160MA-2	11.0	$P_1 = -0.0001.I_{avg}^4 + 0.0076.I_{avg}^3 - 0.1998.I_{avg}^2 + 2.9244.I_{avg} - 10.397$	0.9997
15	T160MB-2	15.0	$P_1 = -0.0001.I_{avg}^4 + 0.0076.I_{avg}^3 - 0.1998.I_{avg}^2 + 2.9244.I_{avg} - 10.397$	0.9997
16	T160L-2	18.5	$P_1 = -0.00003.I_{avg}^4 + 0.0033.I_{avg}^3 - 0.1304.I_{avg}^2 + 2.8966.I_{avg} - 15.313$	0.9997
17	T90S-4	1.1	$P_1 = -1.4439.I_{avg}^4 + 9.9999.I_{avg}^3 - 25.718.I_{avg}^2 + 29.984.I_{avg} - 12.555$	0.9997
18	T90L-4	1.5	$P_1 = -0.1228.I_{avg}^4 + 1.6151.I_{avg}^3 - 7.8909.I_{avg}^2 + 17.617.I_{avg} - 14.083$	0.9997
19	T100LA-4	2.2	$P_1 = -0.0209.I_{avg}^4 + 0.4011.I_{avg}^3 - 2.8889.I_{avg}^2 + 9.8848.I_{avg} - 11.682$	0.9999
20	T100LB-4	3.0	$P_1 = -0.0105.I_{avg}^4 + 0.256.I_{avg}^3 - 2.3204.I_{avg}^2 + 9.957.I_{avg} - 14.82$	1
21	T100LC-4	4.0	$P_1 = -0.0042.I_{avg}^4 + 0.1336.I_{avg}^3 - 1.5599.I_{avg}^2 + 8.6794.I_{avg} - 16.503$	0.9999
22	T112M-4	4.0	$P_1 = -0.0047.I_{avg}^4 + 0.143.I_{avg}^3 - 1.6325.I_{avg}^2 + 8.8789.I_{avg} - 16.503$	0.9999
23	T112MB-4	5.5	$P_1 = -0.0011.I_{avg}^4 + 0.0443.I_{avg}^3 - 0.6943.I_{avg}^2 + 5.5173.I_{avg} - 14.05$	0.9998
24	T132S-4	5.5	$P_1 = -0.0011.I_{avg}^4 + 0.0443.I_{avg}^3 - 0.6943.I_{avg}^2 + 5.5173.I_{avg} - 14.05$	0.9998
25	T132M-4	7.5	$P_1 = -0.0003.I_{avg}^4 + 0.0189.I_{avg}^3 - 0.3983.I_{avg}^2 + 4.3848.I_{avg} - 14.665$	1
26	T132MA-4	9.5	$P_1 = -0.0002.I_{avg}^4 + 0.0146.I_{avg}^3 - 0.3608.I_{avg}^2 + 4.614.I_{avg} - 17.997$	0.9994
27	T132MB-4	11.0	$P_1 = -0.0002.I_{avg}^4 + 0.0132.I_{avg}^3 - 0.3659.I_{avg}^2 + 5.1226.I_{avg} - 22.117$	0.9996
28	T160M-4	11.0	$P_1 = -0.0002.I_{avg}^4 + 0.0158.I_{avg}^3 - 0.414.I_{avg}^2 + 5.449.I_{avg} - 22.117$	0.9996
29	T160L-4	15.0	$P_1 = -0.00005.I_{avg}^4 + 0.0052.I_{avg}^3 - 0.1928.I_{avg}^2 + 3.8262.I_{avg} - 21.235$	0.9998
30	T90L-6	1.1	$P_1 = -0.4738.I_{avg}^4 + 5.5044.I_{avg}^3 - 23.689.I_{avg}^2 + 45.166.I_{avg} - 31.117$	0.9988
31	T100L-6	1.5	$P_1 = -0.0771.I_{avg}^4 + 1.2874.I_{avg}^3 - 7.8991.I_{avg}^2 + 21.619.I_{avg} - 20.774$	0.9998
32	T112M-6	2.2	$P_1 = -0.0364.I_{avg}^4 + 0.7924.I_{avg}^3 - 6.4228.I_{avg}^2 + 23.535.I_{avg} - 30.969$	0.999
33	T132S-6	3.0	$P_1 = -0.017.I_{avg}^4 + 0.469.I_{avg}^3 - 4.8058.I_{avg}^2 + 22.286.I_{avg} - 37.088$	0.9998
34	T132MA-6	4.0	$P_1 = -0.005.I_{avg}^4 + 0.1799.I_{avg}^3 - 2.4321.I_{avg}^2 + 15.125.I_{avg} - 33.398$	0.9998
35	T132MB-6	5.5	$P_1 = -0.0017.I_{avg}^4 + 0.0856.I_{avg}^3 - 1.597.I_{avg}^2 + 13.699.I_{avg} - 41.647$	0.9997
36	T160M-6	7.5	$P_1 = -0.0012.I_{avg}^4 + 0.0677.I_{avg}^3 - 1.3705.I_{avg}^2 + 12.891.I_{avg} - 42.393$	0.9995
37	T160L-6	11.0	$P_1 = -0.0004.I_{avg}^4 + 0.0293.I_{avg}^3 - 0.7967.I_{avg}^2 + 10.231.I_{avg} - 44.506$	0.9997
38	T132S-8	2.2	$P_1 = 0.0699.I_{avg}^4 - 1.5759.I_{avg}^3 + 12.979.I_{avg}^2 - 45.693.I_{avg} + 59.436$	0.9825
39	T132M-8	3.0	$P_1 = 0.0061.I_{avg}^4 - 0.1619.I_{avg}^3 + 1.4787.I_{avg}^2 - 4.6627.I_{avg} + 4.1503$	0.9984
40	T160MA-8	4.0	$P_1 = 0.0007.I_{avg}^4 - 0.0115.I_{avg}^3 - 0.0862.I_{avg}^2 + 2.9167.I_{avg} - 11.246$	0.999

41	T160MB-8	5.5	$P_1 = -0.0002.I_{avg}^4 + 0.0129.I_{avg}^3 - 0.3621.I_{avg}^2 + 4.7935.I_{avg} - 18.571$	0.9993
42	T160L-8	7.5	$P_1 = -0.0001.I_{avg}^4 + 0.0098.I_{avg}^3 - 0.3014.I_{avg}^2 + 4.6642.I_{avg} - 21.618$	0.999

TABLE VI: MODELLED REGRESSION RELATIONSHIPS DATA IN THE IT SUPPORT OF AN ADAPTED MODEL FOR INCREASING THE ENERGY EFFICIENCY OF IE2-INDUCTION-MOTOR DRIVES

№	**Motor**		**Regression model**	R^2
	Type	Nominal power, kW		
1	TH80B-2	1.1	$P_1 = -0.1191.I_{avg}^4 + 1.0295.I_{avg}^3 - 3.3134.I_{avg}^2 + 5.3638.I_{avg} - 2.8356$	0.999
2	TH90S-2	1.5	$P_1 = -0.0499.I_{avg}^4 + 0.5764.I_{avg}^3 - 2.4789.I_{avg}^2 + 5.3475.I_{avg} - 3.7022$	0.999
3	TH90L-2	2.2	$P_1 = -0.0089.I_{avg}^4 + 0.1535.I_{avg}^3 - 0.9931.I_{avg}^2 + 3.4917.I_{avg} - 3.5741$	0.9986
4	TH100L-2	3.0	$P_1 = -0.0057.I_{avg}^4 + 0.1225.I_{avg}^3 - 0.9827.I_{avg}^2 + 4.1088.I_{avg} - 5.2163$	0.9995
5	TH112M-2	4.0	$P_1 = -0.003.I_{avg}^4 + 0.0779.I_{avg}^3 - 0.7442.I_{avg}^2 + 3.8039.I_{avg} - 5.6062$	0.9994
6	TH132SA-2	5.5	$P_1 = -0.0017.I_{avg}^4 + 0.0591.I_{avg}^3 - 0.7596.I_{avg}^2 + 4.8703.I_{avg} - 9.3159$	0.9996
7	TH132SB-2	7.5	$P_1 = -0.0003.I_{avg}^4 + 0.0165.I_{avg}^3 - 0.3043.I_{avg}^2 + 3.0867.I_{avg} - 8.0968$	0.9993
8	TH160MA-2	11.0	$P_1 = -0.00009.I_{avg}^4 + 0.0068.I_{avg}^3 - 0.1794.I_{avg}^2 + 2.711.I_{avg} - 9.5696$	0.9998
9	TH160MB-2	15.0	$P_1 = -0.00008.I_{avg}^4 + 0.0066.I_{avg}^3 - 0.2098.I_{avg}^2 + 3.5377.I_{avg} - 15.77$	0.9993
10	TH160L-2	18.5	$P_1 = -0.00002.I_{avg}^4 + 0.0022.I_{avg}^3 - 0.0932.I_{avg}^2 + 2.4053.I_{avg} - 13.414$	0.9997
11	TH90S-4	1.1	$P_1 = -0.4499.I_{avg}^4 + 4.3332.I_{avg}^3 - 15.434.I_{avg}^2 + 24.737.I_{avg} - 14.376$	0.9998
12	TH90L-4	1.5	$P_1 = -0.1265.I_{avg}^4 + 1.6742.I_{avg}^3 - 8.2143.I_{avg}^2 + 18.355.I_{avg} - 14.836$	0.9997
13	TH132S-4	5.5	$P_1 = -0.0009.I_{avg}^4 + 0.0382.I_{avg}^3 - 0.6235.I_{avg}^2 + 5.1827.I_{avg} - 13.773$	0.9997
14	TH132M-4	7.5	$P_1 = -0.0004.I_{avg}^4 + 0.0221.I_{avg}^3 - 0.4467.I_{avg}^2 + 4.6784.I_{avg} - 15.024$	1
15	TH160M-4	11.0	$P_1 = -0.0001.I_{avg}^4 + 0.0086.I_{avg}^3 - 0.2646.I_{avg}^2 + 4.2026.I_{avg} - 20.133$	0.9996
16	TH160L-4	15.0	$P_1 = -0.00006.I_{avg}^4 + 0.0062.I_{avg}^3 - 0.2346.I_{avg}^2 + 4.5061.I_{avg} - 26.599$	0.9999
17	TH90L-6	1.1	$P_1 = 1.1951.I_{avg}^4 - 11.891.I_{avg}^3 + 42.604.I_{avg}^2 - 64.201.I_{avg} + 34.658$	0.9975
18	TH100L-6	1.5	$P_1 = 0.2693.I_{avg}^4 - 3.4645.I_{avg}^3 + 15.916.I_{avg}^2 - 30.02.I_{avg} + 19.907$	0.9989
19	TH112M-6	2.2	$P_1 = 0.0059.I_{avg}^4 - 0.0551.I_{avg}^3 - 0.2159.I_{avg}^2 + 3.7919.I_{avg} - 8.1502$	0.9981
20	TH132S-6	3.0	$P_1 = -0.0084.I_{avg}^4 + 0.2428.I_{avg}^3 - 2.6394.I_{avg}^2 + 13.298.I_{avg} - 23.665$	0.9995
21	TH132MA-6	4.0	$P_1 = -0.008.I_{avg}^4 + 0.2613.I_{avg}^3 - 3.1897.I_{avg}^2 + 17.823.I_{avg} - 35.82$	0.9998
22	TH132MB-6	5.5	$P_1 = -0.0018.I_{avg}^4 + 0.0862.I_{avg}^3 - 1.5577.I_{avg}^2 + 12.976.I_{avg} - 38.193$	0.9995
23	TH160M-6	7.5	$P_1 = -0.0011.I_{avg}^4 + 0.0623.I_{avg}^3 - 1.3121.I_{avg}^2 + 12.764.I_{avg} - 43.551$	0.9995
24	TH160L-6	11.0	$P_1 = -0.0003.I_{avg}^4 + 0.0221.I_{avg}^3 - 0.6602.I_{avg}^2 + 9.3192.I_{avg} - 44.818$	0.9998

TABLE VII: MODELLED REGRESSION RELATIONSHIPS DATA IN THE IT SUPPORT OF AN ADAPTED MODEL FOR INCREASING THE ENERGY EFFICIENCY OF IE3-INDUCTION-MOTOR DRIVES

№	**Motor**		**Regression model**	R^2
	Type	Nominal power, kW		
1	TP80B-2	1.1	$P_1 = 0.2352.I_{avg}^4 - 1.6141.I_{avg}^3 + 3.6278.I_{avg}^2 - 2.0955.I_{avg} + 0.0811$	0.999
2	TP90S-2	1.5	$P_1 = 0.0288.I_{avg}^4 - 0.1958.I_{avg}^3 + 0.1861.I_{avg}^2 + 1.6038.I_{avg} - 1.7$	0.9991
3	TP90L-2	2.2	$P_1 = -0.0095.I_{avg}^4 + 0.154.I_{avg}^3 - 0.9639.I_{avg}^2 + 3.4308.I_{avg} - 3.3212$	0.9987
4	TP100L-2	3.0	$P_1 = -0.0055.I_{avg}^4 + 0.1157.I_{avg}^3 - 0.9064.I_{avg}^2 + 3.8242.I_{avg} - 4.5439$	0.9996
5	TP112M-2	4.0	$P_1 = -0.0033.I_{avg}^4 + 0.0829.I_{avg}^3 - 0.7653.I_{avg}^2 + 3.806.I_{avg} - 5.3504$	0.9994
6	TP132SA-2	5.5	$P_1 = -0.002.I_{avg}^4 + 0.0686.I_{avg}^3 - 0.8423.I_{avg}^2 + 5.1291.I_{avg} - 9.4059$	0.9995
7	TP132SB-2	7.5	$P_1 = -0.0006.I_{avg}^4 + 0.0276.I_{avg}^3 - 0.4533.I_{avg}^2 + 3.8939.I_{avg} - 9.2561$	0.9993
8	TP160MA-2	11.0	$P_1 = -0.0002.I_{avg}^4 + 0.0102.I_{avg}^3 - 0.248.I_{avg}^2 + 3.2711.I_{avg} - 11.065$	0.9998
9	TP160MB-2	15.0	$P_1 = -0.00005.I_{avg}^4 + 0.0045.I_{avg}^3 - 0.1513.I_{avg}^2 + 2.8823.I_{avg} - 13.17$	0.9992
10	TP160L-2	18.5	$P_1 = -0.00003.I_{avg}^4 + 0.0034.I_{avg}^3 - 0.1336.I_{avg}^2 + 2.9375.I_{avg} - 15.704$	0.9997
11	TP112M-4	4.0	$P_1 = -0.0055.I_{avg}^4 + 0.155.I_{avg}^3 - 1.6427.I_{avg}^2 + 8.4069.I_{avg} - 14.679$	0.9999
12	TP132S-4	5.5	$P_1 = -0.0012.I_{avg}^4 + 0.0477.I_{avg}^3 - 0.7199.I_{avg}^2 + 5.5177.I_{avg} - 13.533$	0.9997
13	TP132M-4	7.5	$P_1 = -0.0004.I_{avg}^4 + 0.0196.I_{avg}^3 - 0.3982.I_{avg}^2 + 4.2786.I_{avg} - 13.768$	1
14	TP160M-4	11.0	$P_1 = -0.0002.I_{avg}^4 + 0.0171.I_{avg}^3 - 0.4438.I_{avg}^2 + 5.7516.I_{avg} - 23.639$	0.9997
15	TP160L-4	15.0	$P_1 = -0.00006.I_{avg}^4 + 0.0057.I_{avg}^3 - 0.2086.I_{avg}^2 + 4.0389.I_{avg} - 22.729$	0.9999
16	TP132MA-6	4.0	$P_1 = -0.0081.I_{avg}^4 + 0.2586.I_{avg}^3 - 3.0771.I_{avg}^2 + 16.808.I_{avg} - 32.817$	0.9997
17	TP132MB-6	5.5	$P_1 = -0.0027.I_{avg}^4 + 0.1162.I_{avg}^3 - 1.8683.I_{avg}^2 + 13.88.I_{avg} - 36.24$	0.9994
18	TP160M-6	7.5	$P_1 = -0.0014.I_{avg}^4 + 0.0748.I_{avg}^3 - 1.4788.I_{avg}^2 + 13.492.I_{avg} - 42.903$	0.9995
19	TP160L-6	11.0	$P_1 = -0.0003.I_{avg}^4 + 0.0226.I_{avg}^3 - 0.6633.I_{avg}^2 + 9.199.I_{avg} - 43.003$	0.9998

V. THEORETICAL STUDY

The developed adapted model covers three energy efficiency measures for induction motor drives (Fig. 8).

In the following case alone, none of these measures can be applied:

- lack of technological capabilities for increasing the drive load;
- the existing induction motor of the drive is of energy class IE3;
- the difference between the rated power of the existing motor and the actual mechanical power transferred by its shaft is smaller than the

difference between the rated power of the existing motor and the rated power of the smaller motor frame size available

Measure 3 (see Fig. 8) is the only option available in the presence of the following constraints:

- lack of technological capabilities to increase the load of the induction drive;
- the drive motor is correctly sized and the difference between the rated power of the existing motor and the rated power of the smaller motor frame size available is greater than the difference between the rated power of the existing motor and the actual mechanical shaft power of the existing motor.

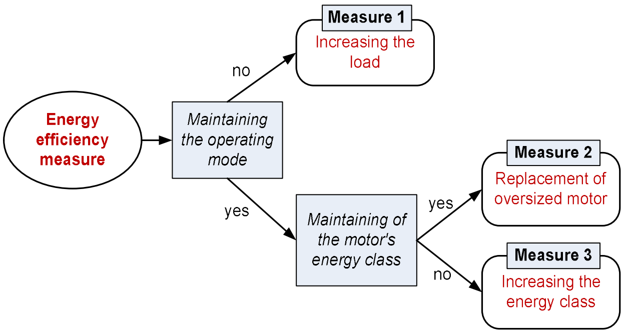


Fig. 8. Classification and conditions for the implementation of energy-efficiency improvement measures for induction motor drives.

Where there are no technological capabilities to increase the load, Measure 2 and Measure 3 are possible under the following conditions:

- the existing induction motor is not of energy class IE3;
- the difference in the rated powers of the existing motor and the nearest smaller motor frame size is greater than the difference between the mechanical power in the actual operating mode of the existing motor and the rated power of the replacement motor.

To allow room for extending the scope of these theoretical studies, they are designed to be conducted in the presence of capabilities to apply all three measures considered, which is achieved under the following conditions:

- practical capabilities exist to optimize (increase) the load;
- the existing engine is of energy class IE1 or IE2;
- existing capability, as described above, to reduce the rated power of the motor while keeping it from the same energy class.

In order to conduct the theoretical studies, a simulation of the developed adapted model was performed in the MATLAB Simulink programming environment. The graphical interpretation of the developed simulation model is shown in Fig. 9.

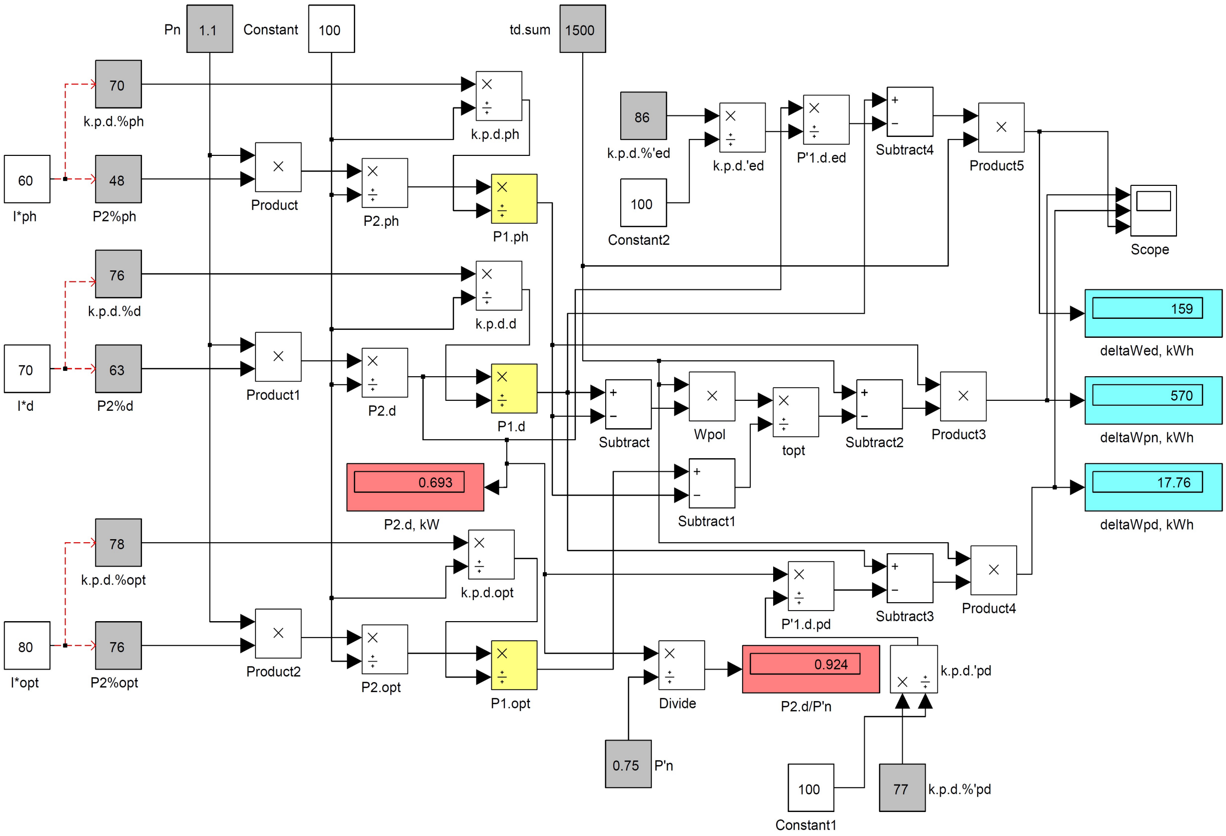


Fig. 9. Simulation computational model for theoretical studies of the energy-saving measures for induction motor drives.

The simulation model was composed of 50 blocks. Of these, three blocks were auxiliary, 14 were used to set constant values, five blocks were intended for visualising calculated values, and one block was for the graphical interpretation of results. The remaining employed blocks were operational. The simulation model algorithm was run three times. After the initial run, the model determined the energy savings from increasing the drive load as well as the shaft load of the existing motor in the actual mode. Based on this load, the rated power of a replacement motor of the same energy class was selected. The simulation was run again, whereby the replacement motor shaft power was visualised in nominal relative units and was used to determine and enter the efficiency of this motor as a percentage value. The efficiency of the higher energy class replacement motor was also entered at this stage. The model was run once again and provided the final results for all energy savings under consideration.

During the multiple runs of the model, the simulation scenario variants presented in Table VIII, Table IX and Table X were adopted. Induction motors of the manufacturer Elrpom Troyan were used. The following notations are used in the tables: I_{*ph} – current at idle mode of the induction motor drive in percentage of the rated current; I_{*d} - current in the actual mode of operation of the induction motor drive as a percentage of the rated current; I_{*opt} - current at increased load of the drive as a percentage value.

Table VIII: Data on a Variant-Based Theoretical Study of an Adapted Model for Increasing the Energy Efficiency of Induction Motor Drives with Synchronous Motor Speed 3000 min^{-1}

Scenario	Existing motor	Replacing motor	I_{*ph} %	I_{*d} %	I_{*opt} %
1	T80B-2, 1.1 kW, IE1	–	60	70	80
		T71C-2, 0.75 kW, IE1			–
		TH80B-2, 1.1 kW, IE2			
1.1		–			100
		T71C-2, 0.75 kW, IE1			–
		TH80B-2, 1.1 kW, IE2			
1.2		–			80
		T71C-2, 0.75 kW, IE1			–
		TP80B-2, 1.1 kW, IE3			
2	T132SB-2, 7.5 kW, IE1	–	60	70	80
		T132SA-2, 5.5 kW, IE1			–
		TH132SB-2, 7.5 kW, IE2			
2.2		–			100
		T132SA-2, 5.5 kW, IE1			–
		TH132SB-2, 7.5 kW, IE2			
2.2		–			80
		T132SA-2, 5.5 kW, IE1			–
		TP132SB-2, 7.5 kW, IE3			
3	T160MA-2, 11 kW, IE1	–	60	70	80
		T132SB-2, 7.5 kW, IE1			–
		TH160MA-2, 11 kW, IE2			
3.1		–			100
		T132SB-2, 7.5 kW, IE1			–
		TH160MA-2, 11 kW, IE2			
3.2		–			80
		T132SB-2, 7.5 kW, IE1			–
		TP160MA-2, 11 kW, IE3			
4	T160L-2, 18.5 kW, IE1	–	60	70	80
		T160MB-2, 15 kW, IE1			–
		TH160L-2, 18.5 kW, IE2			
4.1		–			100
		T160MB-2, 15 kW, IE1			–
		TH160L-2, 18.5 kW, IE2			
4.2		–			80
		T160MB-2, 15 kW, IE1			–
		TP160L-2, 18.5 kW, IE3			
		TP90L-6, 1.1 kW, IE3			

Table IX: Data on a Variant-Based Theoretical Study of an Adapted Model for Increasing the Energy Efficiency of Induction Motor Drives with Synchronous Motor Speed 1500 min-1

Scenario	Existing motor	Replacing motor	I_{*ph} %	I_{*d} %	I_{*opt} %
5	T90S-4, 1.1 kW, IE1	–	60	70	80
		T80B-4, 0.75 kW, IE1			–
		TH90S-4, 1.1 kW, IE2			
5.1		–			100
		T80B-4, 0.75 kW, IE1			–
		TH90S-4, 1.1 kW, IE2			
5.2		–			80
		T80B-4, 0.75 kW, IE1			–
		TP90S-4, 1.1 kW, IE3			
6	T132S-4, 5.5 kW, IE1	–	60	70	80
		T100LC-4, 4 kW, IE1			–
		TH132S-4, 5.5 kW, IE2			
6.1		–			100
		T100LC-4, 4 kW, IE1			–
		TH132S-4, 5.5 kW, IE2			
6.2		–			80
		T100LC-4, 4 kW, IE1			–
		TP132S-4, 5.5 kW, IE3			
7	T132MB-4, 11 kW, IE1	–	60	70	80
		T132M-4, 7.5 kW, IE1			–
		TH160M-4, 11 kW, IE2			
7.1		–			100
		T132M-4, 7.5 kW, IE1			–
		TH160M-4, 11 kW, IE2			
7.2		–			80
		T132M-4, 7.5 kW, IE1			–
		TP160M-4, 11 kW, IE3			
8	T160L-4, 15 kW, IE1	–	60	70	80
		T132MB-4, 11 kW, IE1			–
		TH160L-4, 15 kW, IE2			
8.1		–			100
		T132MB-4, 11 kW, IE1			–
		TH160L-4, 15 kW, IE2			
8.2		–			80
		T132MB-4, 11 kW, IE1			–
		TP160L-4, 15 kW, IE3			

Table X: Data on a Variant-Based Theoretical Study of an Adapted Model for Increasing the Energy Efficiency of Induction Motor Drives with Synchronous Motor Speed 1000 min-1

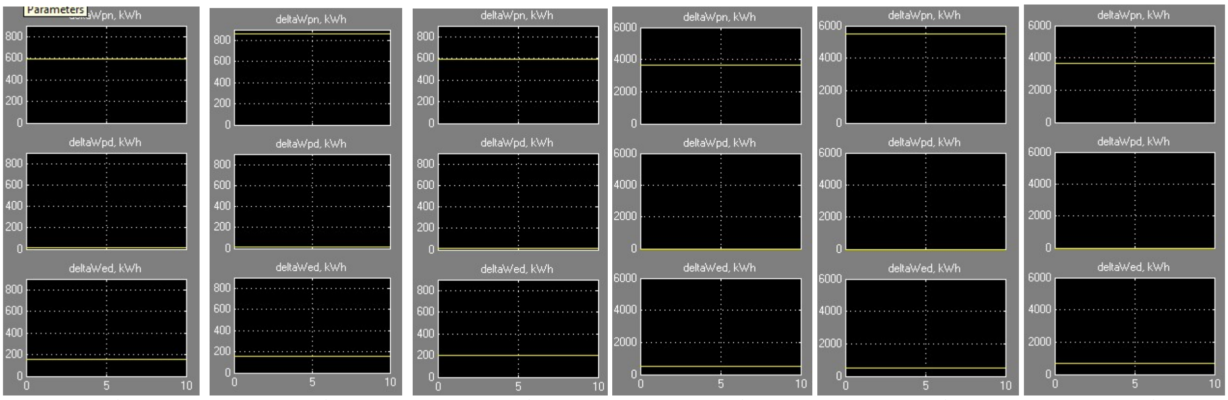
Scenario	Existing motor	Replacing motor	I_{*ph} %	I_{*d} %	I_{*opt} %
9	T90L-6, 1.1 kW, IE1	–	58	60	80
		T71B-6, 0.25 kW, IE1			–
		TH90L-6, 1.1 kW, IE2			
9.1		–			100
		T71B-6, 0.25 kW, IE1			–
		TH90L-6, 1.1 kW, IE2			
9.2		–			80
		T71B-6, 0.25 kW, IE1			–
		TP90L-6, 1.1 kW, IE3			
10	T132MA-6, 4 kW, IE1	–	52	54	80
		T90L-6, 1.1 kW, IE1			–
		TH132MA-6, 4 kW, IE2			
10.1		–			100
		T90L-6, 1.1 kW, IE1			–
		TH132MA-6, 4 kW, IE2			
10.2		–			80
		T90L-6, 1.1 kW, IE1			–
		TP132MA-6, 4 kW, IE3			
11	T160M-6,	–	47	49	80

	7.5 kW, IE1	T100L-6, 1.5 kW, IE1			–
		TH160M-6, 7.5 kW, IE2			
11.1		–			100
		T100L-6, 1.5 kW, IE1			–
		TH160M-6, 7.5 kW, IE2			
11.2		–			80
		T100L-6, 1.5 kW, IE1			–
		TP160M-6, 7.5 kW, IE3			
12	T160L-6, 11 kW, IE1	–	43	45	80
		T112M-6, 2.2 kW, IE1			–
		TH160L-6, 11 kW, IE2			
12.1		–			100
		T112M-6, 2.2 kW, IE1			–
		TH160L-6, 11 kW, IE2			
12.2		–			80
		T112M-6, 2.2 kW, IE1			–
		TP160L-6, 11 kW, IE3			

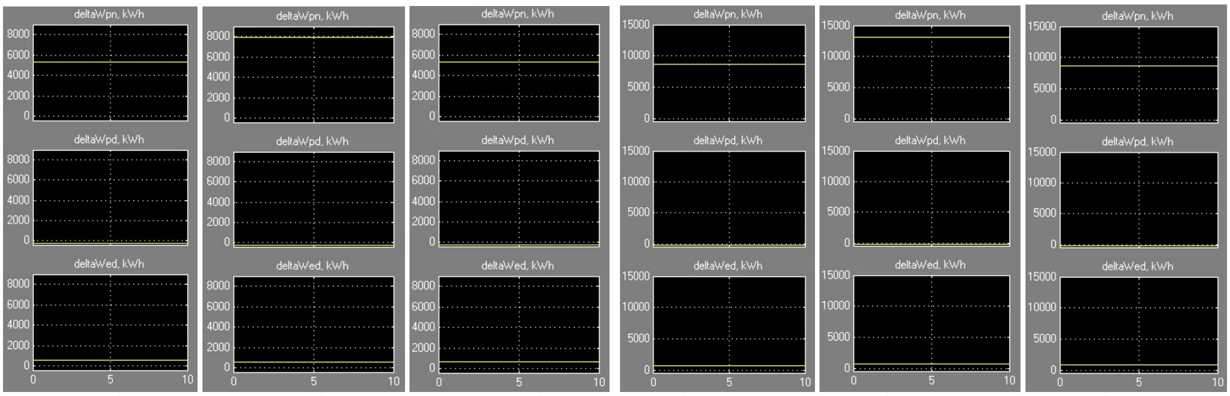
The no-load current levels are considered with regard to the fact that in the most electric drives in the field, the resistive torque of the driven mechanisms is relatively high, and the machine's no-load current is significantly higher than the no-load current of the drive motor. The current at the simulated actual load is 10% higher than that at no-load operation. This level was chosen based on observations [23, 24], showing that production machines operate in operating modes close to the no-load operation, as well as due to the need for a comprehensive demonstration of the energy-saving potential resulting from the increased load. In two of the cases, the optimal level was chosen to be 20% below the rated motor load, considering that technological barriers often limit load increases. In the variant scenarios from Table VIII, the levels of consumed current differ the from typical values in order to avoid negative energy savings when replacing oversized motors. These negative values result from the relatively flat shape of the efficiency curve after 50% load, as well as from the increase in the rated efficiency with the rise in the motor's rated power.

Four motors were covered for each of three typical synchronous rotational speeds. One baseline and two competing variants were defined for each individual motor. The baseline variants took the numbers 1, 2, ⋯, 12, while the competing ones were with numbers 1.1, 1.2, 2.1, 2.2, ⋯, 12.1, 12.2. The first competing variant was set in such a way as to provide conditions for maximum energy savings realized from the increase in the drive load, while with the second competing variant the same conditions were created but this time considering the replacement of the drive motors with higher efficiency ones.

A part of the results obtained from the simulation studies are presented in Fig. 10.



Scenario 1 Scenario 1.1 Scenario 1.2 Scenario 2 Scenario 2.1 Scenario 2.2



Scenario 3 Scenario 3.1 Scenario 3.2 Scenario 4 Scenario 4.1 Scenario 4.2

Fig. 10. Graphical interpretation of the theoretical energy saving levels of induction motor drives.

In the scenarios numbered 9 to 12.2, the simulated drives had motors operating in a near-idle mode. The energy savings were determined for a one-year period.

The presented results show that the energy savings ΔW_{ed} resulting from the use of energy-efficient motors with higher efficiency varied in the range from 8.44 kWh to 911.9 kWh with an average value of 368.8 kWh.

The energy savings ΔW_{pn} from increasing the load on the drive varied in the range from 357.8 kWh to 13150 kWh with an average level of just over 3400 kWh. The saved energy ΔW_{pd} from replacing oversized motors varies from −303.4 kWh to 112.2 kWh with an average saved amount of approximately −75 kWh. The explanation of the negative values comes from the essentially flat motor efficiency curve at motor loads above 40% of the rated load, as well as the structural reduction in the rated efficiency as the rated power of the motor was reduced. Energy savings ΔW_{pd} from replacing oversized motors are generally observed in drives whose motors operate in near-idle modes. Under such conditions, however, the ΔW_{pn} value of change in the saved energy due to an increase in load is less pronounced.

The ΔW_{ed} savings did not increase significantly when the highest energy class motors were used instead of IE2 class motors. A substantial increase was seen in the energy savings ΔW_{pn} when the drive motor load was increased from about 65% to 70% to loads that were close to the rated ones.

The savings from increasing the load of the drives were considerably higher compared to the other two energy efficiency measures considered. The average level of the averaged savings ΔW_{ed} and ΔW_{pd} was 146.9 kWh. It was nearly 24 times less than the arithmetic mean of ΔW_{pn}.

VI. CONCLUSIONS

The selected input/output parameters of the developed model provide adapted practical capabilities for a wide-range application and improvement of the conditions for the implementation of measures to increase the energy efficiency of induction motor drives.

The studies conducted on the appropriateness of the induction-motors energy characteristics, available in the software product Measur, provide grounds to recommend their use for determining the consumed active power through contactless measurement of the consumed current. It is assumed that this approach gives more accurate results for squirrel-cage induction motors when using manual-scale clamp ammeters.

The proposed generalized analytical description and mathematical modelling, together with the conducted extensive systematic theoretical studies via 36 simulation scenarios justify the development of the adapted model for increasing the energy efficiency of induction motor drives through a set of researched, scientifically sound approaches and measures for its improvement.

The adequate regression models built for three series of manufactured induction motors of different energy classes justify and prove the capabilities of modelling their operational mode characteristics in terms of IT support of the proposed adapted theoretical model. The average level of the obtained coefficient of determination is 0.999.

The variant-based theoretical studies presented provide reasons to define recommendations for prioritising the measure of increasing the induction motor drive loads where technological possibilities exist, considering that this measure does not involve any capital investment. On the other hand, generally, there are no limitations to the applicability of the other two energy efficiency measures that have been considered. Due to the substantially higher average energy savings, between the two measures mentioned, a preference should be given to the implementation of energy-efficient motors with higher efficiency. The replacement of oversized motors with ones of the same efficiency class should not be excluded from the energy analysis, because energy savings are observed also in the cases where the drive motors operate in their near-idle mode.

The developed simulation model for theoretical studies demonstrates a generalized computational algorithm that creates the preconditions and a basis for the development of specialized software-based products to automate scientific research and energy audits in the field of energy efficiency of induction motor drives.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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