GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

24-25 SEPTEMBER, 2025

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

УНИВЕРЗИТЕТ „ГОЦЕ ДЕЛЧЕВ“, ШТИП
ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

GOCE DELCEV UNIVERSITY, STIP
FACULTY OF ELECTRICAL ENGINEERING

ТРЕТА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
THIRD INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2025

ЗБОРНИК НА ТРУДОВИ
CONFERENCE PROCEEDINGS

24-25 септември 2025 | 24-25 September 2025

ISBN: 978-608-277-128-1
DOI: https://www.doi.org/10.46763/ETIMA2531

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Универзитет „Гоце Делчев”, Штип / Goce Delcev University, Stip
Електротехнички факултет / Faculty of Electrical Engineering

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Пош. фах 201, Штип - 2000, С. Македонија / PO BOX 201, Stip 2000, North Macedonia
E-mail: conf.etf@ugd.edu.mk

CIP - Каталогизација во публикација
Национална и универзитетска библиотека "Св. Климент Охридски", Скопје

62-049.8(062)
004-049.8(062)

МЕЃУНАРОДНА конференција ЕТИМА (3 ; 2025 ; Штип)
Зборник на трудови [Електронски извор] / Трета меѓународна конференција ЕТИМА 2025, 24-25 септември 2025 ; [главен и одговорен уредник Сашо Гелев] = Conference proceedings / Third international conference, 24-25 September 2025 ; [editor in chief Saso Gelev]. - Текст во PDF формат, содржи 357 стр., илустр. - Штип : Универзитет "Гоце Делчев", Електротехнички факултет ; Stip : "Goce Delchev" University, Faculty of Electrical engineering, 2025

Начин на пристапување (URL): https://js.ugd.edu.mk/index.php/etima/en. - Наслов преземен од екранот. - Опис на изворот на ден 30.10.2025. - Трудови на мак. и англ. јазик. - Библиографија кон трудовите

ISBN 978-608-277-128-1

а) Електротехника -- Примена -- Собири б) Машинство -- Примена -- Собири
в) Автоматика -- Примена -- Собири г) Инфоматика -- Примена -- Собири

COBISS.MK-ID 67297029

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24-25 Септември 2025
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PREFACE

The Third International Conference "Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry" (ETIMA'25), organized by the Faculty of Electrical Engineering at the "Goce Delchev" University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA'25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA'25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA'25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA'25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата" (ЕТИМА'25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев" – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА'25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА'25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА'25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА'25 и нејзината научна вредност.

Организационен одбор на конференцијата

СОДРЖИНА / TABLE OF CONTENTS:

Трета меѓународна конференција ЕТИМА
Third International Conference ETIMA
UDC: 621.313.3-027.236
https://www.doi.org/10.46763/ETIMA2531167s

MEASURES AND RECOMMENDATIONS FOR EFFICIENCY IMPROVEMENT OF ELECTRICAL MOTORS

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Abstract

Awareness of the efficient use of electrical energy is becoming increasingly important, both in daily life and in industrial settings. Electric motors, which serve as the primary driving force in various applications, are the largest consumers of electrical energy. Enhancing their efficiency not only reduces electricity consumption and lowers costs but also decreases CO_2 emissions, contributing to a cleaner environment. The strict regulations imposed by the EU on motor manufacturers regarding efficiency classes of electric motors require a thorough evaluation of all design parameters that impact efficiency. Some key factors include the number of conductors per stator slot (slot fill factor), motor length and outer diameter, air gap length, and the replacement of aluminum in the rotor squirrel cage winding with copper, among others. Beyond design, the efficiency of electric motors also depends on operational factors such as loading conditions and cooling. Additionally, for a given application, multiple motor types may meet the drive requirements. For decades, asynchronous squirrel cage motors have dominated industries worldwide. However, the emergence of modern technologies and advanced materials, combined with the growing demand for higher efficiency, has made synchronous motors a viable alternative to traditional asynchronous squirrel cage motors. Synchronous motors can be categorized into several types, including line-start synchronous motors, permanent magnet synchronous motors with surface-mounted magnets, and permanent magnet synchronous motors with embedded magnets. This paper aims to provide recommendations for improving the efficiency of both asynchronous and synchronous motors, considering both design and operational aspects. It provides an overview of the construction details of asynchronous motors and various types of synchronous motors, while also comparing their operating characteristics. Finally, the advantages and drawbacks of each motor type are highlighted, with concluding remarks on their respective fields of application.

Key words

energy efficiency of electrical motors, recommendations efficiency improvement, efficiency classes of electrical motors

Introduction

Electric motors are the largest end-users of electricity. In electrical drives (ED), the majority of electricity consumption is attributed to the motors themselves, while only a small portion is used by auxiliary circuits. To highlight the significance of electric motors in overall electricity usage, several key facts should be noted [1]:

- Electric motors and the systems they power constitute the largest category of electricity end-use, consuming more than twice the amount of electricity used for lighting, which is the second-largest end-use sector.

- Electric motor-driven systems (EMDS) are estimated to account for approximately 43% to 46% of global electricity consumption, resulting in around 6,040 million tones (Mt) of CO_2 emissions.
- By 2030, in the absence of comprehensive and effective energy-efficiency policy measures, energy consumption from electric motors is projected to rise to 13,360 TWh per year, with associated CO_2 emissions reaching approximately 8,570 million tones (Mt) annually. Currently, end-users spend an estimated USD 565 billion per year on electricity for electric motor-driven systems (EMDS); this expenditure could increase to nearly USD 900 billion by 2030.

A clearer understanding of electricity consumption can be achieved by analyzing the distribution of electrical energy use across various sectors.:

Table 1: Electricity consumption by electric motors per sectors [1]:

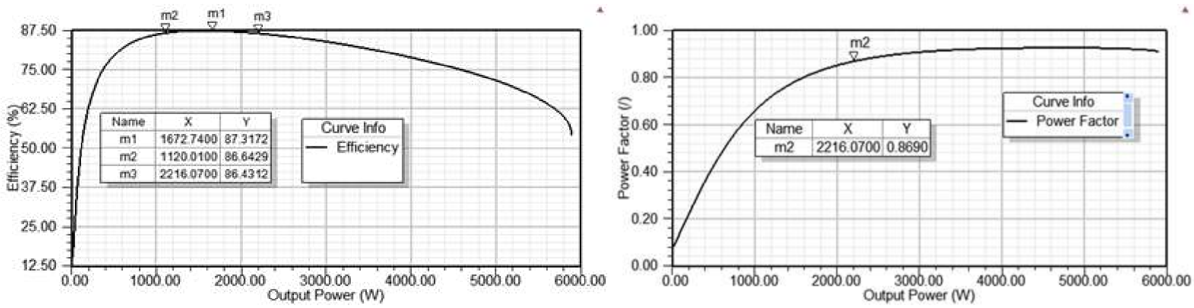
Sector	Electricity consumption	% of all ED electricity	% of sector electricity
Industrial	4.488 TWh/year	64 %	69%
Commercial	1.412 TWh/year	20 %	38%
Residential	948 TWh/year	13 %	22%

Most electric motors are integrated into a wide range of small-scale applications and operate at power levels below 0.75 kW. Predominantly used in the residential and commercial sectors, these motors account for only about 9% of total electricity consumption. In contrast, the majority of electric motors in use fall within the power range of 0.75 kW to 375 kW. This category encompasses a variety of motor designs and technologies; however, alternating current (AC) induction motors are the most widely used and account for the highest share of electricity consumption among all motor types. The third category includes motors with output power exceeding 375 kW. Although these motors are typically custom-designed and not mass-produced, they account for approximately 23% of total electricity consumption attributable to electric motors. Improving motor efficiency is of paramount importance for reducing overall electricity consumption. The energy efficiency of an electric motor is defined as the ratio of mechanical output power to electrical input power:

$$\eta=(P2/P1) * 100\ (\%) \qquad (1)$$

η - electrical efficiency of the motor
P_1-input electrical power
P_2- output mechanical power

The difference between the electrical input power and the mechanical output power represents the motor losses. Reducing the electrical input power directly decreases electricity consumption and contributes to a more efficient motor. The efficiency of an asynchronous (induction) motor—which remains the most widely used motor type in electric motor-driven systems (EMDS)—is not constant across the entire operating range; rather, it varies with the load. A typical efficiency curve for an asynchronous induction motor, illustrated for a 2.2 kW motor, is presented in Fig. 1a [2]



(a) efficiency **(b) power factor**

Fig. 1. Efficiency and power factor for various loads at three phase asynchronous induction motor

Figure 1 demonstrates that motors achieve their highest efficiency near the rated load. Since the electrical input power is the product of current, voltage, and power factor, an increase in power factor reduces the motor's line current and, consequently, the input electrical power and overall electricity consumption. The variation of the power factor with load for the 2.2 kW asynchronous motor is shown in Figure 1b. Losses can occur within the motor itself or in the electromechanical system to which the motor is coupled. A typical system comprises the motor, an electrical control system, a variable-speed drive (VSD), and a mechanical load. In addition to the motor and drive system, motor efficiency is highly influenced by operating conditions such as voltage variations, including under-voltage and over-voltage scenarios [3]–[5]. As reported in [6], deviations from the rated voltage—either increases or decreases—reduce motor efficiency, while the power factor varies inversely with voltage changes. Equally important is the motor's power rating; generally, motors with lower power ratings exhibit lower efficiency compared to higher-power motors [7]. The improvement of electric motor efficiency, specifically through the use of energy-efficient motors, is regulated under European legislation. The Regulation on electric motors and variable speed drives (EU) 2019/1781, which came into effect on 1 July 2021, replaced the earlier Ecodesign Regulation for electric motors (EC) 640/2009. Some aspects of this legislation are discussed in the following section. The subsequent section provides an overview of the most commonly used types of induction motors in electric drives, highlighting their advantages and drawbacks in terms of efficiency, construction, and operational characteristics. The third section offers recommendations for improving motor design and operating conditions to enhance motor efficiency. Finally, the concluding remarks are presented in the last section.

1. Legislative for motor efficiency

According to EU- standard IEC 60034-30-1 all motors are classified into four classes of efficiency:

- Class IE1- Standard efficiency
- Class IE2- High efficiency
- Class IE3- Premium efficiency
- Class IE4- Super premium efficiency

The Regulation on electric motors and variable speed drives (EU) 2019/1781 came into effect on 1 July 2021, replacing the Ecodesign Regulation for electric motors (EC) 640/2009. In 2021, Regulation (EU) 2019/1781 was amended by Commission Regulation (EU) 2021/341, which aims to clarify and improve certain aspects of the Ecodesign regulations adopted in 2019 [8]. Under the current regulation, motors are required to meet the IE2, IE3, or IE4 efficiency levels, depending on their rated power and other characteristics. For example, three-phase motors with rated outputs between 0.75 kW and 1000 kW must achieve at least the IE3 efficiency level by July 2021. Motors with power ratings between 75 kW and 200 kW are required to meet the IE4 level as of July 2023 [8]. An exception applies to immersed motors. For variable speed drives, only two efficiency classes, IE1 and IE2, are specified. Almost for all variable speed drives IE2 class is required. Requirements for eco design of electrical motors are obligatory for all producers of motors in EU and cover motors from two to eight poles, single-phase and three phase, output power of 0.12 kW to 1000 kW, rated voltage from 50 V to 1000 V and that are aimed for direct putting into operation and continuous operation. For example: 4 poles motor 1.5 kW at 50 Hz has [9]:

- IE1 class –efficiency of 77.2 %
- IE2 class- efficiency of 82.8 %
- IE3 class- efficiency of 85.3 %

For larger motors for example 200 kW and frequency 50 Hz

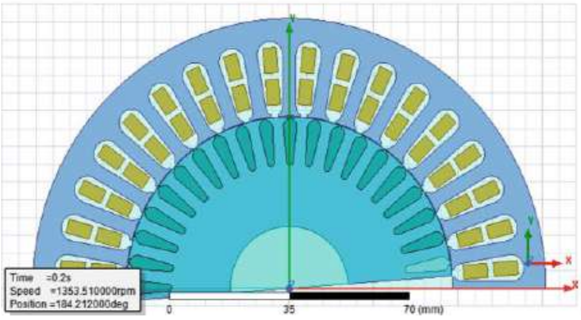
- IE2 efficiency of 95.3 %
- IE3 efficiency of 95.8 %

These strict requirements for achieving specific efficiency classes have introduced new challenges for motor designers. While synchronous motors can readily attain high efficiency classes due to their operating principles, asynchronous motors (AM) demand greater attention to design details. This is because their efficiency is significantly lower than that of synchronous motors, primarily due to the induced current in the rotor winding, which causes electrical losses in the rotor. In contrast, the synchronous motor operates at synchronous speed, with no induced current or associated losses in the rotor. Its operation is further enhanced by the incorporation of permanent magnets embedded within the rotor core, alongside the squirrel cage winding. This configuration is commonly referred to as the line-start synchronous motor (LSSM).

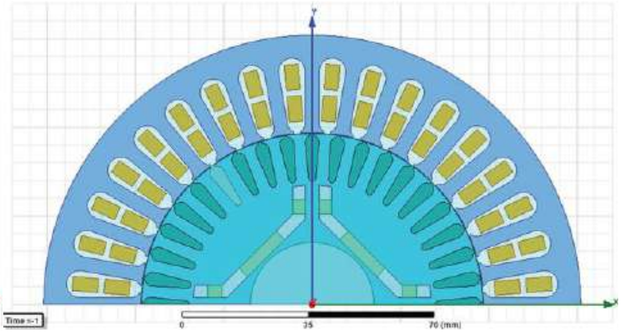
Permanent magnets may be positioned on the rotor surface, a configuration known as the surface permanent magnet motor (SPMM) or embedded within the rotor core in various positions and arrangements, referred to as the synchronous motor with embedded magnets (SMEM). The primary construction features, advantages, and drawbacks of each type, along with their operating characteristics—especially efficiency and power factor—are discussed in the following section.

2. Three phase motors in industrial applications: advantages and drawbacks

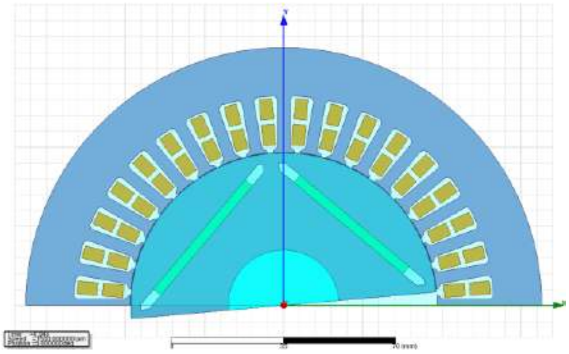
The three-phase asynchronous squirrel cage motor is the most commonly used industrial motor and has dominated industries for several decades. This prevalence is attributed to its simple construction, low production and maintenance costs, and robust design. However, its efficiency and power factor are relatively low, primarily due to its operating principle and design constraints. In addition to copper losses in the rotor that reduce efficiency, manufacturing limitations related to the air gap length contribute to a lower power factor, resulting in higher line current and further efficiency reduction. A smaller air gap improves both efficiency and power factor; however, it also increases air gap harmonics in the magnetic field, leading to higher noise and vibration levels. The speed of an asynchronous motor is not constant across its entire operating range, as it varies with load. Consequently, it is unsuitable for high-precision applications. On the other hand, the motor is self-starting—once connected to the power supply, it begins operation immediately (subject to limitations imposed by the motor and load moment of inertia)—and its speed can be easily controlled using frequency inverters. The high inrush current commonly experienced during direct motor starting can be effectively mitigated using soft starters. A cross-section of the asynchronous motor (AM) is shown in Figure 2a. The advantages and drawbacks of this motor type are summarized in Table 2.



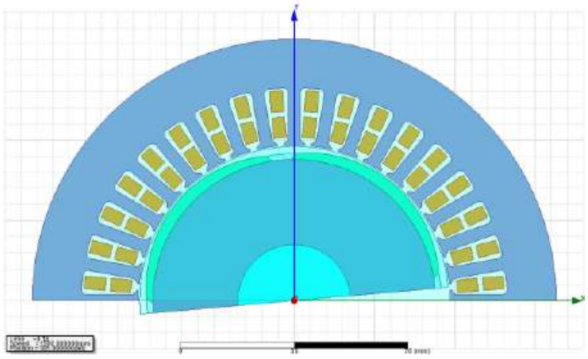
(a) AM



(b) LSSM



(c) SMEM



(d) SPMM

Fig. 2. Coss-section of various types of three -phase motors

Regulations imposed to improve the energy efficiency of electrical motors have introduced new challenges for motor manufacturers. Enhancing the efficiency of three-phase squirrel cage motors often involves additional costs, such as design modifications that require larger motors with increased diameter or axial length, the use of copper instead of aluminum in the rotor squirrel cage winding, or the implementation of high-quality laminations with lower specific losses. Consequently, the three-phase synchronous motor has emerged as a favorable alternative to the asynchronous motor. It readily achieves high efficiencies due to its operating principle, which involves no induced current in the rotor and thus reduces electrical losses. Additionally, the use of permanent magnets enhances the electromagnetic field in the air gap. The power factor of synchronous motors tends toward unity, which is advantageous in industrial settings where reactive power costs can be significant. As mentioned, there are various design alternatives for the three-phase synchronous motor. The line-start synchronous motor offers the benefit of direct starting when connected to the voltage supply. This design eliminates the need for frequency inverters during startup by incorporating a squirrel cage winding that provides starting torque, while permanent magnets embedded in the rotor enable the motor to achieve synchronism. The cross-section of the line-start synchronous motor (LSSM) is shown in Figure 2b. The advantages and drawbacks of this motor type are summarized in Table 2. Synchronous motors without squirrel cage windings can have various configurations depending on the magnet placement. Magnets may be embedded within the rotor, as illustrated in Figure 2c, or mounted on the rotor surface, as shown in Figure 2d. Both configurations lack a squirrel cage winding and, therefore, are not self-starting; frequency inverters are required for motor startup, which adds to the overall application cost. The surface permanent magnet motor (SPMM) exhibits equal inductances along the d- and q-axes. Its construction is simple and cost-effective, as the magnets can be affixed directly to the rotor surface. SPMMs are commonly employed in high-speed applications due to their extended flux-weakening capability. Consequently, bandage is often applied around the magnets to secure them, preventing detachment from the rotor at elevated speeds. For a given power rating and machine size, surface permanent magnet motors (SPMM) require a smaller quantity of permanent magnet material compared to motors with embedded magnets. However, SPMMs are more susceptible to magnet demagnetization, particularly when thin magnets are employed. Synchronous motors with embedded magnets (SMEM) utilize a greater amount of permanent magnet material but benefit from higher air-gap flux density, resulting in increased torque per unit rotor volume compared to surface magnet motors. The risk of demagnetization is lower in SMEMs. Additionally, the q-axis inductance exceeds that of the d-axis. These motors are commonly applied in electric mobility applications. A comprehensive comparison and overview of synchronous motors with surface and embedded magnets is provided in [10]. Cross-sectional views of both motor types are shown in Figures 2c and 2d, while their respective advantages and disadvantages are summarized in Table 2.

Table 2: Advantages and drawbacks of various types of motors

	Asynchronous squirrel cage motor (AM)	Line-start synchronous motor (LSSM)	Surface permanent magnet motor (SPMM)	Synchronous motor with embedded magnets (SMEM)
Advantages	Simple design Low production costs Reliable Robust Easy maintenance	High efficiency High power factor Easy maintenance Reliable Robust Self-starting	High efficiency High power factor Simple construction Constant speed Smaller dimensions than AM for the same power rating	High efficiency High power factor Constant speed Lower risk of demagnetization Smaller dimensions than AM for the same power rating
Drawbacks	Higher classes of efficiency are difficult for achieving and require extra costs Lower power factor Speed varies with the load	Increased costs due to magnets and rotor laminations	Risk of demagnetization of magnets Extra bandage is required at rotor for higher speeds Frequency converter is required for motor starting Costs due to magnet usage Thin magnets increase the risk of demagnetization Cogging torque	More complicated construction due to rotor laminations stamping Frequency converter is needed for starting Cogging torque

Table 3 presents typical operating characteristics for a 2.2 kW asynchronous motor that has been redesigned into a line-start synchronous motor, a synchronous motor with surface-mounted magnets, and a synchronous motor with embedded magnets. The comparison is conducted under the condition of unchanged external motor dimensions.

Table 3: Comparison of operating characteristics of 2.2 kW motors: synchronous and asynchronous

	AM	LSSM	SPMM	SMEM
Output power (kW)	2.2	2.2	2.2	2.2
Rated speed (rpm)	1346	1500	1500	1500
Rated torque (Nm)	15.6	14	14	14
Rated current (A)	4.9	3.7	3.56	4.96
Efficiency (%)	78.8	94.9	93.7	91
Power factor (/)	0.85	0.94	0.996	0.99

3. Measure and recommendations for efficiency improvement

Several factors can influence motor efficiency. These may arise from the motor's design, operating conditions, characteristics of the power supply network, or maintenance practices. Each of these factors will be analyzed, accompanied by recommendations for improving motor efficiency. From a design perspective, motor losses are generally categorized into two main groups: fixed losses and variable losses. Fixed losses include core losses as well as friction and windage losses, while variable losses comprise copper losses and stray load losses. Stray load losses, which vary with the square of the load current, are primarily caused by leakage flux. These losses generally account for approximately 4% to 5% of the total motor losses. However, IEEE Standard 112 specifies typical values in the range of 0.9% to 1.8%, as shown in Table 4.

Table 4: Motor rating and stray load losses

Motor power (kW)	Stray losses
0.75-92	1.8 %
93-373	1.5 %
374-1864	1.2 %
Above 1864	0.9 %

Friction and windage losses are classified as mechanical losses, arising from friction within the rotating components of the motor. According to IEEE standards, these losses are typically estimated at approximately 1% of the output power for a 3.7 kW motor [11]. Core losses, also referred to as magnetic losses, depend on several factors including the type of magnetic material used and its specific losses per kilogram, the geometry of the magnetic core, and the applied input voltage. Core losses consist of hysteresis losses and eddy current losses. Copper losses are classified as variable losses, as they depend on the temperature-dependent resistance of the stator and rotor windings, as well as on the square of the load current, which varies with the load. It is important to note that both efficiency and power factor significantly decrease at low load conditions. Therefore, it is essential to operate the motor under appropriate loading conditions, ensuring that the motor's power rating closely matches the required load torque. The majority of total motor losses typically occur in the rotor. In the following section, key strategies and recommendations for improving motor efficiency will be outlined from the following perspectives:

- Constructional aspects
- Operational conditions
- Power supply characteristics
- Maintenance practices

3.1 Measures and recommendations for efficiency improvements from a constructional perspective

Iron core losses are categorized as fixed losses. The use of thinner steel laminations effectively reduces eddy current losses, while high-grade steel laminations with low specific losses (W/kg) can significantly decrease the total iron core losses. Furthermore, the precise determination of motor dimensions is critical in minimizing these losses. In asynchronous squirrel cage motors, increasing the axial length and the stator's outer diameter improves efficiency by lowering the magnetic flux density, thereby reducing operational losses.
Stator copper losses can be reduced by increasing the slot fill factor, i.e., by raising the number of conductors per slot or the number of turns in the stator winding. Additionally, using conductors with a larger cross-sectional area lowers the winding resistance, thereby reducing copper losses. Since stator copper losses are proportional to the square of the load current, decreasing the line current can significantly diminish these losses. An increase in the power factor leads to a reduction in line current. In asynchronous motors, this can be achieved by decreasing the air gap length. However, beyond manufacturing limitations, an excessively small air gap may introduce higher-order harmonics in the air gap magnetic field, resulting in increased motor vibrations and acoustic noise. Moreover, a reduced air gap can compromise the motor's overload capability. Therefore, it is essential to evaluate the load characteristics prior to installing an energy-efficient motor.
Rotor copper losses can be reduced by using conductors with larger cross-sectional areas, which decrease the resistance of the rotor winding. However, achieving higher efficiency classes for asynchronous motors (IE3 and IE4) is challenging; therefore, replacing aluminum conductors with copper is a viable option. While this substitution reduces rotor winding resistance and associated losses, it also leads to increased manufacturing costs.
The use of high-quality bearings and regular lubrication can reduce friction and windage losses. Additionally, implementing a low-loss fan design can further minimize losses associated with air movement.

3.2. Operational Measures and Recommendations for Improving Efficiency

Monitoring and proper matching of all components within the electric drive system are essential for improving the overall efficiency of the complete drive. In recent years, electric motors have increasingly been integrated with various electronic devices that enhance different aspects of motor operation, such as starting and variable-speed control. For constant-speed applications, motor starters offer a cost-effective and energy-efficient solution. Common types of starters include direct-on-line (DOL) starters using contactors, star-delta starters, and soft starters. The primary objective of using motor starting devices is to limit the inrush current and reduce energy consumption during the start-up phase. This topic has been extensively examined in the literature, with several technical studies addressing methods for limiting the starting current not only in asynchronous squirrel cage motors but also in synchronous reluctance motors equipped with squirrel cages [12], [13]. The star-delta starter limits the motor’s starting torque to approximately one-third of its rated torque, making it unsuitable for heavy-duty starting applications. In contrast, a soft starter—an electronic circuit typically composed of a triac or a pair of thyristors—gradually increases the voltage supplied to the motor, enabling a smooth ramp-up of the starting current. The voltage continues to rise progressively until it reaches the nominal operating level. The duration of current flow can be controlled by adjusting the relevant parameters set by the user. For variable-speed applications or scenarios requiring speed reduction, frequency inverters provide an energy-efficient solution by electronically matching the supply frequency to the desired operating speed. This approach is more efficient than mechanical speed reduction methods, such as gearboxes. Moreover, variable-speed drives equipped with frequency inverters offer enhanced control, along with reduced noise, transient effects, and vibrations. An additional factor influencing energy efficiency in motor operation is the practice of switching off the motor when it is not in use. However, frequent switching may cause premature wear or operational issues. Equally important is selecting a motor with power and torque ratings that match the application requirements. Motors generally achieve optimal efficiency within 60–100% of their rated load. Efficiency declines rapidly when operating below 60% load; therefore, oversizing a motor does not ensure efficient performance. On the contrary, operating significantly below the rated load can lead to substantial reductions in efficiency (see Fig. 3).

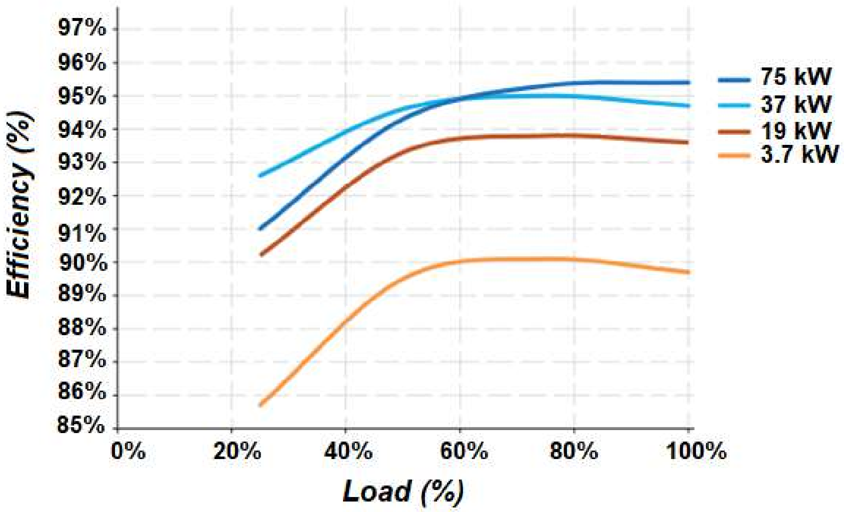


Fig. 3. Variation of efficiency with the load

A common practice in applications with variable loads is to select a motor based on the maximum anticipated load. Consequently, the motor operates at full load only briefly, spending most of the time underloaded and thus operating at reduced efficiency. An energy-efficient alternative is to install a motor with a rating slightly below the anticipated peak load, allowing the motor to operate at overload for short durations while maintaining higher efficiency during typical operating conditions. It is important to note that the motor's overload capacity must be verified prior to installation in the aforementioned application. To reduce mechanical losses, high-quality bearings should be employed, and precise tuning of all rotating components is necessary. Additionally, maintaining lower operating temperatures is critical, as elevated temperatures accelerate insulation degradation and consequently shorten the motor's operational lifespan.

3.3 Factors Affecting Efficiency from the Power Supply Network

The motor efficiency and overall operation is greatly affected by the quality of the input voltage and frequency. Standard IEC 60034-1 defined the voltage and frequency limits for operation of motors or how the variations of voltage and frequency affect the motor operation and temperature rise. The limits of voltage and frequency variations as per standard IEC 60034-1 are given in Fig.4. According to Fig. 4 when power supply variations are within the Zone A, the motors must be capable of performing continuously but they should not be fully compliant with the performance at rated power supply and there might be some deviations in motor operation. The temperature rise may also be higher than at rated supply.

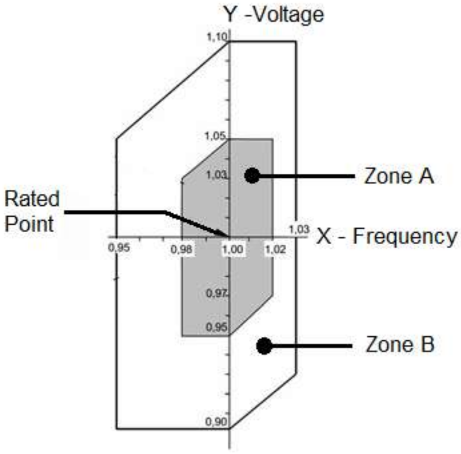


Fig. 4. Voltage and frequency variations (standard IEC 60034-1)

Higher temperature rise is expected in Zone B. Prolongated operation of the motor within the zone B may shorten the life of the motor. To provide the rated power supply conditions at motor terminals following measures should be undertaken: load end power factor improvement by providing the matching capacitor, minimizing the cable lengths and voltage drops, usage of transformer tap changer in case of permanent low voltage situations. The effect of the variations of the voltage on motor efficiency is presented in Fig. 5 whereas an example is used 2.2 kW asynchronous motor 1460 rpm, 4.4 A, efficiency at full load 87.6 %, power factor 0.86. Supply voltage is chosen to be varied from 323 V to 437 V, assuming that the rated voltage is 380 V. The variation of voltage covers the range of -15% to +15 % of the rated voltage, with the increase or decrease of the voltage in all three-phase simultaneously.

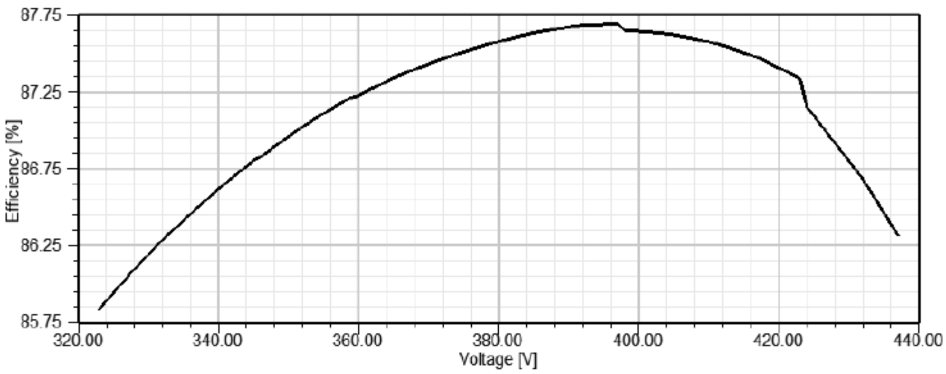


Fig. 5. Variation of efficiency with variation of the supply voltage

As it can be seen from Fig. 5 the under or over voltage decrease the motor efficiency. Around the rated voltage motor has the highest efficiency. Another factor that affects the motor efficiency is the voltage asymmetry. There are several definitions of voltage unbalance. According to NEMA (NEMA (National Equipment Manufacturer's Association) unbalanced voltage is defined as the line voltage unbalance rate (LVUR) given by:

$$LUVR(\%)=\{Max[|V_{ab}-V_{avg}|,|V_{bc}-V_{avg}|,|V_{ca}-V_{avg}|] / V_{avg}\} \cdot 100 \quad (1)$$

The maximal deviation of all three line voltages from the average voltage is used in calculations according to Eq. (1). V_{ab}, V_{bc} and V_{ac} are the line voltages and V_{avg} is the average value of all three-line voltages defined as:

$$V_{avg}=(V_{ab}+V_{bc}+V_{ca}) / 3 \quad (2)$$

There can be several reasons for voltage unbalance. It can be caused by unevenly connected single phase loads within three phases, burn out fuse on one phase or large single-phase loads connected to one phase creating a significant voltage drop. The impact of voltage unbalance on motor operation is evidenced by unequal currents in the three phases; for example, one phase may carry less than the rated current while the other two phases experience increased currents relative to their rated values. Furthermore, voltage unbalance leads to a significant rise in motor temperature. To mitigate voltage unbalance, single-phase loads should be evenly distributed across all three phases, and any loads that disrupt this balance should be supplied from a separate transformer. Voltage unbalance also adversely affects motor efficiency. Under conditions of voltage unbalance, the motor should be derated, meaning it must operate below its rated load. Figure 6 illustrates the relationship between motor derating and voltage asymmetry. As a result of derating, the motor operates at a reduced load, which consequently leads to decreased efficiency.

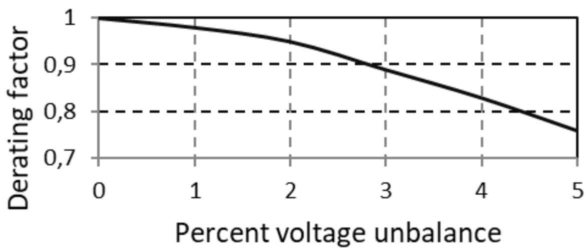


Fig. 6. Derating of the motor in correlation to voltage unbalance

Asynchronous induction motors exhibit a low power factor, which increases the demand for reactive power from the supply network. To improve the power factor, capacitors are typically connected in parallel (shunted) with the motor. Power factor correction reduces copper losses in the upstream cables, decreases voltage drops, and enhances the overall system efficiency. The capacitors improve the power factor from the point of installation upstream toward the power generation source. The size of capacitor required for a particular motor depends upon the no-load reactive kVA (kVAR) drawn by the motor, which can be determined only from no-load testing of the motor. In general, the capacitor is then selected to not exceed 90 % of the no-load kVAR of the motor [14].

3.4 Impact of maintenance on motor efficiency

Proper and timely maintenance has a significant impact on motor performance and efficiency. Inadequate lubrication can lead to increased mechanical losses in the motor and associated components. Additionally, maintaining an optimal operating temperature is critical; thus, adequate ventilation must be ensured, and all cooling ducts should be regularly inspected and cleaned. This facilitates adequate dissipation of excess heat, helping to maintain the motor's operating temperature within the insulation's specified limits. Regular maintenance activities—such as inspection of bearings and ventilation ducts—are recommended to reduce friction losses and prevent temperature increases. Additionally, motor loading should be regularly monitored; it is advisable to operate the motor close to its rated load, avoiding both underloading and overloading conditions. Over-lubrication poses a risk of grease seeping from the bearings into the motor windings, potentially saturating the insulation and causing motor malfunction. To minimize mechanical losses, proper alignment between the motor and the driven equipment is also essential. Another important aspect of motor maintenance is the rewinding of burned-out motors, a common practice in various industries. However, rewinding can lead to a reduction in motor efficiency due to factors such as changes in winding and slot design, the quality of winding materials, and insulation performance. Applying heat to remove the insulation from the old winding can damage the insulation between the laminations, leading to increased eddy current losses. A recommended practice is to measure the stator winding resistance and no-load losses both before and after rewinding. These measurements can assist in estimating the motor's efficiency following the rewinding process.

4. Conclusion

This paper aims to examine multiple facets of motor efficiency by reviewing the latest regulations and offering insights into their proper interpretation and application. Numerous global analyses have demonstrated that even marginal improvements in motor efficiency can yield significant electricity savings, given the widespread use and often inefficient operation of electric motors. Efficiency gains can be realized during the motor design phase through various modifications—particularly for asynchronous motors—such as increasing motor dimensions, utilizing greater amounts of copper, or employing higher-quality laminations with reduced losses. However, these enhancements typically lead to increased manufacturing costs. In addition, motor efficiency is influenced by operational practices, power supply conditions, and maintenance procedures. By addressing each of these factors and providing practical recommendations, this paper offers a comprehensive overview of motor efficiency. It aims to serve as a valuable guideline for electrical engineers throughout the entire motor lifecycle—from selecting the appropriate motor to ensuring its proper operation and maintenance. The adoption of energy-efficient motors often entails higher initial investment costs, particularly when replacing older motors. However, the payback period for this investment is generally short, especially for motors with extended operating hours. Moreover, additional economic benefits arise from reduced electricity consumption, which leads to lower energy bills. The paper aims to emphasize the importance of energy efficiency beyond the well-known domain of illumination, highlighting efficiency in electrical drives, which constitute the largest consumers of electricity. Improving efficiency in these drives can substantially contribute to electricity savings and the reduction of carbon emissions.

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