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Review

Energy Efficiency of Induction Motor Drives: State of the Art, Analysis and Recommendations

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Abstract: Despite activities to introduce low-carbon energy sources worldwide, the share of conventional facilities burning organic fuels remains high. One approach to address this problem is to look for solutions to reduce energy consumption. There are various research projects in the area of energy efficiency that lead to diverse results—such as models, methodologies, new data and theories. On the other hand, induction motor drives are becoming a major consumer of electric power because of their wide range of applications. In this paper, after careful selection and systematization of 151 literature sources, an extensive study and criteria analysis of the existing state of affairs in the area of energy efficiency improvement of induction motor drives has been carried out. Five major and 48 minor research areas in this field have been identified. The results show that issues related to the adaptation of scientific results and the conditions for their effective and wide-ranging application in practice have not been discussed and investigated so far. Adaptation should take into account the possibilities of data acquisition, including data from measurements; the competences of energy managers; and the type of information provided to them. Based on the seven conclusions formulated below, summary recommendations are made to direct future research towards the justification of models for increasing the power efficiency of induction drives, adapted for use by energy managers.

Keywords: electric energy efficiency; induction motor drives; state of the art; research fields; recommendations

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1. Introduction

A number of activities—strategic, political, engineering and other ones—are currently being developed to introduce low-carbon energy sources. Despite the activities worldwide, the proportion of conventional facilities burning organic fuels remains high. This production is inevitably associated with harmful impacts and is characterized by a significant contribution to the observed climate- and environmental changes.

One of the main approaches to address the problem is to look for solutions to reduce energy consumption. Despite systematic efforts in many countries, energy efficiency remains low. In Bulgaria, for example, the Energy Efficiency Act has been in force since 2004. However, a reference to the Eurostat databases for 2019 shows that the energy intensity (units of energy per unit of GDP) of this country is significantly higher in comparison with some other countries. The intensity is 3.32 times higher than the average level for the European Union and 7.78 times higher than the country with the lowest intensity in the Union [1]. These data are revealing. The statistical information is also confirmed by the results of scientific research conducted for specific sites in Bulgaria. In the investigation of some model technological processes, the efficiency coefficient for the electric power consumed by production machines with electric drive is about 30%, decreasing to 1% for some of the machines due to near no-load operating modes [2,3].

Diverse research projects are conducted in the area of energy efficiency. Each project is characterized by its own specificity and involves scientists and specialists with the relevant

profile and competences working on it. Various types of results are obtained—such as models, methodologies, new data and theories.

In this article, based on a systematized literature sources, a study and analysis of the existing situation in the area of increasing the energy efficiency of induction motor drives are conducted and niches and directions for further development are identified.

2. State of the Art

2.1. Systematization of Publications

Using world-renowned databases of specialized scientific literature, 151 up-to-date literature sources were thematically selected in the area of increasing the energy efficiency of induction motor drives and the production machines and units in which they are applied.

It can be seen from Figure 1a that the covered range of literature sources mainly includes articles—54%—and the rest are reports. According to their type of scientometric indicator, 24% of the sources have an Impact Factor (according to Scopus), 32% are published in journals with an SJR rank (source: Scopus) and the remaining 44% do not have a scientometric indicator (Figure 1b). According to the country of the lead author, it is evident that the highest number of literature sources come from India—21.02%—followed by Russia—16.56%—and Bulgaria—6.37%. China comes fourth with 5.10%. The Impact Factor and SJR indexes are adopted for evaluation due to their wide recognition, especially in Bulgaria.

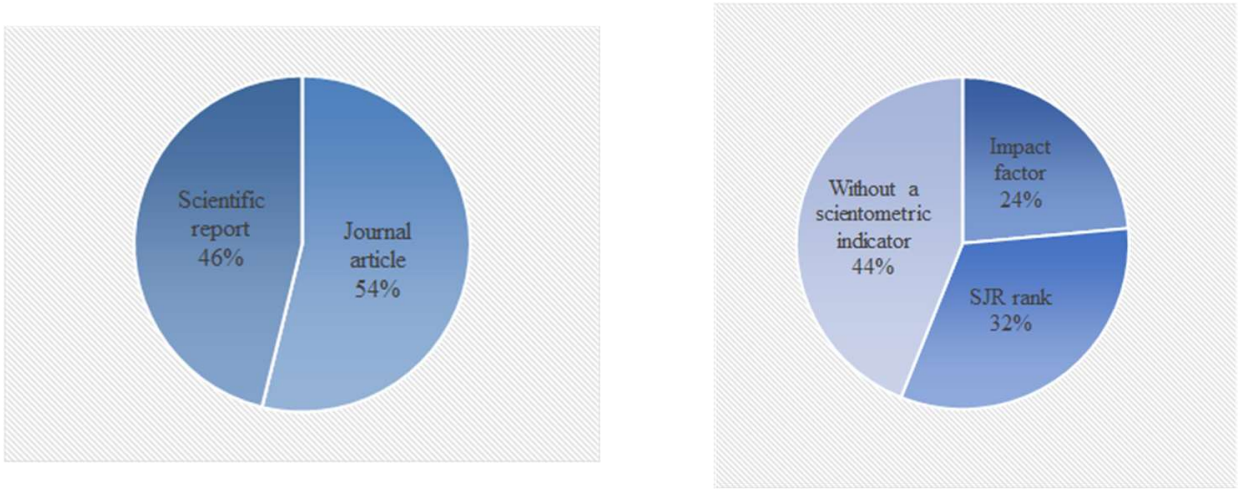


Figure 1. (**a**) Distribution of the range of literature sources covered according to their type; (**b**) distribution of their scientometric indicator (**b**).

A statistical overview by country is presented in Figure 2.

The sources studied are from the period after 2017 and can be tentatively grouped into the following fields of research (Figure 3):

1. Increasing the energy efficiency of the main component of induction motor drives—the induction motor.
2. Improving the components of induction motor drives, e.g., control systems, gears, etc.
3. Achieving energy-efficient operating modes of the drives, especially at highly variable and/or low loads.
4. Improved operational maintenance of electric drives.
5. Achieving energy savings in the drives through improvements in the manufacturing technologies.
6. Other research.

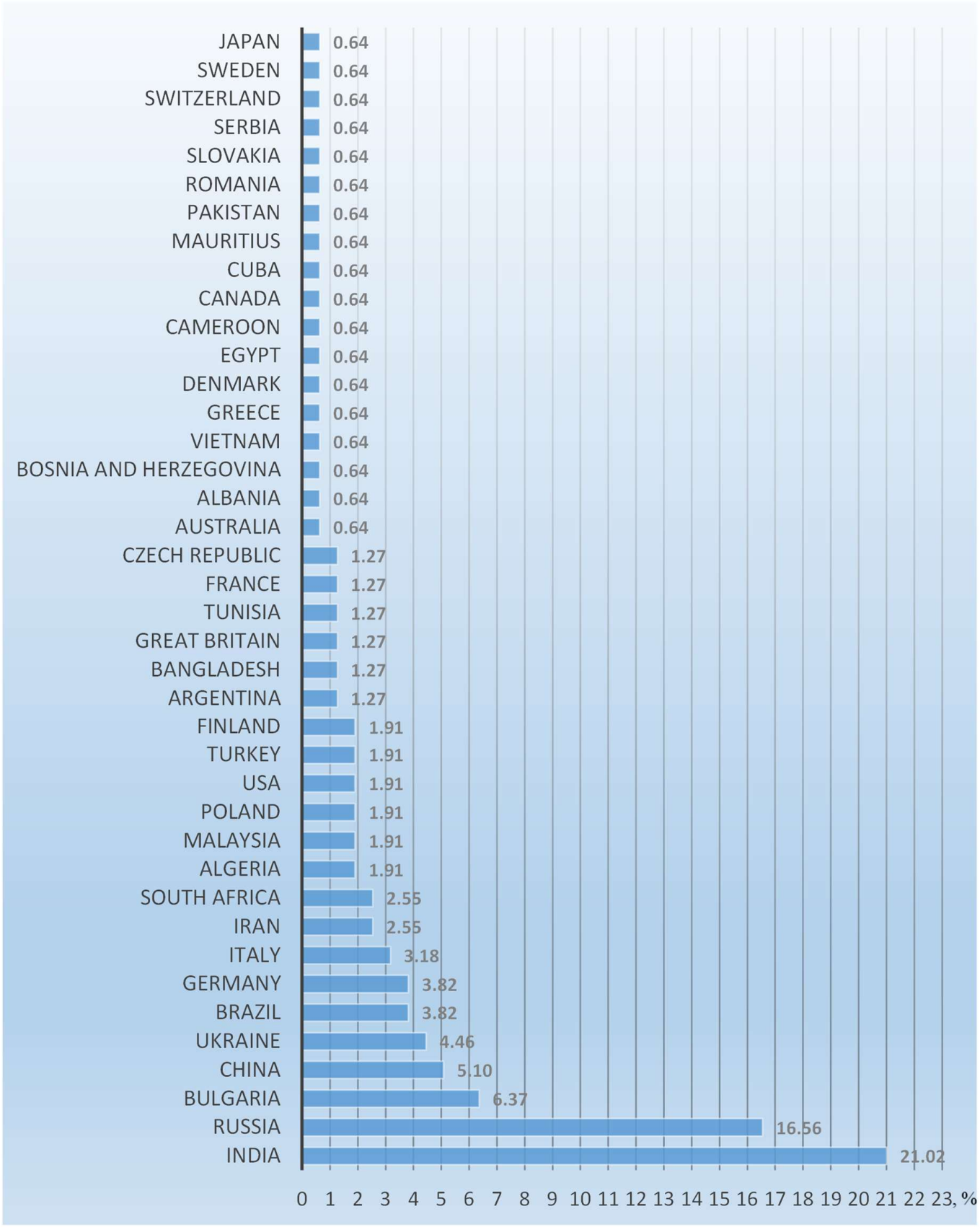


Figure 2. Distribution of the analyzed literature sources according to the lead author's country.

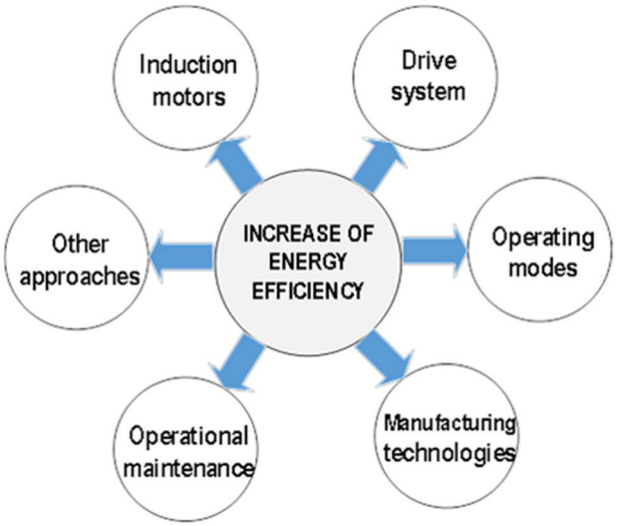


Figure 3. Block diagram of approaches to increase the energy efficiency of induction motor drives.

The distribution of the publications reveals (Figure 4) that those in the area of the application of energy-efficient operating modes hold the largest volume with 39% of the total number. Twenty-two percent of the authors propose improvements to the components of the drives. The third largest volume of the literature sources is taken by papers in the area of the use of energy-efficient induction motors (18%). Improved manufacturing technologies and improved operational maintenance are equal in volume—4%. The remaining 13% of the publications represent various other approaches.

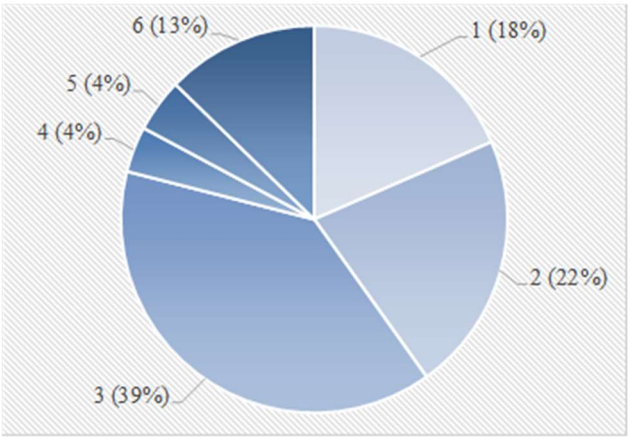


Figure 4. Distribution of literature sources according to the subject area to which they belong: 1—increasing the energy efficiency of induction motors; 2—improving induction motor drives; 3—energy-efficient operating modes of drives; 4—improved operational maintenance; 5—improved manufacturing technologies; 6—other.

2.2. Increasing the Energy Efficiency of Induction Motor Drives

The published data [4] show that about 70% of induction motor drives applied in practice do not need speed control. For these cases, opportunities are mainly sought to improve the power characteristics of the drive motors.

In induction motors, constant and variable losses are observed. The methods for their limitation have been studied and analyzed in the literature, where specific solutions for increasing their energy efficiency are also proposed [5,6]. The reduction in losses leads to the creation of energy-efficient motors, the use of which in manufacturing plants is a recommended practice according to a number of authors [7]. The current trends predetermine the motors in the IE4 and IE5 efficiency classes as being energy-efficient

according to the international standard IEC 60034-30 [8]. It is considered that there are real opportunities for cage-rotor induction motors to be modernized, to increase their efficiency and to upgrade to a higher energy class according to the mentioned standard [9].

To improve energy efficiency in industry, one of the possible methods is to replace IE1 energy class motors with IE3 motors. In [10], the authors propose a methodology that is based on calculating the possibility of energy savings by performing a prior estimation of the savings and identifying some economic opportunities for the replacement of motors with higher-efficiency ones. The method does not evaluate all the motors in the studied facilities but uses the potential energy savings to select the motors for evaluation. As a result, a full economic evaluation of the final solution is provided based on the discounted cash flow methods.

The induction motor replacement approach is also adopted in accordance with energy efficiency legislation in Brazil. Actions have been taken there to replace motors in the chemical industry with higher-efficiency ones. The multi-criteria model has been used according to the "FITradeoff" procedure [11]. In another developing country, India, it has been found that the electric motors used in industry are mainly of the IE1 energy class or lower-efficiency motors, and the need for their replacement is again reported in order to reduce electricity consumption [12]. The same measure to achieve energy efficiency in industry is recommended in a comparative study in 2020 [13]. In it, the authors state assumptions of economic barriers to the deployment of energy-efficient motors given their increased cost. The economic barriers are expected to gradually fall away.

Along with the advantages, certain difficulties in the introduction of energy-efficient motors are described. For example, a 2020 study found that under standard operating conditions, some IE4 energy class induction motors have a lower consumption but, in some cases, behave as non-linear consumers and introduce harmonic disturbances to the power grid [14].

In order to improve the energy efficiency of a cage-rotor induction motor, in [15], a field orientation control simulation was performed. One of the effects is the reduction of power losses. On the other hand, it is found that when the thickness of the laminations making up the stator package of a 0.37 kW three-phase induction motor is reduced, the efficiency increases by 1.4% and the power losses decrease [16]. In another study to improve the performance characteristics of a cage-rotor induction motor, an improved design was developed [17]. In it, a combination of magnets and coils is used for the stator, and the aluminum rotor is replaced by a copper one. Software is used for the simulation. Improvements in the design were also developed with a focus on the magnetic core of the machine. For example, in [18], there is a report of high efficiency achieved even at frequencies lower than the rated one. The improvement was implemented through appropriate analytical modeling and changes in the used materials and in the design of the magnetic cores for the magnetic circuits. The developed design is applied in induction motors operating at different rotational speeds and a wide range of supply voltage frequencies.

A simplified methodology for the optimization of the magnetic flux between the stator and rotor of induction machines is proposed. The methodology allows for energy-efficient control of the machine to be performed in a dynamic mode [19]. The conditions for efficient electromagnetic conversion in the air gap are also significantly affected by the structure and design execution of the stator winding [4]. In this regard, a method for calculating the phase currents and the magnetomotive force for a given stator winding diagram was proposed in 2021. The method was applied for an asymmetrical "12-zone" stator winding, for which an improvement in the operating energy characteristics of the winding was assumed due to the reduction in the levels of the higher harmonics [4]. In another study in the same area, a team of Italian researchers used an open-ended winding configuration as an alternative to drives with constant angular velocity. This approach increases the average efficiency of the induction motor, limits the starting current and compensates for voltage fluctuations, while improving the power factor at the same time [20].

Experimental investigations of an automatic speed control system for an induction motor have been made [21,22], and for this purpose the authors developed a mathematical optimization model. The results show optimized characteristics in terms of the minimum power consumption requirements that have been set.

In addition to the studies reviewed so far, a further seven literature sources were selected and are examined within Section 2.2. A summary systematization of the sources is presented in Tables 1 and 2.

Table 1. Data on systematized research in the area of increasing the energy efficiency of induction motors.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Gavrila H.	Romania	a	SJR 0.334	14
2	de Macedo P.	Brazil	a	IF 10.696	12
3	Tabora J.	Brazil	a	IF 3.252	8
4	Gómez J.	Cuba	a	IF 3.252	7
5	Meshcheryakov V.	Russia	r	SJR 0.237	6
6	Iegorov O.	Ukraine	r	-	5
7	Aarniovuori L.	Finland	r	-	5
8	Foti S.	Italy	r	-	4
9	Dems M.	Poland	a	IF 8.162	4
10	Donolo P.	Argentina	a	SJR 0.33	4
11	Goun V.	Russia	a	SJR 0.346	4
12	Yahya Y.	Malaysia	a	SJR 0.267	3
13	Subramani C.	India	a	IF 2.639	3
14	Khoury G.	France	r	-	2
15	Polnik B.	Poland	a	SJR 0.344	2
16	Hristova M.	Bulgaria	r	-	1
17	Tamboli P.	India	r	-	1
18	Dominic A.	Germany	r	-	1
19	Shukla N.	India	a	SJR 0.803	1
20	Tytyuk V.	Ukraine	r	-	0
21	Hristova M.	Bulgaria	r	-	0
22	Anonymous	Switzerland	b	-	0
23	Agrawal S.	United Kingdom	a	SJR 0.104	0
24	Goun V.	Russia	r	-	0
25	Susdorf V.	Russia	r	-	0
26	Sun X.	China	r	-	0
27	Mao H.	USA	r	-	0
28	Iegorov O.	Ukraine	r	-	0

a—article; r—report; b—brochure.

Table 2. Data on systematized research in the area of increasing the energy efficiency of induction motors (continued).

No.	Subject Area/Core Contribution
1	Trends in energy-efficient induction motors [9]
2	An approach for the replacement of inefficient induction motors [11]
3	Higher harmonics in induction motors [14]
4	A techno-economic evaluation of high-efficiency induction motors [10]
5	Connection diagram of the stator and rotor winding of a wound-rotor induction motor with variable rotational frequency of the rotor [23]
6	Improved stator winding to reduce the degree of field ellipticity in the air gap [24]
7	Analytical determination and separation of the losses of a four-pole cage-rotor induction motor in the IE3 energy class [25]
8	Application of "open end" windings in directly grid-connected constant- speed induction drives [20]

Table 2. *Cont.*

No.	Subject Area/Core Contribution
9	Design improvements of induction motors to increase efficiency when operating at reduced frequencies [18]
10	Difficulties in energy-efficient induction motors [13]
11	Optimization of the parameters of energy-efficient control parameters of an induction motor [21]
12	Influence of the lamination thickness [16]
13	Motor design improvements using software [17]
14	Energy-efficient control and losses in steel [15]
15	Energy recuperation at mining sites [26]
16	Constant losses in induction motors and reduction of these losses [5]
17	Analysis of induction motors in industry [7]
18	Improvement of the rotor magnetic flux of an induction machine [19]
19	A hybrid algorithm for increasing increase the efficiency of induction motors at loads below the rated ones [27]
20	Modeling the magnetomotive force of an induction motor with asymmetrical windings [4]
21	Variable losses in induction motors and reduction of those losses [6]
22	Standards for motor efficiency classes [8]
23	Energy-efficient motors [12]
24	Improvement in the parameters of an induction motor for transient modes [22]
25	Energy-efficient serial control of drives [28]
26	An optimized induction motor with variable number of active poles [29]
27	Dynamic number of poles for energy-efficient induction motors [30]
28	Optimization of winding parameters [31]

2.3. Improvement of Induction Motor Drives

In addition to the main component of induction drives—the electric motor—efforts are also focused on all the other components, namely the control and monitoring systems, electromagnetic transducers, conversion mechanisms, etc.

In [32], a generalized control optimization model for continuous transport systems involving descending belt conveyors is presented. The simulation shows that considerable energy savings can be provided through the use of recuperative drives and speed control. The payback period of the investment is less than 5 years. In [26], justification is provided that the recuperative braking process is one of the significant factors for improving the energy efficiency of drives in the mining industry. In another study from the same year, opportunities to increase the energy efficiency of drives mainly operating in transient states are considered, and an approach to synthesize energy-efficient serial drive control and optimize the rotational frequency is proposed [28].

Particular attention is paid in the literature to control and management systems. In [33], an energy-efficient scalar control of cage-rotor induction motors that takes total losses into account is presented. The method is based on modifying the stator flux in order to track the operating point with the highest efficiency. The results show an improvement in the efficiency of the drive when the flux is optimized, especially in cases of low loads. The approach is applicable in variable-speed drives such as pumps, compressors and fans. In another study, published a year later, the authors point out that the energy efficiency of an induction drive is increased when a programmable logic controller is used, as it helps to automate the operating modes of the system [34]. Hardware and software results are obtained and analyzed and are then presented for the multi-starter control of a single system.

With the help of an adaptive neural network controller, connected in a circuit with direct control of the torque of an induction motor, the energy efficiency, quality and reliability of the electric drive control in an industrial plant are improved [35].

For the improvement of the energy efficiency of induction motor drives, a method using artificial intelligence-based controllers has also been proposed in the literature. These

are tuned using optimum values of the current, obtained via mathematical calculations [36]. Once again in the area of control devices, in [37] an algorithm to minimize the power losses of three-phase high-efficiency induction drives is presented. The algorithm is implemented using a microcontroller and is experimentally tested in the control of a drive of 5.5 kW rated power.

A model of a vibrating centrifugal grain separator with an induction motor was implemented in a MatLab (Simulink) environment [38]. The induction motor is used for vibration transmission, which transmits the motion of the working body without using additional motion transducers. This avoids the control unit for power switching. Stator starting currents are reduced and the system reliability is increased. Using the Simulink tool again, an efficient control algorithm for an induction motor drive of an electromechanical vibration exciter is developed [39]. This algorithm minimizes the effective values of the stator phase currents.

In 2017, a system was designed to monitor the efficiency of an induction motor [40]. The system does not require dismantling of the motor from the drive and no additional connections to the terminal box are used. Both the variable and constant energy losses are taken into account. Efficiency is measured accurately without the need to use a torque meter and primary speed transducer.

A published article analyzes belt drive transmissions that transfer energy from induction motors to various mechanisms and units [41]. This publication states that many organizations recommend the use of toothed- and V-belts instead of smooth belts for the purpose of increasing energy efficiency. The choice of a cross section and length of toothed V-belts depends on the motor power, and the calculations are time consuming. Therefore, the authors of the article developed a table of standard cross sections and belt lengths with the calculated power.

Energy efficiency and safety improvements in coal mining areas can be achieved by using modernized electric drives on the main machines, thereby also reducing maintenance staff [42]. In the garment industry in some developing countries, more than half of the drives prove to be inefficient due to the use of clutches. In order to save electric power, in [43] a more efficient sewing machine with a single-phase drive with a frequency converter is presented.

With the use of pumps, it is possible to improve the energy efficiency of each component of the drive. In [44], the authors indicate the following options to increase the energy efficiency of induction motor drives of pump units: correct selection of the power rating for the induction motor and the pump; pump speed control via a variable speed drive.

In addition to the studies discussed so far, a further 19 literature sources were selected and are examined within Section 2.3. A summary systematization of the sources is presented in Tables 3 and 4.

Table 3. Data on systematized research in the area of upgrading induction motor drives.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Amerise A.	Italy	a	IF 4.079	25
2	Mathaba T.	South Africa	a	IF 3.134	17
3	Kopylov K.	Russia	a	SJR 0.415	16
4	Bruno A.	Italy	a	IF 4.079	5
5	Solodkiy E.	Russia	r	-	5
6	Baykov D.	Russia	a	SJR 0.343	5
7	Khoury G.	France	a	IF 0.808	4
8	Rozhkov V.	Russia	r	-	4
9	Linenko A.	Russia	a	SJR 0.296	3
10	Mamizadeh A.	Turkey	r	-	3
11	Patel P.	India	r	-	3

Table 3. *Cont.*

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
12	Polnik B.	Poland	a	SJR 0.344	2
13	Davydov V.	Russia	r	SJR 0.249	2
14	Sever F.	USA	a	SJR 0.165	1
15	Jung C.	Brazil	a	IF 8.162	1
16	Voytenko V.	Ukraine	r	-	1
17	Mecke R.	Germany	a	SJR 0.148	1
18	Parreiras T.	Brazil	r	-	1
19	Mugalimov G.	Russia	r	-	1
20	Patel P.	India	a	SJR 0.148	1
21	Bhardwaj S.	India	a	IF 1.877	1
22	Susdorf V.	Russia	r	-	0
23	Usha S.	India	a	SJR 0.107	0
24	Shukla N.	India	a	SJR 0.102	0
25	Simakov G.	Russia	r	-	0
26	Khan M.	Bangladesh	r	-	0
27	Spahiu A.	Albania	r	-	0
28	Syed W.	India	r	-	0
29	Haq S.	Bangladesh	r	-	0
30	Dubey M.	India	r	-	0
31	Patel P.	India	a	SJR 0.421	0
32	Verucchi C.	Argentina	r	SJR 0.202	0
33	Mecke R.	Germany	a	SJR 0.148	0
34	Han Z.	China	r	SJR 0.161	0

a—article; r—report.

Table 4. Data on systematized research in the area of upgrading induction motor drives (continued).

No.	Subject Area/Core Contribution
1	Reduction in losses in the auxiliary converter of open-end winding induction motors with dual power supply [45]
2	Efficient operating modes of descending belt conveyors [32]
3	Modernization and automation of drives in a mining plant [42]
4	An online algorithm for minimizing losses through the estimation of the optimum magnetization flux of an induction motor [37]
5	Optimum balancing of a pump unit based on rotational speed and torque [46]
6	Simulation modeling of a “matrix” frequency converter [47]
7	Scalar drive control and losses in steel [33]
8	Improving the energy efficiency of the induction motor drive of a crane via energy recuperation [48]
9	Ways to improve the energy efficiency of a separator [38]
10	An adapted induction motor monitoring system [40]
11	Energy recuperation under deceleration of a torque-controlled induction motor drive [49]
12	Energy recuperation in mining sites [26]
13	Improving the energy efficiency of a drive using a neural network-based controller [35]
14	Improved belt transmissions of drives [41]
15	Adaptive loss control of induction drives [50]
16	Comparative energy analysis of multi-motor induction motor drives [51]
17	Multistage inverters for energy-efficient induction motor drives [52]
18	Improved recuperative braking of induction motor drives in overhead cranes [53]
19	Individual instead of centralized power factor compensation [54]
20	Kinetic energy utilization during braking of industrial induction motor drives by means of two-way converters [55]

Table 4. *Cont.*

No.	Subject Area/Core Contribution
21	Improved transistors for reduction of the harmonic distortions of the inverter and improvement of the efficiency and power factor [56]
22	Energy-efficient serial control of drives [28]
23	Improved start-up mode by means of a programmable logic controller [34]
24	Artificial intelligence controllers for induction motor drives [36]
25	Vibration exciter control algorithm [39]
26	Frequency control for efficiency improvement [43]
27	Reduction of the electricity consumption of a pump unit [44]
28	Filtering of the harmonics and power factor improvement of an induction motor drive with a fuzzy logic controller [57]
29	Selection of an energy-efficient method for pulse-width modulation of a multistage inverter [58]
30	Avoiding DC-DC conversion in the control of an induction motor electric drive for microclimate conditioning via a photovoltaic power source [59]
31	Induction motor drive control unit with inverter recuperative braking capability [60]
32	Efficiency assessment of drives with shaft misalignment and optimum selection of flexible couplings [61]
33	Overview and analysis of frequency converters and energy savings during their use [62]
34	Study on the efficiency of frequency inverters and additional losses in the induction motor from harmonic distortions at nominal frequency of the supply voltage [63]

2.4. Energy-Efficient Operating Modes of Drives

Increasing the utilization of electric power can be achieved by more than design improvements of drives. Even drives with a high level of design perfection can prove to be inefficient when the operating mode is changed. In many cases, a significant change in the operating modes of induction drives occurs during operation. It may be due to process requirements, climatic factors, environmental conditions, etc. The energy-efficient regulation of the performance or the operating mode, respectively, is the subject of targeted efforts. These efforts mainly refer to changes in the angular velocity of the motor, but there is also a fair amount of research in the area of rational load distribution, torque control, improved starting modes, etc. In the literature, particular attention is paid to low-load modes.

Appropriate load is a measure mostly applied to large electric drives with high annual consumption. To reduce energy losses, an energy-saving method of balancing the load of powerful hydraulic presses is proposed in [64]. The method is based on the analysis of the energy flow characteristics, and the results show that the reduction in electric power consumption can reach 36%. The authors specify a configuration of two presses in which the overload energy of the first press can be used as input energy for the second one. It appears that for some process operations the energy efficiency of the drive system is improved. In a study of other facilities with high power consumption, namely pneumatic systems, methods for the evaluation of the power of these systems are presented and an analysis of the power consumption distribution is performed. This lays the basis for the optimization of the operating modes and energy-efficient design process [65].

In some mining sites, drives with a variable rotational speed powered at medium voltage were installed to achieve energy efficiency in the ventilation systems [66]. In addition to speed variation, torque regulation is also applied. A study from 2020 proves that with the help of a thyristor voltage source converter, which has a static regulator and a constant reference speed signal, an energy-efficient mode of operation of an induction motor at torques smaller than the rated values can be achieved [22]. Energy-efficient control is also possible through current regulation. In this regard, simulation models of controls with current control relays were synthesized in 2014.

In order to increase the energy efficiency and improve the performance characteristics of induction motors, a sensorless speed control method was developed, which allows for a

symmetrical and balanced mode of motor operation at all operating points in the rotational speed range [67]. A phase-shift algorithm was developed to implement this method. In the same publication, a first-of-its-kind model for continuous start-up of the motor at very low frequencies is reported. The engine simulation shows positive results in terms of the energy efficiency of the proposed method. For dynamic drives with rapidly changing loads, minimization algorithms based on analytical models are also presented in the literature. In [68], such an algorithm is applied to provide real-time control of the torque and losses in steel. The controller was experimentally tested for a laboratory induction motor drive.

In 2018, a team of five researchers proposed an energy-efficient control of the operating modes of variable-speed induction motor drives for pumps, compressors and fans. The results show that if adjustable flow rate pumps are used, a 60% reduction in the electricity consumption of shipboard equipment can be achieved at reduced vessel speeds [69]. The possibilities for savings through frequency control have also been investigated for ventilation systems [70]. A particular approach in these systems involves adjusting the phase angle of the supply voltage under different load conditions of the induction motor. In this way, a reduction in the electric power consumption is achieved without changing the shaft speed of the fan [71].

Significant savings of electric power at low loads of induction motors can also be achieved with optimum characteristics of the machine magnetic flux. In this regard, the authors propose two methods to determine the optimum flux value, namely loss pattern control and demand control. The Matlab platform [72] is used to verify the results.

In [73], the authors investigate the start-up time of electrically driven industrial machines. For industrial drives, particularly machine tools, attention is also paid to the power factor. In 2021, experimental studies were conducted to evaluate the degree of reactive power compensation of such facilities. The results show that based on a proposed phase-shift compensation method, power losses can be reduced. The reactive power consumption is reduced, and the power factor is increased [74].

In [75], a system for vector speed control of an induction motor is presented, which allows for the minimization of heat losses in the windings and of eddy current losses in the magnet line by increasing the energy efficiency of the motor.

Undoubtedly, in some cases, climatic factors also influence the operating modes. It has been demonstrated that ambient air temperature and the amount of precipitation have a significant influence on the power consumption and energy efficiency of induction drives. In 2020, this dependence was established for the electricity consumption of the drives of water supply systems [76].

In addition to the studies discussed so far, a further 45 literature sources were selected and are studied within Section 2.4. A summary systematization of the sources is presented in Tables 5 and 6.

Table 5. Data on systematized research in the area of energy-efficient operating modes of induction drives.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Dere C.	Turkey	a	IF 11.072	33
2	Li L.	China	a	SJR 2.095	29
3	Zarchi H.	Iran	a	IF 1.737	17
4	Nel A.	South Africa	a	IF 11.072	13
5	Shi Y.	China	a	IF 2.964	10
6	Almani M.	Pakistan	a	IF 3.476	8
7	Ekong U.	Japan	a	SJR 0.589	8
8	Pal A.	India	a	IF 2.639	7
9	Ahmed A.	Egypt	a	IF 4.152	5
10	Djagarov N.	Bulgaria	r	-	5

Table 5. *Cont.*

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
11	Sreejeth M.	India	a	IF 0.939	5
12	Urwashi	India	r	-	5
13	Choudhary P.	India	a	SJR 0.489	4
14	Semenov A.	Russia	r	-	4
15	Frigerio N.	Italy	a	IF 9.498	3
16	Biswal A.	India	r	-	3
17	Ammar A.	Algeria	r	-	3
18	Pugachev A.	Russia	r	-	3
19	Sequeira M.	Australia	a	SJR 0.533	3
20	Tolochko O.	Ukraine	r	-	2
21	Baranidharan M.	India	a	IF 3.252	2
22	Graciola C.	Brazil	a	SJR 0.375	2
23	Balasubramanian G.	India	r	-	2
24	Bizhani H.	Iran	r	-	2
25	Eftekhari S.	Iran	r	SJR 0.329	2
26	Rai K.	India	a	SJR 0.148	2
27	Jeyashanthi J.	India	a	SJR 0.206	2
28	Xiao H.	China	a	IF 3.134	1
29	Seizovic A.	Serbia	r	-	1
30	Abdelati R.	Tunisia	a	IF 1.276	1
31	Nesri M.	Algeria	a	IF 1.630	1
32	Tutaev G.	Russia	a	SJR 0.129	1
33	Jadeja R.	India	a	SJR 0.148	1
34	Ho S.	Vietnam	a	SJR 0.148	1
35	Latchoomun L.	Mauritius	a	SJR 0.148	1
36	Shvartsburg L.	Russia	a	SJR 0.190	0
37	Goun V.	Russia	r	-	0
38	Mosaddegh H.	Iran	a	IF 1.737	0
39	Rachev S.	Bulgaria	r	-	0
40	Krasteva A.	Bulgaria	r	-	0
41	Tchoffo E.	Cameroon	a	IF 3.134	0
42	Lažek T.	Czech Republic	r	-	0
43	Devi M.	India	r	-	0
44	Zhang J.	China	r	-	0
45	Pant K.	India	r	-	0
46	Golsorkhi M.	Denmark	a	IF 2.838	0
47	Inkov Y.	Russia	a	SJR 0.343	0
48	Iegorov O.	Ukraine	r	-	0
49	Behera P.	India	a	SJR 0.148	0
50	Pal A.	India	a	IF 2.112	0
51	Karlovsky P.	Czech Republic	r	-	0
52	Raptis S.	Greece	r	-	0
53	Sharma A.	India	r	-	0
54	Caruso M.	Italy	r	-	0
55	Goh W.	Malaysia	r	-	0
56	Ammar A.	Algeria	r	-	0
57	Gong F.	China	r	-	0
58	Shukla N.	India	a	SJR 0.129	0
59	Bobrov M.	Russia	a	SJR 0.129	0
60	Rai K.	India	a	SJR 0.233	0

a—article; r—report.

Table 6. Data on systematized research in the area of energy-efficient operating modes of induction drives (continued).

No.	Subject Area/Core Contribution
1	Load optimization of pump units [69]
2	Energy saving through balancing the load on hydraulic presses [64]
3	Real-time indirect control method to ensure minimum losses per unit torque [77]
4	Speed control in ventilation systems of medium voltage [66]
5	Evaluation of electricity consumption of pneumatic systems [65]
6	Improved starting and operating modes of induction drives [67]
7	Improvement in the efficiency and mechanical response at high rotational speed of an inverter-controlled induction motor through magnetic field weakening [78]
8	Development of a strategy to increase the energy efficiency of an induction motor drive with sensorless speed control [79]
9	Frequency control for composite pump units [80]
10	A new method for adaptive vector control of an induction motor drive using a modal stabilizer [81]
11	Increasing the efficiency of an induction motor drive through optimization of the stator current and reduction in the rotor magnetic flux [82]
12	Loss minimization through Grey Wolf optimization of vector-controlled induction motor drive [83]
13	Energy-efficient modes of operation of induction motor drives in the cement industry [72]
14	Use of frequency converters in the mining industry [84]
15	Modeling the start-up process of metal-working machinery [73]
16	A developed model of an induction motor finding application in vector control of drives [85]
17	Implementation of a method to increase energy efficiency through slip control [86]
18	Scalar control of an induction motor with loss minimization and consideration of the skin effect and ferromagnetic saturation [87]
19	Variable-speed drive with the ability to measure angular velocity and maintain torque within a preset range [88]
20	Vector speed control and loss minimization in copper and steel [75]
21	Methodology for the rotational speed regulation of pump units in parallel [89]
22	Increasing energy efficiency through scalar control of an induction motor [90]
23	Ventilation system performance regulation via frequency converter [91]
24	Comparative analysis of loss minimization methodologies for vector-controlled induction motors [92]
25	Reducing the parameter correlation of a predictive model for control of the torque and magnetic flux of induction motor drives [93]
26	Comparative assessment of adaptive algorithms for stochastic optimization and loss minimization in steel [94]
27	Using the golden section method to optimize the magnetic flux level in the air gap [95]
28	Adjusting the phase of the supply voltage of a centrifugal fan with constant speed [71]
29	Energy-efficient control of induction motor drives through an iterative optimization algorithm [96]
30	Reducing transient losses of induction motors [97]
31	Minimizing the magnetization energy through a vector-control approach for a system of electric drives [98]
32	Methods for evaluation of control algorithms for inverter-fed induction motor drives [99]
33	Magnetic flux optimization through cyclic neural networks [100]
34	Operating mode control of induction motor drives through online energy efficiency optimization [101]
35	Study of the energy efficiency of induction motors with scalar frequency control following a change in the type of resistive torque [102]
36	Compensation of the reactive power of induction drives of machine tools via phase shifting [74]

Table 6. *Cont.*

No.	Subject Area/Core Contribution
37	Improved induction motor parameters for transients [22]
38	Methodology for online energy efficiency control [68]
39	Increasing the energy efficiency of a ventilation system through frequency control [70]
40	Weather factors and energy efficiency of water supply systems [76]
41	Speed regulation of a mill with induction motor electric drive [103]
42	Algorithms for the magnetic field optimization of an induction motor [104]
43	Sensorless slip monitoring of induction motors [105]
44	Predictive power factor control method [106]
45	Extending the frequency range of a dedicated induction motor drive controller [107]
46	Online energy efficiency optimization and sensorless control of induction motors [108]
47	Loss reduction via modeling the dependence of rotor magnetic flux on stator current [109]
48	Analysis of nonlinear magnetization characteristics of induction motors to improve their operating modes [110]
49	Energy savings and improved power factor (cos φ) through voltage regulators on multi-motor induction drives at low loads [111]
50	Online energy efficiency optimization via a speed controller and quadratic interpolation [112]
51	Optimum stator magnetic flux control [113]
52	Optimized-efficiency predictive controller for induction motor drives [114]
53	Speed control of an induction motor drive through an intelligent adaptive system and neural network [115]
54	Experimental investigation on the efficiency improvement of induction motor drives through real-time loss minimization algorithms [116]
55	Optimum stator magnetic flux for energy-efficient control at low torques [117]
56	Improving energy efficiency through an improved method for sustainable direct torque control [118]
57	Strategy for improved vector control by increasing stability at load drift and reducing the losses of an induction motor drive system [119]
58	Controllers with fuzzy logic and search algorithms to optimize energy efficiency through control of the magnetic flux in the air gap [120]
59	Rotor current frequency effect during control with two frequency converters of a wound-rotor induction motor [121]
60	Loss controller based on golden section search algorithms for optimizing the energy efficiency of induction drives [122]

2.5. Improved Operational Maintenance

The improved operational maintenance of induction motor drives leads to the detection of early signs of failures and facilitates timely troubleshooting actions [123]. It ensures accident-free modes and reduces electric power consumption. It appears that the methods for predictive maintenance, or life cycle assessment of induction motors, respectively, allow for operation under rated loads for longer periods of time [124].

For improvements in the efficiency of electric power consumption, a robust monitoring system was described in the literature to detect faults caused by air gap asymmetry in the induction machine at their earliest stage [125].

In 2019, an action planning algorithm was proposed for the maintenance of induction motors with faults leading to operational losses [126]. The same publication reveals how the monitoring of energy efficiency and motor condition can reduce electric power consumption and carbon dioxide emissions.

In addition to the studies discussed so far, a further two literature sources were selected and are studied within Section 2.5. A summary of the systematization of the sources is presented in Tables 7 and 8.

Table 7. Data on systematized research in the area of improved operational maintenance of induction drives.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Selcuk S.	Bosnia and Herzegovina	a	SJR 0.737	160
2	Singh G.	India	a	IF 7.247	18
3	Li D.	Canada	a	IF 2.964	17
4	Ayyappan G.	India	r	-	7
5	Melnykov V.	Ukraine	r	-	2
6	Mugalimov G.	Russia	r	SJR 0.249	0

a—article; r—report.

Table 8. Data on systematized research in the area of improved operational maintenance of induction drives (continued).

No.	Subject Area/Core Contribution
1	Current trends in the predictive maintenance of drives [123]
2	Reducing consumption through energy-efficiency maintenance and monitoring [126]
3	Improving the energy efficiency of induction motors by diagnosing air gap asymmetry [125]
4	Electrical motor maintenance and service life assessment [124]
5	Scalar control in the event of faults in the windings [127]
6	Improvement in the power factor (cos φ) by rewinding the windings with consideration of the ferroresonance phenomena and the current state of steel during overhaul of induction motors [128]

2.6. Improved Production Technologies

The approaches presented so far are classical ones and require improvements to the drives in terms of their design or mode of operation. In contrast to these approaches, the literature also distinguishes a field where a reduction in electric power consumption while performing the same amount of useful work can be achieved without changes to the drives themselves, but by improving or replacing the manufacturing technology. For example, a 2021 study reported the available opportunities for reducing electric power consumption through the application of developed numerical models describing technological processes of wire drawing. The method is based on the use of the reserves of friction forces that are present during idling [129].

In another research project [130], a model for identifying opportunities to increase the energy efficiency of industrial processes using induction motor electric drives is presented and analyzed. The model performs a simplified mapping of energy flows, thereby extending the scope of actions to achieve energy efficiency. To secure the application of the model, an increase in the number of workers in the enterprises is required.

An investigation was also conducted in the mining industry [131]. It presents a developed algorithm for the efficient consumption of electric drives based on improvements in one of the technological processes. In 2019, an evaluation of cutting processes was performed using a geometric physically based simulation and considering the electric power consumption of the machine tool drive [132]. This provided opportunities to optimize the cutting processes, as well as for cost planning. A year later, the introduction of energy-efficient equipment in oil and gas production was proposed, namely electric submersible plunger pumps. The modernization of the units resulted in significant electricity savings [133]. The replacement of existing technology with more efficient options is the subject of yet another publication [134] in the area of the paper industry. Here, vacuum water pumps turn out to be one of the largest consumers of electric power. The author proposes the use of energy-efficient variable-speed turbo technology for water removal, achieving high performance characteristics and satisfactory energy efficiency of the electric drives used in this way.

In [135], a developed structured algorithm is presented that identifies the state of individual electrically driven machine components (spindle, coolant pump, etc.). The process time and energy consumption are determined. The algorithm produces a corresponding process map from which the opportunities to achieve savings can be identified.

A summary of the systematization of the sources from Section 2.6 is presented in Tables 9 and 10.

Table 9. Data on systematized research in the area of improved manufacturing technologies using induction motor drives.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Svensson A.	Sweden	a	IF 11.072	27
2	Sihag N.	India	r	SJR 0.639	18
3	Karandaev A.	Russia	a	IF 2.899	6
4	Golik V.	Russia	a	SJR 0.211	6
5	Wirtz A.	Germany	r	SJR 0.639	6
6	Uimonen J.	Finland	a	SJR 0.110	1
7	Babanova I.	Russia	r	-	0

a—article; r—report.

Table 10. Data on systematized research in the area of improved manufacturing technologies using induction motor drives (continued).

No.	Subject Area/Core Contribution
1	An analytical model for increasing the energy efficiency of production systems [130]
2	A structured algorithm for identifying the state of a machine tool [135]
3	Digital models for changing machine tool settings [129]
4	Energy saving in the mining industry [131]
5	Evaluation of the electrical consumption of machine tools [132]
6	Modernization and energy savings of a vacuum machine [134]
7	The modernization of induction motor drive units by introducing submersible plunger pumps [133]

2.7. Other Research

In [136], mathematical models in MatLab are developed to estimate the main parameters of electric drives in the technological units of mining enterprises. The parameters—angular velocity, power and torque—are estimated for different operating modes. Based on these models, conclusions can be drawn to improve energy efficiency. In [7], energy management systems, as well as energy-efficient motors, are presented. Solutions for various problems in the manufacturing industry are proposed.

Machine tool drives with heavy-duty operating modes consume significant amounts of electricity and are usually driven by induction motors. In a 2019 study, a generalized consumption model was developed. The model is composed of three levels—defining the system boundaries, considering the total energy consumed and detailing the consumption [137]. Based on this, it is possible to predict the power consumption of physically inaccessible machines.

In 2020, a study was conducted to predict the energy consumption of an electric drive with a frequency converter [138]. The authors state that, on the basis of measurement data and data obtained from a statistical regression model that uses a variable frequency drive to control vibrating screens with an induction motor, they performed a prediction of the energy demand of the system. The study performed will help to reduce power consumption and maintain sustainable production. A publication from the same year discusses design measures for the reduction of the power consumption of machine tools and methods for the efficient operation of these facilities. Opportunities for improvement in energy efficiency in mechanical engineering are analyzed [139].

Induction motors emit significant losses when operating in ranges of low loads. To solve this problem, the use of synchronous reactive machines in these ranges is proposed, which results in good energy efficiency [140].

Papers related to the power efficiency of drives in the areas of electric vehicles, rail transport, energy audits and energy management systems and information technology, including the use of artificial intelligence, etc., can also be found in the literature [141–144].

In addition to the studies reviewed so far, a further five literature sources were selected and are studied within Section 2.7. A summary systematization of the sources is presented in Tables 11 and 12.

Table 11. Data on systematized research in the area of energy efficiency of induction motor drives.

No.	Lead Author	Country	Type	Scientometric Indicator	Citations
1	Manfren M.	United Kingdom	a	IF 8.857	38
2	Denkena B.	Germany	a	IF 4.482	30
3	Shang Z.	China	a	IF 8.857	28
4	Semenov A.	Russia	r	-	15
5	Nagaveni P.	India	a	SJR 0.129	13
6	Stopa M.	Brazil	a	IF 4.079	10
7	Adenuga O.	South Africa	a	-	6
8	Uyulan C.	Turkey	a	SJR 0.588	5
9	Aarniovuori L.	Finland	r	SJR 0.252	3
10	Aazmi M.	Malaysia	r	-	2
11	Abdelati R.	Tunisia	a	SJR 0.480	2
12	Lozanov Y.	Bulgaria	r	-	2
13	Popov A.	Russia	a	SJR 0.343	2
14	Tamboli P.	India	r	-	1
15	Bold S.	Germany	r	-	0
16	Lamb J.	USA	r	-	0
17	Kellner J.	Slovakia	r	-	0

a—article; r—report.

Table 12. Data on systematized research in the area of energy efficiency of induction motor drives (continued).

No.	Subject Area/Core Contribution
1	Information assurance of energy systems [142]
2	Energy-efficient machine tools [139]
3	Energy-saving strategies for high-power machine tools [137]
4	Mathematical modeling and efficiency assessment of electric drives [136]
5	Electric power quality audit [143]
6	A tool for estimating the efficiency of adjustable drives under real operating conditions [145]
7	Predicting the energy efficiency of a vibrating screen [138]
8	Torque control and increased energy recuperation [144]
9	Laboratory determination of the losses of a 75 kW class IE3 induction motor fed by different serial frequency converters [146]
10	Comparative analysis of the frequency converters and energy management systems in induction motor drives [147]
11	Loss minimization algorithm for induction machines during transient torques [148]
12	Determination of the losses in an induction motor drive when changing angular velocity and torque [149]
13	Improved controllers for energy-efficient control of motors under dynamic loads [150]
14	Energy efficiency of electric motors in the manufacturing industry [7]
15	Replacement of induction motor machines [140]
16	Smart energy-efficiency solutions [141]
17	Adaptive control of induction motor drives in emergency modes of operation [151]

3. Summary Analysis

The study of the topics and contents of published papers makes it possible to summarize and group the scientific sub-fields in the area of increasing the energy efficiency of induction motor drives (Figure 5). Depending on the main group, the number of sub-fields varies from five for the main field, associated with manufacturing technology, to fifteen for the field, regarding improved drive components. The highest efforts are focused on improving the operating modes and components of the drives.

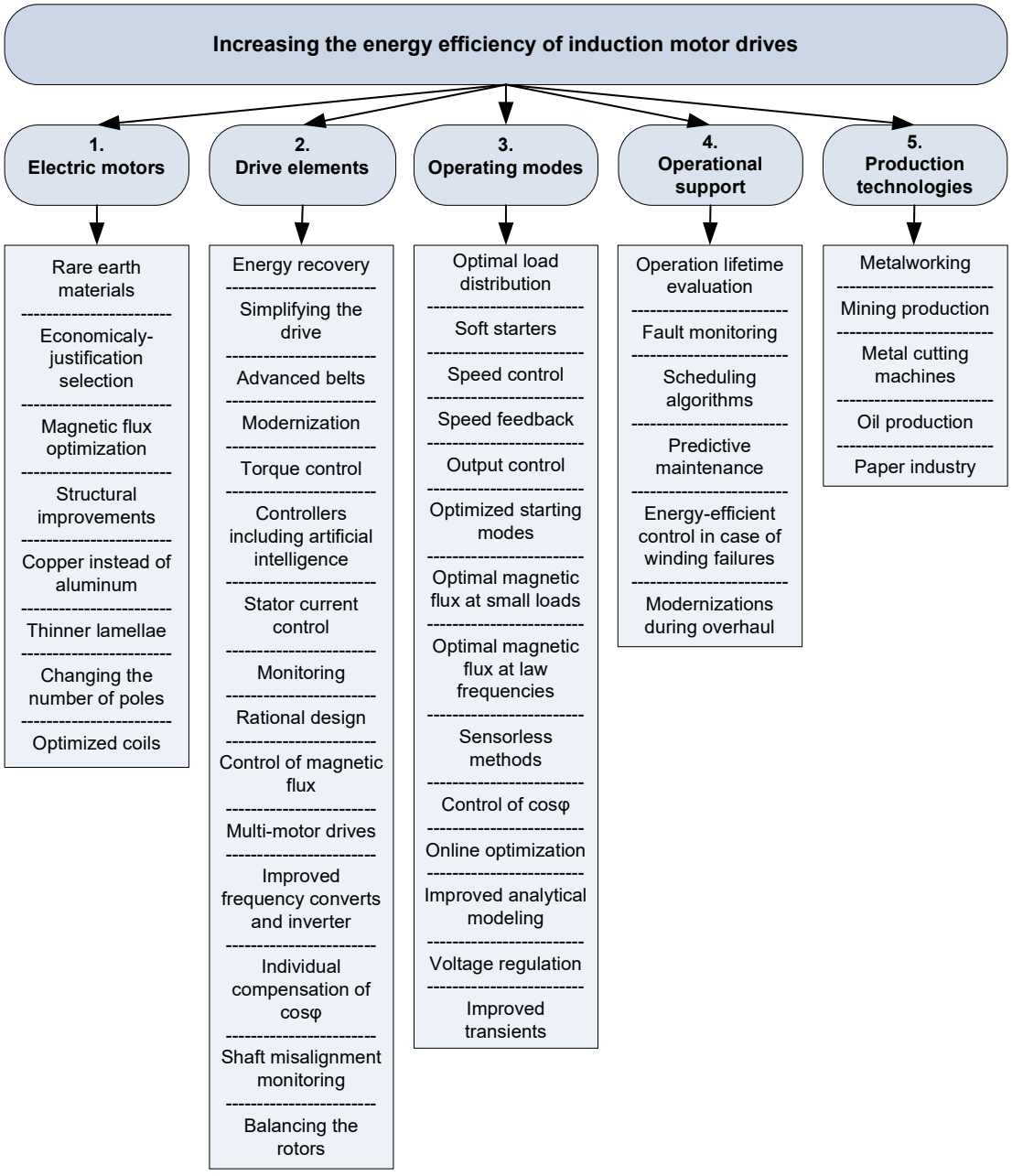


Figure 5. Classification of scientific fields in the area of energy efficiency of induction motor drives.

In order to analyze the research fields, a criteria system is defined. It consists of five criteria presented in Table 13. The criteria are formulated in order to give a wide range of scalar information on the potential, the intensity and the degree of impact of the research fields and subfields. When analyzing the data, the criteria are considered with equal rank.

Table 13. Data on scientific fields in the area of the energy efficiency of induction motor drives.

Scientific Field Number	1	2	3	4	5
Total number of citations in the field	87	102	192	204	64
Total number of publications in the field	28	34	60	6	7
Average number of citations per publication	3.11	3.00	3.20	34.0	9.14
Number of citations of the most cited publication	14	25	33	160	27
Sub-field of the most cited publication	Design improvements	Improved frequency converters and inverters	Optimum load distribution	Predictive maintenance	Metalworking

Table 13 shows summarized data for analyzing the research fields presented so far. It can be observed from the presented data that the highest efforts and significant publication activity have been focused on the main research field regarding the improvement of the operating modes of induction motor drives, mostly by means of rotational speed- and magnetic flux controllers. The main fields that have the greatest impact on the scientific community are once again related to energy-efficient operating modes, but also to the operational maintenance of drives. The most cited publication in the field of "operational maintenance" stands out with 160 citations.

The most relevant scientific sub-fields cover the design improvements of electric motors, the electronic transducers used, the rational load distribution and, especially, the predictive operational maintenance of drives.

4. Conclusions and Recommendations

Based on the conducted study of the selected literature sources, the following main conclusions can be formulated:

1. An inverse correlation between the number of publications in scientific fields and the average number of citations has been identified. Based on this link, and with a view to increasing the research impact, future publications should focus on under-researched areas such as the improvement of operational maintenance and the improvement of manufacturing technologies.
2. Owing to the numerous publications, the scientific sub-field dealing with the improvement of the operating modes of drives through magnetic flux- and rotational speed control systems proves to be sufficiently well-unfolded.
3. Existing research has been performed under controlled laboratory conditions using precise and sophisticated instrumentation, with the results mainly being directed at the scientific community.
4. Issues related to the adaptation of scientific results and the conditions for their effective and wide-ranging application in manufacturing environments are not discussed or investigated in the literature. Other researchers have also identified this conclusion.
5. Due to the diversity and specificity of real-life facilities, science-based instruments should be sought to ensure the implementation of a range of options to improve energy efficiency.
6. Research in the subject area should be expanded in terms of the adapted approaches that create prerequisites for the justified implementation of energy-efficiency improvement measures. This field is relatively under-represented in the literature.
7. The process of adaptation of scientific results should take into account the possibilities of obtaining data, incl. measurement data, the competencies of energy managers and the type of information provided to them.

Taking into account the conclusions of the literature study, a recommendation can be made to direct future research towards the justification of models, properly adapted for energy managers, to increase the energy efficiency of induction motor electric drives and the production machines and units operated by them. These models should include science-based selection and analysis of a set of measures to increase energy efficiency.

The following indicative stages in the justification of the adapted models can be set forth:

1. The selection of parameters, the development of a mathematical description and the conducting of theoretical studies of the adapted model, taking into account the energy characteristics of the drive motors and the conditions for the algorithmization and automation of the experimental studies.
2. Proposing a methodology and description of the facilities subject to study, which will allow one to study the practical applicability and operability of the developed models.
3. Application of the proposed methodologies for typical industrial motor drives and operating modes, providing new data on the facilities under study and the possibility of interpretative analysis.

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